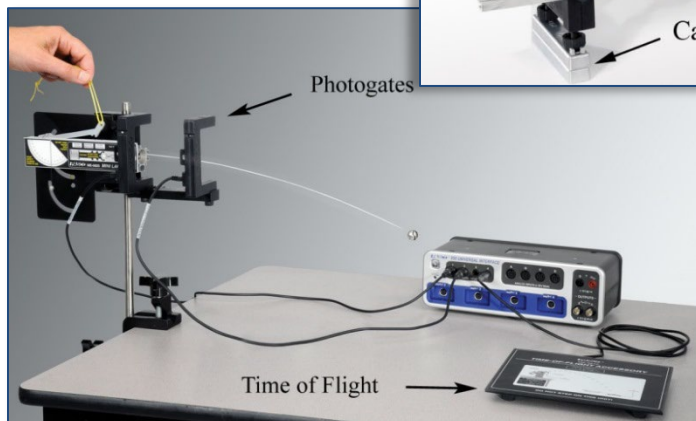
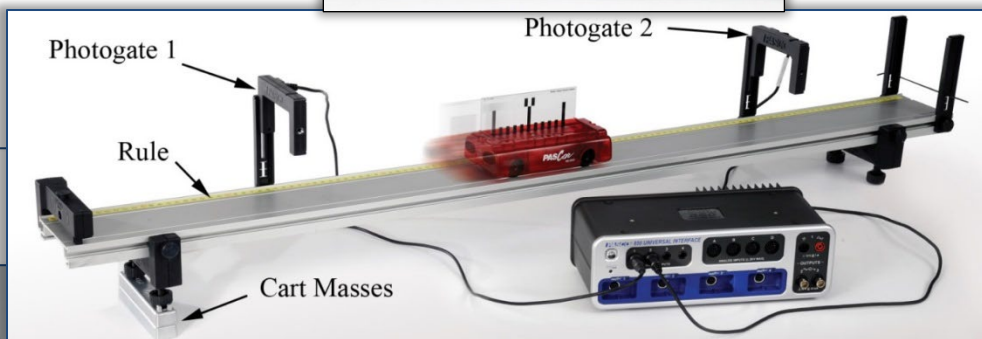
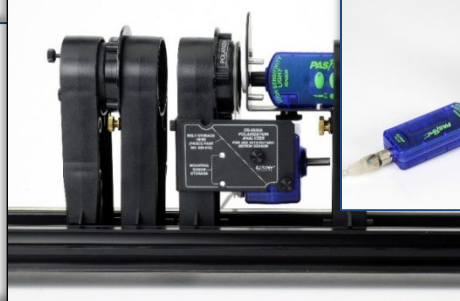
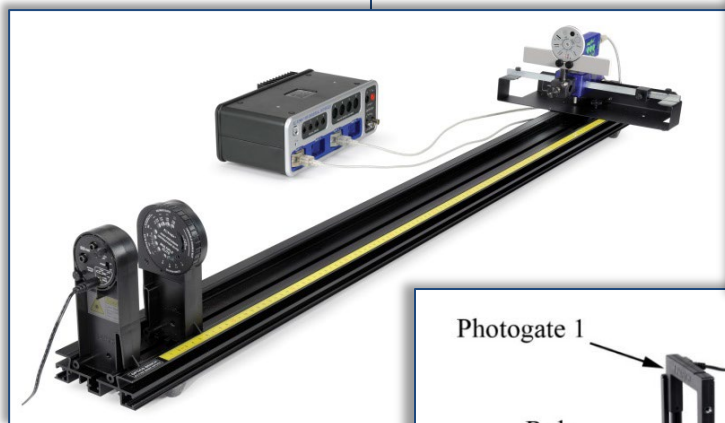
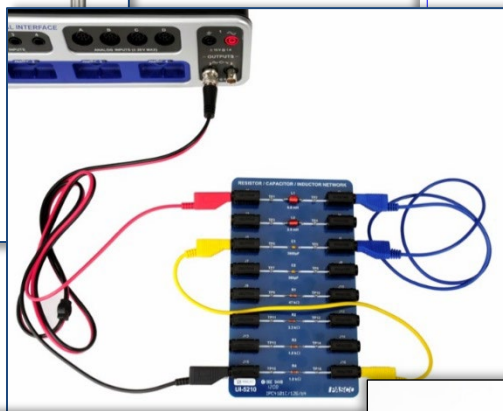
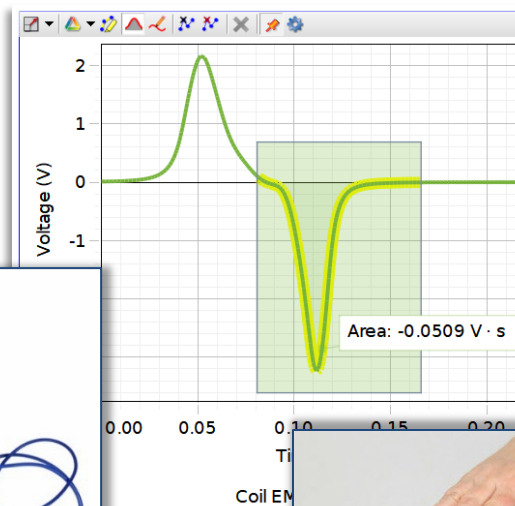
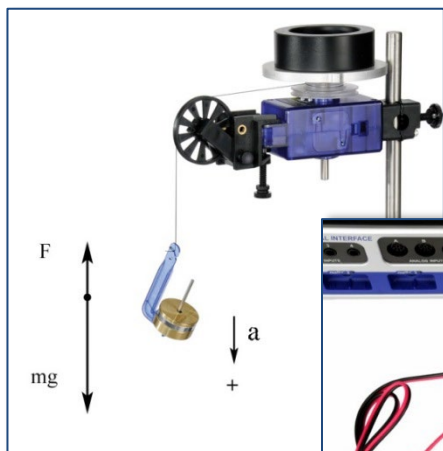


Experiment Manual (UI-5813) for 850 Comprehensive Physics System (UI-5800D)



Components of 850 Comprehensive Physics System (UI-5800B)

2024/02/28



Comprehensive 850 Mechanics (UI-5801C)



Comprehensive 850 Waves, Optics, Thermodynamics (UI-5802A)



Comprehensive 850 Electromagnetism (UI-5803)

850 Comprehensive Physics Experiments For UI-5800D

Equipment List by Bundle

Equipment List by Experiment

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UI-5800D Equipment List

UI-5801C	COMP 850 MECHANICS	QTY
ME-3419	Ring And Disk Set	1
ME-6622	Force Sensor Track Bracket	1
ME-6743	Cart Adapter Accessory	1
ME-6755	Compact Cart Mass	2
ME-6757A	Cart Mass (set of 2)	1
ME-6806	Discover Pi Set	1
ME-6810A	Time-of-Flight Accessory	1
ME-6821A	Photogate Mounting Bracket	1
ME-6825B	Mini Launcher	1
ME-6828	Dynamics Cart Magnetic Damping	1
ME-6829	Mini Ballistic Pendulum Accessory	1
ME-6843	Spring Cart Launcher	1
ME-6933	PAScar Red	1
ME-6934	PAScar Blue	1
ME-6977	Super Fan Cart	1
ME-8569A	Density Set	1
ME-8574	Discover Friction Accessory	1
ME-8735	Large Rod Base	1
ME-8736	Stainless Steel Rod, 45 cm	1
ME-8738	Stainless Steel Rod, 90 cm	1
ME-8933	Picket Fences (2 Pack) - Smart Timer	1
ME-8969	Pendulum Accessory	1
ME-8971	Dynamics Track End Stop (2 pack)	1
ME-8972	Dynamics Track Feet (Pair)	1
ME-8979	Mass and Hanger Set	1
ME-8998	Elastic Bumper	1
ME-8999	Dynamics Track Spring Set	1
ME-9377A	Picket Fence	1
ME-9448B	Super Pulley with Clamp	1
ME-9472	Large Table Clamp	1
ME-9493	Aluminum Dynamics Track, 1.2 m	1
ME-9498A	Photogate Head	2
ME-9506	Pendulum Clamp	1
ME-9507	Multi-Clamp	2
ME-9595	Car Sail	1
ME-9781	Variable Speed Motorized Cart	1
ME-9821	Centripetal Force Pendulum	1
ME-9836	Dynamics Track Rod Clamp	1
PS-2103A	PASPORT Motion Sensor	2
PS-2120A	PASPORT Rotary Motion Sensor	1
PS-2189	PASPORT High Resolution Force Sensor	2
PS-3223	Wireless Acceleration/Altimeter	1
SA-9242	Pulley Mounting Rod	1
SE-7347	No-Bounce Pad	1
SE-8050	Braided Physics String	1
UI-5813	Comprehensive 850 Physics System Experiment Manual	1

UI-5802A	COMP 850 THERMO, WAVES, OPTICS	QTY
ET-8499	Energy Transfer - Calorimeter	1
OS-8453	Precision Diffraction Slits	1
OS-8456	Basic Optics Geometric Lens Set	1
OS-8457	Concave/Convex Mirror	1
OS-8458B	Green Diode Laser	1
OS-8460	Basic Optics Viewing Screen	1
OS-8465	Basic Optics Ray Table	1
OS-8470	Basic Optics Light Source	1
OS-8474	Adjustable Lens Holder	1
OS-8494	Adjustable Focal Length Lens	1
OS-8495	Color Mixer Accessory Kit	1
OS-8496	Color Mixer	1
OS-8508	Optics Track, 1.2 m	1
OS-8516A	Ray Optics Kit	1
OS-8519	Accessory Lens Set	1
OS-8525A	Red Diode Laser	1
OS-8533A	Polarization Analyzer	1
OS-8535A	Linear Translator	1
PS-2107	PASPORT Absolute Pressure Sensor	1
PS-2143	PASPORT Quad Temperature Sensor	1
PS-2176	PASPORT High Sensitivity Light Sensor	1
SE-7345	Resonance Boxes: Sympathetic Resonance Box Set	1
SE-9750	Banana Plug Cord-Red (5 Pack)	1
TD-8570A	Radiation Cans	1
TD-8595	Absolute Zero Sphere	1
TD-8596A	Ideal Gas Law Apparatus	1
UI-5101	Sound Sensor with Microphone	1
WA-9605	Mini Speaker	
WA-9606	Resonance Air Column	1
WA-9857A	String Vibrator	1

UI-5803	COMP 850 ELECTROMAGNETISM	QTY
EM-8620	Alnico Bar Magnets (2 Pack)	1
EM-8652	Zero Gauss Chamber	1
EM-8656	AC/DC Electronics Laboratory	1
ES-9042A	Faraday Ice Pail	1
ES-9057C	Charge Producers and Proof Plane	1
ES-9059C	Conductive Spheres	1
ES-9061	Conductive Shapes	1
ES-9077	Electrostatics Voltage Source	1
ES-9078A	Basic Electrometer	1
ES-9079	Basic Variable Capacitor	1
PK-9023	Field Mapper Kit	1
PS-2162	PASPORT 2-Axis Magnetic Field Sensor	1
PS-2184	Current Probe	2
SE-7123	Banana Plug Cord Sets, 30 cm	1
SE-8619	Dip Needle/Oersted's Apparatus	1
SE-8680	Plotting Compass Set (20 Pack)	1
UI-5100	Voltage Sensor (unshrouded)	4
UI-5119	BNC Function Generator Output Cable (unshrouded)	1
UI-5210	Resistor Capacitor Inductor Network	1

UI-5800D Comprehensive 850 Physics System
Equipment Used in Each Experiment

NI=Not Included

Expt #	Mechanics	Part#	Qty
1	Introduction to Measurement		
	PASPORT Motion Sensor	PS-2103A	1
	Density Set	ME-8569A	1
	Pendulum Clamp	ME-9506	1
	Large Rod Base	ME-8735	1
	Large Table Clamp	ME-9472	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Braided Physics String	SE-8050	1
	Meter Sticks, 6 Pack	SE-8827	NI
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
2	Uncertainty and Error Analysis		
	Discover Pi Set	ME-6806	1
3	Relative Motion		
	PASPORT Motion Sensor	PS-2103A	2
	PAScar Red	ME-6933	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Cart Adapter Accessory	ME-6743	1
	Variable Speed Motorized Cart	ME-9781	1
	Car Sail	ME-9595	1
	Elastic Bumper	ME-8998	1
4	Match Graph-Position and Velocity vs. time		
	PASPORT Motion Sensor	PS-2103A	1
	Car Sail	ME-9595	1
	Large Table Clamp	ME-9472	1
	Stainless Steel Rod, 45 cm	ME-8736	1
5	Instantaneous and Average Speed		
	PAScar Red	ME-6933	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Dynamics Track Rod Clamp	ME-9836	1
	Cart Mass (set of 2)	ME-6757A	1
	Picket Fences (2 Pack) - Smart Timer	ME-8933	1
	Elastic Bumper	ME-8998	1
	Elastic Bumper	ME-8998	2
	Photogate Head	ME-9498A	2
6	Position and Velocity		
	PASPORT Motion Sensor	PS-2103A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Variable Speed Motorized Cart	ME-9781	1

7A	Velocity and Acceleration		
	PASPORT Motion Sensor	PS-2103A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Variable Speed Motorized Cart	ME-9781	1
	Super Fan Cart	ME-6977	1
	Elastic Bumper	ME-8998	1
7B	The Great Race		
	PASPORT Motion Sensor	PS-2103A	2
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track Rod Clamp	ME-9836	1
	Variable Speed Motorized Cart	ME-9781	1
	Super Fan Cart	ME-6977	1
	Elastic Bumper	ME-8998	1
8	Equations of Motion		
	PASPORT Motion Sensor	PS-2103A	1
	PAScar Red	ME-6933	1
	Cart Mass (set of 2)	ME-6757A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
9	Acceleration Due to Gravity		
	PAScar Red	ME-6933	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Dynamics Track Rod Clamp	ME-9836	1
	PASPORT Motion Sensor	PS-2103A	1
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Meter Sticks, 6 Pack	SE-8827	NI
10	Acceleration of a Freely Falling Picket Fence		
	Photogate Head	ME-9498A	1
	Picket Fence	ME-9377A	1
	Pulley Mounting Rod	SA-9242	1
	Large Table Clamp	ME-9472	1
	Multi-Clamp	ME-9507	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	No-Bounce Pad	SE-7347	1

11	Constant Acceleration: Graph P, V, A for a Cart on Incline		
	PAScar Red	ME-6933	1
	Cart Mass (set of 2)	ME-6757A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Dynamics Track Rod Clamp	ME-9836	1
	PASPORT Motion Sensor	PS-2103A	1
	Wireless Acceleration/Altimeter	PS-3223	1
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Elastic Bumper	ME-8998	1
12	Projectile Motion		
	Mini Launcher	ME-6825B	1
	Photogate Head	ME-9498A	2
	Photogate Mounting Bracket	ME-6821A	1
	Time-of-Flight Accessory	ME-6810A	1
	Large Table Clamp	ME-9472	1
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	No-Bounce Pad	SE-7347	1
	Plumb Bobs (10 Pack)	SE-8728	NI
	Meter Sticks, 6 Pack	SE-8827	NI
	Measuring Tape, 30 m	SE-8712A	NI
	Carbon Paper (100 Sheets)	SE-8693	NI
13	Projectile Motion-Against Wall		
	Mini Launcher	ME-6825B	1
	Photogate Head	ME-9498A	2
	Photogate Mounting Bracket	ME-6821A	1
	Car Sail	ME-9595	1
	Multi-Clamp	ME-9507	2
	Large Table Clamp	ME-9472	1
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	No-Bounce Pad	SE-7347	1
	Meter Sticks, 6 Pack	SE-8827	NI
	Carbon Paper (100 Sheets)	SE-8693	NI
14	Newton's First Law – No Net Force		
	PASPORT Motion Sensor	PS-2103A	1
	PAScar Red	ME-6933	1
	PAScar Blue	ME-6934	1
	Cart Mass (set of 2)	ME-6757A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Elastic Bumper	ME-8998	1
	Dynamics Cart Magnetic Damping	ME-6828	1
	Digital Calipers	SE-8710	NI

15	Newton's Second Law - Acceleration		
	PASPORT Motion Sensor	PS-2103A	1
	PAScar Red	ME-6933	1
	Cart Mass (set of 2)	ME-6757A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	Force Sensor Track Bracket	ME-6622	1
	Super Fan Cart	ME-6977	1
	Compact Cart Mass	ME-6755	2
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
16	Newton's Second Law – Force & Acceleration		
	PAScar Red	ME-6933	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Dynamics Track Rod Clamp	ME-9836	1
	PASPORT Motion Sensor	PS-2103A	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	Super Pulley with Clamp	ME-9448B	1
	Braided Physics String	SE-8050	1
	Mass and Hanger Set	ME-8979	1
	Compact Cart Mass	ME-6755	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
17	Newton's Second Law – Push-Pull a Cart		
	PAScar Red	ME-6933	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	PASPORT Motion Sensor	PS-2103A	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	Compact Cart Mass	ME-6755	2
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
18	Newton's Third Law – Tug-of-War		
	PAScar Red	ME-6933	1
	PAScar Blue	ME-6934	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	PASPORT High Resolution Force Sensor	PS-2189	2
	Compact Cart Mass	ME-6755	2
	Rubber Band		NI

19	Newton's Laws - Net Force		
	PAScar Red	ME-6933	1
	PAScar Blue	ME-6934	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	PASPORT High Resolution Force Sensor	PS-2189	2
	PASPORT Motion Sensor	PS-2103A	1
	Compact Cart Mass	ME-6755	2
	Elastic Bumper	ME-8998	1
	Braided Physics String	SE-8050	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	1
20	Newton's Second Law – Atwood's Machine		
	Photogate Head	ME-9498A	1
	Super Pulley with Clamp	ME-9448B	1
	Pulley Mounting Rod	SA-9242	1
	Large Table Clamp	ME-9472	1
	Multi-Clamp	ME-9507	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Braided Physics String	SE-8050	1
	Mass and Hanger Set	ME-8979	1
	No-Bounce Pad	SE-7347	1
21	Acceleration Up an Inclined Plane		
	Photogate Head	ME-9498A	1
	Photogate Bracket (in Elastic Bumper)	ME-8998	1
	Super Pulley with Clamp	ME-9448B	1
	PAScar Red	ME-6933	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Dynamics Track Rod Clamp	ME-9836	1
	Large Rod Base	ME-8735	1
	Elastic Bumper	ME-8998	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Braided Physics String	SE-8050	1
	Mass and Hanger Set	ME-8979	1
	Meter Sticks, 6 Pack	SE-8827	NI
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
22	Static Equilibrium		
	PASPORT High Resolution Force Sensor	PS-2189	2
	PASPORT Rotary Motion Sensor	PS-2120A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Centripetal Force Pendulum	ME-9821	1
	Large Rod Base	ME-8735	1
	Large Table Clamp	ME-9472	1
	Multi-Clamp	ME-9507	2
	Stainless Steel Rod, 90 cm	ME-8738	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Braided Physics String	SE-8050	1
	Elastic Bumper	ME-8998	1

23	Coefficients of Static and Sliding Friction		
	PASPORT Motion Sensor	PS-2103A	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Discover Friction Accessory	ME-8574	1
	Variable Speed Motorized Cart	ME-9781	1
	Compact Cart Mass	ME-6755	2
	Braided Physics String	SE-8050	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
24	Friction & Newton's Second Law		
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track Rod Clamp	ME-9836	1
	Photogate Head	ME-9498A	1
	Elastic Bumper	ME-8998	1
	Photogate Bracket (in ME-8998)	ME-8998	1
	Discover Friction Accessory	ME-8574	1
	Mass and Hanger Set	ME-8979	1
	Braided Physics String	SE-8050	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
25A	Magnetic Drag		
	PASPORT Motion Sensor	PS-2103A	1
	PAScar Red	ME-6933	1
	Cart Mass (set of 2)	ME-6757A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Elastic Bumper	ME-8998	1
	Dynamics Cart Magnetic Damping	ME-6828	1
	Meter Sticks, 6 Pack	SE-8827	NI
	Digital Calipers	SE-8710	NI
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
25B	Magnetic Drag Part 2		
	PASPORT Motion Sensor	PS-2103A	1
	PAScar Red	ME-6933	1
	Cart Mass (set of 2)	ME-6757A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Dynamics Track Rod Clamp	ME-9836	1
	Dynamics Cart Magnetic Damping	ME-6828	1
	Dynamics Track Spring Set	ME-8999	1
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Meter Sticks, 6 Pack	SE-8827	NI
	Digital Calipers	SE-8710	NI
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI

26	Air Drag		
	PAScar Red	ME-6933	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Compact Cart Mass	ME-6755	2
	Elastic Bumper	ME-8998	1
	Rotational Inertia Accessory	ME-3420	1
	PASPORT Motion Sensor	PS-2103A	1
	Car Sail	ME-9595	1
	Mass and Hanger Set	ME-8979	1
	Braided Physics String	SE-8050	1
	Meter Stick		NI
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
27	Centripetal Force on a Pendulum		
	PASPORT Rotary Motion Sensor	PS-2120A	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	Centripetal Force Pendulum	ME-9821	1
	Large Table Clamp	ME-9472	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Multi-Clamp	ME-9507	1
	Braided Physics String	SE-8050	1
	Meter Sticks, 6 Pack	SE-8827	NI
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
28	Conservation of Energy - Cart on an Inclined Plane		
	PAScar Red	ME-6933	1
	PAScar Blue	ME-6934	1
	Cart Mass (set of 2)	ME-6757A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Dynamics Track Rod Clamp	ME-9836	1
	Photogate Head	ME-9498A	1
	Elastic Bumper	ME-8998	1
	Picket Fences (2 Pack) - Smart Timer	ME-8933	1
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Elastic Bumper	ME-8998	1
	Meter Sticks, 6 Pack	SE-8827	NI
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
29	Conservation of Energy for a Falling Ball		
	PASPORT Motion Sensor	PS-2103A	1
	Large Table Clamp	ME-9472	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Multi-Clamp	ME-9507	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
	Ball to Drop		NI

30	Conservation of Energy for a Simple Pendulum		
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Density Set	ME-8569A	1
	Multi-Clamp	ME-9507	
	Large Table Clamp	ME-9472	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Stainless Steel Rod, 45 cm	ME-8736	
	Braided Physics String	SE-8050	1
	Meter Sticks, 6 Pack	SE-8827	NI
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
31	Hooke's Law and Elastic Potential Energy		
	Force Sensor Track Bracket	ME-6622	1
	Compact Cart Mass	ME-6755	2
	Spring Cart Launcher	ME-6843	1
	PAScar Red	ME-6933	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Elastic Bumper	ME-8998	1
	Dynamics Track Spring Set	ME-8999	1
	1.2m Starter Dynamics Track	ME-9493	1
	PASPORT Motion Sensor	PS-2103A	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	Braided Physics String	SE-8050	1
32	Work-Energy Theorem: Compare W to ΔE		
	PASPORT High Resolution Force Sensor	PS-2189	1
	PAScar Red	ME-6933	1
	Cart Mass (set of 2)	ME-6757A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track Rod Clamp	ME-9836	1
	PASPORT Motion Sensor	PS-2103A	1
	Force Sensor Track Bracket	ME-6622	1
	Dynamics Track Spring Set	ME-8999	1
	Braided Physics String	SE-8050	1
	Ohaus Triple-Beam Balance (with Tare)	SE-8707	NI
33	Collisions in One Dimension		
	PAScar Red	ME-6933	1
	PAScar Blue	ME-6934	1
	Cart Mass (set of 2)	ME-6757A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Elastic Bumper	ME-8998	1
	Dynamics Track Rod Clamp	ME-9836	1
	PASPORT Motion Sensor	PS-2103A	2
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI

34	Impulse and Change in Momentum		
	PAScar Red	ME-6933	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Force Sensor Track Bracket	ME-6622	1
	Elastic Bumper	ME-8998	1
	Picket Fences (2 Pack) - Smart Timer	ME-8933	1
	Photogate Head	ME-9498A	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
35	Ballistic Pendulum		
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Mini Launcher	ME-6825B	1
	Photogate Head	ME-9498A	2
	Photogate Mounting Bracket	ME-6821A	1
	Mini Ballistic Pendulum Accessory	ME-6829	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Large Table Clamp	ME-9472	1
36	Rotational Inertia of a Point Mass		
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Pendulum Accessory	ME-8969	1
	Mass and Hanger Set	ME-8979	1
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
	Meter Sticks, 6 Pack	SE-8827	NI
37	Rotational Inertia		
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Ring And Disk Set	ME-3419	1
	Mass and Hanger Set	ME-8979	1
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
	Digital Calipers	SE-8710	NI
38	Rotational Kinetic Energy		
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Ring And Disk Set	ME-3419	1
	Mass and Hanger Set	ME-8979	1
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	1
	Digital Calipers	SE-8710	1
39	Conservation of Angular Momentum		
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Ring And Disk Set	ME-3419	1
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Stainless Steel Calipers	SF-8711	NI

40	Static Equilibrium of a Rigid Body		
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Pendulum Accessory	ME-8969	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Large Rod Base	ME-8735	1
	Large Table Clamp	ME-9472	1
	Braided Physics String	SE-8050	1
	Meter Sticks, 6 Pack	SE-8827	NI
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
41	Spring and Mass Oscillations		
	Mass and Hanger Set	ME-8979	1
	PASPORT Motion Sensor	PS-2103A	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	Density Set	ME-8569A	1
	Dynamics Track Spring Set	ME-8999	1
	Braided Physics String	SE-8050	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Multi-Clamp	ME-9507	1
	Large Rod Base	ME-8735	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
42	Oscillations of Cart and Springs		
	PAScar Red	ME-6933	1
	Cart Mass (set of 2)	ME-6757A	1
	1.2m Starter Dynamics Track	ME-9493	1
	Dynamics Track Feet (Set of 2)	ME-8972	1
	Dynamics Track End Stops (Set of 2)	ME-8971	1
	Dynamics Track Rod Clamp	ME-9836	1
	Compact Cart Mass	ME-6755	2
	PASPORT High Resolution Force Sensor	PS-2189	1
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Photogate Head	ME-9498A	1
	Photogate Bracket	ME-8998	1
	Picket Fences (2 Pack) - Smart Timer	ME-8933	1
	Dynamics Track Spring Set	ME-8999	1
	Braided Physics String	SE-8050	1
	Large Table Clamp	ME-9472	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	1
43	Oscillation Equations of Motion		
	PASPORT Motion Sensor	PS-2103A	1
	Pendulum Clamp	ME-9506	1
	Density Set	ME-8569A	1
	Dynamics Track Spring Set	ME-8999	1
	Braided Physics String	SE-8050	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Large Rod Base	ME-8735	1

44	Driven Harmonic Motion – Mass on a Spring		
	Density Set	ME-8569A	1
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Dynamics Track Spring Set	ME-8999	1
	Large Table Clamp	ME-9472	1
	PASPORT Motion Sensor	PS-2103A	1
	Braided Physics String	SE-8050	1
	Banana Plug Cord-Red (5 Pack)	SE-9750	1
	String Vibrator	WA-9857A	1
	Thick construction paper and tape		NI
45	Physical Pendulum		
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Pendulum Accessory	ME-8969	1
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Digital Calipers	SE-8710	NI
	Meter Sticks, 6 Pack	SE-8827	NI
46	Period of a Large Amplitude Pendulum		
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Pendulum Accessory	ME-8969	1
	PASPORT Rotary Motion Sensor	PS-2120A	1
47	Variable-g Pendulum		
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Pendulum Accessory	ME-8969	1
	Wireless Acceleration/Altimeter	PS-3223	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Large Rod Base	ME-8735	1
	Multi-Clamp	ME-9507	1
	Spirit Levels (10 Pack)	SE-8729	NI
	Meter Sticks, 6 Pack	SE-8827	NI
48	Physical Pendulum Minimum Period		
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Pendulum Accessory	ME-8969	1
	Large Rod Base	ME-8735	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
	Meter Sticks, 6 Pack	SE-8827	NI
49	Archimedes' Principle - Buoyant Force		
	Density Set	ME-8569A	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Stainless Steel Rod, 90 cm	ME-8738	1
	Large Rod Base	ME-8735	1
	Multi-Clamp	ME-9507	1
	Braided Physics String	SE-8050	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	Stainless Steel Calipers	SF-8711	NI
	1000 mL Beaker		NI

Waves, Optics, Thermo			
50	Heat and Temperature		
	PASPORT Quad Temperature Sensor	PS-2143	1
	Energy Transfer - Calorimeter	ET-8499	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
51	Transfer of Energy by Radiation		
	Quad Temperature Sensor	PS-2143	1
	Radiation Cans	TD-8570A	1
	Insulation Pads		NI
	Hot water		NI
52	Specific Heat		
	PASPORT Quad Temperature Sensor	PS-2143	1
	Energy Transfer - Calorimeter	ET-8499	1
	Density Set	ME-8569A	1
	Braided Physics String	SE-8050	1
	Ohaus Triple-Beam Balance (without Tare)	SE-8723	NI
	Water container		NI
53	Electrical Equivalent of Heat		
	Energy Transfer - Calorimeter	ET-8499	1
	PASPORT Quad Temperature Sensor	PS-2143	1
	Ohaus Triple-Beam Balance (with Tare)	SE-8707	NI
54	Boyle's Law: P and V of a Gas at Constant T		
	Ideal Gas Law Apparatus	TD-8596A	1
	PASPORT Absolute Pressure Sensor	PS-2107	1
	PASPORT Quad Temperature Sensor	PS-2143	1
55	Absolute Zero		
	Absolute Zero Sphere	TD-8595	1
	PASPORT Absolute Pressure Sensor	PS-2107	1
	PASPORT Quad Temperature Sensor	PS-2143	1
	Hot, warm, and cold water containers		NI
56	Behavior and Characteristics of Sound Waves		
	Mini Speaker	WA-9605	1
	Banana Plug Cord-Red (5 Pack)	SE-9750	1
	Sound Sensor with Microphone	UI-5101	1
	Resonance Boxes: Sympathetic Resonance Box Set	SE-7345	1
57	Standing Waves on a String		
	String Vibrator	WA-9857A	1
	Braided Physics String	SE-8050	1
	PASPORT High Resolution Force Sensor	PS-2189	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Large Table Clamp	ME-9472	1
	Banana Plug Cord-Red (5 Pack)	SE-9750	1
	Meter Sticks, 6 Pack	SE-8827	NI

58	Resonant Modes of Sound in a Tube		
	Mini Speaker	WA-9605	1
	Banana Plug Cord-Red (5 Pack)	SE-9750	1
	Resonance Air Column	WA-9606	1
	PASPORT Quad Temperature Sensor	PS-2143	1
59	Speed of Sound in Air		
	Resonance Air Column	WA-9606	1
	Sound Sensor with Microphone	UI-5101	1
60	Superposition of Sound Waves		
61	Interference of Sound Waves		
	Sound Sensor with Microphone	UI-5101	1
	Resonance Boxes: Sympathetic Resonance Box Set	SE-7345	1
62	Shadow and Color in Light		
	Color Mixer Accessory Kit	OS-8495	1
	Color Mixer	OS-8496	1
	Optics Track, 1.2 m	OS-8508	1
	Basic Optics Viewing Screen	OS-8460	1
63	Object and Image Distances for a Thin Lens		
	Basic Optics Light Source	OS-8470	1
	Basic Optics Geometric Lens Set	OS-8456	1
	Adjustable Lens Holder	OS-8474	1
	Adjustable Focal Length Lens	OS-8494	1
	Basic Optics Viewing Screen	OS-8460	1
	Optics Track, 1.2 m	OS-8508	1
64	Reflection and Refraction		
	Ray Optics Kit	OS-8516A	1
	Basic Optics Light Source	OS-8470	1
	Basic Optics Ray Table	OS-8465	1
65	Focal Length of a Concave Mirror		
	Basic Optics Light Source	OS-8470	1
	Concave/Convex Mirror	OS-8457	1
	Optics Track, 1.2 m	OS-8508	1
66	Optical Instruments: Telescope and Microscope		
	Basic Optics Light Source	OS-8470	1
	Basic Optics Geometric Lens Set	OS-8456	1
	Basic Optics Viewing Screen	OS-8460	1
	Accessory Lens Set	OS-8519	1
	Optics Track, 1.2 m	OS-8508	1
67	Variation of Light Intensity		
	PASPORT High Sensitivity Light Sensor	PS-2176	1
	Basic Optics Light Source	OS-8470	1
	Fluorescent Room Light		NI

68	Light Intensity versus Distance		
	Basic Optics Light Source	OS-8470	1
	Aperture Bracket (included in OS-8533A)	OS-8533A	1
	PASPORT High Sensitivity Light Sensor	PS-2176	1
	Optics Track, 1.2 m	OS-8508	1
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Mass and Hanger Set	ME-8979	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Large Table Clamp	ME-9472	1
69	Polarization: Verify Malus' Law		
	PASPORT High Sensitivity Light Sensor	PS-2176	1
	PASPORT Rotary Motion Sensor	PS-2120A	1
	;	OS-8525A	1
	Polarization Analyzer	OS-8533A	1
	Optics Track, 1.2 m	OS-8508	1
70	Brewster's Angle		
	Basic Optics Ray Table	OS-8465	1
	Green Diode Laser	OS-8458B	1
	Polarization Analyzer	OS-8533A	1
	Red Diode Laser	OS-8525A	1
71	Diffraction of Light		
	Optics Track, 1.2 m	OS-8508	1
	Precision Diffraction Slits	OS-8453	1
	Green Diode Laser	OS-8458B	1
	Red Diode Laser	OS-8525A	1
	Aperture Bracket (included in OS-8533A)	OS-8533A	1
	Linear Translator	OS-8535A	1
	PASPORT Rotary Motion Sensor	PS-2120A	1
	PASPORT High Sensitivity Light Sensor	PS-2176	1

Electromagnetism

72	Electrostatic Charges		
	Basic Electrometer	ES-9078A	1
	Charge Producers and Proof Plane	ES-9057C	1
	Faraday Ice Pail	ES-9042A	1
	Conductive Spheres	ES-9059C	1
	Conductive Shapes	ES-9061	1
	Electrostatics Voltage Source	ES-9077	1
73	Electric Field Mapping		
	Field Mapper Kit	PK-9023	1
	Voltage Sensor (unshrouded)	UI-5100	1
	Banana Plug Cord Sets, 30 cm	SE-7123	1
74	Ohm's Law		
	AC/DC Electronics Laboratory	EM-8656	1
	Banana Plug Cord Sets, 30 cm	SE-7123	1
75	Series and Parallel Circuits		
	AC/DC Electronics Laboratory	EM-8656	1
	Banana Plug Cord Sets, 30 cm	SE-7123	1

76	Kirchhoff's Laws		
	Resistor Capacitor Inductor Network	UI-5210	1
	AC/DC Electronics Laboratory	EM-8656	1
	Voltage Sensor (unshrouded)	UI-5100	3
	Current Probe	PS-2184	2
	Banana Plug Cord Sets, 30 cm	SE-7123	1
77	Capacitance		
	Basic Electrometer	ES-9078A	1
	Basic Variable Capacitor	ES-9079	1
	Electrostatics Voltage Source	ES-9077	1
	Banana Plug Cord Sets, 30 cm	SE-7123	1
78	RC Circuit		
	Resistor Capacitor Inductor Network	UI-5210	1
	Voltage Sensor (unshrouded)	UI-5100	1
	Banana Plug Cord Sets, 30 cm	SE-7123	1
79	Resonant Frequency of an LRC Circuit		
	Resistor Capacitor Inductor Network	UI-5210	1
	Voltage Sensor (unshrouded)	UI-5100	4
	BNC Function Generator Output Cable (unshrouded)	UI-5119	1
	Banana Plug Cord Sets, 30 cm	SE-7123	1
80	General Properties of Diodes		
	Voltage Sensor (unshrouded)	UI-5100	2
	AC/DC Electronics Laboratory	EM-8656	1
	Banana Plug Cord Sets, 30 cm	SE-7123	1
81	Build a Rectifier		
	Voltage Sensor (unshrouded)	UI-5100	2
	AC/DC Electronics Laboratory	EM-8656	1
	Banana Plug Cord Sets, 30 cm	SE-7123	1
82	Transistor 1 – The NPN Transistor as a Digital Switch		
	Voltage Sensor (unshrouded)	UI-5100	1
	AC/DC Electronics Laboratory	EM-8656	1
	Banana Plug Cord Sets, 30 cm	SE-7123	1
83	Transistor 2 – Measure the Current Gain		
	Voltage Sensor (unshrouded)	UI-5100	2
	AC/DC Electronics Laboratory	EM-8656	1
	Banana Plug Cord Sets, 30 cm	SE-7123	1
84	Earth's Magnetic Field		
	PASPORT 2-Axis Magnetic Field Sensor	PS-2162	1
	Zero Gauss Chamber	EM-8652	1
	PASPORT Rotary Motion Sensor	PS-2120A	1
	Dip Needle/Oersted's Apparatus	SE-8619	1
	Large Rod Base	ME-8735	1
	Multi-Clamp	ME-9507	1
	Stainless Steel Rod, 45 cm	ME-8736	1
	Stainless Steel Rod, 90 cm	ME-8738	1

85	Magnetic Field Mapping		
	Alnico Bar Magnets (2 Pack)	EM-8620	1
	Plotting Compass Set (20 Pack)	SE-8680	1
	Paper and Pencil		NI
86	Induction – Magnet Through a Coil		
	PASPORT 2-Axis Magnetic Field Sensor	PS-2162	1
	Voltage Sensor (unshrouded)	UI-5100	1
	Alnico Bar Magnets (2 Pack)	EM-8620	1
	AC/DC Electronics Laboratory	EM-8656	1
	No-Bounce Pad	SE-7347	1
	Braided Physics String	SE-8050	1
87	Magnetic Field in a Current-Carrying Coil		
	PASPORT 2-Axis Magnetic Field Sensor	PS-2162	1
	AC/DC Electronics Laboratory	EM-8656	1
	Zero Gauss Chamber	EM-8652	1

Introduction to Measurement

Objectives

The purpose of this experiment is to measure the period of a simple pendulum and to use scientific methods to determine the relationships between the period of a pendulum and its length, the mass of the pendulum, and the amplitude of the pendulum's motion. A Motion Sensor (see Fig. 1) is used to record the motion of the pendulum as it swings back and forth, and various software tools are used to determine the period.

Background

A simple pendulum consists of a mass m called the pendulum 'bob', attached to a string of length L that has negligible mass. When the bob is pulled away from its equilibrium position and released, it swings back and forth. The period T , is the amount of time for a complete swing back-and- forth (e.g., from position 1 to position 2 and back to position 1) as shown in Figure 2. The amplitude A of the oscillation is measured from the equilibrium position out to the maximum displacement, and is thus half the full swing from position 1 to position 2.

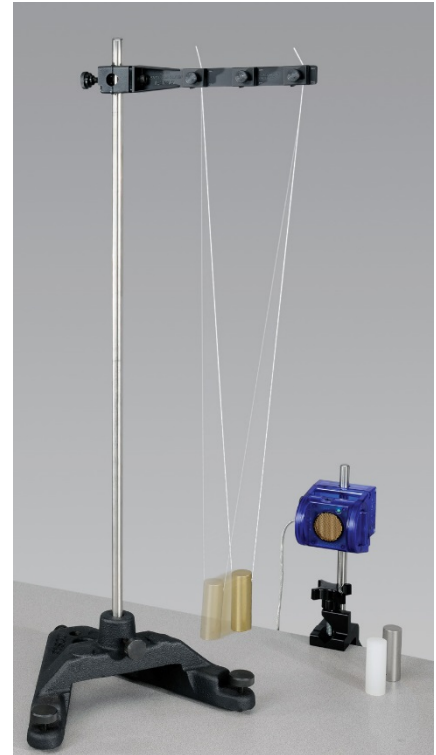


Figure 1: Measuring Pendulum Motion

Equipment

Qty	Items	Part Number
1	Motion Sensor	PS-2103A
1	Density Set	ME-8569
1	Pendulum Clamp	ME-9506
1	Large Rod Base	ME-8735
1	Large Table Clamp	ME-9472
1	Rod, 90-cm	ME-8738
1	Rod, 45-cm	ME-8736
1	String, spool	SE-8050
Required but not included		
1	Meter Stick	SE-8695
1	Balance	SE-8723

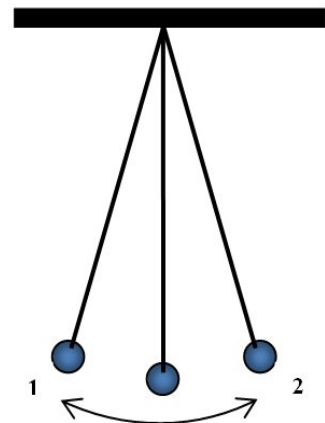


Figure 2: Pendulum Model

Set-up

1. Attach the 90 cm Rod to the Rod Base and attach the Pendulum Clamp to the rod near the top. Attach a piece of string about 2 meters long to the Pendulum Clamp as shown in Figure 3. Run the string through the hole in the brass cylinder and put the ends of the string on the inner and outer clips of the clamp, so the string forms a 'V' shape as it hangs.
2. Adjust the string so the vertical distance from the bottom edge of the Pendulum Clamp to the middle of the pendulum bob is about 70 cm.
3. Using the Table Clamp and the 45 cm Rod, position the Motion Sensor (see Fig. 1) in front of the pendulum so the brass colored disk is vertical and facing the bob, aimed along the direction that the pendulum will swing. Make sure that the range switch on the Motion Sensor is positioned on top. Adjust the Motion Sensor up or down so that it is at the same height as the pendulum bob.
4. Adjust the position of the rod base so that the Motion Sensor is about 25 cm from the pendulum bob. Plug the Motion Sensor into the interface.

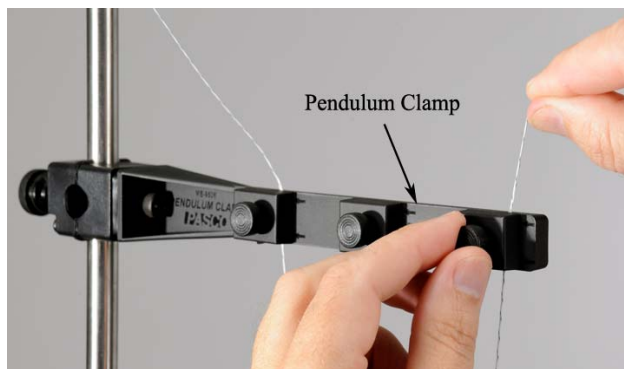


Figure 3: Hanging the Pendulum

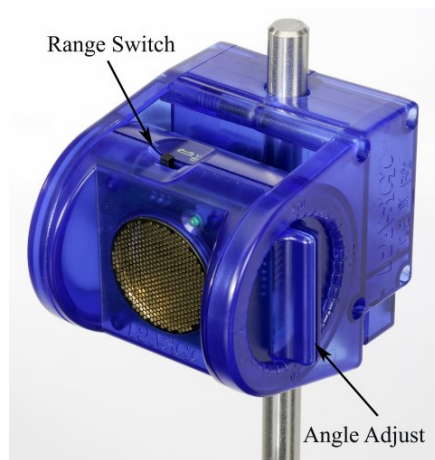


Figure 4: Motion Sensor

Recording Data

1. Build a graph of Position (m) versus Time (s).
2. Start the pendulum swinging: Pull the pendulum bob away from the Motion Sensor about 5 cm and release. Try to get the oscillation as smooth as possible.
3. Start recording data. When the graph gets too cluttered, stop recording and start again. There are tools in the graph tool bar that allow you to change the graph scale. Make sure the amplitude of the swing is about 5 cm.
4. The Motion Sensor cannot detect objects that are closer than 15 cm. If needed, move the pendulum further away from the sensor.

5. Is the resulting data a smooth sine curve?

If No, adjust the position of the range switch on top of the Motion Sensor to find which range setting returns the best data. In general, the position with the cart icon is for smaller, closer objects, and the position with the person icon is for larger objects further away.

6. Are there enough data points per period to define the sine wave?

If No, use the sample rate controls to increase the rate to see the effect. A rate of 50 Hz will work well for this experiment.

7. Try to get a run of data that has a smooth curve with 4 to 6 complete oscillations. You can delete bad runs as necessary: Delete bad runs using the Delete button in the bottom tool bar.

Measurement Tools

1. Measure the period of the pendulum: Using the Coordinates Tool (from the graph tool pallet), determine the time when the peak in each oscillation occurs and subtract adjacent peaks to get the period. Record your results.
2. Do you get the same answer for the period from all cases?
3. When the Coordinates Tool has been selected, you can right click on the cursor (on the graph) to activate the Delta Tool. Try measuring the period using this tool. Record your results.
4. There are various Curve Fit functions available: Select the Sine fit from the graph tool pallet. Is your data a good fit to a sine wave? The general form of a sine wave is:

$$y = A \sin\left(\frac{2\pi}{T} x + \phi\right)$$

where T is the period. Use the values from your curve fit to calculate the period of the oscillation. How does this compare to your previous answers?

5. In the next section you will vary the length of the pendulum. Predict what will happen to the period of oscillation when you **decrease** the pendulum length L . Will the period increase, decrease or stay about the same?

Part 1 – Varying Length

1. In PASCO Capstone, make a table and create a user-entered data set called “L” for Length in units of (m). In the second column, create run-based user-entered set called “T” for Period in units of (s).
2. Create a calculation:
Period = period(10,10,1,[Position (m)]) with units of (s)
Make another table and select the Period calculation in the first column and delete the second column. Then select the mean from the statistics.
3. Use this method to determine the period for various pendulum lengths by recording several periods. Measure from the bottom edge of the pendulum clamp down to the top of the cylinder. The length, L, of the pendulum must be to the center of the "bob", so add half the cylinder's length. Measure values for the length, L, down to 0.1 m. Enter the length and the mean period into the table. Try to keep the amplitude about the same for each oscillation.
4. Shorten the pendulum length by about 0.05 m and repeat. You might need to adjust the height. As you generate each data pair, enter the values in the table. Create a graph of T vs. L.

Curve Fits

1. Data is often graphed such that the resulting curve is a straight line. Click on the measurement name on the horizontal axis of your Period versus Length graph and choose the Quick Calcs to change how the Length is plotted. Try $1/L$, L^2 , etc. Do any of these result in a straight line?
2. Return the horizontal axis to L, and try changing the vertical axis. Try $1/T$, T^2 , etc. You should be able to get the data to be a straight line. Which produced a straight line?
3. Select the Linear curve fit from the graph tool pallet. Record the curve fit coefficients.

Prediction

In the next section, you will vary the amplitude of the pendulum oscillation. Predict what will happen when you **decrease** the amplitude. Will the period increase, decrease or stay about the same?

Part 2 – Varying Amplitude

1. Adjust the length of the pendulum so that the distance from the bottom edge of the pendulum clamp to the top of the cylinder is 40 cm.
2. Create another table and create a user-entered data set called “Amplitude” in units of (cm). In the second column, choose “T” for Period in units of (s).
3. Measure the period for an oscillation with an **amplitude** of about 10 cm. The amplitude is measured from the equilibrium out to the maximum displacement. Record your values in the table. Repeat for an amplitude of 8 cm, 6 cm, 4 cm and 2 cm.

Prediction

In the next section, you will vary the mass of the pendulum bob. Predict what will happen when you **decrease** the mass. Will the period increase, decrease or stay about the same?

Part 3 – Varying Mass

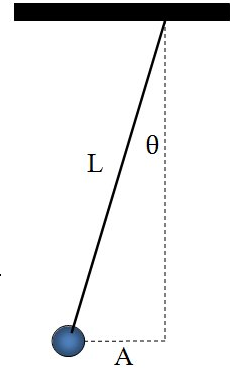
1. In this section, keep the amplitude of the oscillation and the length of the pendulum constant, but vary the mass by changing to the other bobs.
2. Make another table and create a user-entered data set called “bob” with no units. In the second column, create user-entered set called “Mass” with units of (g). Add a third column and select “T”.
3. Enter in Brass, Aluminum, and Plastic into the “bob” column.
4. For the brass cylinder, adjust the length of the pendulum so that the distance from the bottom edge of the pendulum clamp to the top of the cylinder is 60 cm. Measure carefully and keep this the same for all three bobs. Measure the period for an oscillation with an amplitude of about 6 cm.
5. Remove the brass cylinder and measure the mass of each pendulum bob. Record the values in the table.
6. Use the aluminum cylinder as the pendulum bob, carefully measuring so that the distance from the bottom edge of the pendulum clamp to the top of the cylinder is 60 cm. Measure the period for an oscillation with an amplitude of about 6 cm.
7. Repeat for the plastic cylinder.

Summary

How good were your predictions? In general, what happens to the period of a pendulum when you change the length, the mass of the pendulum, and the amplitude of the pendulum's motion? Will the period increase, decrease or stay **about** the same?

For Further Study: Pendulum Amplitude

The amplitude of a pendulum's oscillation is usually measured by the angle through which it swings, not its horizontal displacement. For the last section where you varied the mass, the length of the pendulum was about 60 cm and the max amplitude was about 6 cm. Using trigonometry, calculate the angle of the amplitude. In general, the period of a pendulum is independent of amplitude only if the angle is small (e.g. less than 20°).



For Further Study: Calculating "g".

The theoretical formula for the period of a pendulum is given by:

$$T = 2\pi\sqrt{\frac{L}{g}}$$

Where g is the acceleration due to gravity.

By squaring both sides of the equation, you can show that for a graph of T^2 versus L , the slope of the resulting straight line is given by:

$$\text{slope} = \frac{4\pi^2}{g}$$

Use the slope from your graph of T^2 vs. L to calculate g , the acceleration due to gravity. Write your result here:

$$g =$$

If you take your pendulum to the moon where gravity is less, what will happen to the period? Why?

Uncertainty and Error Analysis

Background

In every measurement you make, there is always some uncertainty in your answer. For example, when measuring the length of an object with a ruler, you must estimate the last digit because the reading falls in between the smallest divisions on the scale. And if the object being measured is not uniform, this introduces even more uncertainty. You should always observe and record the uncertainty in all measurements you make. For example, you might record that the length of an object was $24.2 \text{ cm} \pm 0.3 \text{ cm}$. Note that your measurement must also include units! You should always round your final answers to an appropriate number of digits.



Figure 1: Four Different Diameter Disks

Equipment

Qty	Item	Part Number
1	Discover π Set	ME-6806

Setup

In this lab you will learn to observe and record the uncertainty in measuring the diameter and circumference of four different sized disks (see Fig. 1) using the supplied clear flexible ruled tape. To measure circumference, slip the folded end into the slot on the side of the disk (see Fig. 2) and wrap the tape once around the disk so that it overlaps the zero-line marker. Measure diameter (see Fig. 2) along the line marked on the face of the disk.

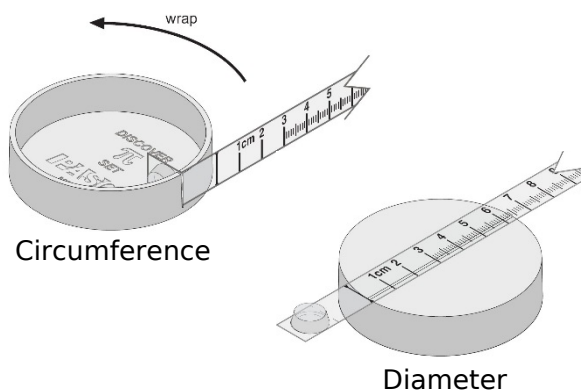


Figure 2: Measuring Diameter and Circumference

Estimating Uncertainty

1. In PASCO Capstone, make a table and create a user-entered data set called “Circumference” with units of (cm). Delete the second column. Then turn on the statistics with the mean and standard deviation turned on.
2. Create a graph of Circumference vs. Index. Turn on the statistics with the mean and standard deviation.
3. One way to estimate uncertainty is to repeat a measurement several times. Try this method for measuring the circumference of the largest disk. The tape is marked to 0.1 cm, but you can measure an additional digit by estimating between the tick marks. Re-wrap the tape and repeat the measurement. Do you get a different answer depending on the tension you apply?
4. Record your two measurements into Table I. These measurements will be plotted on the graph. Have each person in your group take separate measurements without looking at each other's measurements. Record all the values for the circumference of the large disk in Table I.
5. The Standard Deviation is often used as a good estimate of the uncertainty. Record your final value for the circumference in the form "Mean Value" \pm "Standard Deviation". Do you need to do any rounding? Never include more digits than makes sense. Don't forget the units!
6. Create another table (Table II) and create a user-entered set called “Disk” without units. Enter the values Largest, Large, Medium, and Smallest. Create another user-entered data set in the second column called “Circ.” with units of (cm). Record your value for the circumference of the largest disk in the first row. Add another column and create a user-entered data set called “Diameter” with units of (cm).
7. Use the same plastic ruler to measure the diameter of the largest disk. Align the zero-line marker to the edge of the disk, and measure the diameter along the line marked on the face of the disk.
8. What is the uncertainty in this measurement? You do not need to make the large variety of measurements that you did on the previous page, but at least make a few to allow you to estimate the uncertainty.
9. Record the diameter of the largest disk in Table II.
10. Measure and record the circumference and diameter of the other 3 disks.

Analysis

Create a graph of circ. vs. diameter.

1. What is the relationship between the circumference and diameter of a circle? Select the Linear Curve Fit from the graph tool pallet. What is the slope of the line? What is it supposed to be?
2. Note the uncertainty in the value of the slope. This is based on the values you input, but remember that there is an uncertainty in those measurements. Take the \pm uncertainty value you determined before for the circumference of the disk, and add this to the circumference of the largest disk, and subtract it from the circumference of the smallest disk. By how much does this change the slope? This change is a good estimation of the uncertainty in your value for the slope.
3. Record your best value for the slope (including uncertainty).

Percent Error

Often in the lab you are measuring something that has a known or accepted value. To compare your measured result with the accepted value, it is useful to calculate the error in that measurement.

$$\%error = \left| \frac{Measured - Accepted}{Accepted} \right| \times 100$$

Compare your answer to the accepted value by calculating the % error.

Relative Motion in One Dimension

Equipment

2	Motion Sensor	PS-2103A
1	1.2 m PAScar Dynamics System	ME-6955
1	Cart Adapter Accessory	ME-6743
1	Motorized Cart	ME-9781
1	Car Sail	ME-9595
1	Elastic Bumper	ME- 8998
Required, but not included:		
1	850 Universal Interface	UI-5000

Introduction

The purpose of this lab is to study motion relative to a moving reference frame. The speed of the red PAScar (see Fig. 1) as measured by the Motion Sensor at the far right, is not the same as the speed measured by the Motion Sensor located on the moving Motorized Cart. This "relative velocity" of the red car is measured directly by the Motion Sensor and compared to the expected value.

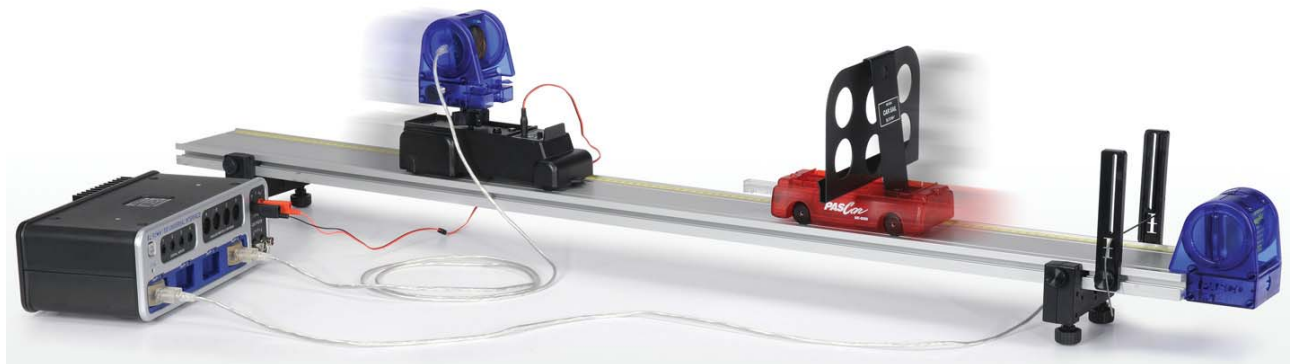


Figure 1: Measuring Relative Motion from Moving Cart

Setup

1. The Motion Sensor connects to the Cart Adapter with the 1/4 -20 screw into the bottom of the Motion Sensor. Fasten Cart Adapter in the Motorized Cart top tray. Position the Motion Sensor so it points forward and use the large knob to lock it into position.
2. The Motion Sensor on the Motorized Cart **MUST** be plugged into PASPORT port #4 as shown in Figure 2. Plug the Motorized Cart power cord into Output #1, and make sure it is on the OFF/EXTERNAL SETTING.
3. It is easier to install the Elastic Bumper (Fig. 3) first. The Motion Sensor then slides onto the end of the track. This second Motion Sensor **MUST** be plugged into PASPORT port #1. Make sure the range switch is on the "cart" icon for **BOTH** sensors.
4. Mount the Car Sail Bracket on the red car. Use the adjustable feet to level the track so that the red car doesn't move when released.
5. The Motion Sensor on the track will measure the motion of the cart. The Motion Sensor on the Motorized Cart will measure from the Car Sail Bracket (mounted on the car) and is thus the relative motion between the two.
6. In the PASCO Capstone Summary, change the default units on the Position of each Motion Sensor to cm. Create a graph of Position, Port P1, vs. time. Then add a similar measurement Position, Port P4, by clicking on the vertical axis Position label and choosing "Add Similar Measurement". The sample rate for both Motion Sensors should be 20 Hz.

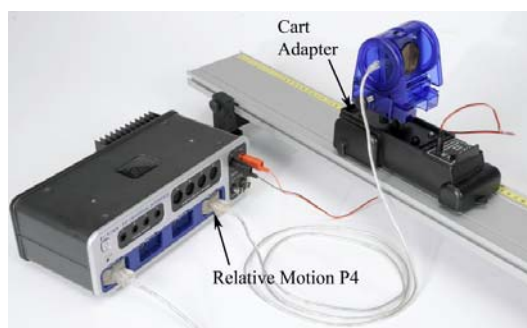


Figure 2: Motorized Cart with Motion Sensor

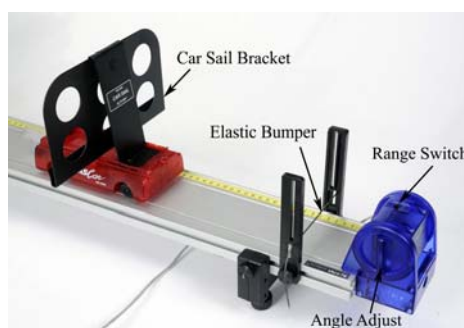


Figure 3: Motion Sensor on Track

Procedure – Measuring Position

1. Position the Motorized Cart on the track at the far end from the Motion Sensor. Place the red car about 20 cm from the Motorized Cart.
2. Start recording, and then move the red Car to the opposite end of the track. Note placement of hand on cart in Figure 4, below. Stop Recording.
3. Identify which data set is for which cart. The data needs to be continuous with no glitches. Turn the handle (Fig. 3) on the Motion Sensor to adjust the angle to improve data. Note that the Motion Sensor cannot measure a distance of less than 15 cm.
4. You can delete unwanted runs using the Delete Run feature in the Control Palette at the bottom.



Figure 4. Moving the Cart

Procedure – Measuring Speed

The speeds measured by the Motion Sensors in this lab are calculations that include an absolute value. Thus all values measured by the computer will be positive.

The Motion Sensor on the track will measure the actual speed of the red car. The Motion Sensor on the Motorized Cart measures the relative speed between the two carts. The actual speed of the Motorized Cart is determined by the voltage applied in the next section.

5. In the Capstone calculator, create two calculations:
V cart=abs(derivative(5,[Position, Ch P1 (cm)],[Time (s)]))
V rel=abs(derivative(5,[Position, Ch P4 (cm)],[Time (s)]))
6. Make a graph of both the velocity calculations vs. time. Right-click on the vertical axis and, in the Properties, make the Axis Label have a custom name called "Speed".
7. With the red car in the middle of the track, start recording. Smoothly move the red car to the left (10 to 20 cm) and then to the right and then back to center in a total time of about 5 seconds.
8. How does it look? Identify which data set was measured where. The data needs to be continuous with a minimum of glitches.
9. Once you have the system working so that you are getting good data from both sensors, delete all runs (using the Delete Run feature in the Control Palette at the bottom) and proceed to the next page.

Motorized Cart

10. Position the Motorized Cart on the track at the far end from the Motion Sensor. Place the red car at rest against the Elastic Bumper.
11. Set DC Voltage Output #1 to 2.00 volts. Start recording, then click the Output "On". Click the output "Off" before the Motorized Cart reaches other end.
12. Note the speed (Vrel) of the Motorized Cart, using graph and digits displays. Set the voltage to 2.10 volts and repeat. How does that change the speed?
13. Adjust the voltage to get the speed of Motorized Cart as close as possible to 10 cm/s.
14. Set the Output to "Auto" mode. This will automatically turn on the Motorized Cart when you start recording, and turn it off when you stop recording. Try a few trial runs to make sure the Motorized Cart turns on and off properly, and that the speed of the Motorized Cart is 10 cm/s.

Relative Motion

15. For this part, use the Speed (of both) vs. Time graph you made previously. Also make a table with a User-Entered Data Set called “Calculated Speed” with units of (cm/s) in the first column and another User-Entered Data Set called “Measured Speed” with units of (cm/s) in the second column.
16. Position the Motorized Cart on the track at the far end from the Motion Sensor. Starting with the red car near the middle, push the red car (away from the Motorized Cart) towards the Motion Sensor on the track, and allow it to bounce off the Elastic Bumper. Start recording as soon as the cart has changed directions. Stop recording before the two collide.
17. Pick a time on the graph where you have smooth speed data for both. Use the coordinate tool to measure the speed of the red car.
18. Calculate the relative speed. Remember that the speed of the Motorized Cart is 10 cm/s. For a head-on collision, how do you calculate the relative speed? Do you add the speeds or subtract?
19. Measure the relative speed off the graph and compare to your calculation. Repeat for two other trials.
20. Repeat for the two carts moving in same direction.

Analysis

21. For each of your data pairs, compare the measured speed to the calculated (accepted) value using the % error calculation:

$$\%error = \left| \frac{Measured - Accepted}{Accepted} \right| \times 100$$

22. Record your values.
23. In general, how well do the values compare?

Graph Matching

Equipment:

1	Motion Sensor	PS-2103A
1	Car Sail	ME-9595
1	Table Clamp	ME-9472
1	45 cm Rod	ME-8736

Required, but not included:

1	PASPORT Interface	
1	PASCO Capstone	

Introduction

The purpose of this activity is to explore plots of position and velocity vs. time. The Motion Sensor is used to detect the motion of a person moving back and forth in front of the sensor along a straight line at different speeds. The challenge is to move in such a way that a plot of the motion ‘matches’ the graph that is provided. This is an excellent way to learn what the graphs mean.

Set-up

1. Use the Rod Clamp and 45 cm Rod to fasten the Motion Sensor to the table, as shown in Figure 1. You will need at least 3 m of empty room in front of the sensor.
2. Connect the Motion Sensor to the Interface. Set the Motion Sensor to the “people” setting.
3. Aim the Motion Sensor at your midsection when you are standing in front of the sensor. You will hold the large blue "sail" from the ME-9595 (see Fig. 1) in front of your body to improve your results, since a reflection from different parts of your body as you move can mimic rapid motion back and forth.
4. Position the computer monitor so you can see the screen while you move away from the Motion Sensor.
5. Open the PASCO Capstone file called “04 Graph Matching.cap”.

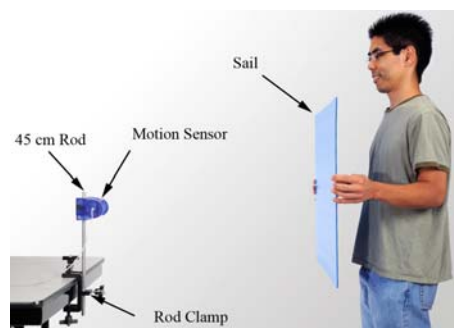


Figure 1: The large blue "sail" from the ME-9595 Car Sail is used as a target to improve the graph results using the Motion Sensor.

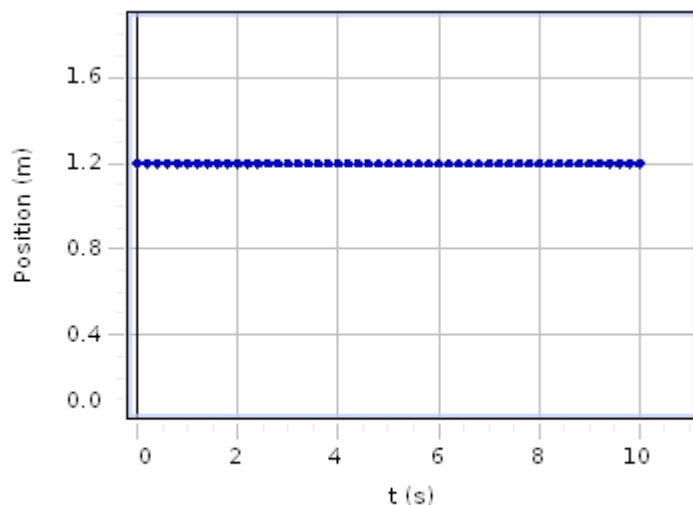
Procedure

Practice

1. You will stand about 1 meter in front of the Motion Sensor, holding the "sail" as shown in Figure 1.
2. Click on Record. The Motion Sensor will make a faint clicking noise and the green LED will flash to tell you it is on. There is a 3-second delay before data begins to be recorded. This delay gives you time to adjust your position.
3. Walk towards and then away from the sensor, watching the graph as you move. The recording will stop automatically after 10 sec. Did the graph correctly record your position?

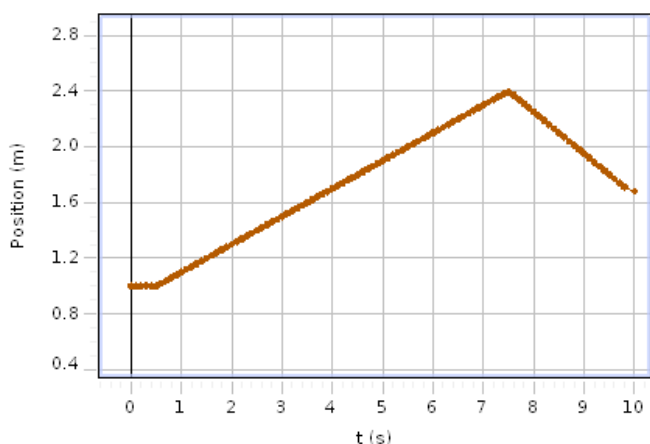
Graph Matching

1. On each of the following pages, there is a graph you will try to match. The first three are position graphs, and the next four are velocity graphs. For the velocity graphs, start about 1/2 meter from the Motion Sensor. For the position graphs, you can see the starting distance on the graph, and you should try to start at that position.
2. Try to match the graph by moving forward or backward. The Score display will show how closely you match the graph. The closer it is to 100, the better. It is fairly easy to get a score above 95 on the position plots. The velocity plots are harder and scores above 80 are good.

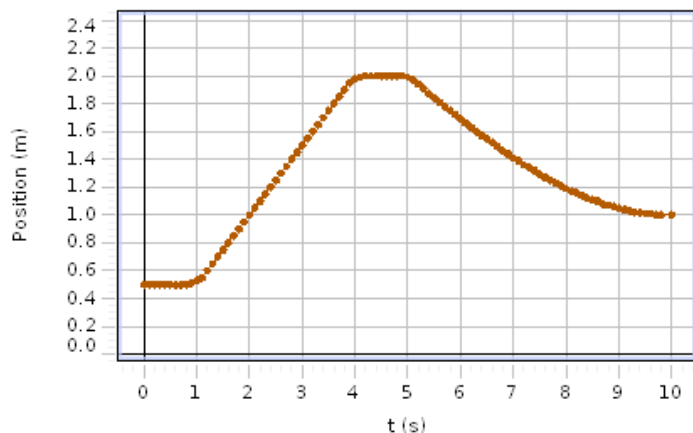


Position 1

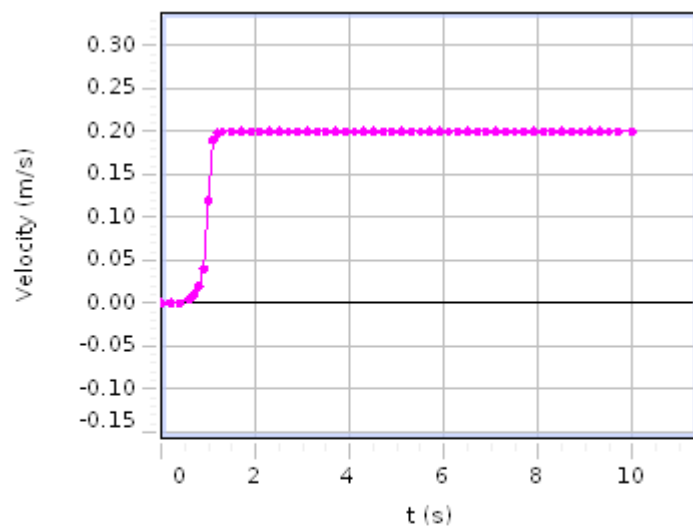
1. Before you click on Record, think about where you should stand initially and how you should move to match the graph. Then click on record. Try to match the graph. The recording will stop automatically after 10 sec.
2. Repeat the data recording process as many times as you need (time permitting) to get your best match.
3. See which lab partner can get the best score. On a piece of paper, note which Run #'s were the best and who did them.
4. You can delete unwanted runs using the Delete feature in the bottom control bar.
5. If you want to examine a previous run, use the black triangle by the Run Select icon in the graph tool pallet above the graph.
6. Repeat the process for the rest of the graphs.



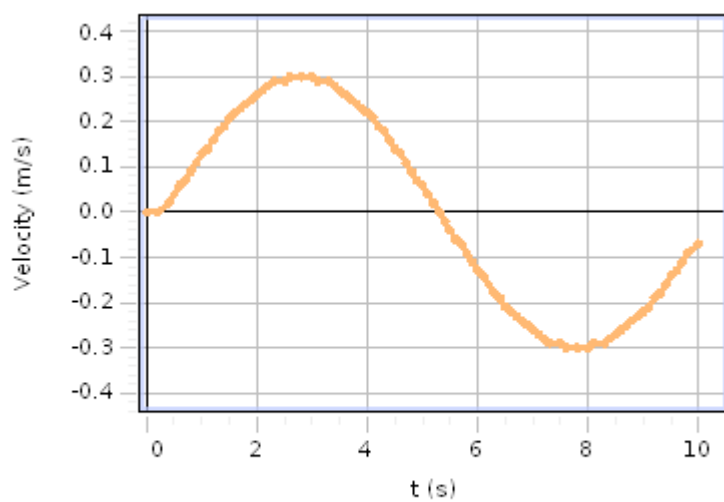
Position 2



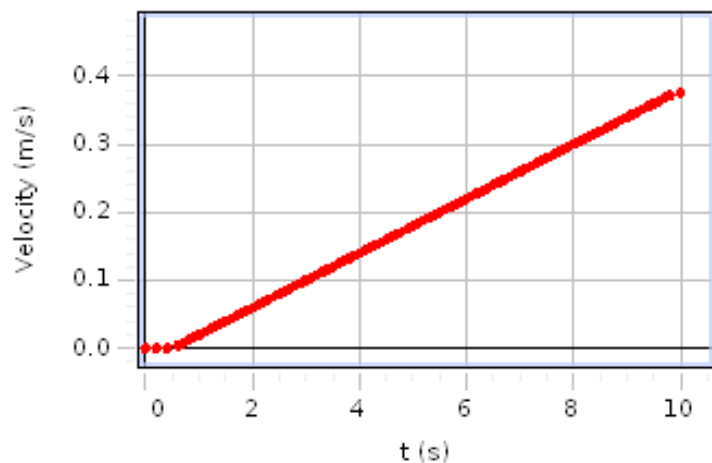
Position 3



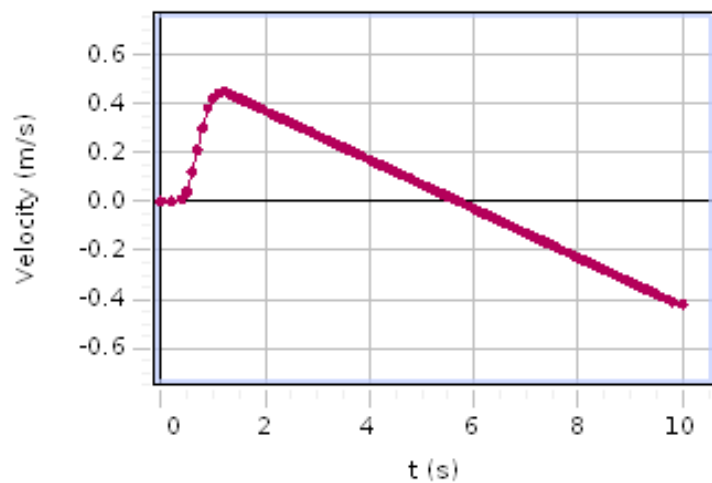
Velocity 1



Velocity 2



Velocity 3



Velocity 4

Analysis

Position Plots

1. What does a horizontal line mean?
2. What is the difference between the parts of the plot with positive slope and the parts with negative slope?
3. On the Position 3 plot, what is happening between 5 and 10 seconds?
4. What parts of the plot were easier to match? What parts of the plot were the hardest to match? Why?

Velocity Plots

1. What does a horizontal line mean?
2. What is the difference between the parts of the plot with positive slope and the parts with negative slope?
3. Consider the Velocity 2 plot. What is the difference between places where the slope is large and places where it is near zero?
4. Consider the Velocity 2 plot. Where is the acceleration largest? What is the speed at that point?
5. Which of the four Velocity plots could qualitatively describe the vertical speed of a ball thrown vertically upward?

Instantaneous and Average Speed

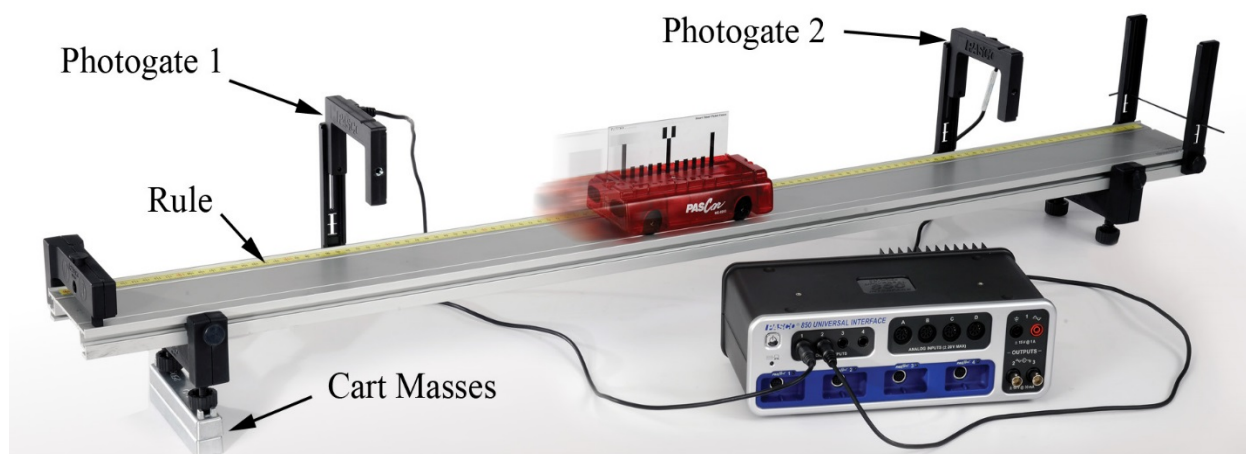


Figure 1: Inclined Dynamics Track

Introduction

The Photogates measure the speed of the PAScar at two places on the inclined track. As the Photogates are moved closer together, the average speed of the cart is calculated over decreasing intervals of distance. In the limit that this interval goes to zero, the average speed approaches the value of the cart's instantaneous speed.

Equipment

Qty	Items	Part Number
1	PAScar Dynamics System	ME-6955
1	Smart Timer Picket Fence	ME-8933
1	Elastic Bumper	ME-8998
2	Photogate Bracket	(In ME-8998)
2	Photogate Head	ME-9498A

Set-up

1. Install the two Photogate Brackets on the track on the side with the rule as shown in Figure 1. Place the Cart Masses under the track feet on one side to incline the track.
2. Install the fixed End Stop at the top of the incline, and an Elastic Bumper at the bottom.
3. The Photogate at the top of the incline MUST be plugged into Digital Input #1, and the Photogate at the bottom of the incline into Digital Input #2 (see Fig.3).

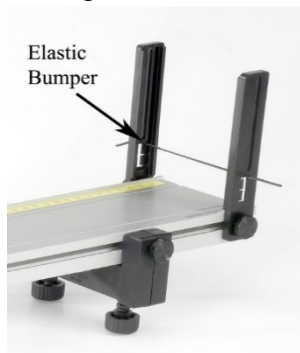


Figure 2: Lower End of Track

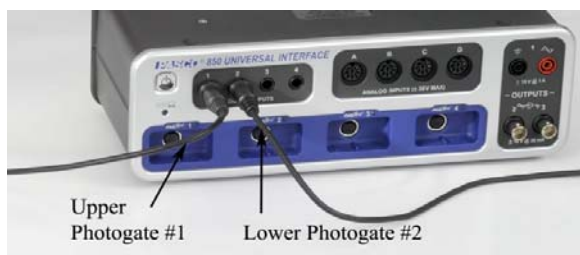


Figure 3: Connecting Photogates to 850

4. Place the PAScar on the track (including Picket Fence), making sure that the end of the car with the Velcro is on the upper end (see Fig. 4). This insures that the magnets in the PAScar and the magnets in the upper fixed End Stop do not interact.
5. Adjust the height of the Photogates so that the "Double Flag" on the top of the Picket Fence breaks the beam as the PAScar moves by. Observe the indicator light on top of the Photogate.

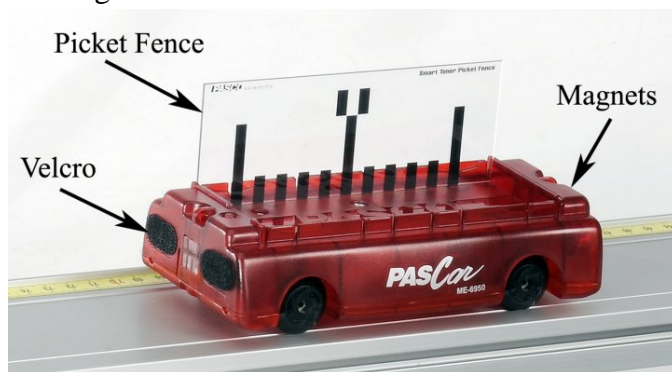


Figure 4: Cart with Double-Flag on Top

6. In PASCO Capstone, use the Timer Setup, choose "Two Photogates (Double Flag)" and select measurements Speed in Gate 1 and Speed in Gate 2. Set the flag length to 0.01 m.

7. Change the Sample Mode to Keep.

8. Create a table:

Table I

	<No Data Selected>	<No Data Selected>
	Speed in Gate 1, Ch 1 (cm/s)	Speed in Gate 2, Ch 2 (cm/s)
1		
2		
3		
4		
Mean	--	--
Std. Dev.	--	--

9. Create another table:

Table II

	Position (cm)	Distance (cm)	Speed 1 (cm/s)	Speed 2 (cm/s)	Avg speed (cm/s)
1					
2					
3					

In the first column, create a User-Entered Data Set called Position with units of cm. This is the position of the lower photogate.

In the second column, create a User-Entered Data Set called Distance with units of cm. This is the distance between the two photogates.

In the third column, create a User-Entered Data Set called Speed 1 with units of cm/s.

In the fourth column, create a User-Entered Data Set called Speed 2 with units of cm/s.

Create a calculation:

$$\text{Avg speed} = ([\text{Speed 2 (cm/s)}] + [\text{Speed 1 (cm/s)}]) / 2 \text{ with units of cm.}$$

and select this calculation in the fifth column.

Measuring Speed

1. Place the upper Photogate at the 100 cm mark, and the lower Photogate at the 20 cm mark.
2. Click on Preview to start Preview Mode. Data will not be stored until you click on Keep Sample. Move the cart to the top of the incline, using the upper fixed End Stop to start the

car in the same position each time. Release the car, allowing it to freely roll down the track, but do not allow it to bounce back through the photogate.

3. When you click on Keep Sample, it will store that pair of data points into your table. Do not press stop. Move the car to the top of the incline and allow it to roll down again. Since there is uncertainty in the measurement, take several runs. Note the mean (average) values are being calculated at the bottom of the table.
4. When you get good steady values for the speeds, click on Stop and record these two numbers in the first row of Table 1 under Speed 1 and Speed 2. Note the Average speed is calculated in the last column.
5. Move the Photogates to the 25 and 95 cm positions and repeat steps 2 through 4.
6. Move the upper photogate down by 5 cm and move the lower photogate up by 5 cm and repeat the measurements. Continue this process until the photogates meet at 60 cm from the top.
7. Move the lower Photogate out of the way (not needed now) and place the upper Photogate at the 60 cm position. Measure the speed of the car several times to get an average. This is the "instantaneous" speed of the car at the midpoint.

Analysis – Instantaneous Speed

1. Make a graph of Avg Speed vs. Distance.
2. Observe the shape of the Avg Speed vs. Distance graph. In the limit that the distance between the photogates goes to zero, the average speed approaches the value of the cart's instantaneous speed at that 60 cm midpoint. If you extrapolate the curve for a distance of zero spacing, what value do you get for the average speed?
3. Try using a curve fit on your data. A polynomial fit should work. If you open the Curve Fit Editor (left Tool Palette) you can try changing the number of terms in the polynomial. What value does this give you for the average speed?
4. Compare your value of the average speed with zero spacing to the actual instantaneous speed you measured in part 7 of the procedure.

Position and Velocity

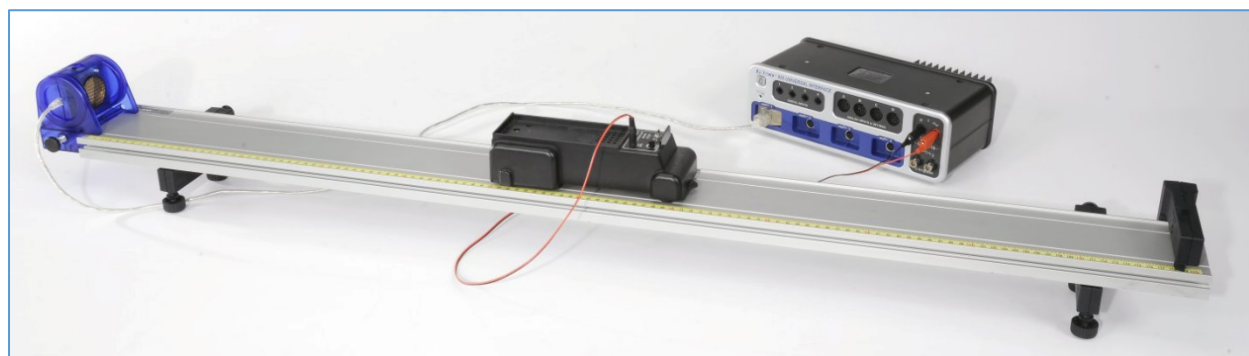
Introduction

The purpose of this experiment is to investigate the relationship between position and velocity. A Motion Sensor is used to measure the position of the motorized cart on the track. Graphs of position vs. time are created, and the velocity is calculated by measuring the slopes of these graphs.

Three different scenarios are implemented to investigate the differences between constant velocity, average velocity, and instantaneous velocity.

Equipment

Qty	Items	Part Number
1	PASCO Motion Sensor	PS-2103A
1	PAScar Dynamics System	ME-6955
1	Motorized Cart	ME-9781



Set-up

1. Set up the track with feet and bumper as shown in Figure 1. Attach the Motion Sensor to the track and connect it to the 850. Make sure the range switch is on the "cart" icon.
2. Plug the motorized cart power cord into the 850 Output #1, and make sure the switch on the cart is in the OFF/EXTERNAL setting.
3. Set a Stop Condition (on the Sampling Bar) to be based on the measurement Position so when the Position is above 0.9 m, sampling will stop.
4. Create a graph of Position vs. Time.

Procedure - Constant Velocity

1. Position the back of the Motorized Cart at the 20 cm mark. This will be the starting position of the Cart for EVERY run. Always return the Cart to this position.
2. Set the 850 Output is set on DC with a voltage of 2 Volts. Turn the Output ON and OFF to ensure that everything works.
3. Start recording data. Turn the Output ON and OFF to ensure that you are getting good position data.
4. You can delete unwanted runs using the Delete Run feature in the Control Palette at the bottom.
5. When everything looks good, click on Auto in the Output Control. This will cause the output to automatically turn on when you start recording. You can stop recording anytime you wish, but there you have also built in a stop condition that will stop the Cart before it reaches the bumper.
6. Get a single good run of position vs. time for the Cart, then repeat for a voltage of 3 V and 4 V.
7. Get three good runs on your graph.

Measuring Slopes

1. Make run #1 active by clicking on it in the Graph Legend. Select a linear Curve Fit from the upper tool palette.
2. What is the physical meaning of the slope? Does it have units?
3. How linear is your data? Was this truly constant velocity?
4. What is the physical meaning of the y-intercept on the graph? Does it have units?
5. Do a linear Curve Fit on the other two curves.

Average Velocity – Non-constant Velocity

1. Set the 850 Output on a Square Wave with a voltage Amplitude of 2 V, and a Voltage Offset of 2 V. With the Frequency set at 1 Hz, the Cart will run for 1/2 second, off for 1/2 second, on for 1/2 second, etc. With the Auto button clicked, the Cart should stop before it reaches the end.
2. Start recording. Get a single good run of position vs. time for the Cart. You can delete unwanted runs using the Delete Run feature in the Control Palette at the bottom.
3. Calculate the average velocity of the Cart for the entire run by measuring the total Δx and Δt .
4. Select a linear Curve Fit. How does this speed compare to your calculation of the total average?
5. Use the Selection Tool to highlight a small section of the data when the Cart is moving at a constant velocity. How does this velocity compare to the average for the entire run?

Instantaneous Velocity

6. Confirm that the 850 Output is set on Positive Ramp with a Voltage Amplitude of 4 Volts, and a Voltage Offset of 1 Volt. With the Frequency set at 0.1 Hz, the Cart will ramp up its speed over a 10 second period, but the automatic stop should stop it before it reaches the end.
7. Start recording. Get a single good run of position vs. time for the Cart. You can delete unwanted runs using the Delete Run feature in the Control Palette at the bottom.
8. Calculate the average velocity of the Cart for the entire run by measuring the total Δx and Δt .
9. Select a linear Curve Fit. How does this speed compare to your calculation of the total average?
10. Use the Selection Tool to highlight only about 1 second of data. You can then move this selection to find the average speed at different locations.
11. Move the Selection Tool to the beginning data, and reduce the size of the box while watching the slope. In the limit that you reduce this size to as small as possible, the slope approaches the instantaneous velocity of the Cart. Using this method, measure the minimum and maximum speed of the Cart.

Velocity and Acceleration

Introduction

This lab uses a Motion Sensor to measure the motion of a motorized cart and a fan cart. Graphs of position and velocity are analyzed for constant velocity, and constant acceleration. The output from the 850 interface is used to control the speed of the motorized cart.

Equipment

Qty	Items	Part Number
1	Motion Sensor	PS-2103A
1	Dynamics System	ME-6955
1	Motorized Cart	ME-9781
1	Fan Cart	ME-6977
1	Elastic Bumper	ME-8998

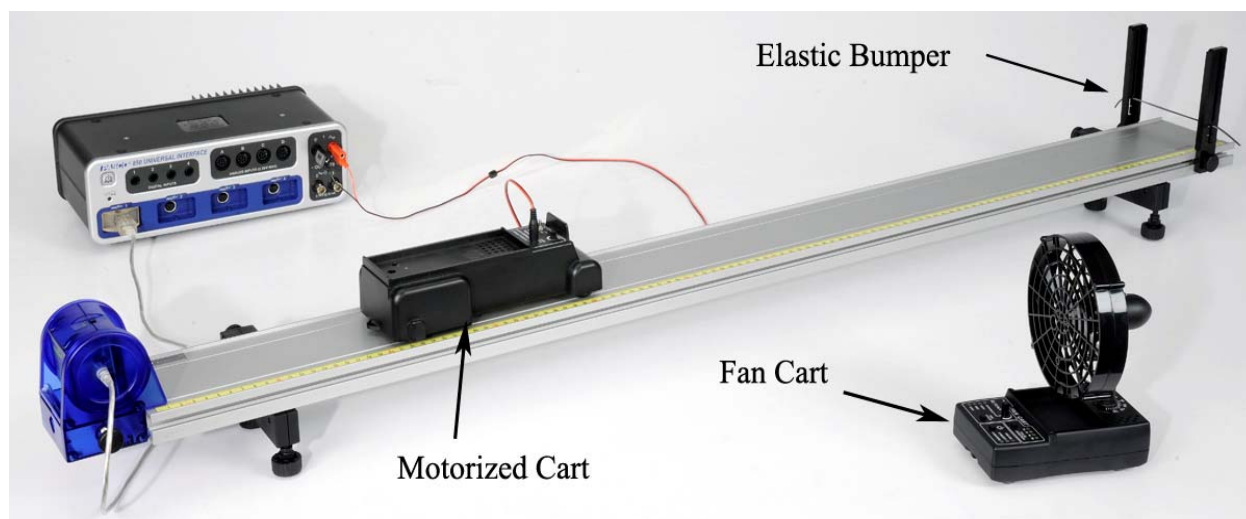


Figure 1: Motion of the Motorized Cart

Set-up

1. Set up the track as shown in Figure 1 with the elastic bumper and feet. Note that the motion sensor is on the end of the track that is the zero point for the yellow rule. Connect the motion sensor to the 850 and make sure the range switch is on the "Cart" icon.
2. Plug the motorized cart power cord into Output #1 on the 850, and make sure it is on the OFF/EXTERNAL SETTING. The fan cart will not be used until later in the experiment.

3. Make a graph of Position versus Time.
4. In the Recording Conditions on the Sampling Bar at the bottom of the page in Capstone, select the Stop Condition and make the Condition Type Measurement Based. Select Position as the Data Source. Make the condition: Is above 0.80.

Procedure – Motorized Cart

1. Position the back of the Motorized Cart at the 20 cm mark. Always start the cart from this position.
2. Confirm that the 850 Output #1 is set on DC with a voltage of 2 Volts. Turn the Output ON and OFF to ensure that everything works.
3. Start recording data. Turn the Output ON and OFF to ensure that you are getting good position data.
4. You can delete unwanted runs using the Delete Run feature in the Control Palette at the bottom.
5. When everything looks good, click on Auto in the Output Control. This will cause the output to automatically turn on when you start recording. You can stop recording anytime you wish, but there is also a stop condition built-in that will stop the cart before it reaches the bumper.
6. Get a single good run of position vs. time, then open the Data Summary window and label this run Motorized Cart.

Velocity

If $x(t)$ is a function that describes the position of an object as a function of time, then the velocity of the object is given by $v(t) = dx/dt$, the first derivative of the position function. Graphically, the velocity is the slope of the position graph.

1. For your position graph of the Motorized Cart, how does the slope vary during the run?
2. Select a linear Curve Fit from the graph tool palette.
3. What is the physical meaning of the slope? Does it have units?
4. How linear is your data? Was this constant velocity?
5. What is the physical meaning of the y-intercept on the graph? Does it have units?

Setup - Fan Cart

1. Place the fan cart on the track as shown in Figure 2. The fan can swivel on its base: It should be pointed back towards the motion sensor with the angle indicator set to zero degrees.
2. Adjust the level of the track so that the cart is rolling slightly downhill, to compensate for frictional drag. Give the cart a slight push to the right (away from motion sensor). If it speeds up, the track is too steep.
3. Turn on the fan cart by pressing its power button. The fan cart is now in Standby mode, and the fan speed should be set on Low. Press the power button again to start and stop the fan.
4. Press the fan speed button to change the speed to the Medium setting. Press the power button again to start and stop the fan.



Figure 2: Motion of Fan Cart



Figure 3: Fan Power



Figure 4: Adjusting Fan Speed

5. In Capstone, create a Start Condition: Position is above 0.20. Make the Stop Condition: Position is above 0.50.

Procedure – Fan Cart

1. Position the back of the fan cart at the 15 cm mark
2. Make sure the fan speed is on the Medium setting. Press the power button to start the fan, but hold on to the cart to keep it at the 15 cm mark.
3. Start recording data, and then release the cart. There will not be any data plotted on the graph until the cart has reached the 20 cm mark due to the start condition. This allows the cart to start moving before actual data collection begins, and gives a better looking graph. You can stop recording anytime you wish, but there is also a stop condition built-in that will stop recording before the cart reaches the bumper.
4. You can delete unwanted runs using the Delete Run feature in the Control Palette at the bottom. Get a single good run of position versus time data, and then rename this run “Fan Cart”.
5. For your position graph of the Fan Cart, how does the slope vary during the run? Was this constant velocity?

Velocity Graph

6. Use the same Start Condition but change the Stop Condition to Position above 0.70.
7. In the graph, click on the Add a Plot Area tool in the toolbar. On the second plot area below the Position plot, select Velocity on the vertical axis.
8. Click on the position graph to make that graph active, then select the Slope tool from the graph tool palette.
9. Move the slope tool to 0.2 seconds on the graph.
10. What is the slope at this point (including units)?
11. How does this compare to the speed on the velocity graph for this same time?
12. Repeat for 0.4 s and 0.6 s.

Constant Acceleration

If $v(t)$ is a function that describes the velocity of an object as a function of time, then the acceleration of the object is given by $a(t) = dv/dt$, the first derivative of the velocity function. Graphically, the acceleration is the slope of the velocity graph.

1. Make a velocity vs. time graph. For your velocity graph of the Fan Cart, how does the slope vary during the run?
2. Select a linear Curve Fit from the graph Tool palette.
3. What is the physical meaning of the slope? Does it have units?
4. How linear is your data? Was this truly constant acceleration?
5. What is the physical meaning of the y-intercept on the graph? Does it have units?

Fan Cart with Short Pulse: Non-Constant Acceleration

1. Remove the Start Condition and keep the Stop Condition as before.
2. On the fan cart, press the Pulse Duration button as shown in Figure 5. With the "1s" LED lit, the fan will run for 1 second and then turn off. When you press the Power Button, there is a 2 second delay before the fan turns on.
3. Press the Power Button, and immediately start recording data. You can stop recording anytime you wish, but there is also a stop condition built-in that will stop recording before the cart reaches the bumper.
4. Get a single good run of velocity versus time data, and then rename this run "Fan Pulsed".



Figure 5. Setting Time of Pulse

Velocity Analysis

5. Label the points on the graph where the acceleration of the cart was zero.
6. Label the points on the graph where the acceleration of the cart was constant, but not zero.
7. How do these points coincide with where the fan was on?
8. Use the Area tool in the graph tool palette to calculate the area under the velocity vs. time graph. What is the physical meaning of the area? What are the units?
9. From the shape of the velocity vs. time graph, predict the shape of the position vs. time graph.

Position Analysis

10. Make a Position versus Time graph.
11. Did you correctly predict the shape of the position vs. time graph?
12. Can you identify the points on the graph where the fan turned on and off?
13. Use the Coordinates tool (from the graph tool palette) to measure the last position data point. How does that point correspond to the area you took on the previous page?
14. When the Coordinates tool has been selected, you can right click on the cursor (on the graph) to activate the Delta tool. Using the Delta tool, measure the total displacement of the cart. How does this value correspond to the area you took on the previous page?

The Great Race

Introduction

The Fan Cart gets off to a slow start, but has a constant acceleration. The Motorized Cart has a constant speed and initially pulls out ahead. But what determines who wins the race? This lab uses Motion Sensors to measure the position of the carts, and the output from the 850 Interface is used to control the speed of the Motorized Cart.

Equipment

Qty	Items	Part Number
2	Motion Sensor	PS-2103A
1	Dynamics System	ME-6955
1	Motorized Cart	ME-9781
1	Fan Cart	ME-6977
1	Elastic Bumper	ME-8998

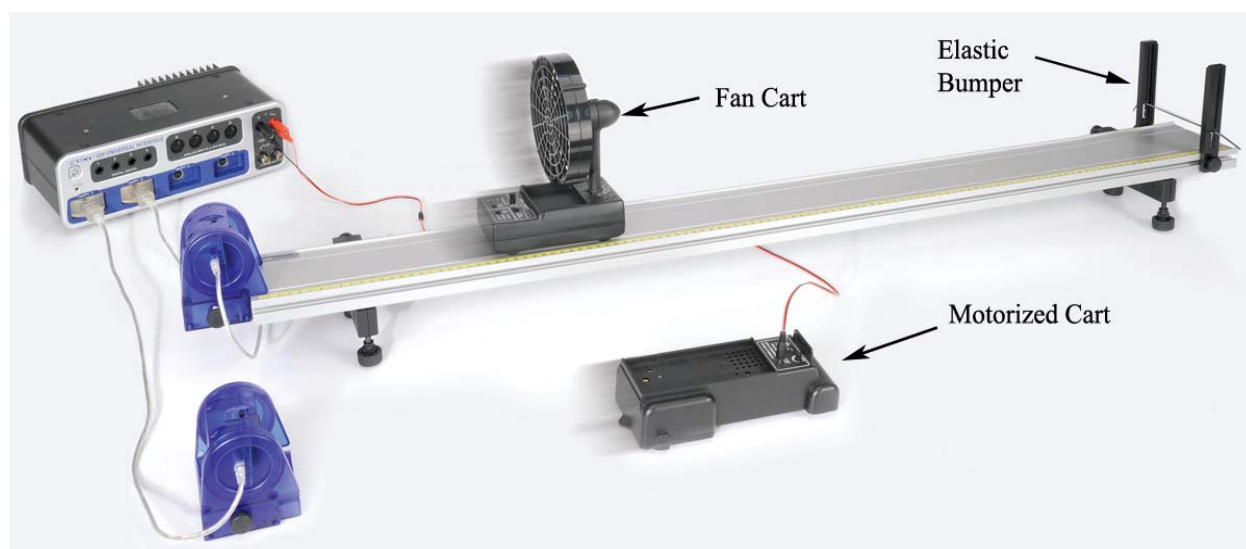


Figure 1: Which cart wins the race?

Set-Up

1. Set up the track as shown in Figure 1 with the Elastic Bumper and feet. Note that the Motion Sensor is on the end of the track with the zero point for the yellow rule.
2. Connect both motion sensors to the 850. Make sure the motion sensor range switches are both on the "cart" icon.
3. Plug the motorized cart power cord into Output #1 on the 850. Make sure the setting on the motorized cart is OFF/EXTERNAL.
4. Place the Fan Cart on the track as shown in Figure 2. The fan can swivel on its base: It should be pointed back towards the motion sensor, with the angle indicator set to zero degrees.

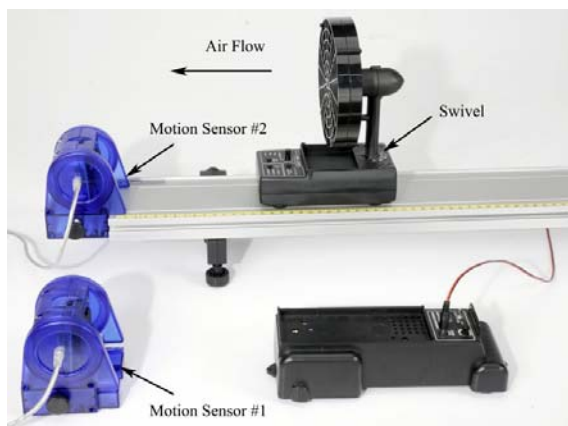


Figure 2: Measuring Motion of Fan Cart and Motorized Cart



Figure 3: Turning on Fan Power

5. Adjust the level of the track so that the cart is rolling slightly downhill, to compensate for frictional drag. Give the cart a slight push to the right (away from motion sensor). If it speeds up, the track is too steep.
6. Turn on the fan cart (see Fig. 3) by pressing its power button. The fan cart is now in Standby mode, and the fan speed should be set on Low. Press the power button again to start and stop the fan.

7. Press the Pulse Duration button as shown in Figure 4. Press it again to toggle through the selections. With the "4s" LED lit, the fan will run for 4 seconds and then turn off. When you press the power button, there is a 2 second delay before the fan turns on.
8. Create a graph of position vs. time for both carts with the position of both carts on the same vertical axis (to do this, choose the fan cart position on the vertical axis and then choose "Add Similar Measurement" on the measurement picker and add the motorized cart position).
9. The sample rate of both the motion sensors should be 20 Hz.



Figure 4: Setting Time of Pulse

Procedure

1. Position the back of the Fan Cart at the 16 cm mark. Position the back of the Motorized Cart so that it is the same distance from its Motion Sensor. This will be the starting position of the carts.
2. Confirm that the 850 Output #1 is set on DC with a voltage of 4 Volts. The Output should be on Auto, so the power to the Motorized Cart will automatically turn on when data recording is started.
3. Confirm that the Fan Cart is on Low Fan Speed and 4 second Pulse Duration.
4. Get ready to start recording data. Press the Power Button on the Fan Cart. There is a 2 second delay before the fan starts. As soon as the fan turns on, start recording data. This will also automatically start the Motorized Cart.
5. Stop recording just before the Fan Cart reaches the bumper. The fan will turn off after it has run for 4 seconds.
6. You can delete unwanted runs using the Delete Run feature in the Control Palette at the bottom. If the Fan Cart can't catch up before the end of the track, try decreasing the speed of the Motorized Cart by lowering the voltage of the 850 Output by a few tenths of a volt. Get at least one good run of data where the Fan Cart wins!

Analysis

1. Which cart won the race?
2. Select the Slope tool from the graph tool palette, and use this to measure the slope of the Motorized Cart data. What was the approximate speed of the Cart?
3. The speed of the Fan Cart was not constant, but you can move the Slope tool around to find the speed at different locations. What was the max speed of the Fan Cart?
4. When do the two carts have the same speed?
5. When are the two carts at the same position?

Equations of Motion for Constant Acceleration

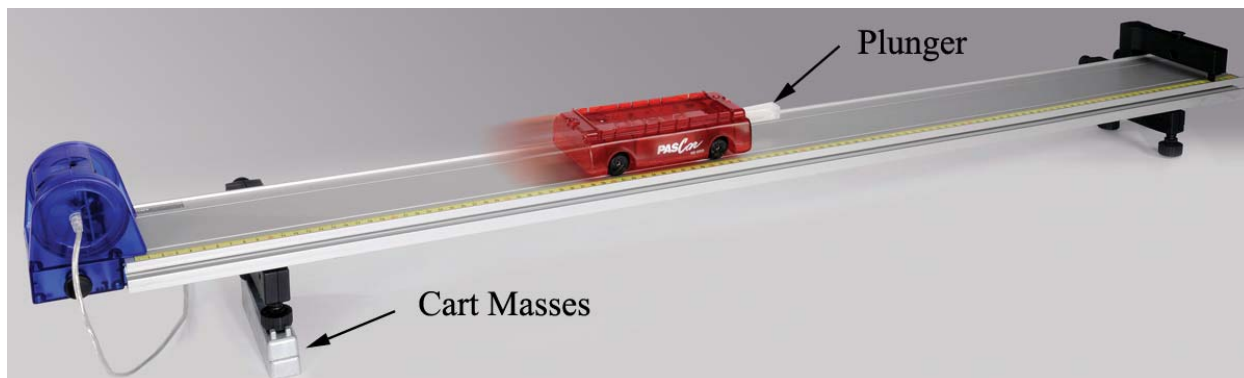


Figure 1: Cart on Incline

Introduction

The motion of a cart as it accelerates down an incline is measured by a motion sensor. Graphs of position and velocity are studied and comparisons are made to the standard equations of motion using User Defined Curve Fits.

Equipment

Qty	Items	Part Number
1	Motion Sensor	PS-2103A
1	Dynamics System	ME-6955

Set-up

1. Set up the track as shown in Figure 1, including feet and endstops. Note that the Motion Sensor is on the end of the track that is the zero point for the yellow rule.
2. Plug the Motion Sensor into the interface, and set the range switch to the "Cart" icon.
3. Make sure the plunger on the cart is on the side towards the endstop.
4. Use the two Cart Masses to incline the track.
5. In PASCO Capstone, create a graph of Position vs. Time.

Procedure

1. Position the back of the cart (closest to the Motion Sensor) at the 16 cm mark as shown in Figure 2. This is the starting position for the cart.
2. Click on Record, and then release the cart. Data collection will NOT start until the cart reaches a position of 18 cm, due to an initial starting condition. This will give you better looking data.
3. You can stop recording at any time, but there is an automatic stop condition that stops the recording when the cart reaches 80 cm.
4. You can delete unwanted runs using the Delete Run feature in the Experiment Control Bar.
5. Get a single good run of position vs. time data.



Figure 2: Starting Position

Position Equation

6. Select a User Defined Curve Fit from the Curve Fit list on the graph toolbar.
7. If the curve fit parameters do not appear in the editor window (at left) click on the curve fit annotation (on the graph) to make it active. Then open the Curve Fit Editor at the left of the screen.
8. The equation for the user curve fit in the editor window will initially be:

$$y = A * t + B$$

Edit this to read:

$$x_0 + v_0 * t + (1/2) * a * t^2$$

To make the subscripted zero, you can right-click and select the subscript.

9. Click on Apply.

10. Record the initial position, x_o , the initial velocity, v_o , and the acceleration, a .

Velocity Equation

11. Create a graph of Velocity vs. Time.
12. Select a User Defined Curve Fit from the graph tool palette.
13. If the curve fit parameters do not appear in the editor window (at left) click on the curve fit annotation (on the graph) to make it active.
14. Edit the equation (in the Curve Fit Editor at left), and change it to
$$y = v_o + a * t$$
15. Click on Apply
16. Record the initial velocity, v_o , and the acceleration, a .

Analysis

1. What is the initial position, x_o ? Remember that the Start Condition (when data was recorded) was when the cart reached 18 cm. How does it compare?
2. How does your value for v_o from the position graph compare to your value for v_o from the velocity graph?
3. How does your value for "a" from the position graph compare to your value for "a" from the velocity graph?
4. Click on the position graph to make that graph active, then select the Slope tool from the graph tool palette.
5. Move the Slope tool to 0.4 seconds. What is the slope at this point (including units)? How does this compare to the speed on the velocity graph for this same time?
6. Repeat for 0.8 s and 1.2 s.

Acceleration Due to Gravity

Introduction

The purpose of this lab is to measure the acceleration of a cart moving down an incline, and compare the measured value to the theoretical.

A cart on an incline will roll down the incline as it is pulled by gravity. The direction of the force of gravity is straight down, but the component of the acceleration due to gravity that is parallel to the inclined surface is only a fraction of the total acceleration due to gravity:

$$a = g \sin\theta$$

where θ is the angle of incline.

Equipment

Qty	Items	Part Number
1	Motion Sensor	PS-2103A
1	Dynamics System	ME-6955
1	Large Rod Base	ME-8735
1	Rod, 45-cm	ME-8736
Required but not included:		
1	Meter Stick	SE-8695

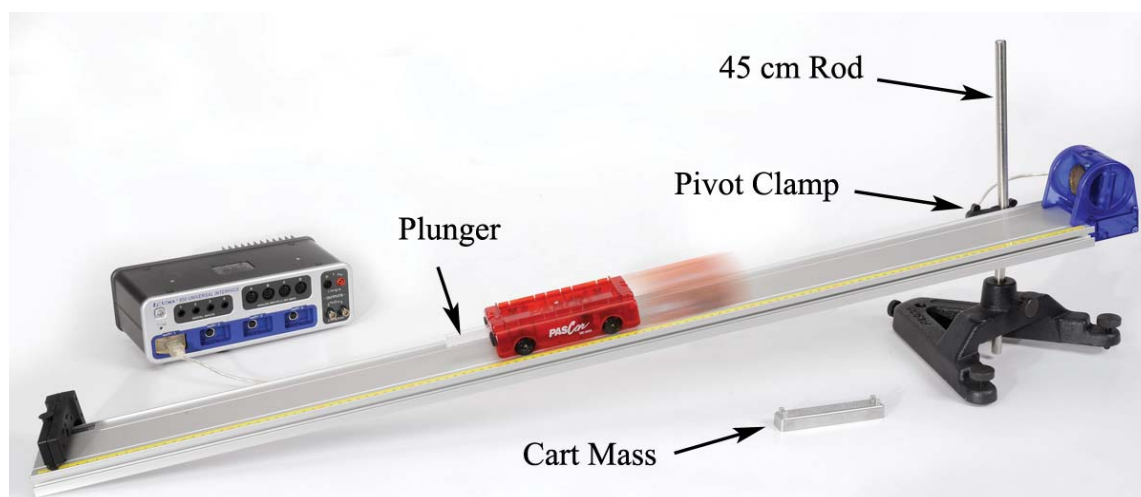


Figure 1: Measuring Acceleration of the Cart Down the Incline

Set-up

1. Set up the track as shown in Figure 1 using the rod base and 45-cm rod. Note that the lower end of the track rests directly on the table, and that the normal track feet are NOT used in this experiment. The square nut on the Pivot Clamp slides into the T-Slot on the track, and allows the track to be secured at various angles.
2. Attach the Motion Sensor to the track and then connect the sensor to the interface. Make sure the range switch on the motion sensor is set to the "cart" icon.
3. The PAScar should be oriented so the plunger hits the Endstop at the bottom of the incline.
4. The Motion Sensor sample rate should be 20 Hz.
5. In PASCO Capstone, make a graph of velocity vs. time.
6. Set a Start Condition based on the Position measurement, is above 0.20 m.
7. Set a Stop Condition based on the Position measurement, is above 0.60 m.

Procedure – Predicting Acceleration

1. Carefully measure the length of the track and record the value below.
2. Adjust the height of the end of the track to about 20 cm.
3. Carefully measure this height and record the value below. The height should be measured to the underside of the track as shown in Figure 2.



Figure 2: Height of Track

4. Calculate the angle, θ , of the track using the height, h , and the length of the track. See Figure 3. Record the value.
5. Using the accepted value for the acceleration due to gravity, calculate the predicted acceleration of the cart down the incline. Record the value below.
6. There is a start condition so that when the cart is released, data does NOT start recording unless the cart is more than 20 cm away from the Motion Sensor. Click on Recording Conditions in the lower Control Bar.
7. There is also a stop condition so that when the cart reaches 60 cm, data collection automatically stops. This makes it easier to take the data, and you can change these values to suit your experiment.

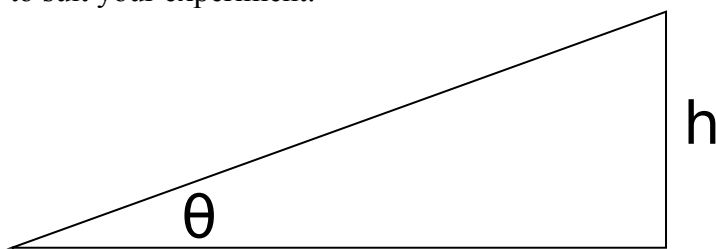


Figure 3: Finding the Angle

Measuring Acceleration

8. Position the cart at the top of the incline, about 15 cm from the Motion Sensor. The cart should be oriented so the plunger hits the Endstop at the bottom of the incline.
9. Start recording data and release the cart. Data will be shown in the graph at right. You can delete unwanted runs using the Delete feature in the lower Control Bar.
10. Select a Linear Curve Fit from the graph tool palette. What is the physical meaning of the slope? Does it have units? What is the uncertainty in your value?
11. Compare to the accepted (theory) value using the % error calculation.

$$\%error = \frac{Measured - Accepted}{Accepted} \times 100$$
12. Was your measured (actual) value high or low? What might account for this?

Further Study

13. Predict how the acceleration of the cart might change if its mass was doubled.
14. Add the mass bar to the cart and measure its new acceleration. How does this compare to your prediction?
15. Change the height of the track by about 5 cm and repeat the experiment for a different angle.

Freefall Picket Fence

Introduction

A Picket Fence is a clear plastic strip with uniformly spaced opaque bands. Each opaque band blocks the photogate beam, and the time from one blockage to the next becomes shorter as the velocity of the falling Picket Fence increases. Using the known distance between the leading edge of each band, and the time interval between photogate blocks, the student calculates the average velocity of the Picket Fence for each interval. The slope of the graph of average velocity versus time gives the acceleration of the falling object.

Equipment

Qty	Items	Part Number
1	Photogate	ME-9498A
1	Picket Fence	ME-9377A
1	Mounting Rod	SA-9242
1	Table Clamp	ME-9472
1	Multi-Clamp	ME-9507
1	90-cm Rod	ME-8783
1	No Bounce Pad	SE-7347



Figure 1. Dropping a Picket Fence

Set-up

1. Fasten the Table Clamp and the 90 cm Rod to the edge of the table as shown in Figure 1.
2. Use the Multi-Clamp to fasten the Photogate to the vertical rod. The Mounting Rod (see Fig. 2) screws directly into the side of the Photogate. Make sure that the Photogate is high enough so that the Picket Fence can pass completely through before it reaches the table.
3. Plug the Photogate cord into Digital Input #1.
4. Position the yellow No-Bounce Pad (see Fig. 1) below the Photogate to protect the falling Picket Fence when it reaches the table.

5. Practice dropping the Picket Fence through the Photogate. Hold the Picket Fence at one end between thumb and forefinger, as shown in Figure 3. The Picket Fence must hang vertical, so that when it is released, it will fall straight without rotating. Make sure the bottom edge of the Picket Fence is just above the Photogate beam when you let go.

Note: The procedure is easier if one person handles the Picket Fence and another operates the computer.

6. There is a built-in timer that will record the times that each opaque band blocks the photogate beam. Click on Timer Set-up in the palette at the left of the screen to view the set-up.

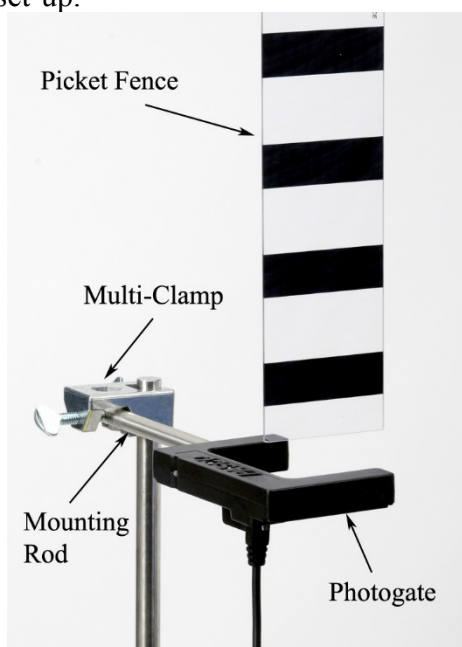


Figure 2. Picket Fence Initial Position

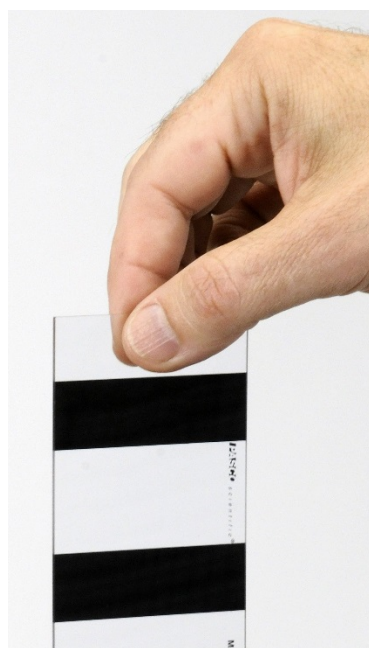


Figure 3. Hold in Center

Hold the Picket Fence at one end between thumb and forefinger, as shown. The Picket Fence must hang vertical, so that when it is released, it will fall straight without rotating. Make sure the bottom edge of the Picket Fence is just above the Photogate beam when you let go.

Procedure

1. Taking Data
 - a. Make a table and put the Block Times in the first column. Then create a user-entered data set named " Δt " with units of seconds. (Remember that you can get a Δ in Capstone by right-clicking where you are typing.) Create a new column and create another user-entered data set called "Average Time" with units of seconds. Create another column with another user-entered data set called " $v = \Delta x / \Delta t$ " with units of m/s.
 - b. Start recording data, then drop the Picket Fence through the Photogate. Stop recording data.

- c. If the Picket Fence hits the Photogate, or if it rotates too much, you should take another run. You should have seven entries in the data table. These are the times that each of the seven bands on the Picket Fence broke the Photogate beam.
2. Calculations
 - a. Calculate the difference (Δt) between block times and enter them into the column in the table. Note that you may have to increase the number of decimal places in each column to see the difference between the numbers. You can do this using the tool at the top of the graph.
 - b. Calculate the average speed of the Picket Fence during the time between the first and second block.

$$v = \frac{\Delta x}{\Delta t} = \frac{\Delta x}{t_2 - t_1}$$
 where t is the time each block occurred. Δx is the spacing between the bands on the Picket Fence, and is measured from the beginning of one band to the beginning of the next. You can measure over several bands to get a more accurate value of Δx . Enter your calculated average speeds into the table. You will end up with only six average speeds in your table.
 - c. To calculate the time that the average velocity actually occurred, calculate the average time between the Block Times. Add adjacent Block Times and divide by two. Enter these times into the table under Average Time.
3. Slope
 - a. Create a graph of the user-entered v vs. Average Time. You may want to turn off the connected lines in the graph and perhaps make the data points bigger.
 - b. Select a Linear Curve Fit from the graph toolbar.
 - c. What is the physical meaning of the slope? Does it have units? What is the uncertainty in your value?
 - d. Compare to the accepted value using the % error calculation.

$$\% \text{ difference} = \frac{\text{Measured} - \text{Accepted}}{\text{Accepted}} \times 100\%$$
 - e. Was your value too high or too low? What might account for that?

Analysis

In the previous sections, you used the Photogate only to measure the time of block, and then calculated the speeds by hand. The computer can also be configured to calculate these speeds automatically, allowing you to take multiple runs in a short period of time. This is set up in the Timer Setup, which you can open at the left of the screen to view.

1. Create a graph Speed (from the Picket Fence) vs. Time (listed under time in the drop-down list).
2. Start recording data, then drop the Picket Fence through the Photogate as before. Stop recording data.
3. The speed vs. time data for this run will be graphed at right. Select a Linear Curve Fit to find the acceleration as before.

4. Repeat several times to get an average value. Also record your highest value.
5. In the set-up procedure, you were instructed to start the Picket Fence as low as possible. This decreases the speed and lowers the amount of air drag. Try letting go of the Picket Fence higher up to see if you can affect the measured acceleration. Do you get a lower value?

Acceleration on an Inclined Plane

Equipment

1	Dynamics System	ME-6955
1	Motion Sensor	PS-2103A
1	Acceleration Sensor	PS-2118
1	Rod Base	ME-8735
1	45 cm Rod	ME-8736
1	Elastic Bumper	ME-8998

Introduction

The purpose of this lab is to study the relationship between position, velocity and acceleration. A Motion Sensor is used to record the motion of a cart as it moves up and down the inclined track (see Fig. 1). The acceleration of the cart is calculated from a velocity graph, and compared to the acceleration measured directly from the Acceleration Sensor on the cart.

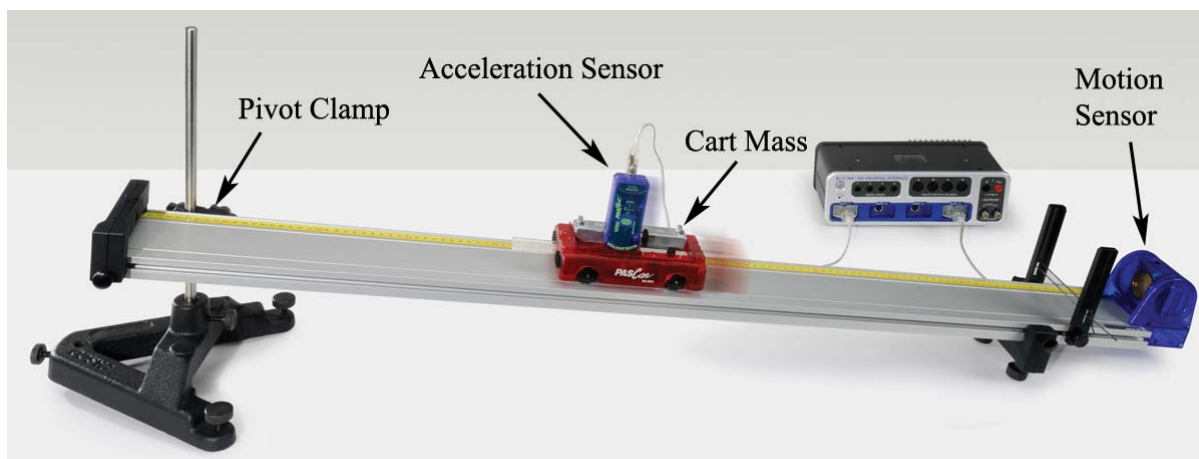


Figure 1: Inclined Track

Setup

1. Use the Pivot Clamp with the Rod Base and the 45 cm Rod to incline the track as shown in Figure 1. The height of the raised end of the track should be about 20 cm.
2. Install the Elastic Bumper (see Fig. 2) at the lower end of the track with the Motion Sensor. Use at least two pieces of elastic cord, as shown.
3. Plug the Motion Sensor into Port P4 of the interface. Make sure the range switch is set on the "Cart" icon.

4. Attach the Acceleration Sensor to the cart using the Mounting Bracket as shown in Figure 3. Plug the sensor into Port P1 of the interface. The LED on the sensor should be off. Place the cart on the incline as shown in Figure 1, including the extra Cart Mass.
5. In PASCO Capstone, create a graph of the Motion Sensor Position vs. time. Add a plot area to the graph and select Acceleration in the x-direction from the Acceleration Sensor.
6. Set the sample rate of the Motion Sensor to 20 Hz and the rate of the Acceleration Sensor to 50 Hz. With the Acceleration Sensor on the control bar at the bottom of the page, click on the zero button to the right of the sample rate. If you change the incline of the track, you must go back and re-zero the sensor.
7. Start recording data, and move the cart up and down the track. Make sure you are getting good clear position data from the Motion Sensor.
8. If the acceleration data is not zero when the cart is at rest, redo step 6 above.

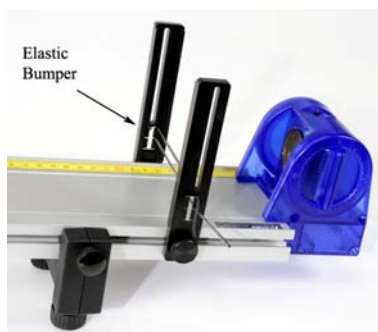


Figure 2: Motion Sensor and Elastic Bumper. Use at least two pieces of elastic cord on the Elastic Bumper



Figure 3: Attaching Acceleration Sensor

Procedure

1. Create a graph of Position vs. Time.
2. On the Experiment Control Bar, set a start condition based on the Position measurement so recording will start when the position rises above 0.30 m. Also set a stop condition based on the Position measurement so recording will stop when the position falls below 0.30 m.
3. With the cart sitting at the bottom of the incline, click on Record. Data collection will NOT start until the cart is more than 30 cm from the sensor, due to an initial starting condition. This will give you better looking data.

4. Throw the cart up the incline as shown in Figure 4. You must quickly get your hand out of the way! Try to get the cart to go close to top, but not hit the bumper at the top. Allow it to coast back down. Try to keep the cord out of way.
5. You can stop recording at any time, but there is an automatic stop condition that stops the recording when the cart comes back down and reaches the 30 cm mark. It is a good idea to try and catch the cart and not just rely on the bumper, but you can't get in way while recording!
6. You can delete unwanted runs using the Delete Run feature in the Experiment Control Bar, below. Get a single good run of position vs. time data.



Figure 4: Give the cart a quick push, and allow it to coast up the incline.

Analysis – Acceleration Data

1. Create a graph of Acceleration in the x-direction versus time. Add an axis and select Position on it.
2. Select the last run you took. How does it look? Try using the Smoothing feature in the Graph tool palette.
3. Is the acceleration positive or negative? What is the significance of the sign?
4. What is the approximate acceleration of the cart? Try using the Coordinates tool in the Graph tool palette. Is there a difference between when the cart was moving up the incline and when it was coming back down?
5. Look at the position graph and note the time when the cart was at the top of the incline. What is the acceleration of the cart at the top of the incline, when its velocity was zero?

Analysis – Velocity Graph

6. Create a graph of velocity versus time and select the last run you took. Select a Linear Curve Fit from the Graph tool palette to find the acceleration.
7. How does this compare to the value you found before?
8. Use the Selection tool from the Graph tool palette to highlight a small section of the data. You can then move this selection to find the slope at different points. Is there a difference between when the cart was moving up the incline and when it was coming back down?
9. When was the cart moving up the track? When was the cart moving down the track?
10. Where was the velocity of the cart zero? What was the acceleration at this time?

Analysis – Position Graph

11. Look one more time at the position data from your run. Using the Annotation tool, label the part of the graph where the cart was moving uphill. What is the sign of the velocity?
12. Label the part of the graph where the cart was moving downhill. What is the sign of the velocity?
13. Label where on the graph the velocity is zero.
14. What is the acceleration at this point? Where is the acceleration zero?

Projectile Motion

Equipment

1	Mini Launcher	ME-6825A
2	Photogate	ME-9498A
1	Photogate Bracket	ME-6821A
1	Time of Flight	ME-6810
1	Table Clamp	ME-9472
1	Rod Base	ME-8735
1	90 cm Rod	ME-8738
1	45 cm Rod	ME-8736
1	No-Bounce Pad	SE-7347
Required, but not included:		
	Plumb Bob	SE-8728
	Meter Stick	SE-8695
	Measuring Tape	SE-8712A
	Carbon paper	SE-8693
	850 Universal Interface	UI-5000
	PASCO Capstone Software	UI-5400

You will also need several sheets of white paper, and some type of non-marring tape, such as painter's tape.

Introduction

In this lab, students use photogates to measure time of flight and the initial launch velocity of the ball. Other activities include finding max range as a function of angle, and predicting the range fired at an angle off the table onto the floor.

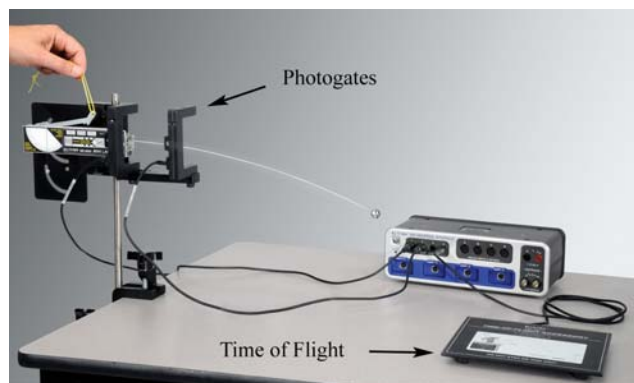


Figure 1: Measuring the time of flight for a horizontal launch.

Setup: Table-Top Launch Height

In this section, the ball is launched from "table top" height (see Fig. 2). You will need 1.5 m to 2 m of table length.

1. The launcher is mounted on the bracket in the lower position (see Fig. 3). Slide the launcher all the way back so that it pivots about the launch position of the ball.
2. Fasten the launcher to the table using the Table Clamp. It is easier to adjust the launcher angle if you remove the knob as shown in Figure 3.
3. Use the No-Bounce Pad with Rod Base and 45 cm Rod (see Fig. 4) as a backstop to help catch the ball.
4. It is critical that you set the angle of launch (see Fig. 5) very carefully. You should be able to read/set the angle to 0.2 degrees (see Fig. 6).

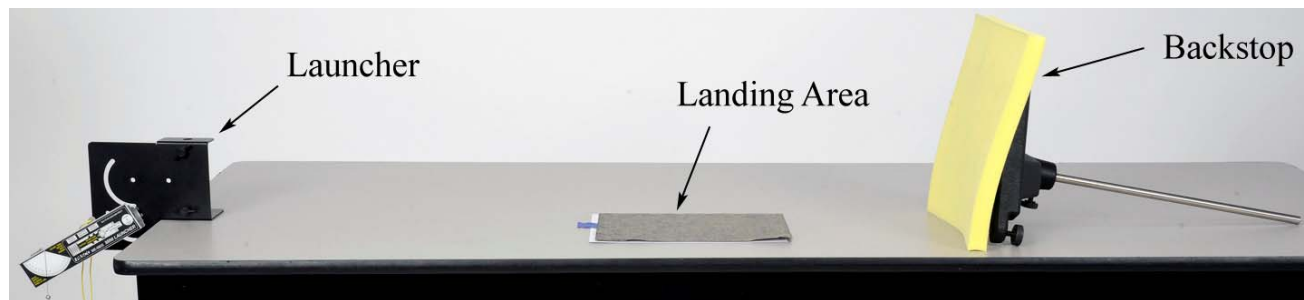


Figure 2: Launching the Ball from "Table Top" Height

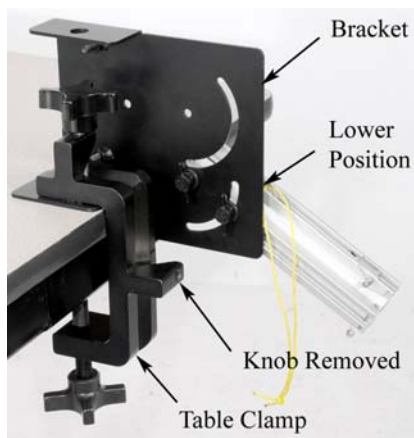


Figure 3: Launcher Mount

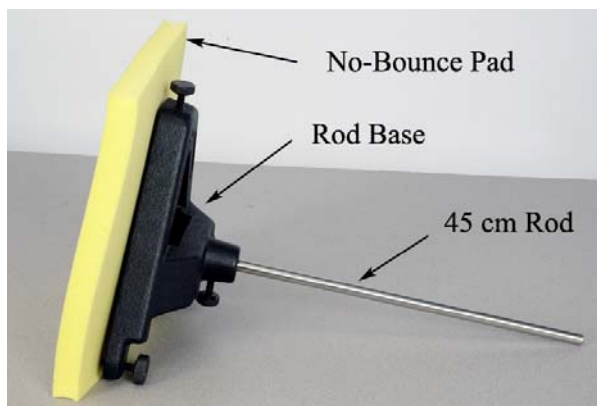


Figure 4: Backstop to Catch Ball



Figure 5: Setting Launch Angle

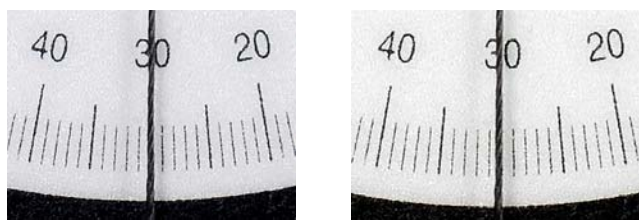


Figure 6: The enlargement on the left shows the string centered on the 30° mark. In the figure at the far right, you can see that the string is slightly closer to 31° than 29° , and might be read as 30.2° .

Procedure:

1. Confirm that the launcher is mounted on the bracket in the lower position (see Fig. 7) so that the ball is launched from "table top" height.
2. To make your results more consistent when launching the ball, always pull on the yellow cord (attached to the trigger) with a quick short pulse. Do NOT pull slowly. Always make sure that everyone is clear before firing!
3. Set the angle for 20° . Place the ball in the piston and depress the plunger one "click" to the short range setting.
4. Launch the ball and note the landing location. Place a blank sheet of paper at this location and tape it in position as shown in Figure 8. Cover with a sheet of carbon paper. You do NOT need to tape the carbon paper.
5. Launch the ball again, and confirm that the contact point is marked. Launch the ball several more times.

6. Use a Meter Stick (see Fig. 9) to measure the ranges. This distance should be measured from the center of the launch position of the ball as shown in Figure 10. Create a table in Capstone with one column with a run-tracked user-entered data set called Distance with units of m. Turn on the statistics in the table and choose mean and standard deviation. Measure each landing point separately (see Fig. 11) and enter them into this table. Rename the run to “20 degrees”.
7. Create a table in Capstone with a user-entered set of Angle with units of degrees. Enter 20, 30, 40, 50, 60, 70, and 80 in this column. In the second column, create a user-entered set called Range with units of m. Enter the average range for 20° in the table.

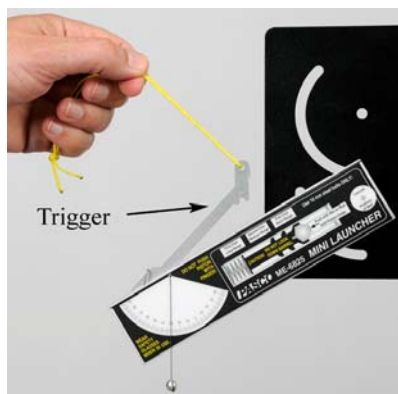


Figure 7: Launching Ball

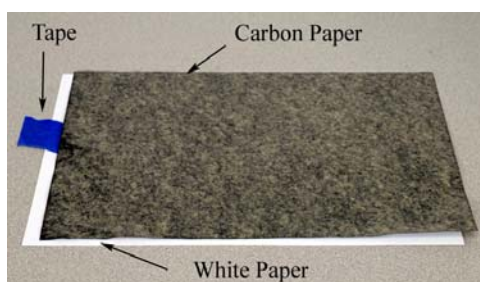


Figure 8: Landing Area

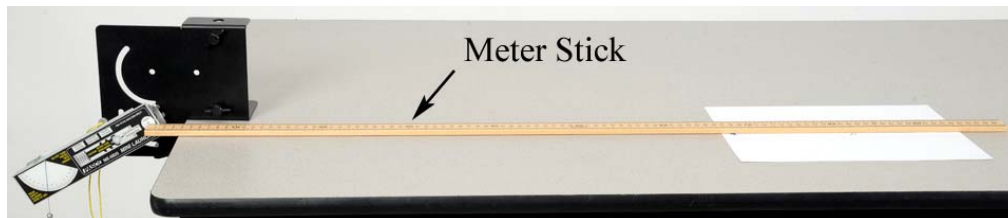


Figure 9: Measuring Range

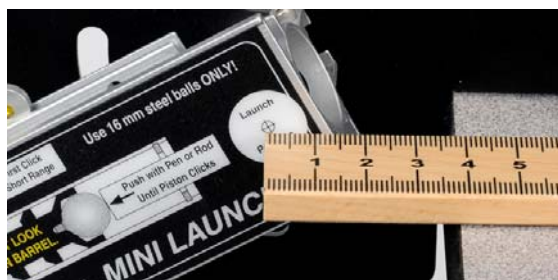


Figure 10: Launch Position

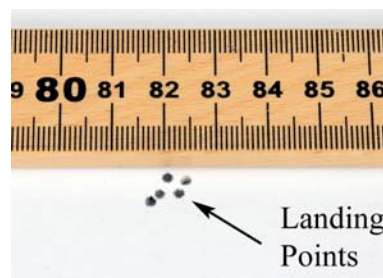


Figure 11: Spread of Points

Max Range:

8. Repeat the procedure and determine the range for angles of 30° , 40° , 50° , 60° , 70° , and 80° .
9. Create a graph of Range vs. Angle. Select a Sine Curve fit from the graph toolbar. If you have trouble with that fit, a Polynomial fit should also work.
10. In theory, the max range should occur at 45° . Does your data confirm this? Click and drag the axis to expand the scale and zoom in on the peak of the curve fit. Locate the angle for max range.
11. Is your angle less than or more than 45° ? What might account for this?
12. What max range does the graph predict for your launcher? Set the launcher at that angle (from your graph) and confirm that the launcher shoots that distance.

Time of Flight Setup

In this section, the ball is launched horizontally from a height above the table, as shown in Figure 1 on the first page.

1. Fasten the launcher horizontally (see Fig. 12) on the bracket using the two screw holes, NOT the cut-out arcs.
2. Slide the launcher forward so that it projects out past the edge of the bracket as shown in Figure 13. This makes it easier to use with the Photogates attached.
3. Use the Table Clamp and 90 cm Rod to support the launcher.
4. Make sure the launch angle is exactly zero and then securely fasten all the screws.
5. Use the No-Bounce Pad with Rod Base and 45 cm Rod (see Fig. 4) as a backstop to help catch the ball.
6. Place the ball in the piston and depress the plunger all the way (three clicks) to the long range setting.
7. Launch the ball and note the landing location. If the range of the ball is too long, decrease the height of the launcher.
8. Measure the distance the ball drops: From the bottom of the ball to the top of the Time of Flight pad (see Fig. 14).
9. Plug the Time of Flight pad into Digital Input #4, and position it at the landing position of the ball.

10. Attach the Photogates to the Photogate Bracket, and slide the bracket into the T-slot on the bottom of the launcher as shown in Figure 15. You want to position the photogates to be as close to the launcher as possible. Plug the first Photogate into Digital Input #1 and the second Photogate into Digital Input #2, as shown in Figure 1.

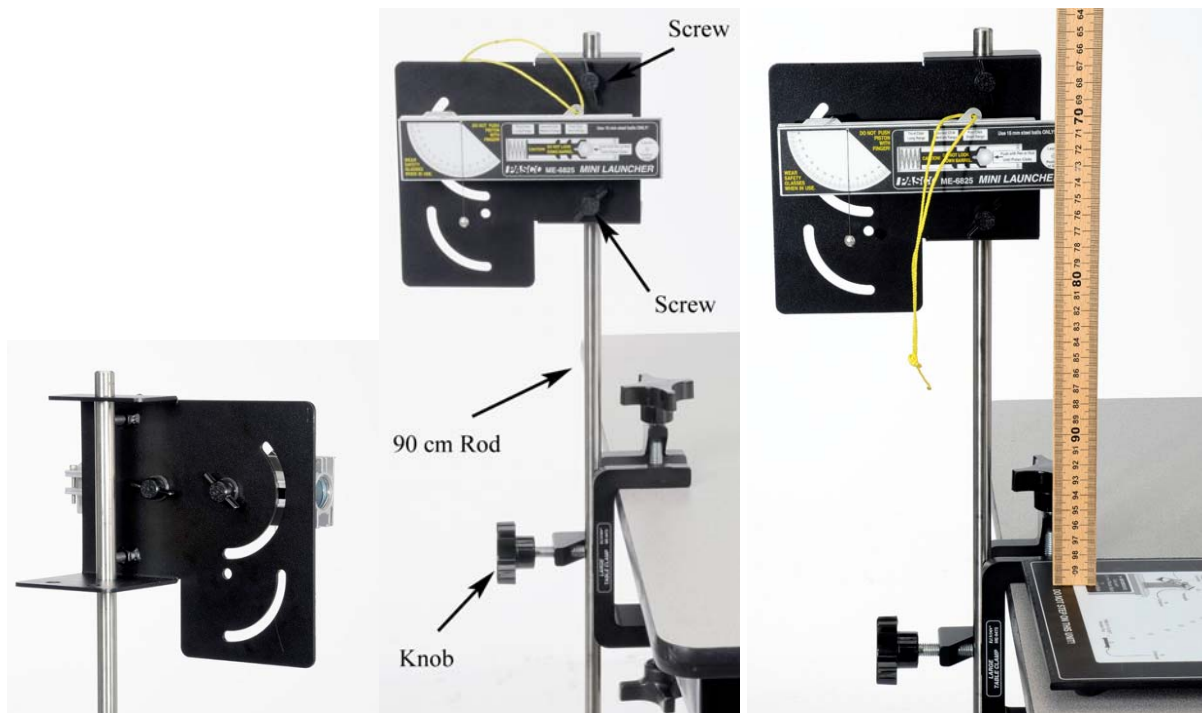


Figure 12: Launcher Mount Figure 13: Horizontal Launch Figure 14: Measuring Height



Figure 15: Photogates

Procedure: 3 Ranges

1. Create two digits displays in Capstone and select the Time-of-Flight in one and Initial Speed in the other. Also create a table with three columns. In the first column, create a user-entered set called "Position" (this is the piston position) with no units and type "Long" in the first three rows, "Medium" in the next three rows, and "Short" in the next three rows. In the second column, create a user-entered set called "Speed" (this is the Initial Speed readings) in m/s. In the third column, create a user-entered set called "Time of" (this is the Time of Flight readings) in seconds.
2. Depress the plunger for long range, then click on Record. Launch the ball. The speed and time of flight should be displayed.
3. Click on Stop, and record the values in the table. Repeat for two more runs on the long range setting.
4. Repeat for the launcher set for medium range and for short range. Record three good trials for each launcher position.
5. Is the time of flight for short range less, more or **about** the same as the time of flight for medium and long range?
6. Calculate the average time of flight for all runs combined. You can use the Statistics feature in the Graph toolbar to calculate this value for you.
7. Using this average time, calculate the height, h , the ball drops

$$h = \frac{1}{2}gt^2 \quad (1)$$

8. Compare to the value for "h" that you measured on the previous page, using the % error calculation.

Theory: At an Angle from a Height

In this section, the ball is launched at an angle from an initial height, y_0 . The initial launch velocity (v_0) is broken down into its horizontal and vertical components

$$v_{0x} = v_0 \cos \theta \quad (2)$$

$$v_{0y} = v_0 \sin \theta \quad (3)$$

where θ is the launch angle. The horizontal and vertical position of the projectile can be calculated using

$$x = v_{0x}t \quad (4)$$

$$y = y_o + v_{oy}t - \frac{1}{2}gt^2 \quad (5)$$

where a sign convention has been adopted with positive upwards.

Setup

1. Mount the launcher on the bracket in the upper position (see Fig. 16). Slide the launcher all the way back so that it pivots about the launch position of the ball.
2. Fasten the launcher to the table using the Table Clamp and 90 cm Rod as shown in Figure 17. This set-up allows you to launch the ball out onto the floor.

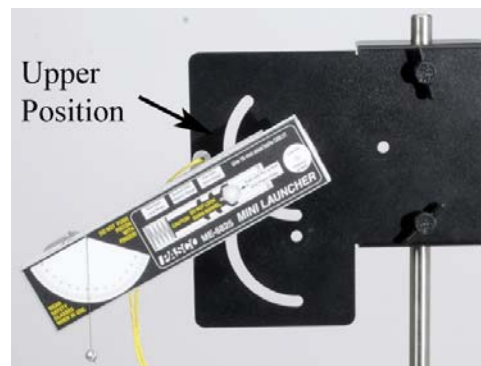


Figure 16: Upper Position

3. You will **not** need the Photogates if you measured the launch speeds in the previous section. You can use the No-Bounce Pad with Rod Base and 45 cm Rod (see Fig. 4) as a backstop to help catch the ball.
4. Set the angle between 20° and 60°, but not at 45°!
5. Measure the initial height, y_o , from the bottom of the ball launch position down to the floor.
6. Using a Plumb Bob, mark the launch position on a piece of tape on the floor below the launcher.
7. In the Capstone calculator, create the following calculations:

	Calculations	Units
1	height=g*t^2/2	m
2	g=9.8	m/s ²
3	t=0.18	s
4	Flight Time=(vy+sqrt(vy^2+2*g*y_o))/g	s
5	y_o=0.91	m
6	vx=v_o*cos(θ)	m/s
7	v_o=[Initial Speed (m/s)]	m/s
8	θ=-20	degrees
9	vy=v_o*sin(θ)	m/s
10	Predicted Range=vx*Flight Time"	m

8. In Capstone, create five digits displays and put in them the calculations: v_o , v_x , v_y , Flight

Time, and Predicted Range

Procedure: Predicting Range

1. Decide which range (short, medium or long range) you are going to use.
2. Using the three values you measured for that range, calculate the average launch speed.
3. For the angle you set your launcher, use Eqn. (2) and Eqn. (3) to calculate the horizontal and vertical components of the initial velocity.
4. Using Eqn. (5), solve for the time of flight. Using Eqn. (4), solve for the predicted range.
5. Measure out from the launch position you marked on the floor, and tape down a piece of paper centered at your predicted range. You will try and hit this paper! Put a line on the paper showing the predicted location.
6. Your calculation was based on the average launch velocity. Using either the highest or lowest value, redo the calculations. By how much does this change your predicted range? Use this information to mark an estimated max and min on your target.
7. Cover your target with a sheet of carbon paper. Place the ball in the piston and depress the plunger to the appropriate position.
8. Make sure that everyone is clear! Launch the ball and note the landing location.
9. If the ball doesn't hit the paper, find out where you made your mistake and try again! Launch a total of five balls. How many hit within your prediction?
10. Measure the distance to all five, and calculate the average. Compare this to the predicted with a % error calculation.



Figure 17: Launch onto Floor

Projectile against a Wall

Equipment

1	Mini Launcher	ME-6825A
2	Photogate	ME-9498A
1	Photogate Bracket	ME-6821A
1	Car Sail	ME-9595
2	Multi-Clamp	ME-9507
1	Table Clamp	ME-9472
1	Rod Base	ME-8735
1	90 cm Rod	ME-8738
1	45 cm Rod	ME-8736
1	No-Bounce Pad	SE-7347
Required, but not included:		
	Meter Stick	SE-8695
	Carbon paper	SE-8693

You will also need several sheets of white paper, and some type of non-marring tape, such as painter's tape.

Introduction

A ball is fired towards a wall at a fixed distance away. At what angle should the ball be launched so that it hits the wall at the highest location? The blue sail material from the Car Sail is used to create a convenient "wall". The yellow No-Bounce Pad helps contain the balls. Photogates are used later in the experiment to measure the launch speed of the ball and the theoretical max angle is calculated.

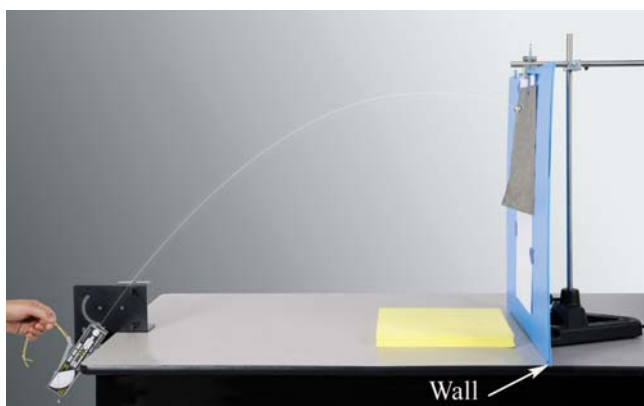


Figure 1: What angle gives maximum height on the "wall"?

Setup

1. The launcher is mounted on the bracket in the lower position (see Fig. 2). Slide the launcher all the way back so that it pivots about the launch position of the ball.
2. Fasten the launcher to the table using the Table Clamp. It is easier to adjust the launcher angle if you remove the knob as shown in Figure 2.
3. Use the largest blue sail from the ME-9595 Car Sail for your "wall". It is held upright using the Rod Stand and 90 cm Rod. The 45 cm Rod and Multi-Clamp hold the top of the material in position, as shown in Figure 3.
4. Tape two pieces of paper to the "wall" as shown in Figure 3.
5. A piece of carbon paper is taped in place (see Fig. 1) to mark the location where the ball hits the wall. The carbon paper is moved up or down as needed, but do not move the white paper or change the position of the wall after you begin taking data.
6. Position the wall so that it is 1.00 m down range from the launch position of the ball.
7. The yellow No-Bounce Pad (see Fig. 1) helps catch the balls!

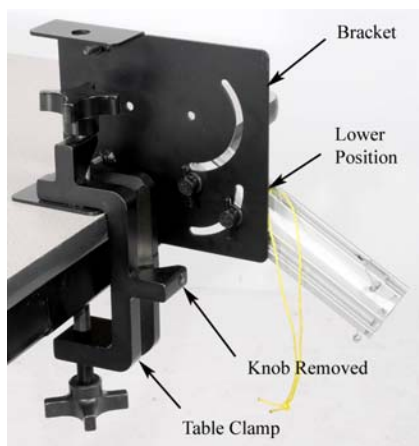


Figure 2: Projectile Launcher

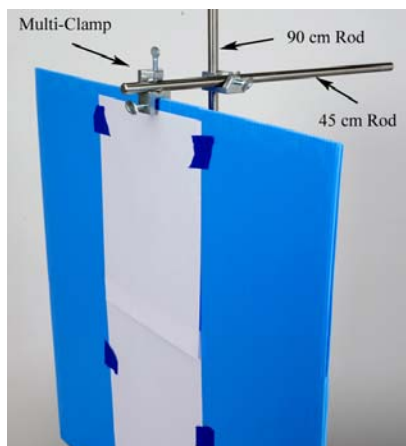


Figure 3: Supporting the "wall"

Procedure

1. To make your results more consistent when launching the ball, always pull on the yellow cord (attached to the trigger) with a quick short pulse. Do NOT pull slowly. Always make sure that everyone is clear before firing!
2. Set the angle for 25° . Place the ball in the piston and depress the plunger two "clicks" to the medium range setting.
3. Launch the ball and note where the ball hits the wall. If it doesn't reach, go on to the next larger angle. Tape the carbon paper into position, and launch the ball again.
4. Confirm that the position is marked, and label on the paper the appropriate angle.
5. Repeat for 30° , 35° , 40° , etc., every 5° , until the ball no longer reaches the wall. Label each position as you take it, so that you don't get them mixed up!
6. Remove the carbon paper, but do NOT move the wall or the white paper. Use a meter stick to measure the height at each angle and enter your values in the table you create in PASCO Capstone. The table should have a user-defined set for the Angle and a user-defined set for the height.
7. Create a graph of height vs. angle.
8. Re-measure the distance from the ball launch position to the wall. If it isn't 1.00 m, record the actual value.

Analysis

9. Select a Polynomial curve fit from the Graph tool palette.
10. By examining the graph, find the angle which gives the maximum height. Click and drag the axis (or use the mouse scroll) to expand the scale and zoom in on the peak of the curve fit. Locate the angle for the maximum height.
11. Launch the ball at this angle and measure the height. Do you confirm that it goes higher? Measure the height and compare with the prediction from the polynomial curve fit. Use this launch angle (θ_{\max}) to calculate what the maximum height should be. Compare to experiment.

Note: If the polynomial curve fit max happens to fall on your measured value, instead of step 11 you can launch a ball at a value 2° above and below that value to prove it is the maximum.

Theory

A ball is fired towards a wall at a distance, x , with an initial launch velocity, v , at an angle, θ , above the horizontal. Show that for the ball to hit at the maximum height on the wall, the launch angle, θ_{\max} is given by

$$\theta_{\max} = \tan^{-1}(v^2/gx)$$

Derive an equation for the maximum height.

Procedure – Measuring Launch Speed

1. Remove the launcher from the table and place it on the Rod Stand as shown in Figure 4. Set the angle for zero, horizontal.
2. Attach the Photogates to the Photogate Bracket, and slide the bracket into the T-slot on the bottom of the launcher. You want to position the photogates to be as close to the launcher as possible.
3. Plug the first Photogate into Digital Input #1 and the second Photogate into Digital Input #2.
4. Create a timer using the Timer Setup at the left of the screen in Capstone. Choose “Two Photogates, Single Flag” and put in the distance between the photogates. Choose to show the “Speed between Gates”.
5. Create a Digits display in Capstone and choose “Speed between Gates”.
6. Depress the plunger for medium range, then click on Record. Launch the ball. The speed should be displayed.
7. Click on Stop, and record the value.
8. Calculate the theoretical angle, θ_{\max} , and compare to your value for θ_{\max} .
9. Calculate the theoretical maximum height and compare to the actual maximum height.

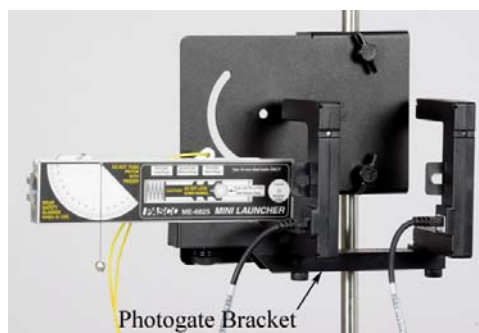


Figure 4: Measuring Launch Speed

Newton's First Law

Equipment

1	Motion Sensor	PS-2103A
1	Dynamics Track	ME-6955
1	Elastic Bumper	ME-8998
1	Magnetic Damping	ME-6828
Useful, but not included:		
1	Calipers	SE-8710

Introduction

The purpose of this experiment is to determine how external forces affect an object's motion. This concept is summarized by Newton's 1st Law of Motion, which can be stated as:

"An object at rest will remain at rest, or an object that is moving will continue moving with constant velocity, only if the net force acting on the object is zero."

Setup

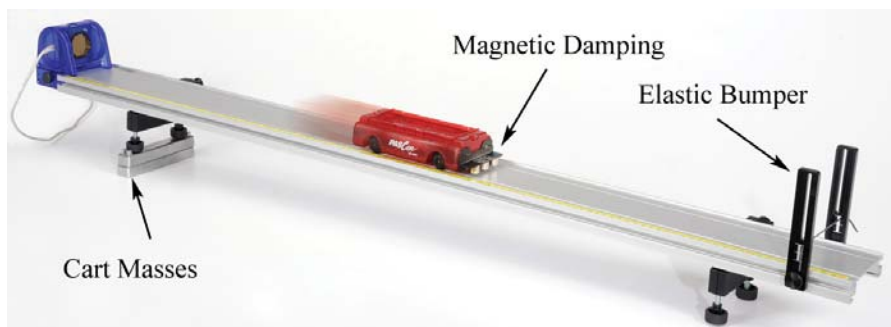


Figure 1. Cart moving at constant velocity down the inclined plane

1. Set up the track as shown in Figure 1 with the Elastic Bumper and feet. Note that the Motion Sensor is on the end of the track that is the zero point for the yellow rule.
2. Plug the Motion Sensor into the interface and make sure the range switch is on the "Cart" icon. In PASCO Capstone, create a graph of Velocity vs. Time. Keep the sampling rate for the Motion Sensor at the default rate of 20 Hz.
3. Create a Start Condition based on the Position measurement so recording will begin when the position is above 0.20 m. Also make a Stop Condition based on the Position measurement so recording will stop when the position is above 1.0 m.
4. Do not install the Magnetic Damping Accessory or incline the track yet!

5. Place the cart at rest on the level track (NOT inclined). If the cart moves, use the adjustable feet to level the track.
6. Install the Magnetic Damping Accessory. It attaches to the end of the cart that does NOT have the plunger. The steel bracket is held in place by the magnets inside the cart, and slides up and down to adjust the amount of drag.
7. Use the two Cart Masses (see Fig. 1) to incline the track.

Procedure – Constant Speed

1. Use some type of spacer (any non-magnetic material will work) to set the magnet spacing to about 4 mm. Slide the bracket down (see Fig. 2) until the magnets are flush with the spacer, then remove the spacer.
2. Position the back of the cart (closest to the Motion Sensor) at the 15 cm mark. This is the starting position for the cart.
3. Click on Record, and then release the cart from rest. Data collection will NOT start until the cart reaches a position of 30 cm, due to an initial starting condition. This will give you better looking data.
4. You can stop recording at any time, but there is an automatic stop condition that stops the recording when the cart reaches 1.0 m.
5. You want to adjust the drag so that the cart speed stays relatively constant. Look at the velocity graph. If the speed is increasing, move the magnets closer to the track by about 1/2 mm.
6. Take another run of data. Is the speed relatively constant? Keep moving the magnet closer until the speed is constant.
7. Get one good run of data. Open up the Data Summary and re-name this run Constant Velocity.

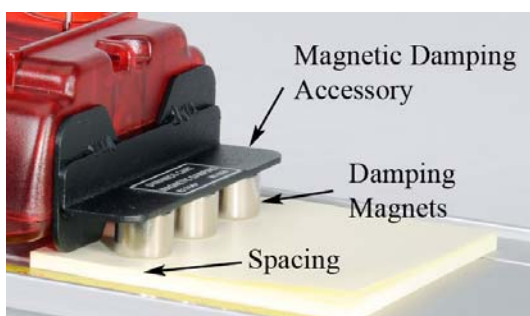


Figure 2. Adjusting Magnetic Damping

Analysis

1. Add a plot area to the v vs. t graph and select Position on the second plot area.
2. What do the position and velocity graphs tell you about the motion of the cart?
3. If the velocity is constant, what is the acceleration?
4. If the acceleration is zero, what is the net force?
5. If the net force is zero, does this mean there are no forces acting on the cart?
6. Identify the two major forces acting on the cart. What do you know about the magnitude and direction of these two forces?

Procedure: Level Track

1. Remove the two cart masses and return the track to level.
2. Change the Start Condition to above 0.30 m and change the Stop Condition to Time-based for 3 seconds.
3. Position the cart at the 15 cm mark, and start recording. Give the cart a quick push away from the Motion Sensor.
4. You can stop recording at any time, but there is an automatic stop condition that stops the recording after 3 seconds.
5. Get one good run of data. Open up the Data Summary and re-name this run Level Track.
6. What do your position and velocity graphs tell you about the motion of the cart? Is the velocity is constant? Is the acceleration constant?
7. Why is the force of gravity no longer a factor?
8. Identify the major force acting on the cart. What do you know about the direction of this force?

Procedure: Object at Rest

1. Place the cart at 40 cm and start recording. You can stop recording at any time, but there is an automatic stop condition that stops the recording after 3 seconds. Re-name this run At Rest.
2. What do your position and velocity graphs tell you about the motion of the cart?
3. What is the acceleration and net force?
4. In general, what happens to an object at rest if the net force applied is zero?
5. In general, what happens to an object in motion if the net force applied is zero?

Newton's Second Law

Equipment

1	Motion Sensor	PS-2103A
1	Force Sensor	PS-2189
1	Dynamics System	ME-6955
1	Force Bracket	CI-6545
1	Fan Cart	ME-6977
2	Compact Cart Mass	ME-6755
Required, but not included		
1	Balance	SE-8723
1	850 Universal Interface	UI-5000
1	PASCO Capstone Software	UI-5400

Introduction

The resulting acceleration of the Fan Cart is measured under two conditions: Variable force (while keeping the mass constant) and variable mass (while keeping the force constant).

The Motion Sensor is used to determine the acceleration, and the Force Sensor is used to measure the force provided by the Fan Cart.

Setup

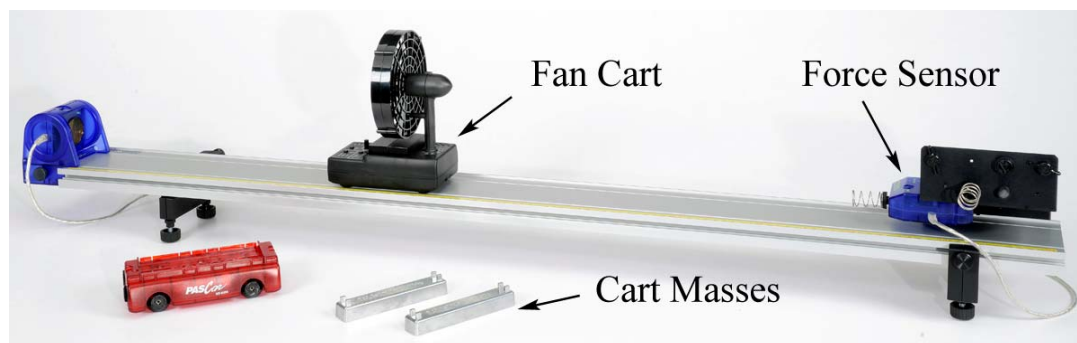


Figure 1: Measuring Acceleration of Fan Cart using Motion Sensor

1. Set up the track as shown in Figure 1 with the Motion Sensor on the end of the track that is the zero point for the yellow rule.
2. Plug the Motion Sensor into Port P1 of the interface and make sure the range switch is on the "Cart" icon.

3. Attach the Force Sensor to the bracket as shown in Figure 2. Use the lighter duty spring bumper.
4. Plug the Force Sensor into Port P2 of the interface.

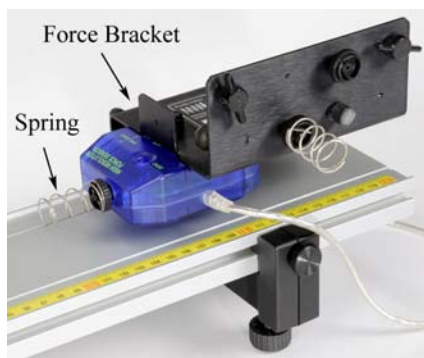


Figure 2: Force Sensor

Leveling the Track:

5. Place the Fan Cart on the track as shown in Figure 3. The fan can swivel on its base: It should be pointed back towards the Motion Sensor, with the Angle Indicator set to zero degrees.
6. Place both of the black Compact Cart Masses in the tray under the fan.
7. In PASCO Capstone, create a graph of Velocity vs. Time. Also create a digits display and put the Force in it. Then change the Sampling Mode from Continuous to Fast Monitor.
8. Adjust the level of the track so that the cart is rolling slightly downhill, to compensate for frictional drag. Give the cart a slight push to the right (away from the Motion Sensor) and click on Monitor on the Experiment Control Bar at the bottom of the Capstone page. Use the velocity graph to adjust the track level so that the cart moves at constant speed.
9. With the Fan Cart at rest against the spring, tare the Force Sensor. Click on Monitor again and view the digits display of force to ensure that the sensor is reading zero. Press tare again if needed.
10. Turn on the Fan Cart (see Fig. 3) by pressing its power button. The Fan Cart is now in standby mode, and the fan speed should be set on low. Later in the experiment you will change the fan speed, as shown in Figure 4. Press the power button again to start and stop the fan.



Figure 3: Fan Cart



Figure 4: Changing Speed

Procedure – Varying Force

1. On the Force digits display, turn on the statistics on the toolbar and select the average. Change the Sampling Mode back to Continuous.
2. Click on the Recording Conditions on the Experiment Control Bar and create start and stop conditions as shown below:

▼ Start Condition	
Condition Type	Measurement Based
Data Source	Position (m)
Condition	Is Above
Value	0.18
Pre-Record	<input type="checkbox"/>

▼ Stop Condition	
Condition Type	Measurement Based
Data Source	Position (m)
Condition	Rises Above
Value	0.60

3. Create a table in Capstone and create three user-defined measurements called “Level”, “F” with units of N, and “Accel” with units of m/s^2 . Enter the values shown in Table I for the Level.

Table I: Varying Force

	Level	F (N)	Accel (m/s ²)
1	Low		
2	Low		
3	Medium		
4	Medium		
5	High		
6	High		

4. Turn on the fan. It should be set on low.
5. With the Fan Cart at rest against the spring, click on Record. The digits display shows the running average of the fan's force, and should quickly show a constant reading. If the value is gradually changing, stop and restart recording.
6. Stop recording. Enter the force in the table. Ignore the sign.
7. With the fan still running, position the back of the Fan Cart at the 15 cm mark. Always start the cart from this position.
8. Click on Record, and then release the cart from rest. Data collection will NOT start until the cart reaches a position of 18 cm, due to an initial starting condition. This will give you better looking data. Try and catch the cart before it hits the Force Sensor!
9. You can stop recording at any time, but there is an automatic stop condition that stops the recording when the cart reaches 60 cm.
10. Select a Linear curve fit on the Velocity vs. Time graph to find the acceleration of the cart, and enter the value in the table. Repeat with the fan speed set on Medium and High.

Procedure: F vs. a

11. Create a graph of F vs. accel. This graph shows your table values of applied force and the resulting acceleration. What physical property does the slope of a Force vs. Acceleration graph represent? Hint: What are the units of the slope?
12. Select a Linear curve fit and determine the slope.
13. Use a balance to find the actual mass of the cart plus mass bars, and compare to your value.

14. The graph shows that the applied force is directly proportional to the resulting acceleration. What is the proportionality constant? Write the equation in the form

$$F = (?) a$$

What is the name of this equation?

Procedure: Varying Mass

15. Create another table with three User-Entered measurements: "Load", "mass" with units of kg, and "a" with units of m/s^2 . Enter the values shown below for the Load.

Table II: Varying the Mass

	Load	mass (kg)	a (m/s^2)
1	Fan + PAScar		
2	+ one mass		
3	+ two masses		
4	+ three masses		
5	+ four masses		

16. Remove the masses from the Fan Cart, and use a balance to measure the mass of the "Fan Cart + PAScar". Record the value into Table II.
17. Place the PAScar in front of the Fan Cart as shown in Figure 5. The tray of the PAScar will be used to hold extra mass, but start out with it empty. Note that the silver Cart Masses stack, to make more room.



Figure 5: Fan Cart Pushing PAScar

18. Turn on the fan, set for **Medium** speed.
19. Click on Record, and then release the cart from the 15 cm mark. There are start and stop conditions as before.
20. Use the slope to find the acceleration as before, and enter the value in Table II.
21. Add a mass bar and repeat. Use all your mass bars, including the black Compact Masses. They will fit in the PAScar, too.

Analysis:

1. Create a graph of “a” vs. “mass”. This graph shows your Table II values of the resulting acceleration vs. mass. Is this graph linear? Should it be?
2. Click on the mass axis and choose a 1/m Quick Calc.
3. Select a Linear curve fit and determine the slope. What physical property does the slope represent? What are the units?
4. Compare this to the actual value you measured earlier.
5. In general, what happens to the acceleration of an object when the applied force is increased? (Assume constant mass).
6. In general, what happens to the acceleration of an object when its mass is increased? (Assume constant force).

Force and Acceleration

Equipment

1	Dynamics System	ME-6955
1	Motion Sensor	PS-2103A
1	Force Sensor	PS-2189
1	Pulley (part of CI-6691)	ME-9448B
1	Braided String	SE-8050
1	Mass and Hanger Set	ME-8979
1	Compact Cart Mass	ME-6755
Required, but not included:		
1	Balance	SE-8723

Introduction

The purpose of this lab is to investigate the relationship between the net force applied to an object and the resulting acceleration of that object.

A force is applied to a low friction cart using hanging masses over a pulley, and the magnitude of the force is measured directly by the Force Sensor on the cart. The resulting movement of the cart is measured by the Motion Sensor, and its acceleration is measured from a velocity vs. time graph.

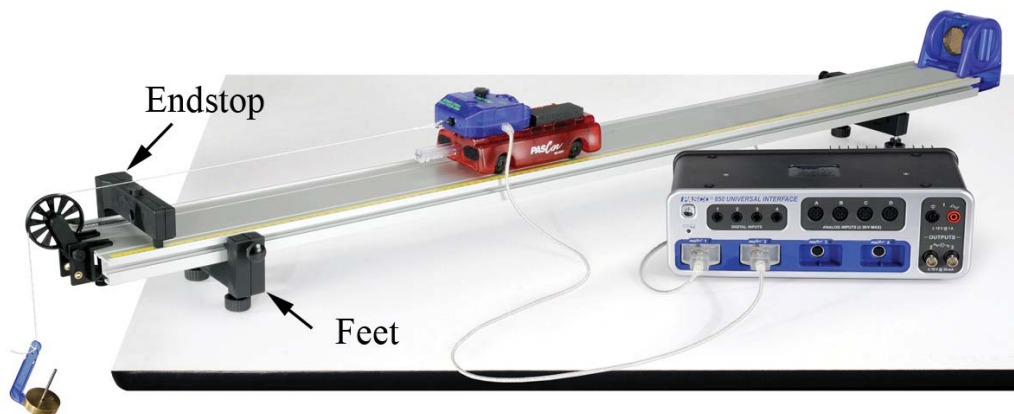


Figure 1. Measuring Force and Acceleration

Setup

1. Set up the track as shown in Figure 1, including feet and endstop.
2. Connect the Motion Sensor to the interface, and attach it to the track. Adjust the alignment knob on the side of the Motion Sensor so that it points parallel to the track. Make sure the switch on the top of the Motion Sensor is set to "cart."
3. Connect the Force Sensor to the interface. In PASCO Capstone, set the sampling rate for the Force Sensor to 100 Hz and set the Motion Sensor to 50 Hz.
4. Create a graph of Velocity vs. Time. Add a plot area and select Force on the vertical axis.
5. Using the long thumbscrew, attach the Force Sensor to the cart. Make sure the plunger (see Fig. 2) on the cart is out before attaching the Force Sensor.
6. Place the Cart/Force Sensor assembly on the track. You can increase the mass using the Compact Cart Masses.
7. Make sure the pulley is connected to the clamp using the upper set of holes (see Fig. 3). Clamp the pulley to the end of the track, and place this end over the edge of the table.
8. Use the adjustable feet on both ends to level the track. It is easiest to use a spirit level, but you can also use the motion of the cart.
9. Tie a loop in one end of a one meter length of string. Hang a mass hanger from the loop. Add 15 g to the hanger for a total of 20 g (including the 5 g hanger.) Tie a loop in the other end of the string and attach the loop to the hook of the Force Sensor. Hang the mass hanger over the pulley. Adjust the string so the mass is just above the floor when the cart plunger strikes the endstop.
10. Level (eyeball it) the string by adjusting the pulley. The string must clear the top of the endstop.

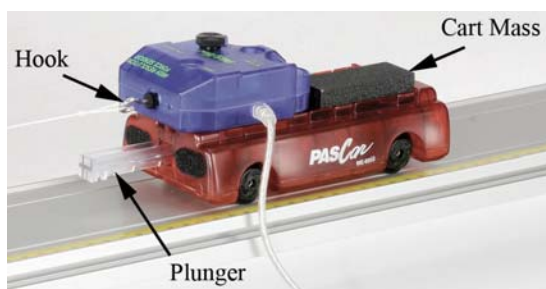


Figure 2. Cart

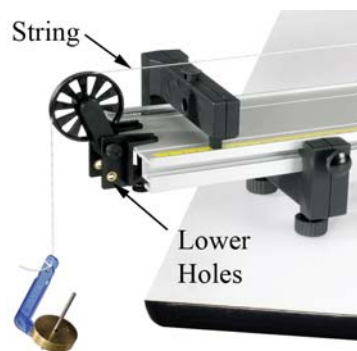


Figure 3. Pulley

Procedure

1. Remove the string from the Force Sensor hook and press the "ZERO" button on the Force Sensor. Then replace the string.
2. Pull the cart back as far as possible without allowing the mass hanger to contact the pulley. Click on Record and release the cart.
3. Make sure the Force Sensor cord does not impede the cart's motion. To do this, hold the cord with your hand at least 30 cm above the cart and keep your hand directly above the cart as it moves so the cord does not push or pull on the cart.
4. Click STOP after the cart strikes the endstop. If you see noise spikes in your velocity data, try adjusting the angle of the Motion Sensor and moving all objects away from the track including yourself. You can delete unwanted runs using the Delete Run feature in the Control palette at the bottom.
5. When you get a good run, open the Data Summary in the Tool palette at left and re-name this run 20 g.
6. Add 10 g to the mass hanger (now 30 g total), and repeat the procedure to collect data for the 30 g run.
7. Repeat for 40 g, 50 g, and 60 g.

Analysis – Force Data

1. Click the Run Select tool (in the graph), and select the "20 g" run.
2. The Statistics tool (in Graph toolbar) should be turned on, displaying the Mean (average) value on the graph. You can use the Highlight Tool (in Graph toolbar) to select the range over which the average is calculated.
3. Create a table with a User-Entered set called Mass (in grams) in the first column and a User-Entered set called F (in Newtons) in the second column. Enter 20, 40, 50, and 60 into the Mass column. Record the Mean force value in a table. Ignore the sign.
4. Repeat for the other values.
Note: The force, F , is measured directly by the Force Sensor. Since the cart is accelerating, this force is NOT simply the weight of the hanging mass.

Velocity Data

1. Make a graph of v vs. t . Click the Run Select tool and select the "20 g" run.
2. Select a Linear curve fit. You can use the Selection tool to restrict the range over which the average is calculated.
3. What is the physical meaning of the slope? Does it have units?
4. Add a column to the table and create a User-Entered set called "a" with units of m/s^2 . Record the acceleration in the table. Repeat for the other mass values.

F vs. Acceleration

1. Make a graph the User-Entered set F vs. the User-Entered set "a". What physical property does the slope of a Force vs. Acceleration graph represent? Hint: what are the units of the slope?
2. Select a Linear curve fit and determine the slope. How well does your slopes match what you should expect? Use the mass balance to measure the actual mass of the Cart + Force Sensor and compare.
3. The graph shows that the applied force is directly proportional to the resulting acceleration. Write the equation in the form $F = (?) a$
4. What is the name of this equation?

Inertia and Newton's Second Law

Equipment

1	Dynamics System	ME-6955
1	Motion Sensor	PS-2103A
1	Force Sensor	PS-2189
2	Compact Cart Mass	ME-6755
Required but not included:		
1	Balance	SE-8723

Introduction

When you try to shake an object back and forth, you feel a "resistance" to the acceleration you are trying to impart. We commonly refer to this as the "inertia" of the object.

In this lab, a force is applied directly to the cart by pulling and pushing on the attached Force Sensor. The resulting acceleration is measured by the Motion Sensor, and the analysis of a Force vs. Acceleration graph allows the concept of "inertia" to be quantified.

Setup

1. Set up the track as shown in Figure 1, including feet and endstop. Use the adjustable feet to level the track.

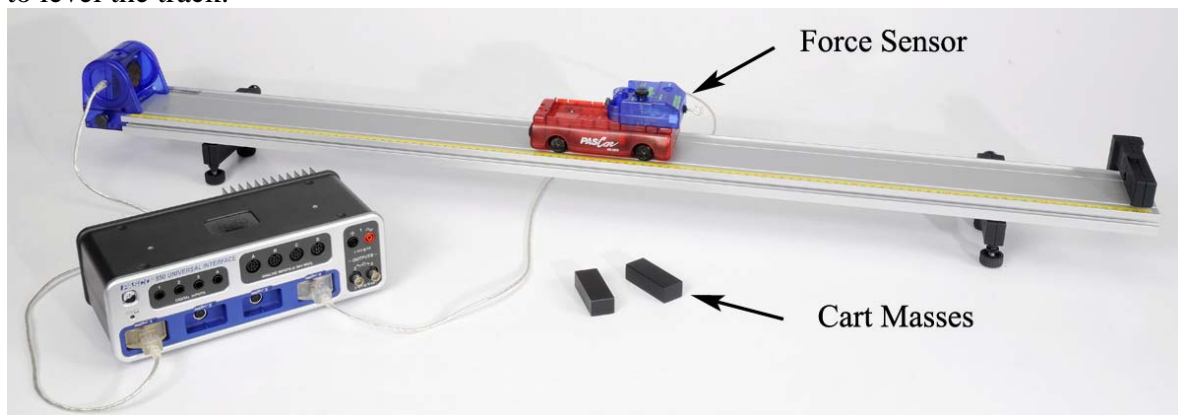


Figure 1: The cart is accelerated by pulling directly on the Force Sensor.

2. Connect the Motion Sensor to the Interface, and attach it to the track. Adjust the alignment knob on the side of the Motion Sensor so that it points parallel to the track. Make sure the switch on the top of the Motion Sensor is set to "cart."
3. Connect the Force Sensor to the Interface.

4. Using the long thumbscrew, attach the Force Sensor to the cart. Place the Cart/Force Sensor assembly on the track.
5. In PASCO Capstone, make a graph of Position vs. Time and then add a second plot area and put Velocity on the second vertical axis. Set the sample rates for the Force sensor and the Motion sensor to 20 Hz.
6. Set the recording mode to Fast Monitor. In this case the data rate is not fast but we don't want the runs recorded.

Procedure

1. Place the cart about 30 cm from the Motion Sensor and click on Monitor.
2. Move the cart away from the Motion Sensor about 30 cm and then back. Check the Position and Velocity graphs to ensure that you are getting good, smooth, continuous data. Click on Stop.
3. Next you will "shake" the cart back and forth. The Motion Sensor will measure the resulting acceleration of the cart, but you also want to record the force you apply. To make the cart oscillate, push and pull only on the Force Sensor hook, as shown in Figure 2.
4. Create a Force vs. Acceleration graph. Change the recording mode back to Continuous. Change the sample rate of the Force sensor to 1 kHz and keep the sample rate of the Motion sensor at 20 Hz.
5. Try to push and pull only along the direction of motion, not sideways or up and down. Place the Force Sensor cord so that it affects the cart as little as possible.
6. Press the Zero button to tare the Force Sensor.

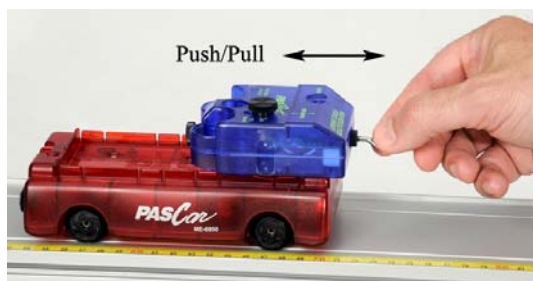


Figure 2: "Shaking" the Cart.

Force and Acceleration

7. With the cart about 40 cm from the Motion Sensor, make the cart oscillate about 10 cm by pushing and pulling on the Force Sensor hook. Try to make at least one oscillation per second.
8. While the cart is oscillating, record about 5 seconds of data. Note that the graph is Force vs. Acceleration.
9. The graph won't look like a single line, but you can still do a linear curve fit to find average slope. Ignore the sign.
10. What physical property does the slope of a Force vs. Acceleration graph represent? Hint: what are the units of the slope?
11. The graph shows that the applied force is directly proportional to the resulting acceleration. Write the equation in the form $F = (?) a$
12. What is the name of this equation?

Faster!

13. In Capstone, create a Run Tracked User-Entered Data Set called "Slope with cart empty" and assign the units that match the units of the slope of the Force vs. Acceleration graph. Create another Run Tracked User-Entered Data Set called "Slope extra mass" and assign the units that match the units of the slope of the Force vs. Acceleration graph.
14. Create a table and put "Slope with cart empty" in the first column and put "Slope extra mass" in the second column. Turn on the Mean and the Standard Deviation in the Statistics.
15. Take some more runs of data. Try shaking the cart as fast as you can, but the cart wheels must stay on the track in the grooves! Remember to pull straight on the hook.
16. Take several runs, with different people shaking the cart. Enter your values in column one of Table I.
17. How well does your average slope match what you should expect? Use the Balance to measure the actual mass of the cart plus Force Sensor and compare.
18. Add one or two mass bars to the cart and try again. Enter your values in column two of Table I.
19. How well does your average slope match what you should expect? Use the Balance to measure the actual mass of the cart plus Force Sensor plus extra mass and compare.

Newton's Third Law

Equipment

1	Dynamics System	ME-6955
2	Force Sensor	PS-2189
2	Compact Cart Mass	ME-6755
Required, but not included:		
1	Rubber Band	

Introduction

Newton's Third Law states that for every force (the action) there is an equal and opposite force (the reaction).

The purpose of this experiment is to determine the relationship between forces forming an action-reaction pair. Two Force Sensors are used to measure the paired forces in a rubber band tug-of-war (shown here) and the paired forces in a collision of two carts.

Setup

1. Connect two Force Sensors to the 1 and 4 PASPORT inputs on the 850 Universal Interface. In PASCO Capstone, set the sample rate of both Force sensors to 200 Hz.
2. Attach the hooks to the Force Sensors. 3. Open the Calibration at left and choose to calibrate one of the force sensors. Hang the force sensor up on a rod with the hook end hanging down.
3. Choose to calibrate with two points. Set the first point to zero. With nothing connected to the force sensor, press the "ZERO" button on the force sensor and click accept in the calibration window.
4. For the second point, hang a 100 g mass from the force sensor hook. Enter the value of mass times the acceleration due to gravity (in newtons) for the expected value. Click accept.
5. With nothing connected to the Force Sensors, press the "ZERO" buttons on the Force Sensors.
6. Hook the Force Sensors to the ends of a long rubber band as shown in Figure 1.
7. In PASCO Capstone, create a graph of "Force, Ch.P1" vs. Time. Then click on the "Force, Ch.P1" on the vertical axis and select Add a Similar Measurement. Then add "Force, Ch.P2". Click on the measurement selector on the vertical axis again and choose

a QuickCalc of $(-F)$. Normally, the Force Sensor records a pull as negative value, but the QuickCalc will make these values positive.



Figure 1: Tug-of-war Setup

Procedure – Tug-of-war

1. Click on Record to start collecting data.
2. Play a small-scale game of tug-of-war with neither person "winning", but try to vary the force. Do not exceed 50 N.
3. After 10 seconds or so, click Stop. To delete unwanted data, click the Delete Last Run button.
4. Examine the two curves to see if the forces exerted by person A and person B are the same. You will probably have trouble seeing the two sets of data at the same time. The best way is to toggle back and forth between the two data sets. In the Graph Legend, click on the icon under "F, P1" (force at the PASPORT 1 input) to highlight the data in channel 1. Then click on the icon under "F, P4" to highlight that data. Go back and forth to see if you can detect any difference.
5. Are the action/reaction forces equal in magnitude (size)? Even if one person is winning the tug-of-war? Was the force exerted by person A opposite in direction to that exerted by person B? Explain how you know.

Cart Setup

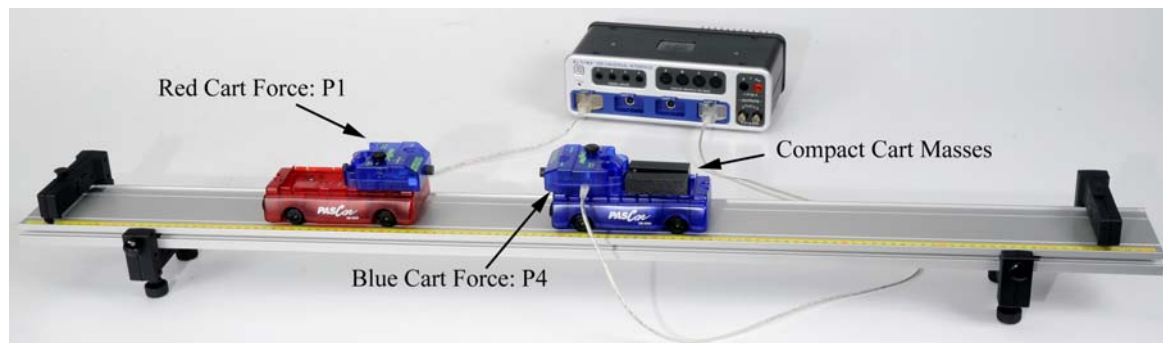


Figure 2: Carts Setup

1. Set up the track as shown in Figure 2. Place the carts on the track and level the track enough so that the carts don't begin to roll. Exact level is not necessary.
2. Remove the hooks from the Force Sensors. Replace them with the rubber bumpers.
3. Using long thumbscrews, attach the Force Sensors to the carts as shown in Figure 3. Force Sensor 1 should be on the Red Cart, and Force Sensor 4 should be on the Blue Cart.
4. Place both Cart Masses in the Blue Cart.
5. With nothing touching the bumpers on the Force Sensors, press the "ZERO" buttons on the Force Sensors.



Figure 3: Fasten Force Sensor

Push Red Cart:

6. Change the sample rate of both Force sensors to 1 kHz.
7. With the two carts touching, click on Record to start collecting data.
8. Push on the Red Cart as shown in Figure 4, pushing both carts to the right. Try and keep the two bumpers in contact as long as possible, but catch the cart before it hits the endstop.

9. Click on Stop.
10. Open the Data Summary and re-name this run Red Push.
11. You can also change the color of each trace, so that the Red Cart Force Sensor data (P1) is red and the Blue Cart Force Sensor data (P4) is Blue. This makes it easier to keep track.



Figure 4: Pushing on Red Cart

Push Blue Cart:

12. With the two carts touching, click on Record to start collecting data.
13. Push on the Blue Cart as shown in Figure 5, pushing both carts to the left. Try and keep the two bumpers in contact as long as possible.
14. Click Stop.
15. Open the Data Summary and re-name this run Blue Push. You can also change the color of each trace, so that the Red Cart Force Sensor data (P4) is red and the Blue Cart Force Sensor data (P1) is Blue. This makes it easier to keep track.



Figure 5: Pushing the Blue Cart

Analysis

1. Use the Run Select tool on the Graph tool palette and select the “Red Push” run.
2. Examine the two curves to see if the forces exerted by the two carts are the same.
3. Now repeat steps 1-2 for the "Blue Push" data set.
4. Are the action/reaction forces equal in magnitude (size)? Even if one car is more massive?
5. If a low mass car (Volkswagon) has a head-on collision with a high mass car (Suburban), which car will experience the larger force?

External Forces and the 3rd Law

Equipment

1	Dynamics System	ME-6955
2	Force Sensor	PS-2189
1	Motion Sensor	PS-2103A
2	Compact Cart Mass	ME-6755
	Elastic Cord	(in ME-8998)
	Braided String	SE-8050
Required but not included:		
	Balance	SE-8723

Introduction

In the first part of the experiment (shown above), the forces are examined that are exerted on the two sensors by the connecting string. In the second part of the experiment, the external force, exerted by hand on the elastic cord, is compared to the internal forces created by the tension in the string.

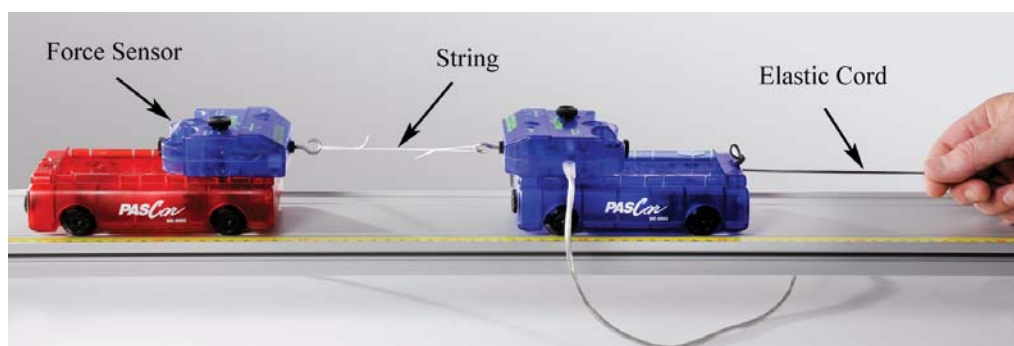


Figure 1: The two carts are accelerated to the right by pulling on the elastic cord.

Setup

1. Set up the track as shown in Figure 2 with feet and endstop. Note the orientation of the yellow rule: The Motion Sensor will be on the zero end.
2. Place the carts on the track and level the track enough so that the carts don't begin to roll.
3. Connect the Motion Sensor to the PASPORT input P1. Attach it to the track and adjust the alignment knob on the side of the Motion Sensor so that it points parallel to the track. Make sure the switch on the top of the Motion Sensor is set to "cart."
4. Using long thumbscrews, attach the Force Sensors to the carts as shown in Figure 3. Note the orientation of the two carts (see Figure 2): It is best to have them both facing the

direction as shown, so that the magnets in the ends of the carts do not interact.

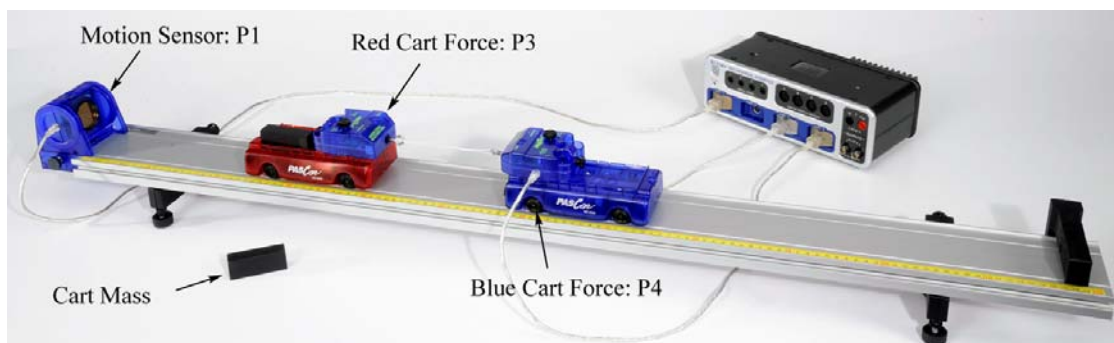


Figure 2: Setup for measuring Action-Reaction pairs



Figure 3: Attaching Sensor to cart

5. Use the Balance to record the mass of Cart + Force Sensor for both carts.
6. Plug the Force Sensor on the red cart into input P3 and the Force Sensor on the blue cart into input P4. Position the cords so they have as little effect as possible.
7. In PASCO Capstone, set the Common Sample Rate to 40 Hz. Create a graph of Position vs. Time. Then add a plot area by clicking on the Add New Plot Area button on the graph toolbar. Select the Velocity on the vertical axis in the new plot area.
8. Change the Sampling Mode from Continuous to Fast Monitor.
9. With nothing touching the hooks on the Force Sensors, press the "ZERO" buttons on the Force Sensors. Position the red cart about 30 cm from the Motion Sensor and click on Monitor.
10. Move the cart away from the Motion Sensor about 30 cm and then back. Check the Position and Velocity graphs to ensure that you are getting good, smooth, continuous data. Click on Stop.

11. Cut a piece of string about 25 cm in length. Tie non-slip loops on each end, with the final length of the string about 10 cm to 15 cm. This string connects the two Force Sensors, as shown in Figure 1.
12. Cut a piece of elastic cord about 30 cm long. Attach one end to the blue cart as shown in Figure 1.
13. Practice (without recording data) pulling on the carts with the elastic cord. Start with the back end (nearest the Motion Sensor) of the red cart at the 15 cm mark. In the following sections, this will always be the starting position.
14. Hold the elastic cord to put a small amount of tension in the string connecting the two sensors without causing them to accelerate yet. Then pull on the cord, accelerating the carts. Pull in such a way that the string stays in tension as far as possible.

Procedure: Action-Reaction Pairs

1. Change the Sampling Mode from Fast Monitor to Continuous.
2. Create a graph of Force P3 vs. time. Click on the Data Selector on the Force axis, select “Add Similar Measurement” and select ForceP4. Then select a QuickCalc of negative force. This will make the force values positive.
3. Click on Recording Conditions on the Sampling bar at the bottom of the page. Create a Start Condition based on the Position, “is above” 0.20 m. Then create a Stop Condition based on the Position, “is above” 0.50 m
4. Position the back of the red cart at the 15 cm mark. Click on Record. Data collection will NOT start until the cart reaches a position of 20 cm, due to an initial starting condition. You can stop recording at any time, but there is an automatic stop condition that stops the recording when the cart reaches 50 cm.
5. Pull on the elastic cord, accelerating the carts.
6. Get one good run of data. Open the Data Summary and re-name this run "Action-Reaction". You can also change the color of each trace, so that the Red Cart Force Sensor data is red and the Blue Cart Force Sensor data is blue. This makes it easier to keep track.
7. Examine the two curves to see if the forces exerted are the same. You will probably have trouble seeing the two sets of data at the same time. The best way is to toggle back and forth between the two data sets. In the Graph Legend, click on the icon under “F P3” to highlight that data. Then click on the icon under “F P4” to highlight that data. Go back and forth and see if you can detect any difference.
8. Are the action/reaction forces equal in magnitude (size)?

- Place both Cart Masses in the red cart and repeat the procedure. Place both Cart Masses in the blue cart and repeat the procedure. Are the action/reaction forces still equal in magnitude?

Internal vs. External

Setup

- Move the Force Sensor on the blue cart to the opposite end as shown in Figure 4. Do not just turn the cart around because the magnets in the ends of the carts would interact.
- The string connecting the carts should now be fastened to the thumbscrew on the back of the Force Sensor on the blue cart (see Fig. 4) and the Elastic Cord is connected to the Force Sensor hook.
- The black Cart Mass is shown in the photo to make the string show up better, but start with no masses in the trays.
- You will pull on the Elastic Cord to accelerate the carts in the same manner as before. However, the Force Sensor on the blue cart will now measure the External Force you apply to the system. The Force Sensor on the red cart will measure the tension in the string as before.



Figure 4: Setup for measuring internal and external forces

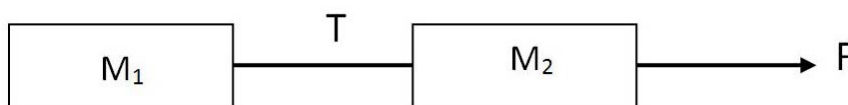


Figure 5: Force Diagram

Theory

An external force, F , is applied to the two mass system (as shown in Figure 5) causing an acceleration, a . The two masses are connected by a string with tension, T . Applying the 2nd Law to the system yields

$$F = (M_1 + M_2)a \quad (1)$$

The two masses can also be treated separately. What is the direction that the internal force, T, exerts on M₁? On M₂?

Applying the 2nd law to M₁ yields

$$T = M_1 a \quad (2)$$

and applying the 2nd law to M₂ yields

$$F - T = M_2 a \quad (3)$$

Show that equation (2) and Equation (3) combine into Equation (1).

Procedure: Equal Mass Carts

1. Position the back of the red cart at the 15 cm mark. Click on Record. There are the same start and stop conditions as before. Pull on the elastic cord, accelerating the carts.
2. Get one good run of data. Open the Data Summary and re-name this run "External Force". You can also change the color of each trace, so that the Red Cart Force Sensor data is red and the Blue Cart Force Sensor data is blue. This makes it easier to keep track.
3. Examine the two curves to see if the forces are the same. Should they be? Why are these not Action-Reaction pairs?
4. Pick a point in time and measure both forces using the Multi-Coordinates tool from the graph tool palette. For example, the peak force makes a convenient location, but you can pick any point where you have good data. Record your values.
5. Use Equation (1) to calculate the theoretical acceleration, a, and record the value.

Analysis

1. Use Equation (2) to calculate a theoretical value for T. Record your value and compare to the measured value using the % error calculation

$$\% \text{ error} = \frac{\text{Measured} - \text{Accepted}}{\text{Accepted}} \times 100$$

2. On the force graph, add a plot area by clicking on the Add New Plot Area button on the graph toolbar. Select the Velocity on the vertical axis in the new plot area.
3. Use the Slope tool (graph tool palette) on the velocity graph to measure the acceleration during the same time period as before and compare.

Procedure: Unequal Mass Carts

1. Add both masses to the blue cart and repeat. Get one good run of data and rename this run Unequal Mass.
2. Pick a point in time and measure both forces.
3. Use Equation (1) to calculate the theoretical acceleration, a , and Equation (2) to calculate a theoretical value for T . Record your values and compare.
4. Use the Slope tool (graph tool palette) on the velocity graph to measure the acceleration and compare.

Atwood's Machine

Equipment:

1	Photogate	ME-9498A
1	Pulley (part of CI-6691)	ME-9450A
1	Mounting Rod	SA-9242
1	Table Clamp	ME-9472
1	Multi-Clamp	ME-9507
1	90 cm Rod	ME-8738
1	Braided String	SE-8050
1	Mass and Hanger Set	ME-8979
1	No-Bounce Pad	SE-7347

Introduction

The purpose of this lab is to study an Atwood's Machine apparatus, built with a PASCO Super Pulley. The Photogate is used to measure the velocity of both masses as one moves up and the other moves down. The slope of the graph of velocity vs. time is the acceleration of the system. Careful measurement when there is no net force allows the student to compensate for friction.



Figure 1: m_1 (on right) $>$ m_2

The Table Clamp is used to support the 90 cm Rod. The yellow No-Bounce Pad is used to protect the falling Mass Hanger when it reaches the table. The Photogate must be plugged into Digital Input #1.

Setup

Building the Apparatus:

1. Fasten the table clamp and the 90 cm rod to the edge of the table as shown in Figure 1.
2. Attach the pulley to the photogate using the mounting rod as shown in Figure 2.
3. Use the multi-clamp (see Fig. 3) to fasten the photogate to the vertical rod. Plug the photogate cord into Digital Input #1.
4. Position the yellow No-Bounce Pad (see Fig. 1) below the photogate to protect the falling mass hanger when it reaches the table.
5. Cut a 1.2 m piece of the braided string and tie loops on each end to hold a mass hanger. Loop the string up and over the pulley as shown in Figure 3.
6. Add a single 100 g mass and a single 20 g mass to one mass hanger (5 g) for a total mass of 125 g. We will call this mass hanger m_1 . To a second mass hanger (call it m_2) add a single 100 g mass for a total of 105 g. Hang the masses on the string over the pulley.
7. Adjust the height of the pulley or length of string so that when mass hanger m_1 is touching the No-Bounce Pad, mass hanger m_2 is a few centimeters below the pulley. The Photogate should be horizontal so the string does not pull sideways on the pulley.

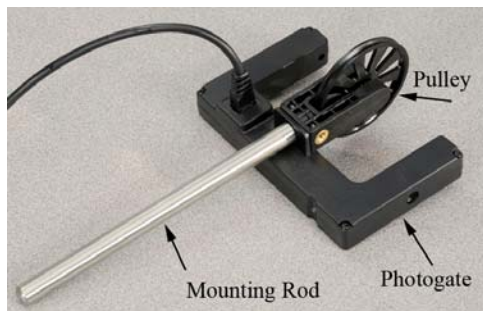


Figure 2: Pulley and Photogate

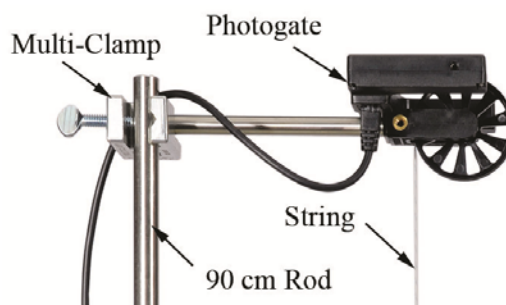


Figure 3: Rods and Clamp

Theory

An Atwood's Machine consists of two unequal masses connected by a single string that passes over an ideally massless and frictionless pulley as in Figure 4. When released, the heavier object accelerates downward while the lighter object accelerates upward.

The free-body diagrams (Fig. 5) show the forces acting on each of the masses. T is the tension in the string. With $m_1 > m_2$, m_1 is descending mass and m_2 is the ascending mass. The magnitude of the acceleration, a , is the same for each mass, but the masses accelerate in opposite directions. We adopt the convention that down is positive. Applying Newton's 2nd Law ($F_{\text{net}} = ma$) to the descending mass, m_1 , gives

$$m_1 g - T = m_1 a .$$

Applying Newton's 2nd Law to the ascending mass, m_2 , gives

$$m_2 g - T = m_2 (-a) .$$

Eliminating T between the two equations and solving for the acceleration yields:

$$a = \left(\frac{m_1 - m_2}{m_1 + m_2} \right) g \quad \text{Eqn. (1)}$$

Show that Equation (1) reduces to the expected result in the following limiting cases. Explain why each case is expected:

Case 1: $m_1 = m_2$

Case 2: $m_1 = 0$

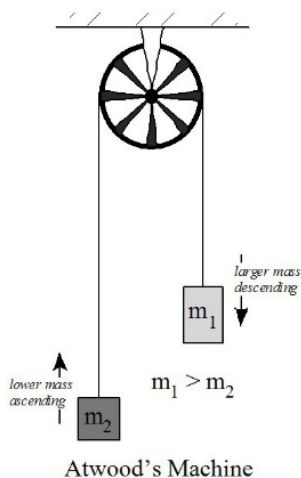


Figure 4: Atwood's Machine

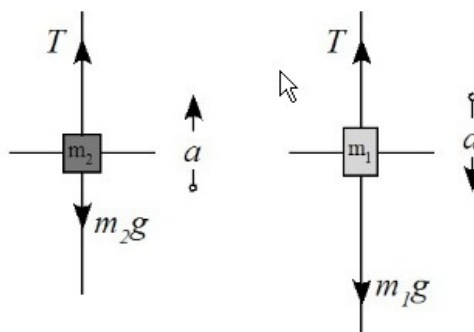


Figure 5: Free Body Diagrams

Procedure

1. In PASCO Capstone, create a graph of Linear Speed vs. Time.
2. Move m_2 to its lowest point. Click on Record. Release m_2 .
3. Stop recording just before m_1 strikes the pad.
4. The masses may touch as they pass each other. If so, repeat the run. You can delete unwanted runs using the Delete Run feature in the control palette below. You should see a linear region on the speed graph as the masses move freely.
5. Select a Linear Curve Fit from the graph tool palette. What is the physical meaning of the slope? Does it have units?
6. Using Eqn. 1, calculate the theoretical value for the acceleration.
7. Calculate the percent difference between the experimental and theoretical value.

Accounting for Friction

8. Add an additional 20 g mass to m_2 . The two masses should now balance. If there were no friction, and we gave m_1 a push downward, it would continue at constant speed.
9. Move m_1 to its highest point. Click on Record. Give m_1 a gentle push downward and release it. You should see that the speed is decreasing.
10. Add 1 g to mass m_1 and repeat the measurement. Does the speed still decrease?
11. Using the 1/2 g, and 1 g masses, adjust the mass of m_1 until the speed stays as constant as possible.
12. Record this added "frictional" mass. The weight of this mass is the extra force needed to overcome the frictional force, and thus does not contribute to the acceleration. To account for friction, this mass should be subtracted off from the actual value of m_1 .

Analysis

1. Re-calculate the theoretical acceleration using Eqn (1), but subtract off the frictional mass from m_1 in the numerator.
2. Compare your measured value for the acceleration to this adjusted theoretical (accepted) value using the % error calculation.

$$\% \text{ error} = \frac{\text{Measured} - \text{Accepted}}{\text{Accepted}} \times 100\%$$

3. How did the correction for friction affect your final results?

Acceleration up an Inclined Plane

Equipment

1	Photogate	ME-9498A
1	Photogate Bracket	(in ME-8998)
1	Pulley (part of CI-6691)	ME-9450A
1	Dynamics Track System	ME-6955
1	Large Rod Base	ME-8735
1	Elastic Bumper	ME-8998
1	45 cm Rod	ME-8736
1	Braided String	SE-8050
1	Mass and Hanger Set	ME-8979
Required, but not included:		
	Meter Stick	SE-8695
	Balance	SE-8723

Introduction

The hanging mass is connected to the cart by a string that runs up and over the pulley. The falling mass pulls the cart up the inclined track. The speed is measured by the photogate and pulley, and the acceleration is calculated from a speed vs. time graph. The acceleration is compared to the theoretical value, and corrections are made to account for frictional forces.

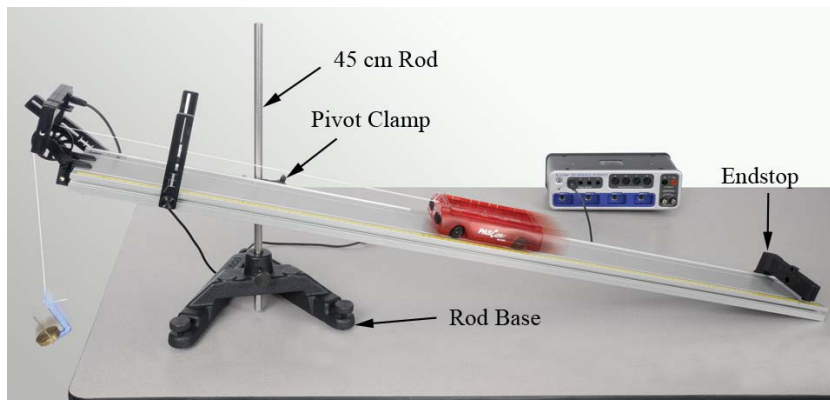


Figure 1: Measuring Cart Acceleration

Setup

1. Set-up the inclined track using the Large Rod Base, 45 cm Rod and Pivot Clamp as shown in Figure 1. Note that the feet are NOT used on the track for this experiment.
2. Raise the end of the track about 18 to 20 cm above the table.
3. Install the endstop at the lower end of the track.
4. The Elastic Bumper should be placed about 15 cm from the end of the track as shown in Figure 2. The Clamp-on Pulley should have the pulley in the upper set of holes as shown.

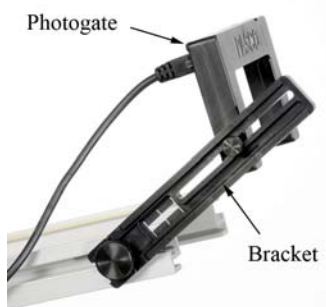


Figure 2: Pulley in upper set of holes

Figure 3: Reversed Bracket

Figure 4: String

5. The Photogate Bracket (see Figure 3) is cantilevered out over the end of the track. Note that the bracket is put on "reversed" so that it doesn't key into the track. This allows you to angle the bracket and Photogate.
6. Plug the Photogate into Digital Input #1.
7. In PASCO Capstone, click on Digital Input #1 and select Photogate with Pulley.
8. Determine the mass of the cart before attaching string! Record value below.
9. Cut a piece of string about 1.2 m long. Tie one end of the string to the upper loop on the cart as shown in Figure 4.
10. Run the string over the pulley and down to the floor. When the cart reaches the top of the track, you want it to hit the Elastic Bumper before the hanging mass reaches the floor. If necessary, shorten the string.

11. Tie a loop in the string to hang the mass. Add one 50 g mass to the mass hanger.
12. Adjust the pulley height so the string runs parallel to the track. Adjust the position of the Photogate so that the pulley spokes break the beam.
13. Carefully measure the length of the track, and the height the track is raised above the table. Use this to calculate the track's angle of incline.

Theory

The mass on the hanger (see Fig. 6) is sufficiently large to pull the cart up the incline. The free-body diagrams (see Fig. 5) show the forces acting on each of the masses. The tension, T , is assumed equal for both parts of the string. Sign convention is adopted such that acceleration for the cart is positive up the track, and acceleration for the falling mass is positive downward.

Applying Newton's Second Law

($F_{\text{net}} = ma$) to each mass separately yields

$$ma = mg - T$$

$$M_{\text{cart}}a = T - M_{\text{cart}}g\sin\theta$$

Combining these two equations (to eliminate T) one can show that the acceleration of the system is given by

$$a = \frac{m - M_{\text{cart}}\sin\theta}{m + M_{\text{cart}}}g \quad (1)$$

1. Use Equation (1) to calculate the theoretical acceleration.
2. Show that Eqn. (1) reduces to the expected result for the limiting case that the cart mass \rightarrow zero. What does this mean physically?

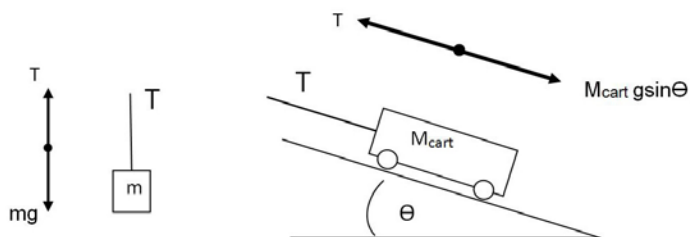


Figure 5: Free-body diagrams for each mass

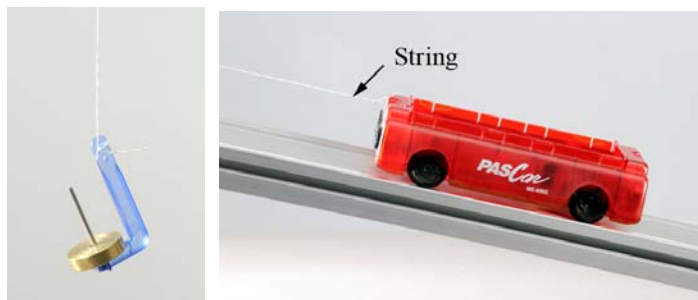


Figure 6: Falling mass pulls cart up the incline

Procedure

1. In PASCO Capstone, create a graph of Linear Speed vs. time.
2. Pull the cart down to the lower part of the track. Click on Record and release the cart. Your data will look better if you click on Stop before the cart hits the Elastic Bumper.
3. Select a linear curve fit from the Graph tool pallet. What is the physical meaning of the slope? Does it have units?
4. Use the Selection tool to highlight only a portion of the data. How does the acceleration of the cart when it is first moving compare to when it has a higher speed? What causes this?
5. Why is your measured value of the acceleration lower than the predicted theoretical value?

Accounting for Friction

1. Adjust the hanging mass so that the cart is balanced. When released from rest, the cart shouldn't move.
2. Give the cart a gentle initial push uphill. Does it speed up? Then you have too much hanging mass.
3. Give the cart an initial push downhill. Does it speed up? Then you have too little hanging mass.
4. Try recording some data. If the system is truly balanced, the slopes for uphill and downhill should be the same.
5. Record this equilibrium mass.
6. Increase the hanging mass so that when you give the cart an initial push uphill, it coasts at a constant speed. Record some data and adjust this as close as possible. Record this extra mass as the friction mass below.

Analysis

1. In the previous section, you adjusted the hanging mass to put the system in equilibrium. Show that for the special case, where the acceleration \rightarrow zero, Eqn. (1) reduces to

$$\sin \theta = m/M_{\text{cart}} \quad (2)$$

where in this case, m is the equilibrium mass.

2. Use Eqn. (2) to calculate the angle of the track. Is it different than what you measured earlier? It is probably a more accurate value. Your initial measurement could be off if the table wasn't level.
3. In the previous section, you added extra mass to the hanging mass to account for friction. That amount of mass goes to overcoming frictional forces, and doesn't add to the acceleration. Redo your calculation for the acceleration using Eqn. (1), but this time let the hanging mass equal 55 g minus the frictional mass. You can also use the new angle in this calculation.
4. Compare this new theoretical value to the measured value (from the graph) using

$$\%error = \frac{Measured - Accepted}{Accepted} \times 100$$

Statics

Equipment

2	High Res Force Sensor	PS-2189
1	Rotary Motion Sensor	PS-2120
1	Dynamics Track System	ME-6955
1	Cent. Force Pendulum	ME-9821
1	Large Rod Base	ME-8735
1	Table Clamp	ME-9472
2	Multi-Clamp	ME-9507
1	90 cm Rod	ME-8738
1	45 cm Rod	ME-8736
1	Braided String	SE-8050
1	Elastic Bumper	ME-8998

Introduction

This lab investigates the addition of vectors in a system that is in static equilibrium. The components of tension from the two parts of the string are compared to the Force Sensor pulling at the center of the string.

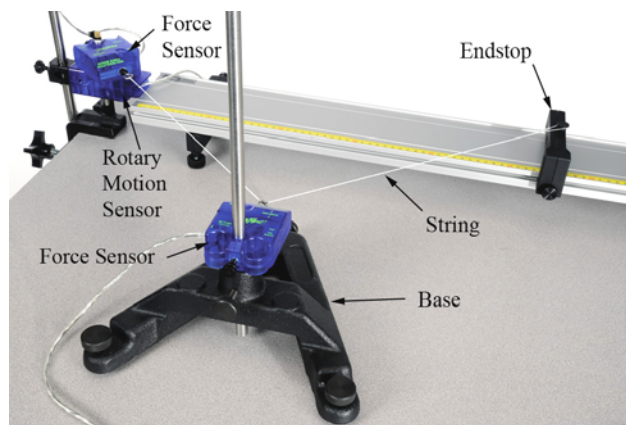


Figure 1: The movable Force Sensor (on the Base) applies a measured force to the center of the string, and the second Force Sensor (mounted on the Rotary Motion Sensor) measures the resulting Tension in the string. The string angle is measured directly using the Rotary Motion Sensor. By sliding the Endstop to the left or right, this angle can be easily varied.

Setup

1. Use the 90 cm Rod and Table Clamp (see Figure 2) to suspend the Rotary Motion Sensor.

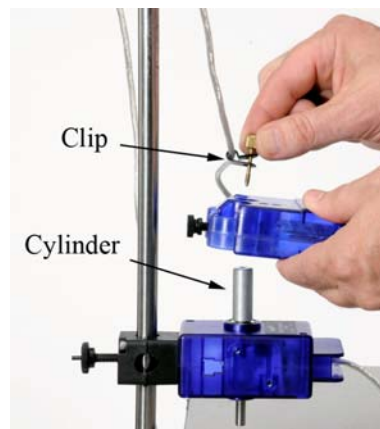


Figure 3: Connecting Force Sensor

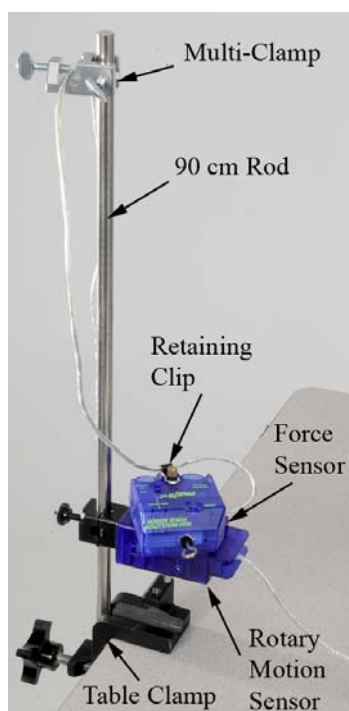


Figure 2: Rotating Force Sensor

2. The Force Sensor fastens to the Rotary Motion Sensor as shown in Figure 3. Slide the aluminum cylinder (from the Centripetal Force Pendulum) onto the shaft, then drop the Force Sensor onto the cylinder.

3. The brass screw and clip (from the Centripetal Force Pendulum) hold the Force Sensor cord at the rotation point, decreasing the unwanted torque of the cord. Slide the clip onto the cord (see Fig. 3) and use the brass screw to fasten it to the shaft of the Rotary Motion Sensor.
4. Tighten the black thumb screw on the Force Sensor to secure it to the aluminum cylinder.
5. Drape the Force Sensor cord over the Multi- Clamp (see Fig. 2). Keeping the cord vertical minimizes the torque of the cord.
6. Plug the mounted Force Sensor into Port P1 as shown in Figure 4. Plug a second Force Sensor into Port P4. Plug the Rotary Motion Sensor into Port P2.

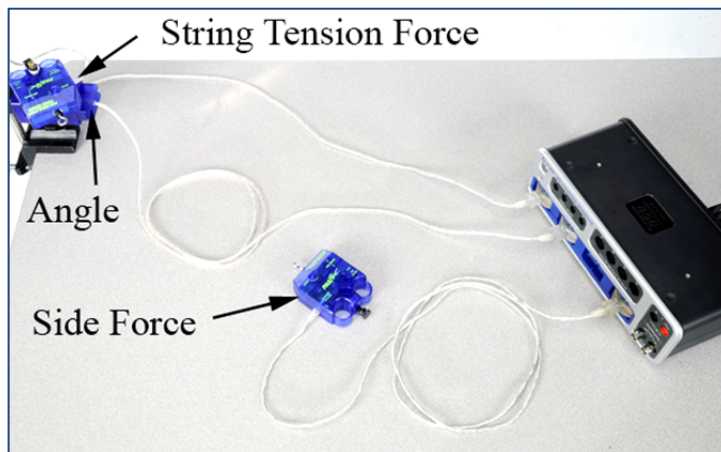


Figure 4: Plugging in Sensors

7. The Force Sensor that applies the sideways force is supported by the 45 cm Rod and Base (see Fig. 5). Slide the Force Sensor all the way down on the Rod until it rests on the Base shoulder as shown in Figure 6.
8. Adjust the height of the Rotary Motion Sensor so that the hooks of the two Force Sensors are the same height. Make sure the axle on the Rotary Motion Sensor doesn't touch the Table Clamp.
9. The edge of the track rests up against the Rotary Motion Sensor. Use the Screw Feet to adjust the height of the track to match the edge of the Rotary Motion Sensor as shown in Figure 7.

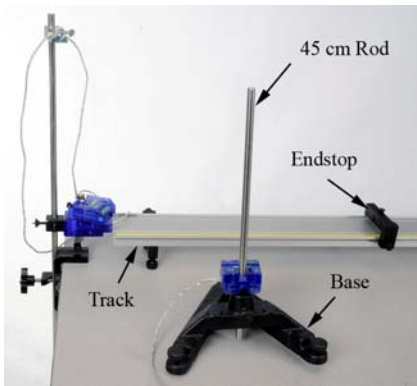


Figure 5: Adding Track

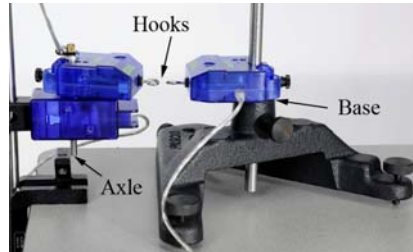


Figure 6: Force Sensor Height

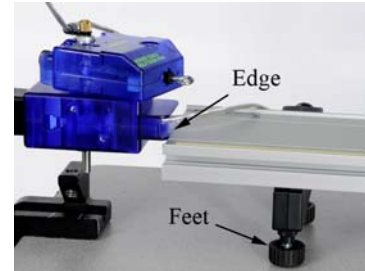


Figure 7: Track Height

10. In PASCO Capstone, create three digits displays: Select Angle, Force Ch. P1, and Force Ch. P4.
11. Change the Sampling Mode to Fast Monitor Mode.
12. Create a table with five columns: Create a new User-Entered data set in the first column called String Angle (units of Degrees); create a User-Entered data set in the second column called String Tension (units of N); create a User-Entered data set in the third column called Side Force (units of N); create a calculation in the fourth column (units of N):

Calculated Side Force = $2 * [\text{String Tension (N)}] * \sin([\text{String Angle (}^\circ)])$

and a calculation in the fifth column (units of %):

Percent Error = $\frac{\text{abs}([\text{Calculated Side Force (N)}] - [\text{Side Force (N)}])}{[\text{Calculated Side Force (N)}]} * 100$

String Center

The Force Sensor pulls at the "center" of the string as shown in Figure 8. One end of the string is attached to the second Force Sensor and the other end connects to the Endstop. Since we measure the angle only on one side, we must make both angles the same. To accomplish this, follow the steps below:

1. Cut a piece of string about 1 meter long and tie a non-slip loop on each end. Place the loops over the Force Sensor hook and the Brass Screw used to fasten the Force Sensor in place as shown in Figure 9.
2. Loop the string around the Endstop Post, and adjust the Endstop position to tighten the string.
3. Hold the string as shown in Figure 10, and loosen the Endstop. Mark the "center" position at the end of the loop. Whenever you apply a force to the string, you must make sure that the Force Sensor hook is pulling at this location.

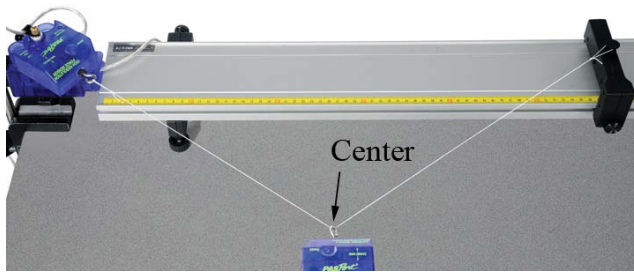


Figure 8: The length of the string on the right must equal the distance from the center Force Sensor out to the pivot point on the mounted Force Sensor. This makes the two angles equal.



Figure 9: Finding “center” of the String



Figure 10: Marking “center” of String

Theory

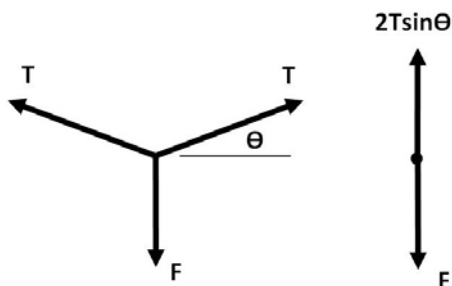
The Force Sensor (see Fig. 11) pulls on the center of the string with a force, F . Since the two lengths of string are the same, the angle, θ is the same for both sides (see Fig. 12), and thus the tension, T , is the same in both sides of the string. Breaking the two tensions into their components, one can show that for Static Equilibrium,

$$F = 2 T \sin\theta \quad (1)$$

Percent Error

Often in lab you are measuring something that has a known or accepted value. To compare your measured result with the accepted value, it is useful to calculate the error in that measurement.

$$\%error = \frac{Measured - Accepted}{Accepted} \times 100 \quad (2)$$



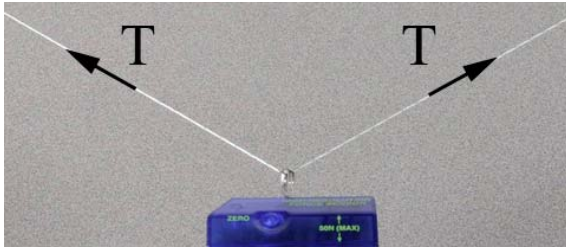


Figure 12: Tension Forces in the String

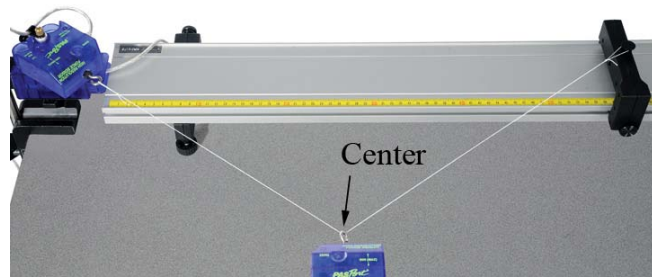


Figure 11: Pulling on the String

Procedure

1. Remove the string and zero both Force Sensors. Replace the loop over the hook on the "String" Force Sensor: Don't get the ends switched!
2. Hold the other end of the string over the center of the post on the Endstop as shown in Figure 13. Have the Endstop as far from the Rotary Motion Sensor as possible. Click on Monitor in the Experiment Control Bar. The Rotary Motion Sensor will zero on start at this initial position. Note that the Angle and Forces are shown in the Digits display.
3. Use the "Movable" Force Sensor (mounted on the movable Rod Base) to pull sideways on the string as show in Figure 14. Adjust the position of the Endstop for an angle between 10° and 15° . By gently moving the Rod Base, adjust the Side Force to be about 5 N. Check that the "String" Force Sensor is free to rotate and reads the correct angle.
4. Make sure the Movable Force Sensor hook is at the "center" of the string, and is square to the track: The string must pull straight out on the hook. It helps to loosen the thumb screw (see Fig. 14) and then re-tighten.
5. Recheck that the Side Force is about 5 N.
6. Click on Stop.

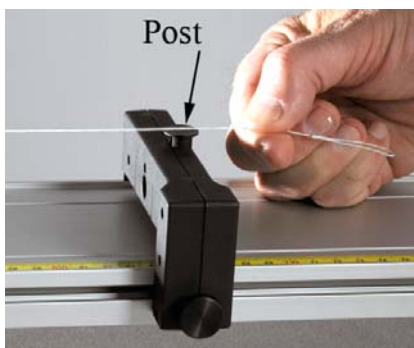


Figure 13. Setting Zero Angle

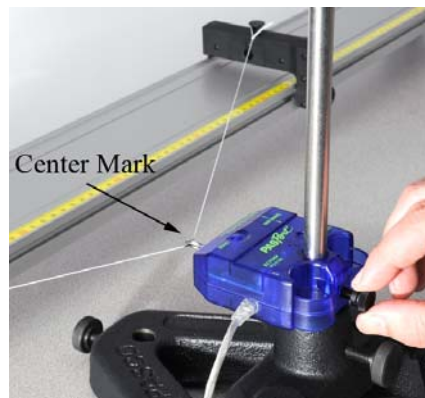


Figure 14. Movable Force Sensor

Changing Angle

7. Record your values in row 1 of Table I.
8. Using the angle and the measured tension in the string, use Eqn. (1) to calculate the expected Side Force, and enter in column 4 of the Table.
9. Compare this Calculated Force to your measured value using Eqn. (2) and enter this error in column 5 of the Table.
10. Move the Endstop about halfway towards the Rotary Motion Sensor. Hold the end of the string over the center of the post on the Endstop as before to set the zero. Click on Monitor.
11. Adjust the position of the Endstop for an angle between 45° and 50° .
12. By gently moving the Rod Base, adjust the Side Force to be about 5 N as before.
13. Check all measurements as before, then click on Stop.
14. Record all values in row 2.
15. Repeat for an angle between 70° and 75° . If the track tends to move, have someone hold it in place when pulling on the string.
16. Record all values in row 3.

Analysis

1. How do your calculated values for the Side Force compare to your actual measured values?
2. What might account for the discrepancies? Which angle was the most accurate? Why?
3. At your largest angle, which is bigger, the Tension in the string or the Side Force?
4. In the limit that $\theta \rightarrow 90^\circ$, what is the Tension in the string compared to the Side Force?
5. What is the physical arrangement of the string?
6. At your smallest angle, which is bigger, the Tension in the string or the Side Force?
7. In the limit that $\theta \rightarrow \text{zero}$, what is the Tension in the string?

Setup - Elastic

You will now replace the String with Elastic Cord (from the ME-8998 Elastic Bumper). This allows you to take continuous data as the cord is stretched (see Fig. 15) and the angle is changed.

1. Cut a piece of Elastic Cord about 0.8 m long and tie a non-slip loop on each end.
2. Stretch the Elastic Cord between the Force Sensor and the Endstop. Move the Endstop back to about 1m, to create a large enough force to turn the Force Sensor on the Rotary Motion Sensor. Don't pull sideways on the cord with the Force Sensor on the Base yet!

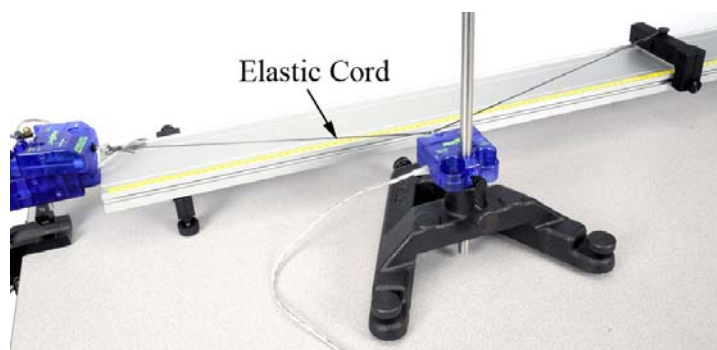


Figure 15: Using Elastic Cord

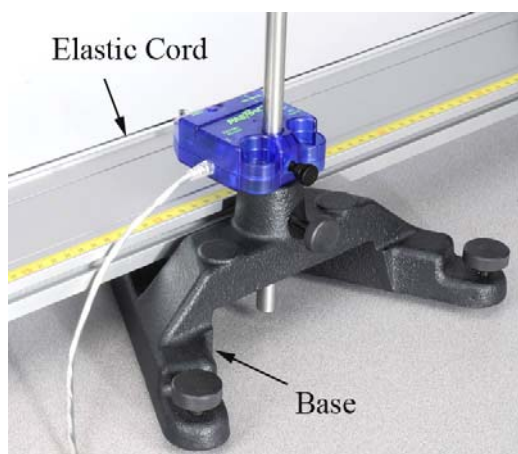


Figure 16: Notice how the Base slides under the Track. This allows the Force Sensor to reach clear to the middle of the Track.

Elastic Data

3. Create a table with three columns: Angle in the first column, Force Ch. P4 (side force) in the second column, and Force Ch. P1 (tension) in the third column.
4. Change the Sampling Mode to Keep Mode.
5. With the Cord stretched straight along the Track, click on Preview in the Experiment Control Bar below. The program is in "Preview" mode and will not record the data until you press "Keep Sample". Note that the current values for the two forces and the angle are displayed in Table II on row 1.
6. Tap the Force Sensor (on the Rotary Motion Sensor) to make it oscillate slightly: This breaks loose the friction and allows it to settle down to its true equilibrium position. If the Angle doesn't read zero, stop and restart recording.
7. Use the "Movable" Force Sensor to pull sideways on the cord (as before). Pulling at the center of the cord, adjust the force to achieve an angle of about 1° . Note that the Base slides under the track as shown in Figure 16. Tap the Force Sensor to make it oscillate to break loose the friction.
8. Click on "Keep Sample" to store the values. Do NOT press stop!
9. Increase the sideways pull to achieve an angle of about 2° . Click on "Keep Sample" to store the values.
10. Repeat for angles of about 3° , 5° , 7° , 10° , 15° , 20° , 25° , 30° , 35° , and 40° .
11. Click on Stop

Normalized Tension

Since both forces were changing each time you made a measurement, it is difficult to see the trend.

Create a table with four columns: In the first column, create a calculation (with units of degrees)

$$|\text{Angle}| = \text{abs}([\text{Angle } (^\circ)])$$

In the second column, select the Force Ch. P4; In the third column, select the Force Ch. P1; and in the fourth column, create a calculation (with units of N)

$$\text{Normalized Tension} = [\text{Measured String Tension, Ch P1 (N)}] / [\text{Measured Side Force, Ch P4 (N)}]$$

The "normalized" Tension ratio shows you at a glance how much bigger (or smaller) the Tension in the string is.

Another way to view this calculated value is to say that if you had always made the Side Force be 1 N, then this value would be the actual Tension Force in Newtons.

1. Take the ratio of a few of the values to make sure the calculation is correct.
2. In general, what happens to the Tension in the string as the angle, θ , gets smaller?
3. Create a calculation:

$$\text{sine}(|\theta|) = \sin(\text{abs}([\text{Angle} (^{\circ})]))$$

4. Make a graph of Normalized Tension vs. $\text{sine}(|\theta|)$.
5. Is this graph linear? Should it be?
6. Try an Inverse Fit from the Curve Fit Tool. How does it fit?
7. What is the relationship between the tension, T , and the sine of the angle?

Coefficients of Friction

Equipment:

1	Motion Sensor	PS-2103A
1	Force Sensor	PS-2189
1	Dynamics System	ME-6955
1	Discover Friction	ME-8574
1	Motorized Cart	ME-9781
2	Compact Mass	ME-6755
1	Braided String	SE-8050
Required, but not included:		
1	Balance	SE-8723

Introduction

The Friction Trays have different materials on their bottom surface. The Motorized Cart (see Fig. 1) is used to pull the trays in a controlled manner along the track, as the Force Sensor directly measures the frictional force. All parameters are investigated, including speed, normal force, and surface area.

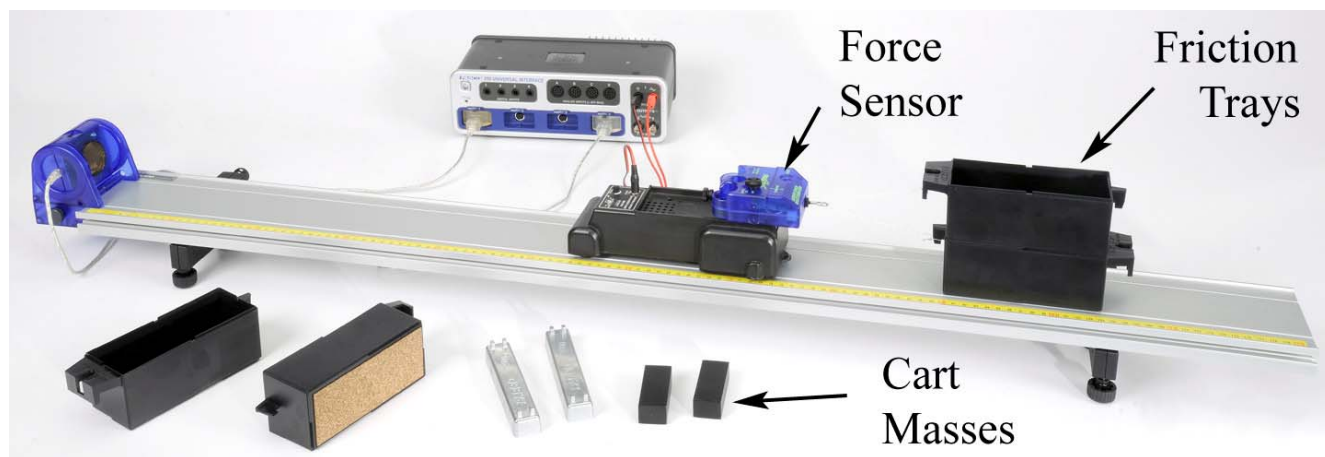


Figure 1: Measuring Sliding Friction

Setup

1. Set up the track as shown in Figure 1, and use the adjustable feet to level the track.
2. Connect the Motion Sensor to the PASPORT input P1, and attach it to the track. Make sure the switch on the top of the Motion Sensor is set to “cart”.

3. Connect the Force Sensor to the PASPORT input P4. Using the long thumbscrew, attach the Force Sensor to the cart as shown in Figure 2. Place the Cart/Force Sensor assembly on the track. Change the sample rate to 10 Hz. Open the properties for the Force Sensor in the Data Summary and check the Change Sign box.
4. Connect the Motorized Cart power cord to Output #1, and make sure the cart is on the OFF/EXTERNAL setting. With the DC Voltage set to 2 volts, turn the output on and off to ensure that the cart is working. You can open and close the output window by clicking on the Signal Generator icon in the tool palette.
5. Connect the Friction Trays to the Force Sensor using string as shown in Figure 2. The lower tray should have the black felt surface. You must always pull with two carts stacked, so that the Force Sensor pulls level. For the top tray, use one of the trays with the white plastic on the bottom. The lower end of the string is just looped around the tray hook: This makes it easier to swap out the lower tray to change the surface.
6. Place both silver cart masses in the upper friction tray. If the Motorized Cart has trouble pulling the load, add the black Compact Masses to the cart in front of the Force Sensor. If you still have trouble, remove one of the silver masses from the tray.

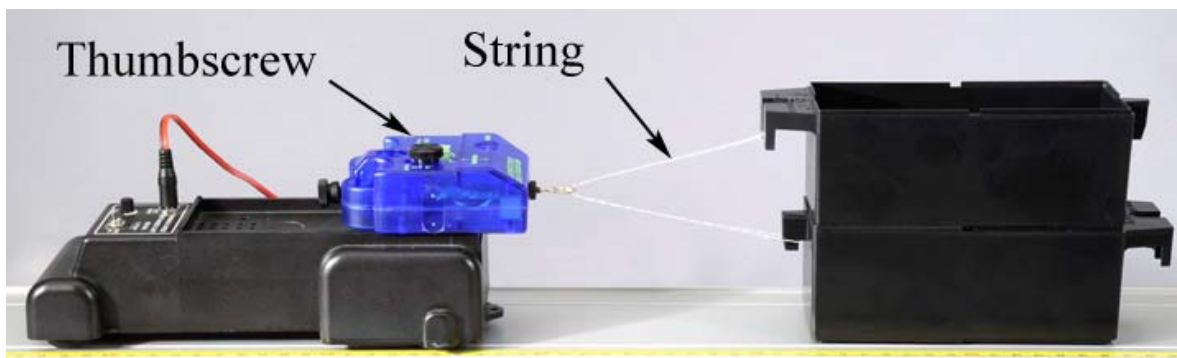


Figure 2: Towing the Friction Carts

7. Make a graph of velocity vs. time and add a plot area and put force in the second plot area. Select a Quick-Calc for the velocity ($-v$) to change the sign of the velocity so it will be positive.

Procedure: Measuring Speed and Force

1. Position the cart and trays at the far end of the track, opposite the motion sensor. This is the starting position for all the runs.
2. Open the Signal Generator window, and set the voltage for 1.0 volt DC. The output should be set on Auto, which will automatically turn on the cart when you start recording data, and stop the cart when data collection is ended.
3. Click on Record. Stop recording before the cart hits the motion sensor.
4. If the Motorized Cart can't pull the load, increase the voltage to 1.5 volts.
5. Adjust the Motion Sensor if necessary to get good velocity data.
6. The force data will be noisy, but you will be able to get an average reading. Try using the Smoothing tool in the Graph tool palette.

Changing Speed:

1. Change the sample rate of all the sensors to a common rate of 20 Hz.
2. Create a table with three columns: In the first column, create a User-Entered data set called Voltage (units of V); In the second column, create a Run-Tracked User-Entered data set called Speed (units of cm/s); In the third column, create a Run-Tracked User-Entered data set called Friction (units of N).
3. Use the Coordinates tool to measure the speed and the frictional force. Pick a time that has reasonably good data for both.
4. Record your values in the table.
5. Repeat for voltages of 1.5 V, 2.0 V, 2.5 V, etc. up to 5.0 volts.
6. Create a graph of Friction vs. Speed. What trend can you see in the data? How does the frictional force depend on the speed?
7. Take the ratio of the fastest speed/ slowest speed. By what factor did you vary the speed? By what factor did the resulting frictional force change? Would you say that the friction changed a little or a lot?
8. Does your data support the concept that it is a useful approximation to assume that sliding friction is independent of speed?

Changing Normal Force:

1. Create a table with four columns: In the first column, create a Run-Tracked User-Entered data set called Tray (unitless); In the second column, create a User-Entered data set called Mass (units of g); In the third column, create a calculation (units of N)

$$\text{Normal Force}_1 = [\text{Mass (g)}] * 9.8 / 1000$$

In the fourth column, select Friction.

2. Replace the lower felt tray with a tray that has a white plastic surface. Start with both trays empty, and use the balance to determine the mass. Calculate the combined weight, and enter this as the normal force in the table below.
3. Set the voltage output to 1.5 volts. Click on Record. Stop recording before the cart hits the motion sensor.
4. Using the graph, note the approximate speed and, if necessary, adjust the voltage in later runs to keep the speed the same.
5. Record the frictional force in the table. Add the 4 mass bars (one at a time) and repeat. You should end up with 5 values.
6. Create a graph of Friction vs. Normal Force₁. What trend can you see in the data? Try a linear Curve Fit. Is your data linear?
7. Most text books make the assumption that

$$f = \mu N \quad (1)$$

where f = friction, N = normal force, and μ = the frictional coefficient. Does your data support this assumption? What are the units for μ ?

Changing Surface Material:

1. Create a table with four columns: In the first column, create a User-Entered data set called Cart Material (unitless); In the second column, create a User-Entered data set called Normal Force (units of N); In the third column, create a User-Entered data set called Frictional Force (units of N); In the fourth column, create a calculation (unitless)

$$\mu = [\text{Frictional Force (N)}]/[\text{Normal Force (N)}]$$

2. Remove all but one of the mass bars. Click on Record, and use the graph to measure the frictional force.
3. Coefficients are always between two surfaces. What is the other surface?
4. Replace the lower plastic tray with a tray with black felt and repeat. Replace the lower felt tray with a tray with brown cork material and repeat.
5. Which material has the largest coefficient? Which has the least?
6. What type of friction are you measuring: Static or Sliding (Kinetic) friction?

Changing Area:

1. Connect the trays as shown in Figure 3. The bottom two trays should both be the white plastic. Place one of the silver mass bars in each of the two upper trays, and perform the pull test as before.
2. Measure the force from the graph and use equation (1) to calculate the coefficient of friction for the white plastic material.
3. How does this value (with twice the surface area) compare to your previous values? Most text books assume that sliding friction is independent of surface area. Do you agree?



Figure 3: Changing Surface Area

Static Friction:

1. Increase the sample rate of the force sensor to 2 kHz (the maximum).
2. On the graph, change the negative velocity to the Position.
3. Remove the trailing two trays, returning to the original set-up pulling only two trays. The lower tray should be cork. Place both silver masses in the upper tray, and both black masses on the Motorized Cart in front of the Force Sensor. If the cart won't pull the trays, remove one of the silver masses.
4. The Signal Generator is now set to ramp up its voltage, to slowly increase the pulling force over a 10 second period. If the trays don't break free and move in that time, increase the voltage amplitude.
5. Click on Record. As soon as the tray starts to slide, click on stop.
6. Examine your data on the graph. You can see from the position data where the tray starts to slide, and the value of the sliding friction force after this point. In the time before this, what does the force data look like?
7. Most materials show a value for static friction slightly larger than for sliding (kinetic) friction. Does your data support this? What is your largest value for the Static coefficient?

Friction and Newton's Laws

Equipment

1	Dynamics System	ME-6955
1	Photogate	ME-9498A
1	Photogate Bracket	(in ME-8998)
1	Elastic Bumper	ME-8998
1	Discover Friction	ME-8574
1	Mass and Hanger Set	ME-8979
1	Braided String	SE-8050
Required, but not included:		
1	Balance	SE-8723

Introduction

The photogate is used to measure the acceleration of the Friction Tray as it is being pulled by the falling mass.

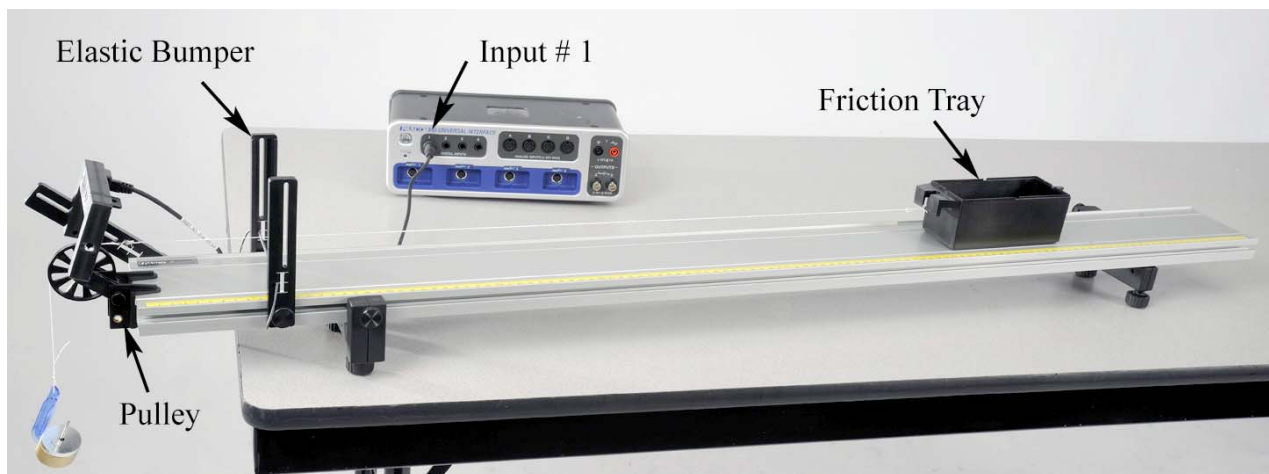


Figure 1: Measuring Sliding Friction

Setup

1. The Elastic Bumper should be placed about 15 cm from the end of the track as shown in Figure 1. The Clamp-on Pulley should have the pulley in the upper set of holes as shown.
2. The Photogate Bracket (see Figure 2) is cantilevered out over the end of the track. Note that the bracket is put on "reversed" so that it doesn't key into the track. This allows you to angle the bracket and Photogate.

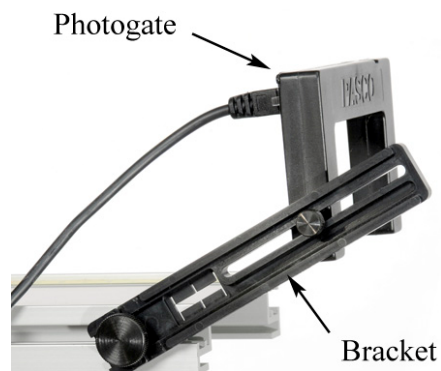


Figure 2: Reversed Bracket

3. Plug the Photogate into Digital Input #1 and choose Photogate with Pulley.
4. Level the track. If you don't have a level, you can use a PAScar, and adjust the track so the cart doesn't roll.
5. Determine the mass of the tray before attaching string! Use the tray with the cork surface.
6. Cut a piece of string about 1.2 m long. Tie to one end of the tray as shown in Figure 4.
7. Run the string over the pulley and down to the floor. When the tray reaches the end of the track, you want it to hit the Elastic Bumper before the hanging mass reaches the floor. If necessary, shorten the string.
8. Tie a loop in the string to hang the mass.
9. Adjust the pulley height so the string runs parallel to the track. Adjust the position of the Photogate so that the pulley spokes break the beam.
10. In PASCO Capstone, create a graph of Linear Speed vs. time.

Theory

The mass on the hanger (see Fig. 4) is falling and the Friction Tray is sliding to the left. The free-body diagrams (see Fig. 3) show the forces acting on each of the masses. The tension, T , is assumed equal for both parts of the string. Sign convention is adopted such that the acceleration, a , for the tray is positive to the left, and acceleration for the falling mass is positive downward.

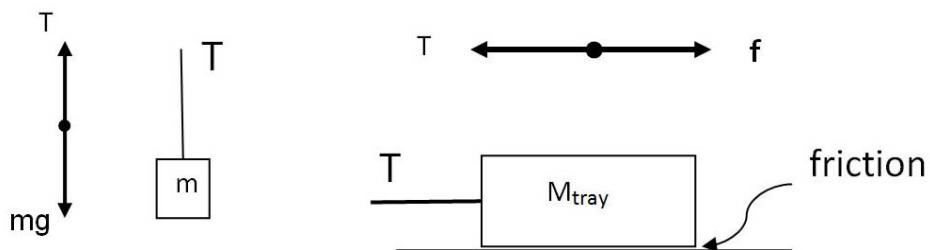


Figure 3: Free-body diagrams for both masses



Figure 4: Falling mass pulls the Friction Tray

m = hanging mass

M_{tray} = total mass of friction tray plus mass bar

Applying Newton's 2nd Law to the hanging mass gives

$$T = m(g-a) \quad (1)$$

Applying Newton's 2nd Law to the friction tray gives

$$M_{\text{tray}} a = T - f \quad (2)$$

where the frictional force, f , is

$$f = \mu N \quad (3)$$

Since the track is level and the string is pulling horizontally on the Friction Tray, the Normal Force, N , is

$$N = M_{\text{tray}} g \quad (4)$$

Procedure – Static Friction

1. Figure 5 shows the forces on the tray perpendicular to the track for this experiment. State at least two examples where Eqn. (4) would not be valid.
2. For the special case of the tray stopped (no acceleration), confirm that equations 1 through 4 can be combined to yield

$$\mu_s = m/M_{\text{tray}} \quad (5)$$

where μ_s is the coefficient of static friction.

3. Place one mass bar in the cork Friction Tray. Make sure the mass bar is centered side to side.
4. Put about 100 g on the mass hanger. You should be able to position the tray on the track and not have it slip, but if you cannot keep it from slipping, decrease the hanging mass.
5. Keep trying to increase the hanging mass. Record the maximum hanging mass that will not cause the tray to break free and move. Try several times in several different track locations. Try pushing down on the tray and releasing as gently as possible. Make sure the hanging mass is not swinging. You do not have to keep track of all your values, just record the single absolute max.
6. Use your max value and Eqn. (5) to calculate the coefficient of static friction.
7. Coefficients of friction are always between a pair of surfaces. One surface is cork: What is the other?

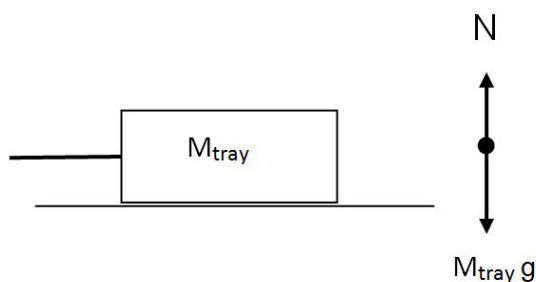


Figure 5: Normal Force

Procedure – Kinetic Friction

8. Place the maximum amount of mass, determined previously, on the mass hanger.
9. Hold the tray in place and click on Record. Release the tray and give it a small push.
10. Click on Stop after the tray reaches the bumper.
11. Use the Slope tool to examine the slope in various areas. If there is not a straight region, try another run. Why is it not more uniform?
12. Take several runs and determine an average acceleration.
13. Use equations 1 and 2 to calculate the frictional force.
14. Use equations 3 and 4 to calculate the kinetic frictional coefficient.
15. How does this compare to the value you got for the static coefficient?

Further Study

16. Decrease the hanging mass by about 50 g. If the tray still moves on its own, decrease the hanging mass even further.
17. Click on Record and give the tray a strong push. You want it to coast most of the way towards the bumper before it stops. Click on Stop
18. Calculate the kinetic frictional coefficient as you did previously. Hint: You must take into account the negative acceleration! How does this value compare?
19. Add the second mass bar to the tray, and add enough mass to the hanging mass so that it easily breaks free by itself.
20. Use equations 1 through 4 to predict the acceleration.
21. Measure the acceleration and compare to your prediction.

Magnetic Drag

Equipment

INCLUDES:

1	Motion Sensor	PS-2103A
1	Dynamics Track	ME-6995
1	Elastic Bumper	ME-8998
1	Magnetic Damping	ME-6828
NEEDED, BUT NOT INCLUDED:		
1	Meter Stick	SE-8827
1	Calipers	SE-8710
1	Balance	SE-8723

Introduction

As the cart moves along the aluminum track, the magnets on the accessory bracket induce eddy currents in the track. This causes opposing magnetic fields that result in a drag force applied to the cart. The magnitude of this force is measured by analyzing the deceleration of the moving cart. The relationship between the drag force and the speed of the cart is determined.

Setup



Figure 1: The Magnetic Damping Accessory attaches to the end of the cart that does NOT have the plunger. The steel bracket is held in place by the magnets inside the cart. It slides up and down to adjust the amount of drag: The closer the three silver magnets are to the track, the more damping there is.

1. Set up the track as shown in Figure 1, including feet and elastic bumper.
2. Connect the Motion Sensor to the interface, and attach it to the track. Adjust the alignment knob on the side of the Motion Sensor so that it points parallel to the track. Make sure the switch on the top of the Motion Sensor is set to "cart."
3. Set the cart on the track (including the two extra masses), but do NOT attach the Magnetic Damping Accessory yet.

4. In PASCO Capstone, leave the sample rate at the default rate of 20 Hz.
5. Create the following calculations in the PASCO Calculator:

$\text{speed} = \text{abs}([\text{Velocity}])$	with units of m/s
$\text{Mag Force} = -\text{mass} * \text{derivative}(6, [\text{Velocity}], [\text{Time}])$	with units of N

6. Create a graph of speed vs. time.
7. Create a graph of Mag Force vs. Velocity.

Procedure

1. Starting with the cart near the Motion Sensor, give it a small push away from the sensor, and click on Record. Your data will look better if you stop recording before the cart hits the bumper.
2. Using the screw feet, adjust the level of the track so that the cart travels at a constant speed when moving away from the Sensor. By setting up the track so that it is slightly downhill, you will be measuring only the magnetic drag on the cart. The unwanted frictional forces will have been compensated for.
3. Attach the Magnetic Damping Accessory to the cart (see Fig. 1) and determine the cart mass, with and without the two extra masses.
4. The amount of magnetic damping is determined by the distance between the magnets and the track (see Fig. 2). Use some type of spacer (any non-magnetic material will work) to set the distance to about 3 mm. Slide the bracket down until the magnets are flush with the spacer, then remove the spacer.



Figure 2: Magnetic Spacing

Magnetic Force:

5. Place both masses in the cart. Starting with the cart near the Motion Sensor, give it a small push away from the sensor, and click on Record. Your data will look better if you stop recording before the cart stops moving.

- Open the Calculator in the Tool Pallet. The Magnetic Force is calculated using Newton's 2nd Law:

$$\text{Mag Force} = ma$$

where m is the mass of the cart and the acceleration (a) is calculated using a derivative of velocity. Line 3 in the calculator shows the approximate mass of the cart, but you can edit that equation to change it to your cart mass.

- The graph of the calculated magnetic force versus the cart's velocity should be a linear relationship, although the data may be noisy. You may have to take several runs to get a good looking graph.
- Select a linear curve fit from the Graph Tool Pallet. Is your graph linear?
- The slope of the graph is called the Drag Coefficient. Record this value.

Equations of Motion

We will assume that the magnetic drag force, f , is proportional to the velocity, v

$$f = b v$$

where b is the drag coefficient.

On a level track, assuming no other sources of friction, the drag force is the only force acting on the cart along its axis of motion. Therefore, by Newton's 2nd Law,

$$m a = b v \quad (1)$$

where m is the mass of the cart and a (the acceleration) is the derivative ($a = dv/dt$) of the velocity. Thus Equation (1) can be written as

$$\frac{dv}{dt} - \frac{b}{m} v = 0$$

The solution to this differential equation is

$$V(t) = V_0 e^{-\frac{b}{m}t} \quad (2)$$

The velocity vs. time graph shows your data from the previous page. Does the velocity decay exponentially? Select an exponential curve fit from the Graph Tool Pallet.

Damping Coefficient

1. Create a graph of velocity vs. time. Select the exponential curve fit for your data. The constant in the exponential for the curve fit is b/m . Record this value. What are the units?
2. Record several more runs of data, and record the values of b/m for each. Put all the data into a table column and turn on the Statistics with the Mean and the Standard Deviation.
3. Use the average value of b/m and the mass of your cart, m , to calculate the drag coefficient, b .
4. What are the units of b ?
5. Use the standard deviation to calculate the uncertainty in your value.
6. How does this value for b compare to what you measured earlier from your Mag Force vs. Velocity graph?

Terminal Velocity: Inclined Track

As the cart accelerates down the incline (see Fig. 4), the magnetic drag force ($f=bV$) increases. Eventually, this backwards drag force grows to equal the component of the gravitational force down the plane ($mg\sin\theta$), and the cart reaches terminal velocity, (V_T). Assuming no other forces (such as air friction, etc.),

$$bV_T = mg\sin\theta$$

which can be written as

$$V_T = (mg/b) \sin\theta \quad (3)$$

1. Remove the two masses from the cart. You will use them to incline the track as shown in Figure 3. Be sure NOT to move the Magnetic Drag Accessory, or you will have to re-measure the coefficient.
2. Use calipers to measure the height of the two stacked mass bars, and a meterstick to measure the distance between the feet. Calculate the angle of incline for the track.
3. Use Eqn. (3) to predict the terminal velocity of the cart on the inclined track. Hint: The mass, m , has changed from the previous part of the experiment.

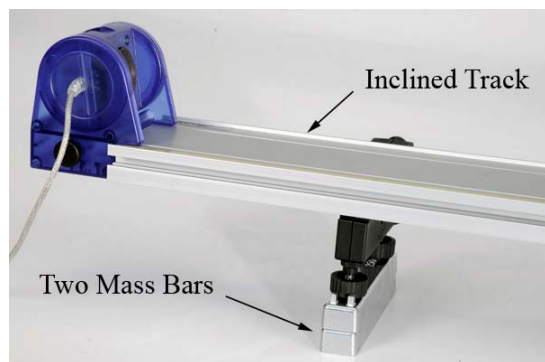


Figure 3: Inclined Track

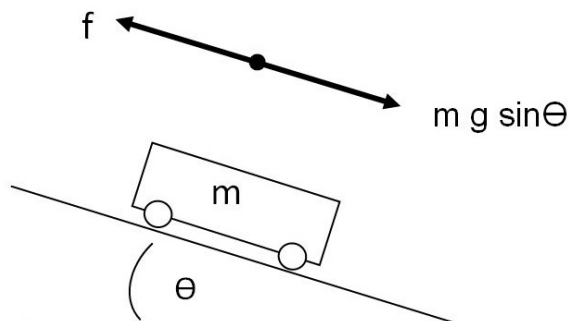


Figure 4. Free-body Diagram

Analysis

1. Starting with the cart about 20 cm from the Motion Sensor, release the cart from rest, and click on Record. Your data will look better if you stop recording before the cart hits the bumper.
2. Examine the velocity vs. time graph. What is the terminal speed of the cart?
3. How does it compare to your predicted value?

Magnetic Damped Oscillations

Equipment

Includes:

1	Motion Sensor	PS-2103A
1	Dynamics Track	ME-6995
1	Magnetic Damping	ME-6828
1	Spring Set	ME-8999
1	Rod base	ME-8735
1	45 cm Rod	ME-8736
Required, but not included:		
1	Meter Stick	SE-8827
1	Calipers	SE-8710
1	Balance	SE-8723

Introduction

As the cart oscillates on the aluminum track, the magnets on the accessory bracket induce eddy currents in the track. This causes opposing magnetic fields that result in a drag force applied to the cart. The amount of damping is varied by changing the spacing between the magnets and the track. Systems are investigated that are Under Damped, Over Damped and Critically Damped.

Setup

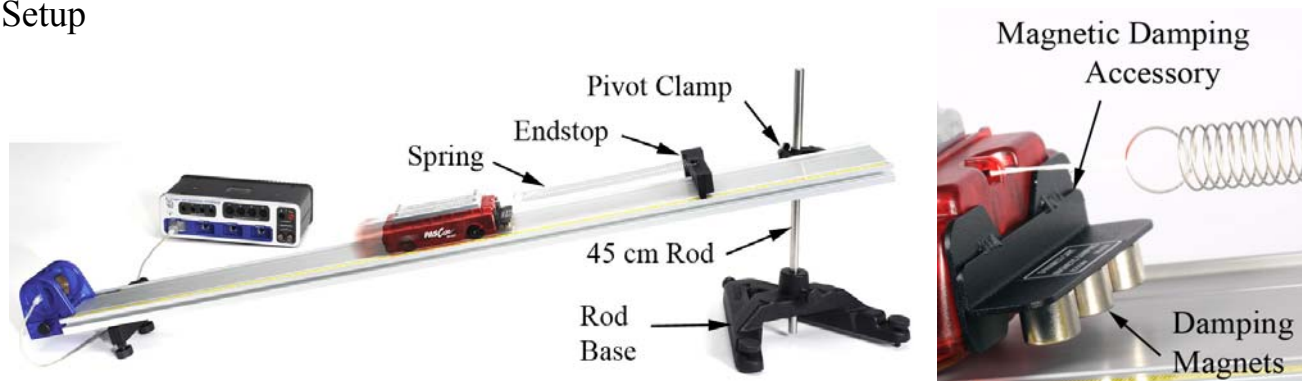


Figure 1: The Magnetic Damping Accessory attaches to the end of the cart that does NOT have the plunger. The steel bracket is held in place by the magnets inside the cart. It slides up and down to adjust the amount of drag: The closer the three silver magnets are to the track, the more damping there is.

1. Attach the endstop to the track as shown in Figure 1, then incline the track (about 30 cm) using the Pivot Clamp with the Rod Base and 45 cm Rod.

2. Connect the Motion Sensor to the interface and attach it to the track. Rotate the alignment knob on the side of the Motion Sensor so that it points parallel to the track. Make sure the switch on the top of the Motion Sensor is set to "cart."
3. In PASCO Capstone, keep the sample rate at the default 20 Hz. Create a graph of Position vs. time.
4. Attach the Magnetic Damping Accessory to the cart (see Fig. 2) and determine the cart mass including the accessory.
5. The Spring Set contains three each of four different springs. Start with one of the stiffer, longer springs. When new, this spring has a small dab of red paint on one end.
6. It is easier to attach the spring to the cart using a short loop of string as shown in Figure 2. The other end of the spring loops directly over the post on the Endstop.
7. The amount of magnetic damping is determined by the distance between the magnets and the track (see Fig. 3). Use some type of spacer (any non-magnetic material will work) to set the distance to about 8 mm. Slide the bracket down until the magnets are flush with the spacer, then remove the spacer.
8. Put both of the Cart Masses into the cart.
9. The spring should be stretched enough so that you can displace it from equilibrium (uphill) 15 cm and not have the spring go slack. Increase the incline of the track if needed.

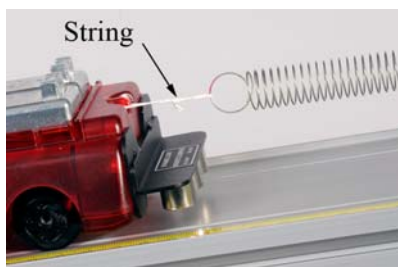


Figure 2: Attaching Spring to Cart



Figure 3: Magnet Spacing

Damped Oscillation Theory

The equation of motion for damped oscillation is given by

$$x(t) = x_0 e^{-Bt} \sin(\omega t + \varphi)$$

where $B = b/m$, the ratio of the magnetic damping constant (b) to the mass of the cart (m). The angular frequency (ω) of the oscillation is related to the period (T) by

$$\omega = \frac{2\pi}{T}$$

Procedure

1. Displace the cart up the track about 15 cm from its equilibrium position.
2. Release the cart and click on Record. Allow the cart to oscillate up and down several times. Your data will look better if you stop recording before the cart stops oscillating.
3. Select a Damped Sine Curve Fit from the graph tool pallet. How well does it fit your data? You can use the Selection Tool to highlight only a portion of the data.

Drag Constant

1. Using ω from the curve fit, calculate the period of oscillation.
2. Use the Coordinates tool to measure the period directly from the graph. How does it compare to your value from part (4)?
3. Use the parameter, B , in the exponent of your curve fit and the mass of the cart to calculate the damping constant, b .

$$B = b/m$$

4. Remove one of the masses and repeat. What values change?
5. Re-calculate the damping constant, b . How does it compare? Is it about the same value?

Critical Damping

1. Remove the masses from the cart. Replace the single stiff spring with two of the weaker long springs, as shown in Figure 4.
2. Adjust the incline of the track so that the cart is about midway between the Motion Sensor and the endstop. Note where the equilibrium position is.
3. Displace the cart up the track about 15 cm from its equilibrium position. When you release the cart, it will overshoot the equilibrium position and oscillate back and forth. Move the Damping Accessory down closer to the track (by about 1/2 mm) to create more drag. Try again. Does it still overshoot and then come back up the track?
4. Keep increasing the damping until it comes to a stop without overshooting the equilibrium position. You can record data to see the oscillation more clearly.
5. You want to find the least amount damping (biggest gap) that will still make the cart stop without overshooting. This is called Critical Damping.
6. You can delete unwanted runs using the Delete feature in the Experiment Control Bar.



Figure 4: Change to Weaker Springs

Analysis

For the following cases, always release the cart from the same initial position.

1. When you have the magnet spacing adjusted so that the least amount of damping (biggest gap) still makes the cart stop without overshooting, take one good run of data. Open up the Data Summary and re-name this run Critically Damped.
2. Slide the Damping Accessory up, increasing the spacing by about 1 mm so that the cart oscillates one or two times before coming to rest. Take one good run of data and re-name this run Under Damped.
3. Place a single piece of paper under the magnets, and then slide the Damping Accessory all the way down. Remove the paper. Take one good run of data and re-name this run Over-Damped.

4. For the Critically Damped run, how much time does it take for the cart to reach its equilibrium?
5. Note that for the Under-Damped run, the cart reaches the equilibrium point faster, but it overshoots. How much time does it take for the cart to come to rest at its equilibrium point?
6. In general, what is the condition in which an oscillating system damps out in the least amount of time?

Air Drag

Equipment

Includes:

1	Motion Sensor	PS-2103A
1	Dynamics Track	ME-6955
1	Elastic Bumper	ME-8998
1	Car Sail	ME-9595
1	Pulley (part of CI-6691)	ME-9450A
2	Compact Cart Mass	ME-6755
1	Mass and Hanger Set	ME-8979
	Braided String	SE-8050
Required, but not included		
1	Meter Stick	SE-8695
1	Balance Scale	SE-8723

Introduction

The large blue sail causes drag, slowing the moving cart. Three different size sails are used to study the relation between the drag force and the area of the sail. The effect of cart speed is also investigated, including the concept of terminal velocity.

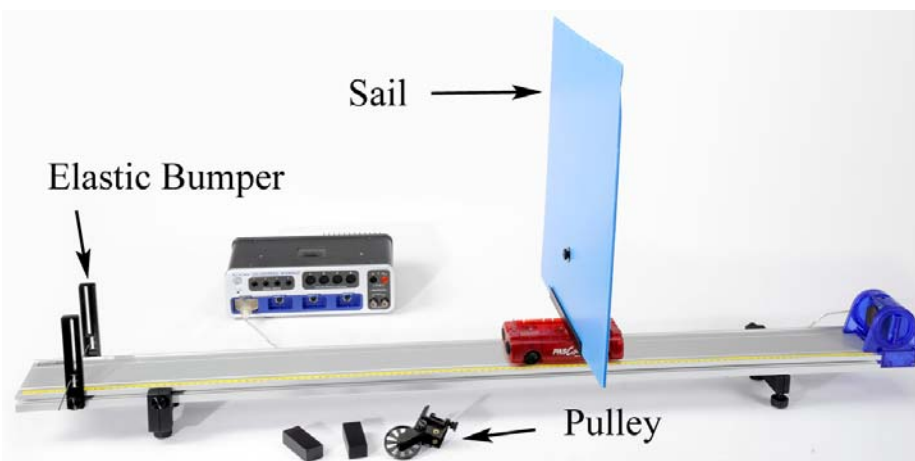


Figure 1: Measuring Air Drag

Setup

1. Set up the track as shown in Figure 1, including the feet and the Elastic Bumper.
2. Connect the Motion Sensor to the interface, and attach it to the track.
3. In PASCO Capstone, set the sample rate for the Motion Sensor to 10 Hz.
4. Create a graph of velocity vs. time.
5. The Pulley and black Compact Cart Masses will be used in another part of the experiment.
6. Connect the Sail Bracket to the cart as shown in Figure 2. Do NOT connect the sail yet! Use a balance scale to measure the mass of the "cart + bracket", and the masses of the three sails. Record these values.



Figure 2: Cart Sail Bracket







7. Adjust the level of the track using the cart and the adjustable feet. Place the cart on the track **without** the sail. Starting with the cart near the Motion Sensor, give it a small push away from the sensor, and click on Record. Your data will look better if you stop recording before the cart hits the bumper.
8. Using the screw feet, adjust the level of the track so that the cart travels at a constant speed when moving **away** from the sensor. By setting up the track so that it is slightly downhill, you will be measuring only the air drag on the sail. The unwanted frictional forces will have been compensated for.
9. Attach the large sail to the cart as shown in Figure 1.
10. Change the sample rate to 25 Hz.

11. Create a table with six columns as shown below: Create User-Entered Data Sets called “Sail” with no units, “mass” with units of kg, “a” with units of m/s^2 , and “Size” with units of cm. Also create the calculations:

$$\text{Drag Force}_1 = [\text{mass}] * [\text{a}] \quad \text{with units of N}$$

$$\text{Area} = [\text{Size}]^2 \quad \text{with units of cm}^2$$

Table I: Sail Data

	 Set	 Set	 Set	 Set	 Set	 Set
	Sail	mass (kg)	a (m/s^2)	Drag Force ₁ (N)	Size (cm)	Area (cm^2)
1	Large Sail					
2	Medium Sail					
3	Small Sail					

Procedure

- Starting with the cart near the Motion Sensor, give it a quick push away from the sensor, and click on Record. Your data will look better if you stop recording before the cart hits the endstop.
- You want data for a velocity between (approximately) 0.3 m/s and 0.2 m/s. If your data is not in this range, or if the data is too noisy, take another run.
- Select a linear curve fit from the Graph tool palette. Is your graph linear? If not, use the Selection tool to find the acceleration of the cart when its speed was about 0.25 m/s. Record this value.
- Repeat for several trials. Record your average value.
- Repeat for the Medium and Small Sail. Try to determine the acceleration of the cart in that same speed range of about 0.25 m/s. Record your average values.

Drag vs. Area

1. Use the mass data from the Setup page to calculate the mass of "cart + bracket + sail" for all three cases. Record your values in Table I.
2. The Drag Force is calculated using Newton's 2nd Law

$$\text{Drag Force} = ma$$

where "m" is the total mass of the cart and "a" is the average acceleration. This is the calculation for the force in Table I.

3. Use a meter stick to measure the length of one side of each of the square sails, and enter the values in Table I.
4. Create a graph of the Drag Force vs. Area. Does the data look linear?
5. What can you deduce about the relationship between air drag force and the area of the sail?

Changing Velocity

1. Change the sample rate to 20 Hz.
2. Create a table as shown below: Create User-Entered Data Sets called "Hanging Mass" with units of grams and "speed" with units of m/s. Create a calculation:

$$\text{Weight} = [\text{Hanging Mass}] * 9.8 / 1000 \quad \text{with units of N.}$$

Table II: Calculated Weight

Weight=[Hanging Mass (g)]*9.8/1000			
	Hanging Mass (g)	Weight (N)	speed (m/s)
1	5	0.049	
2	6	0.059	
3	7	0.069	
4	8	0.078	
5	9	0.088	
6	10	0.098	

3. Clamp the Pulley on the end of the track with the Elastic Bumper.
4. Cut a length of string about one meter long and tie one end to the cart. Tie a loop in the other end and hang a Mass Hanger from the loop. Hang the Mass Hanger over the Pulley, and adjust the string so the mass is just above the floor when the cart reaches the Endstop.
5. Level (eyeball it) the string by adjusting the Pulley. The string must clear the elastic on the Endstop.
6. Starting with the cart near the Motion Sensor, release it from rest, and click on Record. Your data will look better if you stop recording before the cart hits the Endstop.
7. Look at the shape of the graph. Is the slope increasing or decreasing? Is the net force on the cart constant?

Terminal Velocity

As the falling mass accelerates the cart down the track, the drag force increases. Eventually, this backwards drag force grows to equal the force of the falling mass, and the cart reaches terminal velocity.

Drag vs. Velocity

1. Create a graph of speed (terminal velocity) vs. Weight.
2. Place both Compact Cart Masses in the cart. With just the 5 g Mass Hanger over the Pulley, give the cart a small push and record its velocity as before. If the cart does not reach terminal velocity, increase the initial starting speed.
3. Use the Coordinates tool to measure the terminal speed on the Velocity vs. Time graph and enter your value in Table II.
4. Adding 1 g to the hanger at a time, repeat the above procedure for the masses listed in Table II.
5. Why is this weight equal to the drag force?
6. What does the graph show? In general, how does the drag force caused by the air depend on the velocity?

Centripetal Force

Equipment

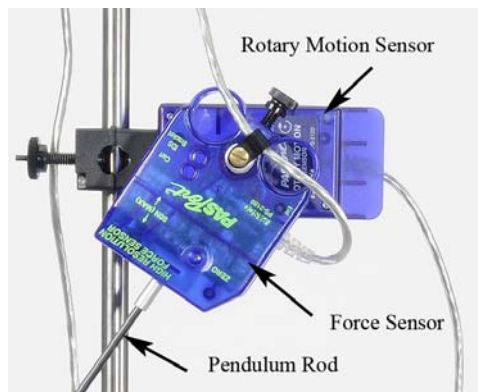
Qty	Items	Part Number
1	Rotary Motion Sensor	PS-2120
1	High Res Force Sensor	PS-2189
1	Centripetal Force Pendulum	ME-9821
1	Table Clamp	ME-9472
1	90 cm Rod	ME-8738
1	Multi-Clamp	ME-9507
1	Braided String	SE-8050
Required but not included:		
1	Meter Stick	SE-8695
1	Balance Scale	SE-8723

Introduction

For an object moving in a circle, the Centripetal Force is the name given to the sum of the components of all the forces acting on the object directed toward the center of the circle.

In this experiment, the Centripetal Force is directly measured using a Force Sensor. The dependence of Centripetal Force on radius and angular velocity is investigated.

The Force Sensor, supporting the pendulum, mounts directly onto the shaft of the Rotary Motion Sensor. As the pendulum oscillates back and forth, both force and angular velocity are recorded.



Setup

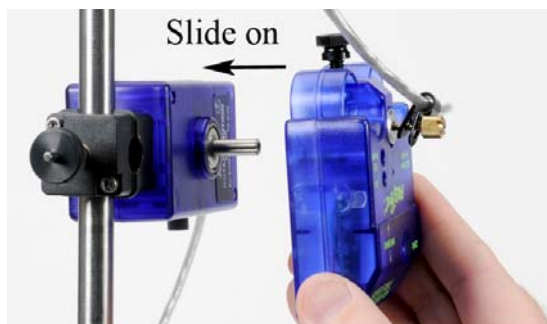
1. Use the Table Clamp and 90 cm rod to support the Rotary Motion Sensor as shown in Figure 1. Plug the Rotary Motion Sensor into the interface.



Figure 1: Setup

Figure 2: Force Sensor on Rotary Motion Sensor

2. Use the thumb screw and clip (see Figure 3) to fasten the Force Sensor cable at the center of rotation. This greatly reduces the effect of the cord on the motion of the pendulum.



: Cord through Clip Figure 4: Attach Force Sensor to Rotary Motion Sensor

3. Slide the Force Sensor with mounting post onto the Rotary Motion Sensor shaft as shown in Figure 4, and tighten the brass thumbscrew. The black plastic thumbscrew fastens the Force Sensor to the mounting post.
4. Use the multi-clamp to support the Force Sensor cable directly above as shown in Figure 1. Plug the Force Sensor into the interface.
5. Use the two thumb screws to attach the two-piece brass pendulum mass to the rod as shown in Figure 5. Later in the experiment, the mass will be located at various radii, but for now place the bottom of the mass flush with the end of the rod.
6. Screw the pendulum rod into the Force Sensor as shown in Figure 2.

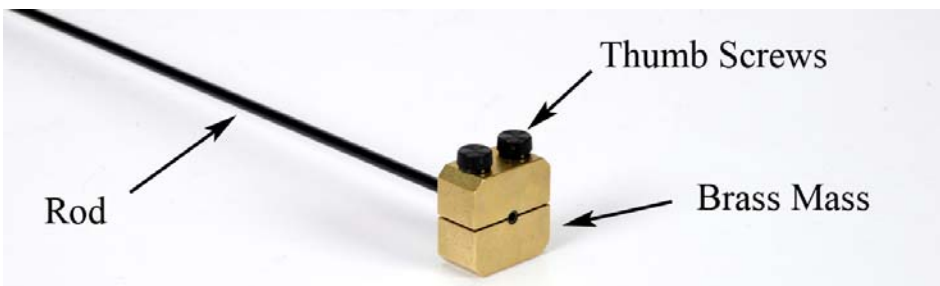


Figure 5: Attaching the Brass Mass

7. In PASCO Capstone, set the Common sample rate to 100 Hz.
8. Create a graph of Angular Velocity vs. Time. Add a plot area and put the Force on the vertical axis.

Procedure for Constant Radius

1. With the pendulum stationary, tare the Force Sensor using the zero button on the case. This will tare out the weight of the pendulum, so that during the experiment, the Force Sensor will be measuring only the force due to the pendulum's rotation.
2. Displace the pendulum from equilibrium (as shown in Figure 1), click on Record and release the pendulum. Immediately click on Stop: You want to record only 1/2 of a cycle.
3. Check the sign of the angular velocity data as it was released from rest. It needs to be **positive**. Open the Data Summary and click on the properties icon (gear) for the Rotary Motion Sensor. Note the check box to change the sign. You should also click on the "Zero Now" button: This will make the angle zero when the pendulum is at rest. You can also zero the Rotary Motion Sensor on the Experiment Control Bar at the bottom of the page.
4. Check the sign of the **force** data. It also needs to be **positive**. If necessary, open the Data Summary and click on the properties icon for the Force Sensor and change the sign. Once you are sure that everything is correct, delete all data runs.

In the next part, you will let the pendulum oscillate continuously while you take several short data sets. Each data set only needs to be about one or two cycles long. You want to see at least one maximum in the angular velocity data: This corresponds to when the pendulum is at the bottom of its swing.

5. Displace the pendulum from equilibrium, turning it nearly upside down. Release the pendulum: After it has oscillated one cycle, click on record and take data for one or two cycles, and then click on stop. Without touching the pendulum, record data for another couple of cycles. The only important part of each data run is that you see a maximum value for the angular velocity data. Keep recording more cycles (without disturbing the pendulum) until the angular velocity maximum is below 1 rad/s. You should get at least 10 runs.

Force and Speed Data

6. Create a table as shown: Create User-entered data sets called "Max F" with units of N and "Max ω " with units of (rad/s).
7. Using the data selector in the graph tool bar, select run #1. Turn on the statistics with the maximum selected.

Table I: Max Force and Speed data

	Max F (N)	Max ω (rad/s)
1		
2		
3		
4		
5		
6		
7		
8		

8. Make sure that the two maxima are for the same time. Turn on the Multi-coordinates tool.

9. If the data seems too noisy, try using the smoothing tool.
10. Enter the values for the maximum force and speed in Table I. Repeat for your other runs.

F vs. Speed

11. Create a graph of Max F vs. Max ω . In general, the Centripetal Force is the sum of the components of **all** the forces acting on the pendulum mass directed toward the center of the circle, which should include the weight of the pendulum. But for this data, the force data **is** the centripetal force. Why?
12. Is your data linear? Is the centripetal force directly proportional to the angular velocity?
13. Use a QuickCalc and change the horizontal axis to ω^2 . Is the data linear now? How does the centripetal force depend on the angular velocity?
14. Use a linear fit and record the slope for later use. What are the units?

Vary Radius

15. In this section, you will vary the radius. Slide the brass mass up the rod, and use a meter stick (see Fig. 6) to position the **top** of the mass 20 cm from the center of rotation.



16. Add a digits display and put the angle on it. For each run, you want the initial amplitude of the angular velocity to be about 4 rad/s. This is determined by the initial angular displacement, and thus it helps to watch the angle.

17. With the pendulum at rest, click on Record. Displace the pendulum about 30° and release. If the initial max angular velocity is not about 4 rad/s, then stop recording and try another run, adjusting your initial displacement accordingly.

18. You want to record data until the angular velocity amplitude is below 3 rad/s.

19. In this section, you will vary the radius, but the force will always be read when the angular velocity is about 3 rad/s.

20. Since there is a lot of uncertainty in this measurement, you will take several measurements at each radius.

Figure 6: Radius

21. Create Table II as shown: Create a User-Entered data set called “Force1” with units of N. Turn on the Mean and Standard Deviation statistics.
22. Create Table III as shown: Create User-Entered data sets called “Radius” with units of cm and “Avg F” with units of N.

Table II: Average Force

	Force1 (N)
1	
2	
3	
4	
5	
Mean	--
Std. Dev.	--

Table III: Force and Radius Data

	Radius (cm)	Avg F (N)
1	20	
2	25	
3	30	
4	34	
5	40	
6	45	

23. Examine the data carefully. You want to find the time when the amplitude angular velocity is as close as possible to 3 rad/s (in either direction). At that time, measure the maximum **positive** force.
24. Once you have a good run, use the Multi-coordinates tool to measure the force (Force1) at 3 rad/s. and enter your values in Table II. When you get a good solid average, enter that average force in Table III. Repeat for all radii listed in Table III.
25. Create a graph of Avg F vs. Radius. Is your data linear?
26. How does the centripetal force depend on the radius?

Analysis

In this experiment, you found that the centripetal force on an object travelling in circular motion is directly proportional to the radius (r) of the circle, and proportional to the square of the angular velocity (ω). This can be summarized as

$$F_c = mr \omega^2$$

where m is the mass of the object in circular motion. Thus a graph of F vs ω^2 results in a straight line with a slope equal to “ mr ”.

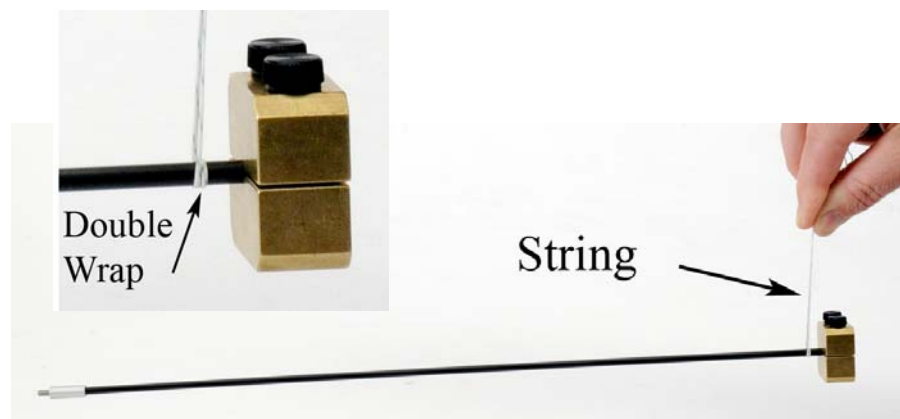


Figure 7: Finding the Center of Mass of the Pendulum

1. Reposition the brass mass back flush with the end of rod, as it was in the first part of the experiment. Measure the distance from the **top** of the mass to the center of rotation. Why is this not the correct radius to use in the equation?
2. Remove the pendulum and rod from the Force Sensor and use a Balance Scale to find its mass.
3. Use this mass and the slope from graph #1 to find the effective radius (r).
4. How does your calculated effective radius compare to the length you measured in part 1, above?
5. Use a piece of string (see Fig. 7) to balance the pendulum and find the center of mass.
6. Determine the distance from the center of mass of the pendulum to the center of rotation. How does your calculated effective radius compare to this value?

Conservation of Energy on an Inclined Track

Equipment

INCLUDES:

1	Dynamics System	ME-6955
1	Photogate Head	ME-9498A
1	Photogate Bracket	(in ME-8998)
1	Smart Timer Picket Fence	ME-8933
1	Large Rod Base	ME-8735
1	45 cm Rod	ME-8736
1	Elastic Bumper	ME-8998
NEEDED, BUT NOT INCLUDED:		
1	Meter Stick	SE-8695
1	Balance Scale	SE-8723

Introduction

As the cart rolls freely downhill, gravitational potential energy is converted to kinetic energy. The cart is released from the same height, multiple times, with the photogate measuring the speed at a different location for each run. This allows values to be calculated for both potential and kinetic energy at various heights.

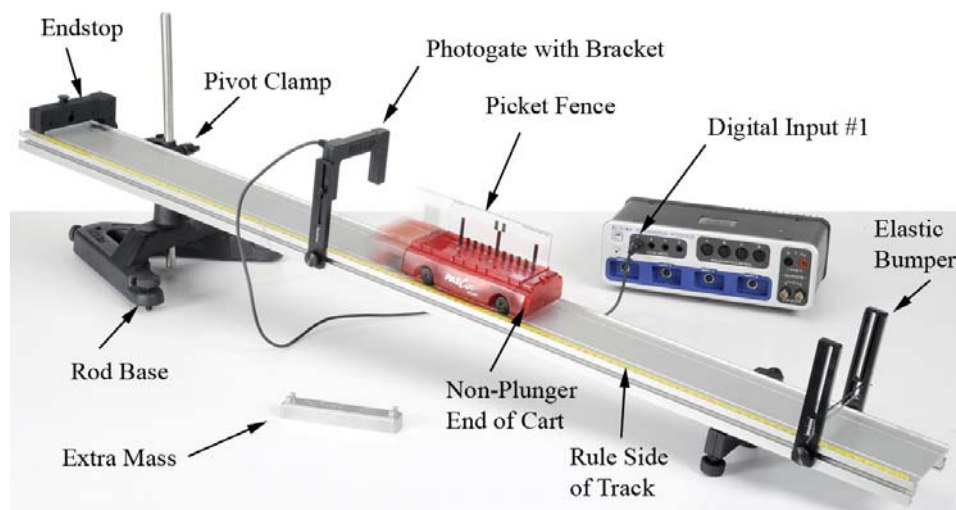


Figure 1: The cart rolls freely down the incline.

Setup

1. Set up the track as shown in Figure 1 using the large rod base and the 45 cm rod. The square nut on the Pivot Clamp slides into the T-Slot on the track, and allows the track to be secured at various angles.
2. Adjust the high end of the track to be about 15 cm to 20 cm above the table.
3. Note the location of the yellow rule on the track. Make sure that zero is at the top (left end) of the track.
4. The Endstop at the top (left end) of the track is used as a starting position for the cart. For each run, the cart will be released (at rest) from this same location.
5. Position the cart so that the non-plunger end is downhill. This end of the cart contains magnets, which must be kept as far as possible from the upper Endstop.
6. Plug the Photogate into Digital Input #1. The Photogate will be placed at various locations to measure the speed of the cart as it rolls downhill.
7. In PASCO Capstone, in the Hardware Setup, select One Photogate (Double Flag) for Digital Input #1 on the interface.
8. Change the data collection mode to Keep Mode on the Experiment Control Bar at the bottom of the page.
9. Create a table as shown: Create Run-Tracked User-Entered data sets called “Mass” with units of kg and “Height” with units of m. The Speed in the second column is the speed recorded from the photogate.

Table I. Height and speed data.

	<No Data Selected>	<No Data Selected>	<No Data Selected>
	Mass (Kg)	Speed (m/s)	Height (m)
1			
2			
3			
4			
5			
6			
7			
8			

10. Adjust the height of the Photogate so that the "Double Flag" on the top of the Picket Fence breaks the beam as the cart moves by.
11. Install the Elastic Bumper at the bottom of the track. The Rubber Cord should be placed so that the cart pushes the cord into the slots, as shown in Figure 2. For safety, it is a good idea to use more than one piece of cord.
12. Each time that the Photogate is moved to a new location, the new height must be measured. A convenient place to measure to is the bottom of the photogate bracket (see Fig. 3). It doesn't matter where you measure to, but you must measure to the same place each time!
13. Make sure that the rod and pivot clamp are secure. You do not want the height of the track to change in the middle of the run!
14. Make sure the endstop at the top of the track is secure. It is your starting position for the cart, and it must be the same for each run.

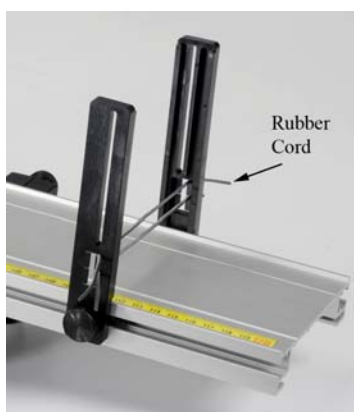


Figure 2: Elastic Bumper

Note that the Rubber Cord should be inserted into the bracket so that when it is hit by the cart, the cord is pushed into the slots. It is a good idea to use more than one piece of cord.

Measuring the height of the track at the Photogate location. It doesn't matter where you measure to, but you must measure to the same place each time!



Figure 3: Photogate Height

Procedure: Recording Data in "Keep Mode"

1. To start recording data, click on Preview in the Experiment Control Bar. Run 1 should appear at the top of each column in Table I. Columns 1 and 3 are user entered data (see below) and column 2 is for the measured speed of the cart. The program is set for "Keep Mode", and the speed value for each part will not be stored until you click on "Keep Sample"
2. Use a balance to measure the mass of the "Cart + Picket Fence". Enter the value in column 1. For this part of the experiment, the mass does not change, but the value will need to be entered for each row of data you take.
3. Position the Photogate near the upper end of the track at the 20 cm mark. It doesn't matter if you line up the mark with the left side or right side of the bracket, but you should do it the same way each time you move the photogate. Measure the height of the track at the Photogate location, and record your value in row 1 of column 3.
4. As a test, move the cart (by hand) through the Photogate. You should see a speed appear in row one of column 2. Move the cart back and forth through the Photogate. You should see a new measured speed each time.
5. Position the cart at the top of the incline, firmly against the Endstop. This is the starting position for the cart each time. Make sure that the non-plunger end of the cart is downhill, away from the Endstop. The plunger should be completely retracted.
6. Release the cart from rest, allowing it to freely roll downhill. The speed of the cart will appear in the table, but will not be stored until you press "keep". Try releasing the cart several times to see how much uncertainty there is in the measurement. When you have a good value, click on "Keep Sample". Do NOT press stop!
7. Position the Photogate at the 30 cm mark, and measure the height of the track at the Photogate, and record your value in row 2 of the table.
8. Release the cart from rest at the top of the incline. You should see the speed appear in row two. When you have a good value, click on "Keep Sample". Repeat for Photogate positions of 40, 50, 60 70 and 80 cm. Do not let the cart bounce back up through the Photogate.
9. Click on Stop.

Calculating Energy

1. Create the following calculations in the Capstone calculator (all with units of J):

$$\text{Potential Energy} = [\text{Mass}] (9.8) [\text{Height}]$$

$$\text{Kinetic Energy} = 0.5[\text{Mass}] [\text{Speed}]^2$$

$$\text{Total Energy} = [\text{Potential Energy}] + [\text{Kinetic Energy}]$$

2. Create a table with the Potential Energy and Kinetic Energy.
3. For one of the data sets in Table I, calculate the potential energy and kinetic energy of the cart for that height. Confirm that the corresponding value is correct in Table II.
4. Create a graph of Potential Energy vs. Index. Use Add Similar Measurement to add Kinetic Energy and Total Energy to the vertical axis.
5. What happens to the relative value of the potential energy and kinetic energy as the cart rolls down the hill?
6. Evaluate the total energy of the cart. Is energy conserved?

Table II. Energy

	<No Data Selected>	<No Data Selected>
	Potential Energy (J)	Kinetic Energy (J)
1		
2		
3		
4		
5		
6		
7		
8		

Change Mass:

1. To start recording a new run of data, click on Preview in the Experiment Control Bar. Run 2 should appear at the top of each column in Table I.
2. Add the Mass Bar to the cart and measure the new mass. Enter the value in column 1.
3. Move the Photogate back up to the 20 cm mark. Start with the cart at rest against the stop, and allow the cart to roll through the Photogate as before. When you have a good value, click on "Keep Sample". Do NOT press stop!
4. Repeat for the other five locations.
5. Click on Stop.

Change Angle

1. To start recording a new run of data, click on Preview in the Experiment Control Bar. Run 3 should appear at the top of each column in Table I.
2. Change the height of the end of the track by a few centimeters. Move the Photogate back up to the 20 cm mark and measure the new height. If the old height values are in the table, you can delete them. Record the new value.
3. Measure height and speed values for all locations.
4. Click on Stop.

Analysis

1. Use the Run Select Tool in the Graph Tool Bar to compare the three runs. Is energy conserved?
2. What effect would friction have on the experiment? Do you see this in your data?
3. When you increased the mass of the cart, how did this affect the Potential Energy of the cart at any given location? How did this affect the Kinetic Energy of the cart? How did this affect the speed of the cart? In Table I, compare the speeds for Run 1 to the speeds for Run 2. Is that what you expected?
4. The height used to calculate the Potential Energy was measured to an arbitrary point on the track. What would change in the experiment if you had chosen a different point?

Gravitational Potential Energy

Equipment

Includes:

1	Motion Sensor	PS-2103A
1	Table Clamp	ME-9472
1	90 cm Rod	ME-8738
1	45 cm Rod	ME-8736
1	Multi-Clamp	ME-9507
Required, but not included:		
1	Balance Scale	SE-8723
1	Ball to Drop	

Introduction

As the ball falls, the Motion Sensor measures both its position and velocity. Calculations are made for gravitational potential energy and kinetic energy. This experiment explores the relationship between potential and kinetic energy for a falling object.

Theory

When you drop a ball and it falls, the total energy of the ball stays constant if there is no air resistance. The ball starts with all gravitational potential energy at the top, and converts the potential energy to kinetic energy as it falls. At any time during its fall, the addition of kinetic plus potential will be constant if the drag may be ignored. For an object in freefall, its velocity (v) increases as its height (h) decreases. At any point in its fall, its potential energy (PE) can be calculated using

$$PE = mgh$$

where m is the mass of the dropped object. Its kinetic energy (KE) can be calculated using

$$KE = \frac{1}{2}mv^2$$

Setup

1. You need a ball to drop. A diameter of 10 to 20 cm is ideal.
2. Attach the table clamp and 90 cm rod to the table, and use the 45 cm rod and multi-clamp to suspend the Motion Sensor out over the floor as shown in Figure 1.
3. You want the Motion Sensor to be at least 1.5 m off the floor, and as far from the edge of the table as possible.
4. Plug the sensor into the interface. In PASCO Capstone, set the sample rate to 40 Hz. Create a graph of Position vs. Time.
5. Set the Range Switch on the Motion Sensor to the "cart" setting. This should work the best, but if you have trouble try switching to the "people" setting. You must have everything back out of the way, so the sensor sees only the ball or the floor. You can also try adjusting the angle of the sensor.
6. Place the ball on the floor directly under the sensor and click on Record. If the data is not smooth or if the distance is not approximately correct, try the suggestions listed above.
7. While recording, lift the ball up close to the sensor. Note that it cannot detect the ball when it is closer than 15 cm. Drop the ball and then click on stop.
8. Practice until you can get data that is reasonably smooth and continuous, then delete all your data.



Figure 1. Dropping the Ball

Procedure: Height

1. Click on Recording Conditions in the Experiment Control Bar and set the Start Condition to Measurement Based for Position when it rises above 0.20 m. Set the Stop Condition to Measurement Based for Position when it is above 1.20 m.
2. Hold the ball close (~10 cm) to the sensor and click on Record. Data will not be collected until you release the ball and it has moved to more than 20 cm from the sensor.
3. An automatic stop condition halts data collection when the ball reaches a distance of 1.2 m. These values can be changed if needed.
4. Get one good run of position data.
5. Open the Calculator in Capstone and create the following calculations:

$h = 1.5 - [\text{Position}]$	with units of m
$PE = m * g * h$	with units of J
$m = 0.100$	with units of kg
$g = 9.8$	with units of m/s^2
$v = \text{derivative}(5, [\text{Position}], [\text{Time}])$	with units of m/s
$KE = 0.5 * m * v^2$	with units of J
$\text{Total} = [PE] + [KE]$	with units of J

6. Look at the height (h) calculation. It subtracts the position of the ball (measured from the sensor) from 1.5 m, thus creating a measurement that is referenced to the floor.
7. Click on Position in the vertical axis of your graph, and pick "h" from the pull-down menu. Now you have a graph of the height of the ball as a function of time. You can change the value of 1.5 m in the calculator if you want, to adjust the zero value for your data.
8. Examine the graph of height. What happens to the height of the ball as time proceeds? Measure the initial height off the graph and record it.

Potential Energy:

9. Open the Calculator window and look at the potential energy (PE) calculation. It assumes a mass (m) of 0.1 kg, but you can measure the mass of the ball and change it in the calculation.
10. Create a graph of PE (potential energy) vs. Time. Measure the initial value off the graph and record it.

11. Using the initial height from the h vs. t graph, calculate the initial potential energy and confirm with your measured value off the graph.
12. What happens to the potential energy of the ball as time proceeds?
13. Click on "time" in the horizontal axis of your graph, and pick " h " from the pull-down menu. Now you have a graph of potential energy vs. the height of the ball. How does the potential energy of an object depend on its height?

Kinetic Energy:

14. Create a graph of the speed of the ball vs. time. Measure the initial speed of the ball off the graph, and calculate the initial kinetic energy.
15. Use the pull-down menu on the vertical axis to change to the graph of kinetic energy (KE). What happens to the kinetic energy of the ball as time proceeds?
16. Measure the initial kinetic energy off the graph and confirm with the value you calculated.
17. Click on "time" in the horizontal axis of your graph, and pick " v " from the pull-down menu. Now you have a graph of kinetic energy vs. the speed of the ball. How does the kinetic energy of an object depend on its speed?
18. Click on the horizontal axis of your graph, and pick " h " from the pull-down menu. Now you have a graph of kinetic energy vs. the height of the ball. How does the kinetic energy of the ball depend on its height?

Total Energy:

19. Create a graph of kinetic energy (KE) vs. time and use Add Similar Measurement to add potential energy (PE) and the Total (energy). In general, what happens to the potential and kinetic energies as the ball falls?
20. The total energy ($KE + PE$) is also shown on this graph. In general, what happens to the total energy as the ball falls?
21. Is the graph of total energy what you expected? In general, how would this graph change if you could add in more air drag?
22. Click on the horizontal axis of your graph, and pick " h " from the pull-down menu. Now you have a graph of total energy vs. the height of the ball. How does the total energy of the ball depend on its height?

Work and Energy:

23. Use the Position vs. Time graph. Take another run of data, but now start with the ball about 1 m below the Motion Sensor. Note you must remove the start condition so data collection will start immediately.
24. With data being collected, lift the ball up so that it is about 20 cm from the sensor. Hold it there for a second or two, then drop it. Data collection should stop automatically as before.
25. If the data is too noisy, try again. Get a single good run.
26. Note the time when the ball was dropped.
27. Click on "Position" in the vertical axis of your graph, and pick "Total" from the pull-down menu. You now have a graph of the total energy of the ball.
28. Is the total energy of the ball constant as it is being lifted? Where does the energy come from?
29. Examine the graph of total energy just before and after it is dropped. What do you see?

Conservation of Energy of a Simple Pendulum

Equipment

Includes:

1	Rotary Motion Sensor	PS-2120A
1	Density Set	ME-8569
1	Multi-Clamp	ME-9507
1	Large Table Clamp	ME-9472
1	Rod, 90-cm	ME-8738
1	Rod, 45-cm	ME-8736
1	String	SE-8050
Required, but not included:		
1	Meter Stick	SE-8827
1	Balance	SE-8723

Introduction

When a pendulum swings, potential energy is transformed into kinetic energy, and then back again to potential energy as the speed and elevation of the pendulum vary during the motion. In this experiment (see Figure 1), the motion of the pendulum is measured by the Rotary Motion Sensor. The height, h , of the pendulum "bob" is calculated using the angle, θ , and the length of the pendulum, L , as shown in Figure 2. Using trig, it can be shown that

$$h = L (1 - \cos\theta) \quad (1)$$

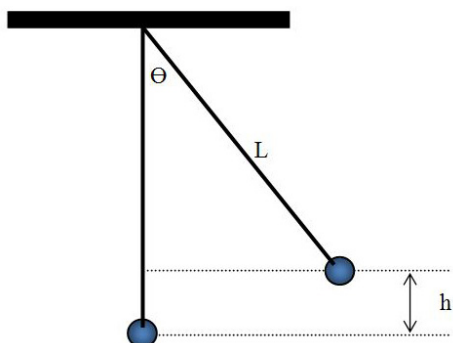


Figure 2: Calculating height, h .

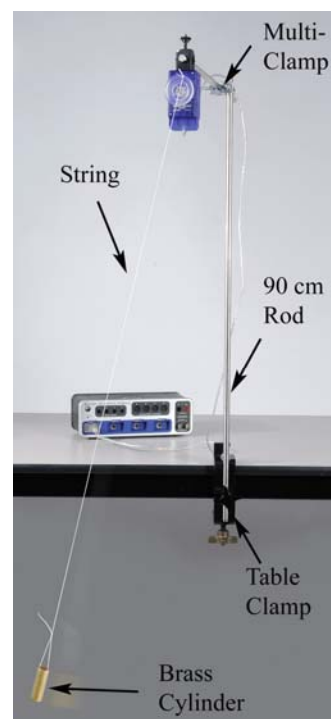


Figure 1: Simple Pendulum

Setup

1. Attach the table clamp and 90 cm rod to the table as shown in Figure 1. Use the multi-clamp and 45 cm rod to suspend the Motion Sensor out over the floor.
2. Use a balance scale to determine the mass of the brass cylinder from the density set.
3. Cut a length of string about 1.5 m long and thread one end through both holes in the Rotary Motion Sensor pulley as shown in Figure 3. Tie a knot at the top to keep the string from pulling back through.
4. Tie the brass mass to the other end of the string. You want the string as long as possible, without the mass touching the floor.
5. As accurately as possible, determine the length, L , of your pendulum. You should measure from the center of rotation down to the center of the cylindrical mass.
6. Plug the Rotary Motion Sensor into Channel P1 on the interface.
7. In PASCO Capstone, set the sample rate to 50 Hz.

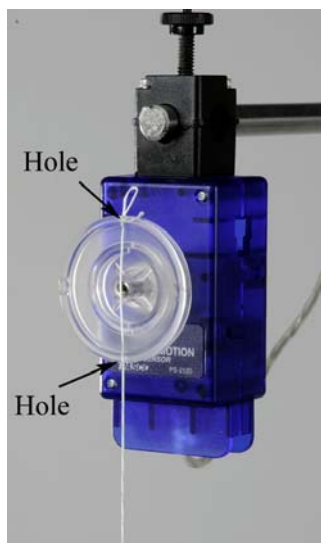


Figure 3. Hanging String

Calculations

1. Open the Capstone Calculator window and create the following calculations:

$v = L * \text{derivative}(7, [\text{Angle}(\text{rad})], [\text{Time}])$	with units of m/s
$L = 1.00$	with units of m
$\text{KE} = 0.5 * m * v^2$	with units of J
$m = 0.300$	with units of kg
$U = m * g * L (1 - \cos([\text{Angle}(\text{rad})]))$	with units of J
$g = 9.8$	with units of m/s^2
$\text{Total} = \text{KE} + U$	with units of J

2. Change the default values for the pendulum mass (m) and length (L) to the values for your pendulum.
3. The calculation for the velocity uses the relationship between tangential speed (v) and the angular rotation speed (ω)

$$v = \omega r \quad (2)$$

where the radius (r) is equal to L, the length of the pendulum. The angular rotation speed (ω) is calculated by taking the derivative of the angle, θ .

Speed and Kinetic Energy:

1. Create a graph of v vs. t and add a plot area and put KE on the vertical axis of the second plot area.
2. Make sure that the pendulum is absolutely still, then start recording.
3. Immediately pull the pendulum sideways about 30° and smoothly release.
4. You only need two or three oscillations, then click on Stop.
5. The data needs to be completely smooth and free of spikes. If the pendulum is not released smoothly, there will be unwanted secondary oscillations. Repeat until you have one good, smooth run.
6. Use the Multi-Coordinates tool to measure the first maximum speed of the pendulum.
7. Using this speed and the mass of the pendulum, calculate the maximum kinetic energy.
8. Measure the kinetic energy off the graph for the same time and compare.

Potential Energy (U):

9. Create a graph of Angle vs. Time. Then add a plot area and put the potential energy (U) on the vertical axis of the second plot area.
10. Use the Multi-Coordinates tool to measure the first maximum in the angle for the pendulum.
11. Using Eqn. (1), calculate the resulting height, h .
12. Using this height and the mass of the pendulum, calculate the maximum potential energy.
13. Measure the potential energy off the graph for the same time and compare.
14. How does this maximum potential energy compare to the maximum kinetic energy from the previous page? What should they be?

Kinetic Energy and Potential Energy:

15. Create a graph of Potential Energy (U) vs. Time. Then use the Add Similar Measurement to add the Kinetic Energy (KE) to the vertical axis.
16. In general, what can you say about the two curves? For example, as one curve decreases, what is happening to the other?
17. Using annotations on the graph, label where the pendulum is at the top of its swing and where it is at the bottom.

Total Energy:

18. On the energy graph, use the Add Similar Measurement to add the Total Energy (Total = $KE + U$).
19. What can you conclude about energy transformations and conservation of energy for the motion of a pendulum?
20. In general, does the total energy tend to decrease or increase? What is the reason for this?

Hooke's Law and Elastic Potential Energy

Equipment

Includes:

1	Motion Sensor	PS-2103A
1	High Resolution Force Sensor	PS-2189
1	Dynamics System	ME-6955
1	Elastic Bumper	ME-8998
1	Spring Cart Launcher	ME-6843
2	Compact Cart Mass	ME-6755
1	Braided String	SE-8050
Required, but not included:		
1	Balance Scale	SE-8723

Introduction

The Force and Motion Sensors are used to measure the spring constant, and the amount of potential energy stored in the compressed spring.

The cart is then launched, and its final kinetic energy is measured and compared to the stored energy in the spring.

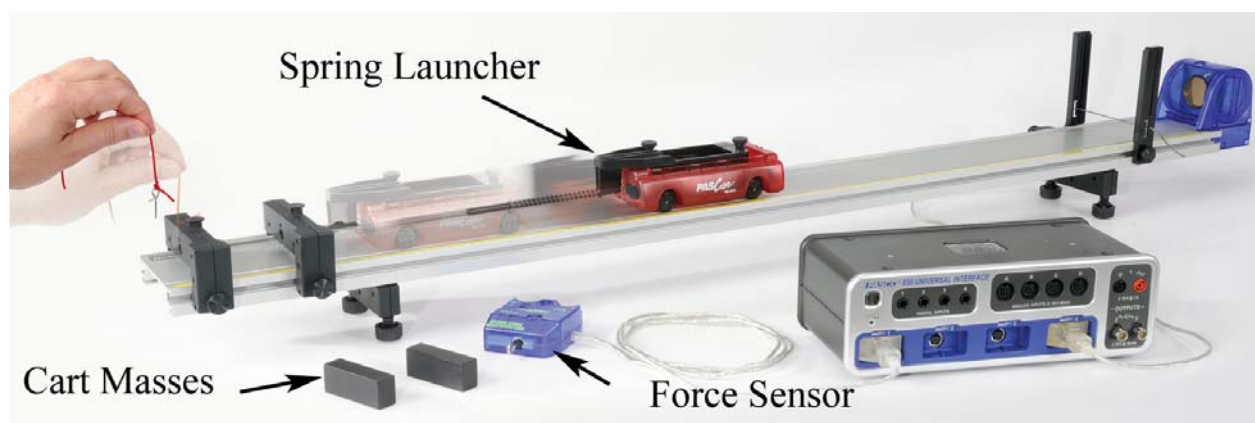


Figure 1: When the pin is pulled, the potential energy stored in the spring is released.

Theory

When force is applied to a spring, the resulting extension or compression of the spring maintains a linear relationship with the applied force. This is called Hooke's Law and can be written as

$$F = k \Delta x \quad (1)$$

where F is the applied force, Δx is the extension or compression of the spring measured from its unstretched length and k is the spring constant.

The potential energy (U) stored in the spring is given by

$$U = \frac{1}{2} k \Delta x^2 \quad (2)$$

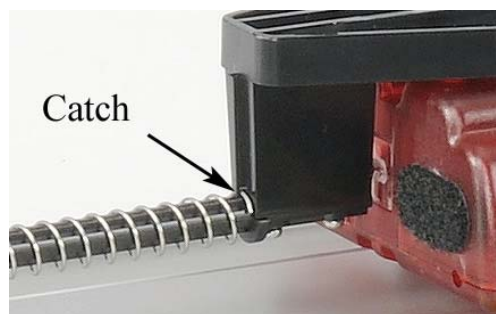
Setup

1. Attach the feet to the track, and then install the Elastic Bumper as shown in Figure 2, below. Attach the Motion Sensor and plug it into the interface. The range switch should be set on the "cart" icon. Later, if you have trouble getting good data from the Motion Sensor, try sliding the Elastic Bumper **closer** to the sensor.



Figure 2: Motion Sensor

2. Attach the Spring Launcher to the cart as shown in Figure 3. Use the strongest spring: It will have a small daub of black paint on one end. Note the orientation of the large end of the spring on the rod. Rotate the spring so that it catches and is attached to the support.



Rotate the spring so that it catches and is attached to the support.



Figure 3: Spring Cart Launcher

3. Figure 1 shows two endstops in use for later in the experiment. For now, you will only use one endstop as shown in Figure 4. Push the rod from the spring launcher through the hole in the endstop and tie a loop of string through the small hole in the end of the rod.

4. Plug the Force Sensor into the interface. With the sensor flat on the surface of the track, press the zero button to tare the sensor. Hook it onto the loop of string as shown in Figure 4.
5. In PASCO Capstone, set the common sample rate to 100 Hz. Create a graph of Force vs. Time. Add a plot area and put the Position on the vertical axis of the second plot area.

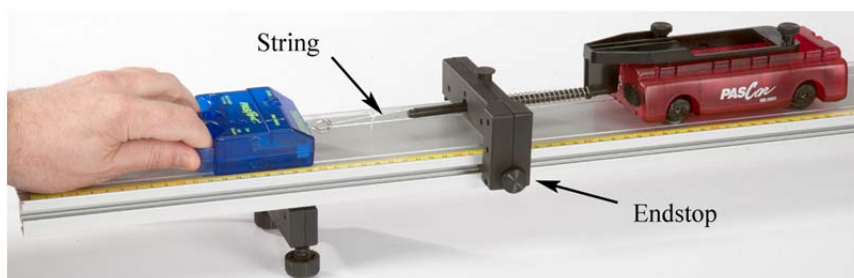


Figure 4: Finding the spring Constant

Procedure – Force and Position Data

1. Pull on the Force Sensor so that the spring is just barely in contact with the endstop.
2. Click on Record, and then slowly increase the pull on the Force Sensor, compressing the spring. Note the original position of the PASCAR and move it 7 cm as the spring compresses (the coils of the spring should not touch each other).
3. If you are not getting good position data from the Motion Sensor, try sliding the elastic bumper **closer** to the Motion Sensor.
4. If your force data is not positive you can open the Data Summary and click on the properties icon (gear) for the Force Sensor. Note the check box to change the sign.
5. Once you are getting good data, delete all the preliminary runs.
6. Now repeat step 2, except this time slowly compress the spring by 7 cm, then slowly allow the PASCAR to return to its original position and then repeat the compression and decompression one more time for a total of two full cycles.
7. Click open Data Summary and label this run as "Force Curve".

Spring Constant:

8. Create a graph of Force vs. Position and select the Force Curve run. Examine the Force vs. Position curve and answer Questions 1 and 2 in the Conclusion.
9. Record the slow 7 cm compression (as in step 2 on previous page.) Hold the spring at the 7 cm compression for about 15 seconds before stopping the recording. Click open Data Summary and label this run as "loading 1". Repeat twice more labeling the runs as "loading 2" and "loading 3".
10. Then do three unloading curves by first holding the spring compressed by 7 cm for 15 seconds and then recording as the tension is slowly released. Label the runs "unloading 1", etc.
11. Repeat step 9 except this time allow your hand to move faster to release the tension more quickly. Label as "fast 1", etc.
12. Create a table with three columns. Create User-Entered data sets called "Loading", "Unloading", and "Fast Unload", all with units of N/m. Turn on the statistics with the mean and standard deviation.
13. Use a Linear curve fit on the force vs. position graph to find the slope of each of the nine lines. Use the Select tool to look at only linear areas of the graph, avoiding the beginning and ending of each run. Record your value in the table.

Spring Energy:

14. Create a graph of velocity vs. time.
15. Connect both endstops (about 9 cm apart) at the end of the track as shown in Figure 5.



Figure 5. Compressed Spring Held with Pin

16. Adjust the separation so that when the spring is almost compressed 7 cm, you can place the pin into the small hole at the end of the rod.
17. Place both of the black compact masses in the cart as shown, but you don't need the spring compressed at this time.
18. Adjust the "level" of the track using the adjustable feet. Place the cart on the track and give it a small push towards the Motion Sensor. Click on Record. Your data will stop automatically when the cart is within 20 cm of the sensor.
19. Using the screw feet, adjust the level of the track so that the cart travels at a constant speed when moving **towards** the sensor. By setting up the track so that it is slightly downhill, you will be eliminating the effects of unwanted frictional forces. Label your final run as "flat run".

Measuring Compression:

20. Create a graph of Position vs. Time.
21. Use a balance scale to measure the total mass of "cart + launcher + extra mass".
22. Move the cart towards the Endstop until the spring is very slightly compressed. You want the Motion Sensor to measure off the end of the cart, so keep your hand in the middle of the cart, not hanging over the end.
23. Click on Record, then compress the spring until you can insert the Pin. Let go of the cart with your hand, letting the Pin hold the cart in place. Click on Stop.
24. Use the Coordinates tool (with Delta tool) to measure Δx , the compression in the spring.
25. Using Eqn. (2) and the mean spring constants you found earlier: calculate the energy stored in the spring using the loading data, and the energy recovered.

Kinetic Energy:

26. Looking at a graph of velocity vs. time, click on Record. Use the string to jerk the pin loose, and release the cart. You must pull upwards on the pin as quickly as you can. See Figure 1. There is a built-in stop condition that should automatically halt recording when the cart reaches the far end. Label the run "KE 1".
27. Repeat twice more.
28. Use the Coordinates tool to measure the max speed of the cart for each of the three runs and record below.
29. Calculate the mean speed.

30. Calculate the resulting kinetic energy of the cart using the mean speed.

Conclusions

1. Does the spring obey Hooke's Law when it is compressed? Explain fully! Is this surprising?
2. Does Hooke's Law appear to hold for any portion of the curve?
3. Can you explain the difference between the loading and unloading force curves in terms of friction in the system? Hint: consider the little "tail" on the loading force curves as the cart was held motionless for 15 seconds and the beginning tail on the unloading curves when the cart was released.
4. How well does the potential energy stored in the spring agree with the kinetic energy gained by the cart? Discuss fully!

Work-Energy Theorem

Equipment

Includes:

1	Motion Sensor	PS-2103A
1	High Resolution Force Sensor	PS-2189
1	Dynamics System	ME-6955
1	Elastic Bumper	ME-8998
1	Elastic Cord	(in ME-8998)
1	Force Bracket	CI-6545
1	Braided String	SE-8050

Introduction

A Force Sensor is used to measure the changing force applied by the stretched elastic cord, while the Motion Sensor records the resulting velocity of the cart. Calculations are made and the work done by the elastic cord is compared to the increase in kinetic energy.

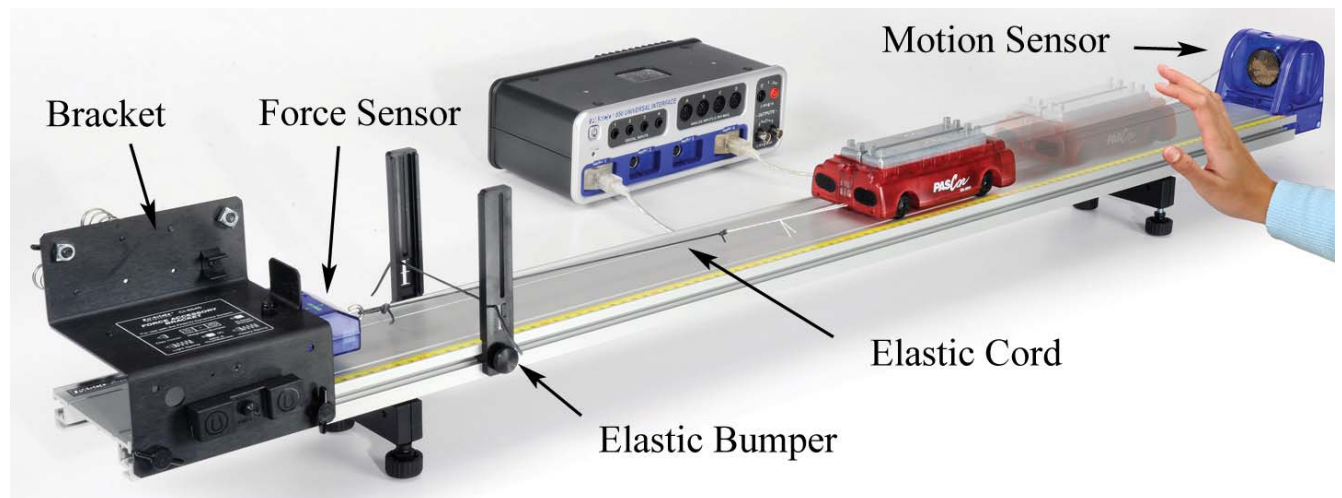


Figure 1: Complete Setup

Theory

According to the Work-Energy Theorem, the resulting change in kinetic energy of an object is equal to the total work done on that object.

$$\Delta KE = \text{Work}$$

In this lab, the amount of work done is calculated by taking the area under the curve on a force versus position graph.

Setup

1. Install the elastic bumper and adjustable feet to the track as shown in Figure 1. Attach the Force Sensor to the track using the force bracket. Plug the Force Sensor into the interface, and press the zero button to tare the sensor.
2. Attach the Motion Sensor as shown and plug it into the interface. The range switch should be set on the "cart" icon.
3. In PASCO Capstone, leave the sample rate of the Force Sensor and the Motion Sensor set at the default sample rate of 20 Hz.
4. Create a graph of Velocity vs. Time.
5. Place both masses in the cart and use a balance scale to measure the total mass.
6. Adjust the "level" of the track using the adjustable feet. Place the cart on the track and give it a small push away from the Motion Sensor. Click on Record. Your data will look better if you stop recording before the cart hits the elastic bumper.
7. Using the screw feet, adjust the level of the track so that the cart travels at a constant speed when moving away from the sensor. By setting up the track so that it is slightly downhill, you will be eliminating the effects of unwanted frictional forces.
8. Tie a short loop of string to the lower tab in the PAScar as shown in Figure 2. Cut a 35 cm long piece of Elastic Cord, and tie it between the Force Sensor hook and the loop of string as shown.

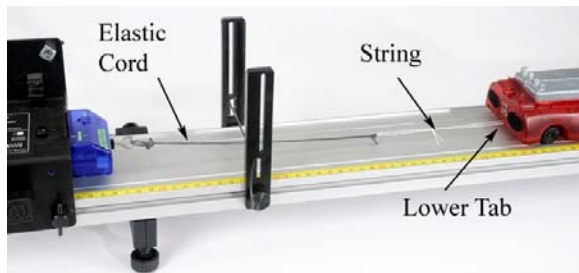


Figure 2: Fasten the Elastic Cord to the Cart

Procedure: Force and Velocity

1. Change the Common sample rate to 50 Hz. Add a plot area to the Velocity vs. Time graph. Put the Force on the vertical axis of the second plot area.
2. Open the Recording Conditions and set the Stop Condition to Measurement Based on Position Is Above 0.55 m.
3. Pull the cart back, stretching the elastic cord, until the cart is 20 cm from the Motion Sensor. You want the Motion Sensor to measure off the end of the cart, so keep your hand in the middle of the cart, not hanging over the end.
4. Click on Record and then release the cart. The stop condition should automatically halt recording before the cart reaches the elastic bumper.
5. If your force data is not positive you can open the Data Summary and click on the properties icon (gear) for the Force Sensor. Note the check box to change the sign.
6. Check that you have good, smooth velocity data. You need to clearly see a maximum in the velocity before it stops. You might need to adjust the automatic stop condition.
7. Get one good run and rename the run "Two Masses".
8. Remove one of the masses from the cart and get another good run. Rename this run "One Mass".

Work Done:

9. Create a graph of Force vs. Position.
10. Use the Run Selection tool to display the run you named "Two Masses".
11. For a Hooke's Law spring, the graph of F vs. x results in a straight line, where the slope of that line is the spring constant. Does the elastic cord used in this lab follow Hooke's Law?
12. Use the Area tool to find the area under the curve. You might need to use the Selection tool to select only the part of the curve.
13. What is the physical significance of the area? What are the correct units?
14. Repeat for the second run.

Change in Kinetic Energy:

15. Create a graph of Velocity vs. Position.
16. Use the Run Selection tool to display the run you named "Two Masses". Find the maximum velocity of the cart. Turn on the statistics showing the maximum, or you can also use the coordinates tool.
17. Use this velocity and the mass of the cart to calculate the kinetic energy of the cart.
18. Compare this to the work done by the elastic cord. What do you conclude?
19. Repeat for the second run. Remember the mass changed! Which of the following changed a lot from run one to run two, and which did not change much at all?
 - a. Work done by cord
 - b. Change in cart kinetic energy
 - c. Change in cart velocity

Collisions in One Dimension

Equipment

Includes:

2	Motion Sensor	PS-2103A
1	Dynamics System	ME-6955
1	Elastic Bumper	ME-8998
Required, but not included:		
1	Balance Scale	SE-8723

Introduction

Elastic and inelastic collisions are performed with two dynamics carts of different masses. Magnetic bumpers are used in the elastic collision and Velcro[®] bumpers are used in the completely inelastic collision. Both the momentum and kinetic energy are examined before and after the collisions.

Theory

The momentum of a cart depends on its mass and velocity.

$$\text{Momentum} = \vec{p} = m\vec{v}$$

The direction of the momentum is the same as the direction of the velocity. During a collision, the total momentum of the system of both carts is conserved because the net force on the two-cart system is zero. This means that the total momentum just before the collision is equal to the total momentum just after the collision. If the momentum of one cart decreases, the momentum of the other cart increases by the same amount. This is true regardless of the type of collision, and even in cases where kinetic energy is not conserved.

The kinetic energy of a cart also depends on its mass and speed but kinetic energy is a scalar. The total kinetic energy of the system of two carts is found by adding the kinetic energies of the individual carts.

$$\text{Kinetic Energy} = KE = \frac{1}{2}mv^2$$

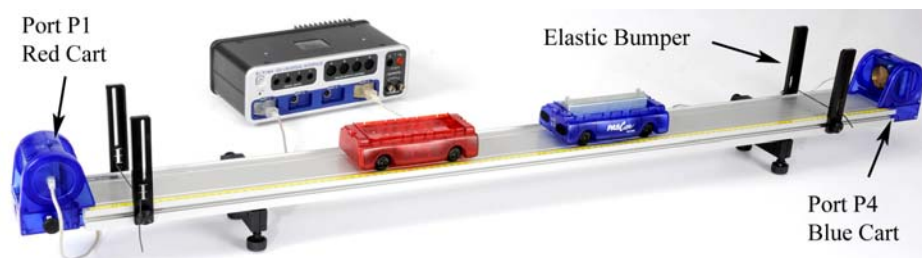


Figure 1: The velocity of each cart is measured using Motion Sensors

Setup

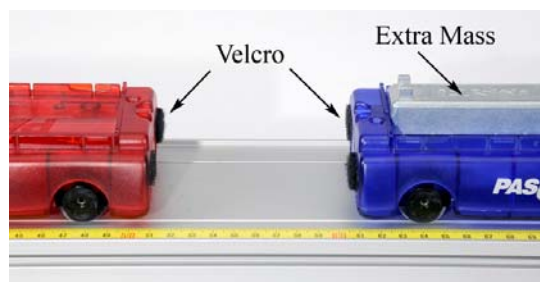
1. Install both elastic bumpers and adjustable feet as shown in Figure 1.
2. Use a balance scale to measure the mass of the red cart, and the mass of the blue cart with extra mass bar.
3. Attach the Motion Sensors to the track. You must keep the orientation shown (see Fig. 1), with the Motion Sensor monitoring the red cart plugged into port P1 on the interface and the Motion Sensor monitoring the blue cart plugged into port P4.
4. Set the Common sample rate to 50 Hz.
5. Create the following calculations:

$V_{red} = [\text{Velocity, Ch P1 (m/s)}]$	units of m/s
$V_{blue} = -[\text{Velocity, Ch P4 (m/s)}]$	units of m/s
$p = M_{red} * V_{red} + M_{blue} * V_{blue}$	units of kg m/s
$M_{red} = 0.25$	units of kg
$M_{blue} = 0.50$	units of kg
$KE = 0.5 * M_{red} * (V_{red})^2 + 0.5 * M_{blue} * (V_{blue})^2$	units of J

Substitute your values for the masses of the carts.

6. Create a graph of V_{red} vs. Time. Then add V_{blue} to the vertical axis using Add Similar Measurement.
7. Level the track using the leveling screws on the track feet. When you place a cart at rest on the track, give it a little push in each direction. It should not accelerate in either direction.
8. Orient the carts so that the Velcro® ends are facing each other, as shown in Figure 2.

Figure 2: Setup for Completely Inelastic Collisions



9. The program is set up so that the velocities of both carts are positive to the right, when the carts are moving away from the Motion Sensor plugged into port P1. Click on Record and give the carts a push to the right. Make sure that you are getting good, clean data, and that the velocities are both positive. Open the Calculator Window to see calculations #1 and #2 where these signs are set.
10. Create a Stop Condition that is Measurement Based on the Position for the Blue Cart when it Falls Below 0.200 m.

Inelastic Procedure

1. Position the blue cart (with extra mass bar) about 40 cm from its Motion Sensor and the red cart about 20 cm from its Motion Sensor.
2. Click on Record and push the red cart towards the blue. The automatic stop condition should halt data collection when the blue cart is closer than 20 cm from the sensor.
3. Get one good run with smooth clean data before and after the collision. Open the Data Summary and rename this run "Inelastic".
4. Using the Coordinates tool, measure the velocity of the red cart just before and after the collision.
5. Calculate the total momentum before and after the collision. What do you conclude? Was momentum conserved?

Elastic Procedure

6. Reverse the two carts so that the ends with the magnets are facing each other, but keep the red cart near the Motion Sensor connected to Channel P1.
7. Position the carts on the track as before. Click on Record and push the red cart towards the blue. Get one good run of data and name this run "elastic".
8. Using the Multi-Coordinates tool, measure the velocity of the red cart just before and after the collision. Hint: Don't ignore the sign of the velocity!
9. Measure the velocity of the blue cart just after the collision.
10. Calculate the total momentum before and after the collision. What do you conclude? Was momentum conserved?
11. Was it harder to determine when to measure for this elastic collision? Why are the curves more rounded at the collision point?

Momentum

12. Add a plot area to the Velocity vs. Time graph. Put p (momentum) on the vertical axis of the second plot area.
13. Open the Calculator Window. Look at calculation #3 which automatically calculates the total momentum of the two carts for the entire data run. You can replace the approximate masses of the carts (calculations #4 and #5) with your actual values.
14. Use the run selector to display the data for the "inelastic" collision.
15. Examine the momentum graph to see what happens before, during and after the collision. Does it look like momentum is conserved?
16. Repeat for the "elastic" collision.

Kinetic Energy

17. On the second plot area, click on " p " on the vertical axis and select "KE".
18. Open the Calculator Window. Look at calculation #6 which automatically calculates the total kinetic energy of the two carts for the entire data run.
19. Use the run selector to display the data for the "inelastic" collision.
20. Examine the kinetic energy graph to see what happens before, during and after the collision. Does it look like energy is conserved? Where did the energy go?
21. Pick a point before and after the collision and calculate the kinetic energy for yourself. Does your calculated value agree with the graph?
22. Select the "elastic" collision. Explain this curve. What happens to the KE during the collision? Why does it decrease during the collision and then come back? Where did it go?

Explosion

23. Position the two carts so that they have the Velcro ends facing each other. Depress the plunger on the red cart to position #3 as shown in Figure 3.
24. Place the two carts in contact with each other in the center of the track.
25. Start recording and tap the trigger release (see Fig. 3) to launch the carts.
26. Get one good run of data and name this run "explosion".

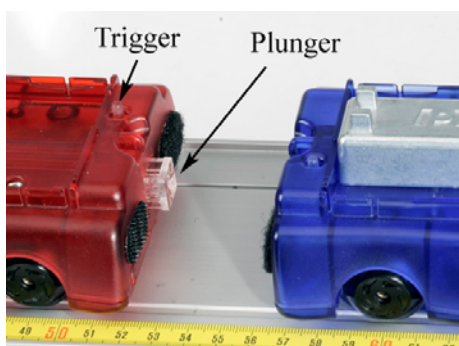


Figure 3: Cart Explosion

Momentum and Kinetic Energy for the Explosion

Answer the following questions before examining the graph of your explosion data!

27. What was the total momentum of both carts before the explosion?
28. What was the total momentum of both carts after the explosion?
29. What was the total kinetic energy of both carts before the explosion?
30. After the explosion, is the total kinetic energy of both carts the same as before?
31. On the graph, select “p” on the vertical axis of the first plot area and “KE” on the vertical axis of the second plot area.
32. Now use the Data selector to display graphs of momentum and energy for the explosion. Did you answer the above questions correctly?

Impulse and Momentum

Equipment

Includes:

1	Dynamics System	ME-6955
1	Photogate Head	ME-9498A
1	Photogate Bracket	(in ME-8998)
1	Picket Fence	ME-8933
1	Force Sensor	PS-2189
1	Force Bracket	CI-6545
1	Table Clamp	ME-9472
1	Dynamics System	ME-6955
Required, but not included:		
1	Balance Scale	SE-8723

Introduction

A cart collides with a Force Sensor equipped with either a spring bumper, clay bumper, or magnetic bumper. The cart experiences a variable force during the time of the collision, causing it to change its velocity. In this experiment, the relationship between momentum, force, and impulse is explored.

Theory

According to Newton's Second Law,

$$\vec{F} = \frac{d\vec{p}}{dt} \quad (1)$$

where F is the force on an object, p is the momentum of the object, and t is time. Rearranging and solving for the impulse (Δp) gives

$$\Delta \vec{p} = \vec{p}_f - \vec{p}_i = \int \vec{F} dt \quad (2)$$

In this lab, the change in momentum is calculated using

$$\Delta \vec{p} = m\vec{v}_f - m\vec{v}_i \quad (3)$$

where m is the mass, v_f is the final velocity, and v_i is the initial velocity. We define the direction of positive velocity to be to the right, in the direction of the initial velocity.

And finally, for a Force vs. Time graph, the area under the curve is the integral of the force.

$$\int \vec{F} dt = Area \quad (4)$$

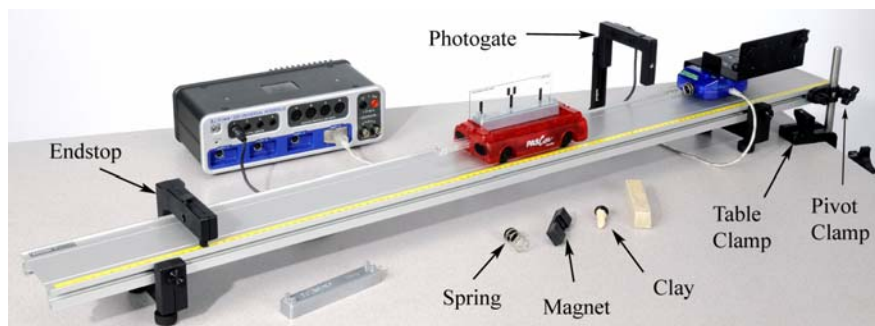


Figure 1: The speed of the cart is measured using a photogate.

Setup

1. Attach the Photogate, feet and endstop to the track as shown in Figure 1. Plug the Photogate into Digital Input #1.
2. Connect the Force Sensor near the end of the track using the Force Bracket as shown in Figure 2. Plug the Force Sensor into the interface and **zero** the sensor.
3. Place the cart on the track with one Mass Bar. Level the track.
4. Attach the Table Clamp with the 45 cm Rod at the end of the table as shown in Figure 1. Fasten the track to the rod using the track Pivot Clamp. This will keep the track from moving during collisions.
5. Attach the weak spring bumper to the Force Sensor. The Clay Bumper (see Fig. 3) will be used later.
6. Mount the Photogate Picket Fence in the cart with the double-flag **up** as shown in Figure 2. Set the position of the Photogate in the vertical direction so the Photogate will be blocked by the double flag.
7. Adjust the position of the Photogate Bracket horizontally on the track so that it is **just** far enough away from the Force Sensor so the flag on the cart will pass through the Photogate before the cart hits the spring (see Figure 2).
8. Compress the cart plunger to the 2nd position and place it against the Endstop as shown in Figure 4. This will be the starting point of the cart for every run. Practice hitting the trigger to launch the cart. One way is to use the spare mass bar to tap the trigger.
9. Use a Balance Scale to determine the mass of "cart + Picket Fence+ mass bar" and record on the next page.

10. In PASCO Capstone, create a graph of Force vs. time.
11. Open the Hardware Setup and click on photogate #1 port on the 850 interface. Select “One Photogate (Double Flag)”.
12. Create a table and select Speed in the first column. Then delete the second column.
13. Set the sample rate for the force sensor to 1000 Hz.
14. Click on Recording Conditions and set the start condition for Measurement Based on the State of the Photogate is above zero. Then set the stop condition on Time Based for 0.3 seconds. You can modify this to see more or less after the collision.

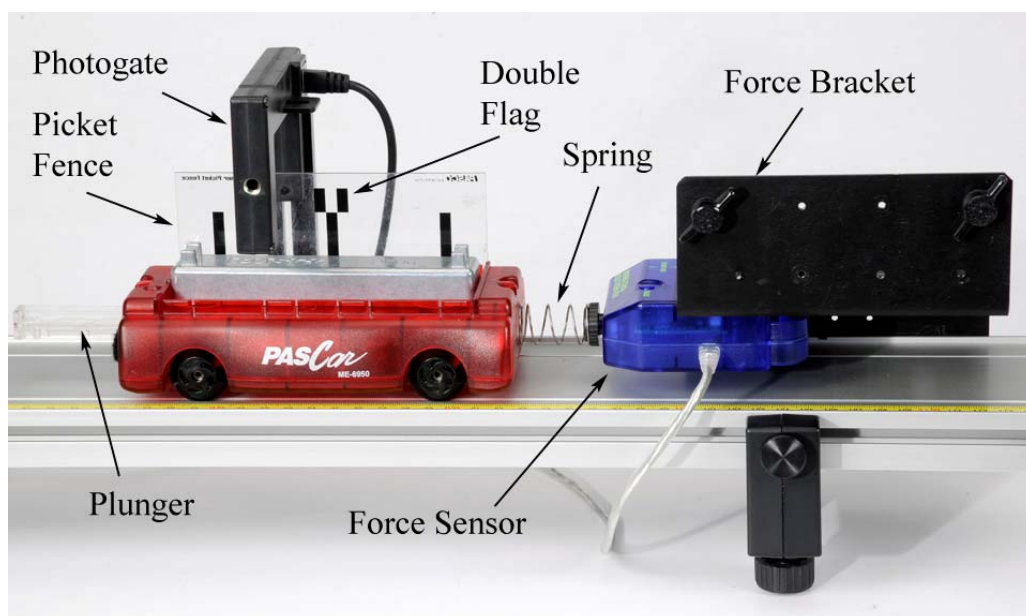


Figure 2: Collision Setup for Spring Bumper



Figure 3: Clay Bumper

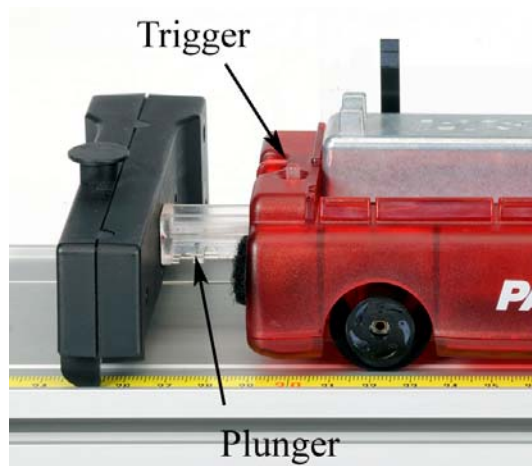


Figure 4: Using plunger to launch cart.

Spring Procedure

1. Make sure the plunger is on the second position, and is resting against the Endstop. Zero the Force Sensor. Click on Record and launch the cart.
2. Get one good run. Rename this run "Light Spring"
3. Record the initial and final velocities. The Photogate only measures the speed of the cart, and the sign must be determined by the student. It is easiest to assign the direction of motion **towards** the Force Sensor as being positive. Record the proper sign.
4. Using Equation (3), calculate the change in momentum, Δp .

Momentum and Energy Procedure

5. Measure the area under the force curve. The spring will vibrate after the collision. You can try using the smoothing function, or use the Highlight tool to select only the area you want.
6. What is the physical significance of the area? Look at Equations (2) and (4). Compare to the expected value using the % error calculation.
7. Calculate the kinetic energy of the cart before and after the collision.
8. What type of collision was this? Elastic, inelastic, or completely inelastic?
9. Replace the Light Spring with the Heavy Spring and repeat the collision. Rename this run "Heavy Spring"
10. How does the shape of the collision curve change?
11. Is the area under the curves for the two springs **about** the same? Should they be?

Clay:

12. Replace the spring with the clay bumper and repeat the collision. The cone shape shown in Figure 3 is just a suggestion. Rename this run "Clay".
13. Record the velocities and calculate the change in momentum, Δp .
14. Measure the area under the force curve, and compare to expected value.
15. Calculate the kinetic energy of the cart before and after the collision. What type of collision was this? Elastic, inelastic, or completely inelastic?

16. How does the shape of the clay collision curve compare to the springs? Is the area under the curves for the springs about the same as the clay? Should they be?

Further Study:

17. Try changing the shape of the Clay Bumper. Who can create a shape that causes the **least** maximum force for the same speed collision?
18. Try the Magnetic Bumper. You will need to remove the mass bar and use a **much** slower speed. Try using the plunger on its lowest setting. How is the shape of this curve different from the spring?
19. Create your own bumper! The example shown in Figure 5 is made with thin graph paper rolled into a tube. It was then taped to the base used for the clay bumper. Have a contest!

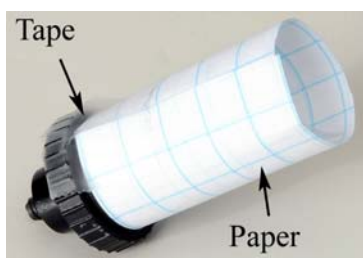


Figure 5. Paper Bumper

Ballistic Pendulum

Equipment

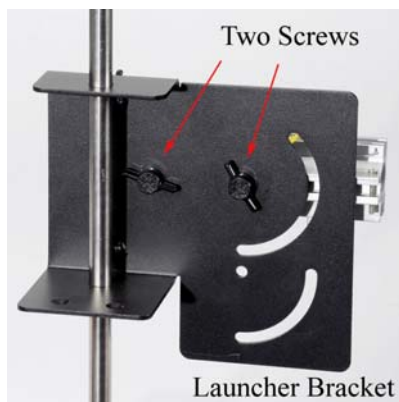
RS-2120	Motion Sensor	
ME-6821	Head	
ME-6821	Bracket	
ME-9472	Table Clamp	
90 cm	Rod	
ME-6821	Launcher	
ME-6821	Pendulum	
NEEDED, BUT NOT INCLUDED:		
RS-5000	Universal Interface	
ME-8827	Stick	
SE-8723		

Introduction

A Ballistic Pendulum is used to determine the muzzle velocity of a ball shot out of a Projectile Launcher. The laws of conservation of momentum and conservation of energy are used to derive the equation for the muzzle velocity.

Setup

1. Attach the Table Clamp with 90 cm rod to the table as shown in Figure 1.
2. Figure 2 shows the back side of the launcher bracket. Fasten the launcher to the bracket using the two thumbscrews through the two holes. Do not use the curved slots.
3. Slide the launcher bracket over the rod, and secure with the two thumbscrews on the front as shown.



Figure



Figure 1: Launching the Ball

Figure 2: Mounting Launcher

4. Attach the 100 g Ballast Mass to the bottom of the pendulum catcher as shown in Figure 3.
5. Slide the Rotary Motion Sensor onto the 90 cm rod, and attach the pendulum to the pulley. Connect the sensor to the interface. Set the sample rate in PASCO Capstone to the default 20 Hz.
6. Create a graph of Angle vs. time.
7. Click on Record, then rotate the pendulum away from the launcher. The angle must be positive. You can change the sign of the angle by using the Rotary Motion Sensor from the other side, or you can change the sign in the properties for the sensor.
8. Adjust the position of the Rotary Motion Sensor so that the square catcher at the bottom of the pendulum aligns with the launcher.
9. If you loosen the two thumb screws on the back of the launcher, you can slide the launcher horizontally. Slide the launcher so that it almost (but not quite) touches the pendulum catcher. Make sure the launcher is set for a launch angle of zero degrees, and then re-tighten the thumb screws.



Figure 3: The pendulum must be adjusted so that the catcher is directly aligned with the launcher. When the ball is launched, it is trapped in the slot in the white foam.

Theory

The Ballistic Pendulum has historically been used to measure the launch velocity of a high-speed projectile. In this experiment, a Projectile Launcher fires a steel ball (of mass m_{ball}) at a launch velocity, v_0 . The ball is caught by a pendulum of mass m_{pend} .

After the momentum of the ball is transferred to the catcher-ball system, the pendulum swings freely upwards, raising the center of mass of the system by a distance h . The pendulum rod is

hollow to keep its mass low, and most of the mass is concentrated at the end so that the entire system approximates a simple pendulum.

During the collision of the ball with the catcher, the total momentum of the system is conserved. Thus the momentum of the ball just before the collision is equal to the momentum of the ball-catcher system immediately after the collision:

$$m_{\text{ball}}v_o = Mv \quad (1)$$

where v is the speed of the catcher-ball system just after the collision, and M is the combined mass of ball + catcher.

$$M = m_{\text{ball}} + m_{\text{pend}} \quad (2)$$

During the collision, some of the ball's initial kinetic energy is converted into thermal energy. But *after* the collision, as the pendulum swings freely upwards, we can assume that energy is conserved and that all of the kinetic energy of the catcher-ball system is converted into the increase in gravitational potential energy.

$$\frac{1}{2}Mv^2 = Mgh \quad (3)$$

where the distance h is the vertical rise of the center of mass of the pendulum-ball system. Combining equations (1) through (3), to eliminate v , yields

$$v_o = \frac{m_{\text{ball}} + m_{\text{pend}}}{m_{\text{ball}}} \sqrt{2gh} \quad (4)$$

The height, h , of the pendulum is calculated using the angle, θ , and the length of the pendulum, L , as shown in Figure 4. Using trig, it can be shown that

$$h = L(1 - \cos\theta) \quad (5)$$

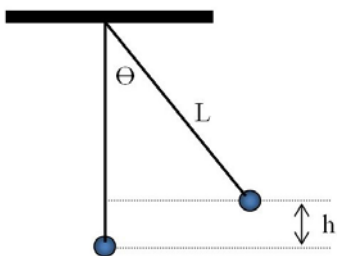


Figure 4: Finding h

The length of the pendulum, L , is measured from the pivot point out to the center of mass of the pendulum. Since in this lab the pendulum is not a point mass, the center of mass is determined by balancing the pendulum on an edge.

Procedure – Measuring Angle

1. Create a table with a user-entered data set called “Max Angle” with units of degrees ($^{\circ}$). In the second column, create a user-entered data set called “L” (for length) with units of m. Insert a third column. In the third column, create a user-entered data set called “Launch Speed” with units of m/s. Turn on the statistics with the mean and standard deviation selected.
2. On the Angle vs. time graph, turn on the statistics with the mean selected.
3. To load the launcher, swing the pendulum out of the way, place the ball in the end of the barrel and, using a pushrod, push the ball down the barrel until the trigger catches in the third (Long Range) position.
4. Return pendulum to its normal hanging position and wait until it stops moving.
5. Click on Record and immediately launch the ball so that it is caught in pendulum. There is a Stop condition that should halt data recording.
6. If the ball is not caught, check the alignment.
7. Record the max angle in the table, and repeat several times. Note that the average value is calculated.
8. Repeat until you get a good solid average value for the angle, then record that angle on the next page.

Calculating the Launch Speed

9. Remove the pendulum from the Rotary Motion Sensor, and balance it on a meterstick as shown in Figure 5. Note that the ball is still in the catcher!



Figure 5: Finding the Center of Mass: Balance the pendulum on the end of the meter stick.

10. Find the point at which the catcher is extended as far as possible out over the edge of the meterstick. When properly balanced, the center of mass is directly over the end of the stick.

11. Record L , the distance from the center of mass out to the pivot (screw). Measure this several times and estimate your uncertainty.
12. Using your average value for L and Equation (5), calculate the height, h .
13. Remove the ball from the catcher and, using a Balance Scale, measure the mass of the pendulum (without ball!) and the mass of the ball.
14. Using Equation (4), calculate the launch speed, v_0 , of the ball. Estimate the uncertainty in your value.

Measuring the Launch Speed

15. Attach Photogates to the launcher using the Photogate Bracket as shown in Figure 6. Slide the bracket so that Photogate #1 is as close to the end of the launcher as possible.
16. Photogate # 1 must be connected to Digital Input #1 and Photogate # 2 must be connected to Digital Input #2. In PASCO Capstone, open the Hardware Setup and click on Digital Input #1 and select a Photogate and click on Digital Input #2 and select Photogate.

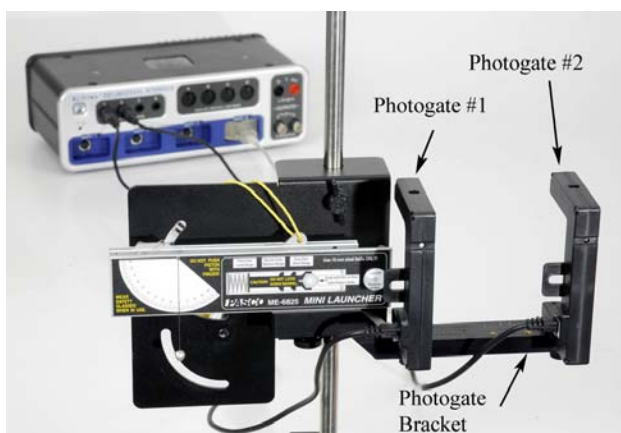


Figure 6: Measuring the Launch Speed

17. Open the Timer Setup and choose a Pre-configured timer, select both photogates, Two Photogates (Single Flag), Speed between Gates, and a photogate spacing of 0.1 m.
18. Create a Digits display and select Speed Ch 1&2.
19. Place the ball in the launcher and compress the spring to the third (long range) setting as before.
20. Make sure no one is in the way of the ball! Click on Record and then launch the ball. There is a Stop Condition that should halt data recording.
21. The measured speed is shown in the Digits Display. Record this value in the table, and repeat several times. Note that the average value is calculated.
22. Repeat until you get a good solid average value for the launch speed. Include the uncertainty in your value.
23. Compare to your calculated value using the % error calculation. Did your two answers agree within the uncertainty?

Newton's 2nd Law for Rotation

Equipment

1	Rotary Motion Sensor	PS-2120A
1	Rotational Accessory	CI-6691
1	Clamp-on Pulley	(in CI-6691)
1	Thread	(in CI-6691)
1	Mass and Hanger Set	ME-8979
1	45 cm Rod	ME-8736
1	Large Rod Base	ME-8735
Required but not included:		
1	Meter Stick	SE-8827
1	Calipers	SE-8710
1	Balance	SE-8723

Introduction

Newton's 2nd Law states that the resulting acceleration (a) of an object is directly proportional to the net Force (F) on that object.

$$F = ma \quad (1)$$

where the proportionality constant (m) is the mass or inertia of the object.

We can also write Newton's 2nd Law for rotation: The resulting angular acceleration (α) of an object is directly proportional to the net torque (τ) on that object.

$$\tau = I\alpha \quad (2)$$

where the proportionality constant (I) is the rotational inertia of the object.



Figure 1: The hanging mass applies a torque to the shaft of the Rotary Motion Sensor and the resulting angular acceleration of the rod and brass masses is investigated.

Setup: Apply Torque by Hand

1. Use the Large Rod Base and the 45 cm Rod to support the Rotary Motion Sensor as shown in Figure 1. Plug the sensor into the interface.
2. Use calipers to measure all three radii on the clear Three-step Pulley.
3. Attach the black rod from the Rotation Accessory to the clear pulley (see Fig. 2) with the two brass masses near the end of the rod.

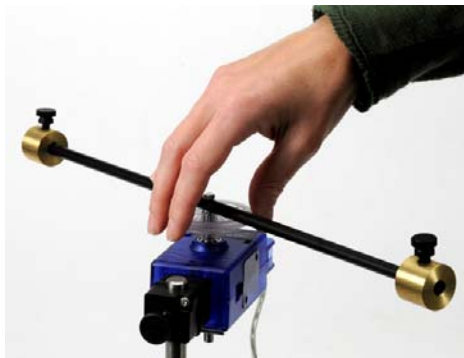


Figure 2: Mass at Large Radius



Figure 3: Mass at Small Radius

4. Plug the Rotary Motion Sensor into the interface.
5. In PASCO Capstone, set the sample rate to 20 Hz. Create a graph of angular velocity vs. time.

6. Click on Record. Grab the clear pulley and try to rotate the rod back and forth as fast as possible. Click on Stop.
7. Move the brass masses closer to the center as shown in Figure 3, and repeat. Which was easier? What does that tell you about rotational inertia?

Apply Constant Torque

8. Cut a piece of thread about 75 cm long. Run the thread through the hole in the medium size pulley, and tie a large knot as shown in Figure 5.
9. The thread will naturally wind up on the medium pulley. Using the slots, you can force the string to wind up on the small radius or the large radius as shown in Figure 6.

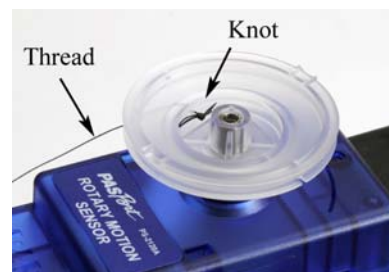


Figure 5: Attaching Thread to Pulley

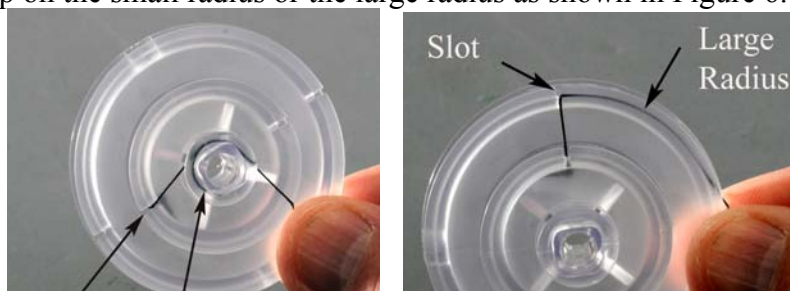


Figure 6: By running the thread through the slot, you can change the radius that the thread is wound around without having to re-tie the thread.

10. Clamp the black pulley onto the Rotary Motion Sensor as shown in Figure 7. Note how the pulley is clamped at an angle to match the tangent to the clear Three-step Pulley. It must also be adjusted vertically using the two thumbscrews, to match the height of the clear pulley being used. Each time you change to a different radius pulley, you will have to re-adjust both the angle and height.
11. Connect a mass hanger to the end of the thread. Adjust the length so that it doesn't quite hit the table. Add a 100 g mass to the hanger.
12. When you wind up the thread onto the Three-step Pulley, make sure the thread winds smoothly with no overlaps. Also, do not place too much thread on the pulley: You only want a single layer of thread, so that the radius stays constant.



Figure 7: Adjusting Angle of Clamp-on Pulley

Procedure – Calculating Inertia

1. Using a meter stick, position the brass masses on the black rod as accurately as possible so that their center of mass is at a radius of 18 cm from the center of rotation.
2. Adjust the pulley for the middle pulley, and wind on a few turns of thread.
3. Click on Record and release the rod. Click on Stop before you get to the end of the thread.
4. Look at the graph. It makes the lab easier if the velocity is positive. To change the sign, wind the thread up in the opposite direction, or you can change the sign of the measurement in the Properties for the sensor.
5. Get a single good positive run and rename this run "medium".
6. Use a linear curve fit to find the slope of the line. If the data is not straight, use the Highlight tool to select data from the beginning of the run when it is moving slower. This should be more accurate because the friction is less.
7. What is the physical significance of the slope? What are the units?
8. Calculate the torque applied by the hanging mass.

$$\text{torque} = \tau = rF \quad (2)$$

where r is the radius of the Three-step Pulley and F is the weight of the hanging mass. Don't forget the mass of the hanger!

9. Use Equation (2) to calculate the rotational inertia (I). Simplify the units as far as possible. The only terms should be mass and length.

Note: The tension in the thread is actually slightly less than the weight of the hanging mass, due to the downward acceleration. Since this has such a small effect for this lab, we can ignore it!

Vary Torque

10. Leaving all other parameters the same, you will now take a run of data using the large pulley on the Three-step Pulley. Adjust the black pulley for the large pulley, and wind on a few turns of thread. Make sure that it is wound on the large pulley. Look at Figure 6 if you have problems.
11. Get a good run of data like before. Rename this run "large"
12. Is the angular acceleration the same? Should it be?

13. Use Equation (3) to calculate the new torque.
14. Use Equation (2) to calculate the rotational inertia (I). Do you get about the same value? Should it be?
15. Now take a run of data using the Small pulley. Do you get about the same value for the rotational inertia? What do you conclude?
16. Leaving all other parameters the same, you will now take a run of data using a different hanging mass. Replace the 100 g mass with a 50 g mass, but keep using the small pulley.
17. Calculate the rotational inertia as before. What do you conclude?
18. In the next part (following pages), you will apply a constant torque. Do not change the hanging mass, and continue to use the small pulley.

Constant Torque

19. Position the brass masses on the rod so that their center of mass is at a Radius (R) of 4 cm from the center of rotation.
20. Create a table with two columns. In the first column, create a User-Entered Data set called "Radius R" with units of m. Fill the values in as shown below. In the second column, create a User-Entered Data set called " α " with units of rad/s^2 .

	Radius R (m)	α (rad/s^2)
1	0.04	
2	0.06	
3	0.08	
4	0.10	
5	0.12	
6	0.14	
7	0.16	
8	0.18	

21. Get a good run of data, and determine the angular acceleration from the slope of the angular velocity vs. time graph. Rename this run "4 cm", and record your value in the table.

22. Repeat for the other radii listed. Remember: Always make sure you are using the small radius on the three-step pulley.

Calculating Inertia

1. Open the Calculator window and create a calculation for the rotational inertia:

$$I = \tau / [\alpha \text{ (rad/s}^2\text{)}] \quad \text{with units of kg m}^2.$$

Add a column to the table and insert this calculation.

2. For one data set in the table, calculate the rotational inertia yourself to confirm that the calculation is correct. Remember that "R" is the position of the brass masses (measured from the center of rotation) and "r" is the radius for the three-step pulley.
3. Create a graph of I vs. Radius R.
4. Is the graph linear? Pick a QuickCalc on the horizontal axis to change to R².
5. Use a linear fit to find the slope of the straight line. What are the units? What is the physical significance of the slope?
6. Use a balance scale to measure the actual mass of the two brass masses and compare to the calculated value.
7. What is the physical significance of the y-intercept from your graph? What else besides the brass masses has inertia?
8. Write a theoretical equation for the rotational inertia of a point mass (M), moving around a circle of radius (R).

Rotational Inertia

Equipment

1	Rotary Motion Sensor	PS-2120A
1	Rotational Accessory	CI-6691
1	Clamp-on Pulley	(in CI-6691)
1	Thread	(in CI-6691)
1	Mass and Hanger Set	ME-8979
1	45 cm Rod	ME-8736
1	Large Rod Base	ME-8735
Required but not included:		
1	Calipers	SE-8710
1	Balance	SE-8723

Introduction

The rotational inertia of an object is a measure of how hard it is to rotate the object. The purpose of this experiment is to find the rotational inertia of a ring and a disk experimentally, and to verify that these values correspond to the calculated theoretical values.

A known torque is applied to the three-step pulley on the Rotary Motion Sensor, causing a disk and ring to rotate. The resulting angular acceleration is measured using the slope of a graph of angular velocity versus time. The rotational inertia of the disk and ring combination is calculated from the torque and the angular acceleration. The procedure is repeated for the disk alone to find the rotational inertias of the ring and disk separately.



Figure 1: Measuring the Rotational Inertia of Ring and Disk

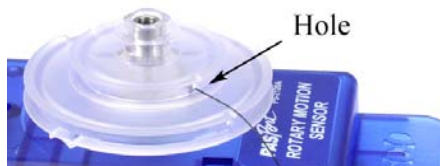


Figure 2: Attaching Thread to Pulley



Figure 3: Adjusting Angle of Clamp-on Pulley

Setup

1. Use the large rod base and the 45 cm rod to support the Rotary Motion Sensor as shown in Figure 1. Plug the sensor into the interface.
2. Use calipers to measure the radius (r) of the medium size pulley on the clear three-step pulley.
3. Cut a piece of thread about 75 cm long. Run the thread through the hole in the medium size pulley as shown in Figure 2. Tie a large knot inside the pulley to keep the thread from pulling through.
4. Clamp the black pulley onto the Rotary Motion Sensor as shown in Figure 3. Note how the pulley is clamped at an angle to match the tangent to the clear three-step pulley. It must also be adjusted vertically using the two thumbscrews, to match the height of the clear pulley being used.
5. Connect a mass hanger to the end of the thread. Adjust the length so that it doesn't quite hit the table.
6. When you wind up the thread onto the three-step pulley, make sure the thread winds smoothly with no overlaps. Also, do not place too much thread on the pulley: You only want a single layer of thread, so that the radius stays constant.
7. In PASCO Capstone, create a graph of Angular Velocity vs. Time. Set the sample rate to 20 Hz.

8. Create a table (shown below) in which all the columns are User-Entered Data sets.

Combined	Hanging Mass (g)	Ang. Acceleration (rad/s ²)	Friction Mass (g)
Ring & Disk			
Disk & Pulley			
Pulley			

Theory

Theoretically, the rotational inertia, I , of a thick ring about an axis passing through the center is given by

$$I = \frac{1}{2}M(R_1^2 + R_2^2) \quad (1)$$

where M is the mass of the ring, R_1 is the inner radius of the ring, and R_2 is the outer radius of the ring, as shown in Figure 4. The rotational inertia of a disk is given by

$$I = \frac{1}{2}MR^2 \quad (2)$$

where M is the mass of the disk and R is the radius of the disk.

To find the rotational inertia of the ring and disk experimentally, a known torque is applied to the ring and disk, and the resulting angular acceleration, α , is measured.

$$\tau = I\alpha \quad (3)$$

where τ is the torque caused by the weight hanging from the thread wrapped around the pulley of radius, r .

$$\tau = r F \quad (4)$$

The tension in the string, F , is less than the weight, due to the downward acceleration. Applying Newton's Second Law for the hanging mass, m , (see Figure 5) yields

$$F = m(g-a) \quad (5)$$

Finally, the linear acceleration, a , is related to the angular acceleration, α , by

$$a = r \alpha \quad (6)$$

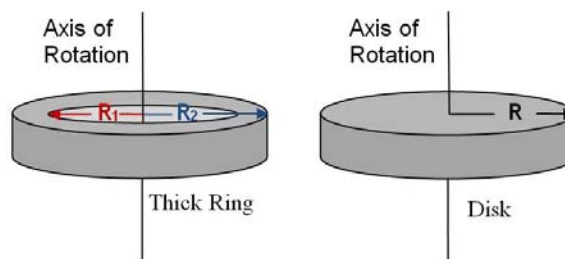


Figure 4: Rotation Axis for Ring and Disk

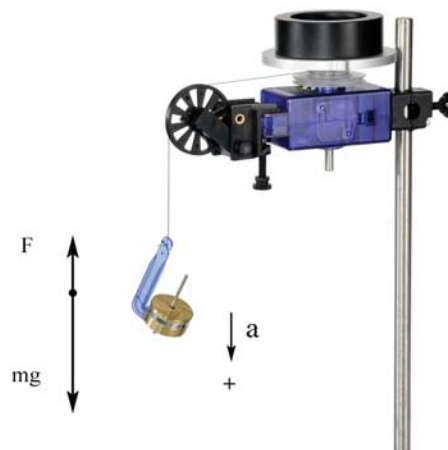


Figure 5: Free-Body Diagram

Procedure

1. Fasten the disk to the shaft of the Rotary Motion Sensor using the thumbscrew. Position the ring on top using the two pins to key it to the disk.
2. Hang about 50 g on the mass hanger, and collect a run of velocity vs. time data. Record all values in table below.
3. Use a linear curve fit to find the angular acceleration.
4. Accounting for Friction: Put just enough mass on the thread to make it fall at a constant speed after you give it a starting push. It will only be about a gram so you won't be able to use the mass hanger! This is called the friction mass, and is subtracted from the hanging mass in the calculations on the next page.
5. Remove the ring, and repeat the above procedure for just the disk. Use about 15g, and find the friction mass, too.
6. Remove the disk and repeat for just the pulley. Use about 1 g, but don't bother with the friction mass: It is too small.

Analysis

1. Use the angular acceleration you measured for the ring & disk to calculate their combined rotational inertia. You will first need to calculate the applied torque using Equations (4) through (6). Remember to subtract the friction mass from your value for the hanging mass before doing the calculation.
2. Use Equation (3) to calculate the rotational inertia of the ring & disk combined.
3. Repeat steps 1 and 2 above to calculate the rotational inertia for the Disk & Pulley.
4. Repeat steps 1 and 2 above to calculate the rotational inertia for the Pulley.
5. Subtract the (Disk & Pulley) inertia from the (Ring & Disk) inertia to calculate the rotational inertia of just the ring.
6. Subtract the (Pulley) inertia from the (Disk & Pulley) inertia to calculate the rotational inertia of just the disk.
7. Measure the mass and radii for the disk and ring.
8. Use Equations (1) and (2) to calculate the theoretical rotational inertias for the ring and disk. Compare to the measured inertia using a % error calculation.

Rotational Kinetic Energy

Equipment

1	Rotary Motion Sensor	PS-2120A
1	Rotational Accessory	CI-6691
1	Mass and Hanger Set	ME-8979
1	Braided String	SE-8050
1	90 cm Rod	ME-8738
1	45 cm Rod	ME-8736
1	Multi-Clamp	ME-9507
1	Large Rod Base	ME-8735
1	No-Bounce Pad	SE-7347
Required but not included:		
1	Calipers	SE-8710
1	Meter Stick	SE-8827
1	Balance	SE-8723

Introduction

The rotational kinetic energy of a rotating object depends on its rotational inertia, I , and its angular velocity, ω .

$$KE = \frac{1}{2} I \omega^2 \quad (1)$$

For a disk of radius, R , and mass M ,

$$I = \frac{1}{2} M R^2 \quad (2)$$

This lab investigates the potential energies for a modified Atwood's Machine (see Fig. 1), where a disk has been added to the Rotary Motion Sensor pulley.

As the hanging mass (m_2) falls, the lighter mass (m_1) rises, but the combined gravitational potential energy of the two decreases, and this energy is converted into the kinetic energy of the system. This includes not only the linear kinetic energy of the two hanging masses, but also the rotational kinetic energy of the rotating disk.

The Rotary Motion Sensor measures the rotational velocity of the disk, as well as the tangential (linear) velocity of the string over the Three-step Pulley.

Setup

1. Use the large rod base as shown in Figure 1 with the 90 cm rod, the 45 cm rod, and the multi-clamp.
2. Attach the Rotary Motion Sensor to the end of the 45 cm Rod and plug it into the interface.
3. In PASCO Capstone, set the sample rate to 20 Hz. Create a graph of Position vs. Time.
4. Measure the mass and radius of the disk and then fasten the disk to the sensor using the Three-step Pulley.
5. Cut a piece of string about 1 m long. Tie a loop on each end and place the string over the large radius pulley, with a mass hanger at each end.
6. Place the yellow No-Bounce Pad under the hanging masses.
7. Add 50 g to the mass hanger (m_1) and add 90 g to the mass hanger (m_2).
8. Pull the lighter (m_1) mass hanger down to the level of the pad. Click on Record and release the hanger. You should try and stop recording just before the other mass hanger hits the pad.
9. You want the velocity to be positive. If it is not, switch the two masses, or you can change the sign in the properties for the sensor.

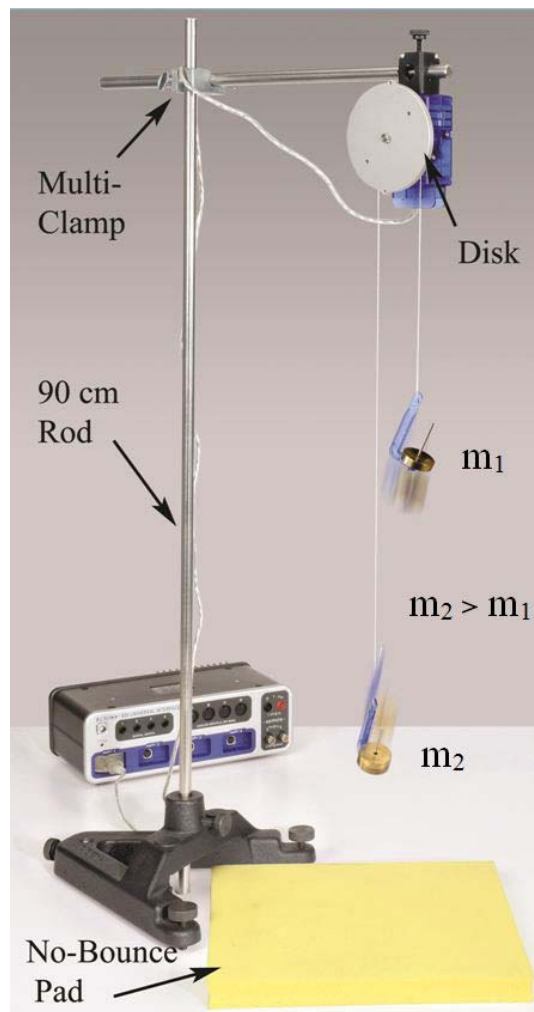


Figure 1: Modified Atwood's Machine

10. Pull the lighter (m_1) mass hanger down to the level of the pad. Measure the height of m_2 above the pad. This initial height, h_0 , will be used in calculating the potential energy of the two masses.
11. In the Capstone calculator, create the following equations:

$PE = m_1 * g * [\text{Position (m)}] + m_2 * g * (h_0 - [\text{Position (m)}])$	units of J
$KE_{\text{linear}} = 0.5 * (m_1 + m_2) * [\text{Velocity (m/s)}]^2$	units of J
$KE_{\text{rot}} = 0.5 * I * [\text{Angular Velocity (rad/s)}]^2$	units of J
$I = 0.5 * M * R^2$	units of kg m^2
$\text{Total} = [PE \text{ (J)}] + [KE_{\text{linear}} \text{ (J)}] + [KE_{\text{rot}} \text{ (J)}]$	units of J
12. Make a graph of the PE calculation vs. Time.

Procedure: Potential Energy

1. Line # 6 of the calculator shows the built-in calculation for the potential energy of the two hanging masses.

$$PE = m_1 g h + m_2 g (h_0 - h)$$

The height, h , is measured directly by the sensor. As one moves down, the other moves upwards. Enter your values for m_1 , m_2 , and h_0 , on lines #3 through #5 in the calculator.

2. Create a graph of PE vs. Time.
3. Pull the lighter (m_1) mass hanger down to the level of the pad. Click on Record and release the hanger. You should try to stop recording just before the other mass hanger hits the pad. You could also try a Stop Condition on the position to automatically halt the recording.
4. Get a single good run of data.
5. In general, what is happening to the total potential energy of the two hanging masses?
6. What is happening to the potential energy of just mass (m_1)?

Procedure: Kinetic Energy

7. Look at line #8 of the calculator. It shows the calculation for the kinetic energy of the two hanging masses.

$$KE_{\text{linear}} = \frac{1}{2} (m_1 + m_2) v^2$$

where v is the tangential (linear) velocity of the string over the pulley, and thus the velocity of the hanging masses.

8. But the rotating disk has kinetic energy, too.

$$KE_{\text{rot}} = \frac{1}{2}I\omega^2$$

where the angular velocity, ω , is measured directly by the sensor. Enter your values for the disk mass and radius on lines #1 and #2 in the calculator.

9. On the PE graph, click on the vertical axis measurement selector and select Add Similar Measurement and add KE_{linear} and KE_{rot} .
10. Display the last run or take a new run of data.
11. Which has more kinetic energy: The hanging masses or the rotating disk? Why? What would you have to change to have it be the opposite?

Total Energy

12. In general, what is happening to the potential energy of the system compared to the kinetic energy of the system?
13. Look at line #11 of the calculator. It shows the calculation for total energy = $PE + KE_{\text{linear}} + KE_{\text{rot}}$
14. On the Energy graph, click on the vertical axis measurement selector and select Add Similar Measurement and add Total.
15. Is energy conserved?
16. If there were no frictional losses, what would the graph show?

Conservation of Angular Momentum

Equipment

1	Rotary Motion Sensor	PS-2120A
1	Rotational Accessory	CI-6691
1	45 cm Rod	ME-8736
1	Large Rod Base	ME-8735
Required but not included:		
1	Calipers	SE-8710
1	Level	SE-8729
1	Balance Scale	SE-8723

Introduction

A non-rotating ring is dropped onto a rotating disk. The angular speed is measured (by the Rotary Motion Sensor) immediately before the drop and immediately after the ring stops sliding on the disk.

The initial angular momentum is compared to the final angular momentum, and the initial kinetic energy is compared to the final kinetic energy.

Theory:

When the ring is dropped onto the rotating disk, there is no net external torque on the system. Therefore, there is no change in angular momentum; angular momentum (L) is conserved.

$$L = I_i \omega_i = I_f \omega_f \quad (1)$$

where I_i is the initial rotational inertia and ω_i is the initial angular speed. The initial rotational inertia is that of a disk about an axis perpendicular to the disk (see Fig. 2) and through the center-of-mass (c.m.) is

$$I_i = I_d = \frac{1}{2} MR^2 \quad (2)$$

where M is the mass and R is the radius of the disk. The rotational inertia of the ring about an axis through its c.m. and parallel to the symmetry axis of the ring is

$$I_{\text{cm}} = \frac{1}{2} M(R_1^2 + R_2^2) \quad (3)$$

where R_1 and R_2 are the inner and outer radii of the ring. If the rotation axis is displaced by a distance x from the c.m., the rotational inertia of the ring can be calculated from the parallel axis theorem and we have

$$I_f = \frac{1}{2} M(R_1^2 + R_2^2) + Mx^2 \quad (4)$$

Note that the final rotational inertia will be the sum of the initial disk plus the ring. The rotational kinetic energy of a rotating object is given by

$$KE = \frac{1}{2} I \omega^2 \quad (5)$$

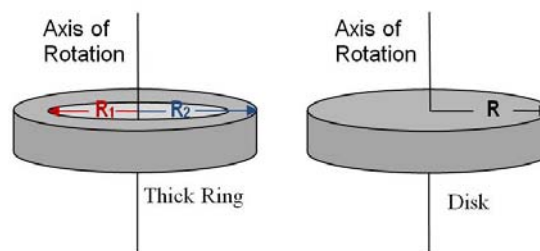


Figure 1: Conservation of Angular Momentum Figure 2: Rotational Axis for Ring and Disk

Setup

1. Use the large rod base and the 45 cm rod to support the Rotary Motion Sensor as shown in Figure 1. Plug the sensor into the interface.
2. Measure the mass and radii for the disk and ring.
3. Attach the disk to the clear three-step pulley on the Rotary Motion Sensor using the thumb-screw.
4. Place a level on the disk and level the system using the adjustable feet on the base.
5. In PASCO Capstone, set the sample rate for the Rotary Motion Sensor to 20 Hz. Create a graph of Angular Velocity vs. Time.

Procedure

1. Hold the ring with the pins up, so the ring is centered on the disk and 2 to 3 mm above it. Dropping from too high causes a large vertical force on the bearing which produces a spike in the frictional drag and results in a torque which decreases the angular momentum. However, it is also critical that your fingers are clear of the ring when it strikes the spinning disk.
2. Spin the disk to give it a positive speed of about 30-40 rad/sec. Start collecting data and after about two seconds, drop the ring onto the spinning disk. Continue to collect data for a few seconds more.
3. It is difficult to end up with the ring centered on the disk. Measure the minimum distance between the ring and the edge of the disk. Measure the maximum distance directly on the opposite side. The distance x that the ring is off-center is half of the difference between these two measurements.
4. Use the Coordinates tool to measure the rotational speed of the last data point just before the collision.
5. Measure the rotational speed of the first data point just after the collision.

Analysis

6. Use Equation (2) to calculate the initial rotational inertia.
7. Use Equation (4) to calculate the final rotational inertia of the ring.
8. Calculate the final rotational inertia of the system.
9. Use Equation (1) to calculate the initial angular momentum of the system.
10. Calculate the final angular momentum of the system and compare with a % error. Was angular momentum conserved?
11. Use Equation (5) to calculate the kinetic energy before and after dropping the ring. Was energy conserved? Where did it go?
12. How can angular momentum be conserved and energy not be?

Static Equilibrium of a Rigid Body

Equipment

1	Rotary Motion Sensor	PS-2120A
1	Rotational Accessory	CI-6691
1	Force Sensor	PS-2189
1	90 cm Rod	ME-8738
1	45 cm Rod	ME-8736
1	Large Rod Base	ME-8735
1	Large Table Clamp	ME-9472
1	Braided String	SE-8050
Required but not included:		
1	Meter Stick	SE-8827
1	Balance Scale	SE-8723

Introduction

The two requirements for an object to be in equilibrium are:

The sum of all forces acting on the object is zero.

$$\sum F = 0 \quad (1)$$

The sum of all torques acting on the object is zero.

$$\sum \tau = 0 \quad (2)$$

Setup

1. Position the Rotary Motion Sensor out over the end of the table using the table clamp and 90 cm rod as shown in Figure 1. Plug the sensor into port P1, but don't attach the black rod yet to the Rotary Motion Sensor.
2. Position the Force Sensor as shown using the rod base and 45 cm rod. Plug the sensor into port P4, and tare the sensor.

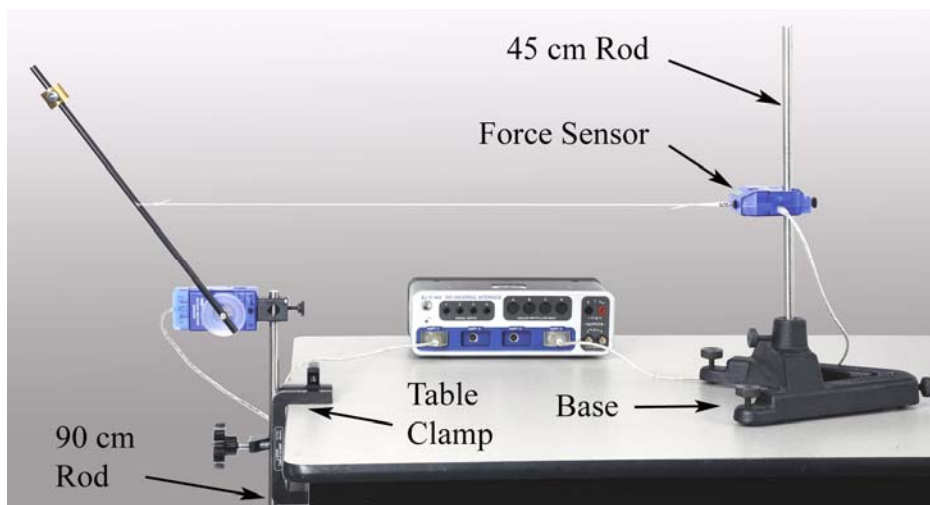


Figure 1. The Rotary Motion Sensor measures the angle of the black rod.

- Remove the silver thumbscrew from the black rod from the Rotational Accessory. Measure the mass of just the rod. Measure the mass of the cylindrical brass mass.
- Measure the distance r_1 , from the pivot hole (near the end) of the rod out to the center hole. See Figure 2. This is the radius you will use to calculate the torque caused by the string, but also the torque caused by the weight of the rod, acting at its center of mass.

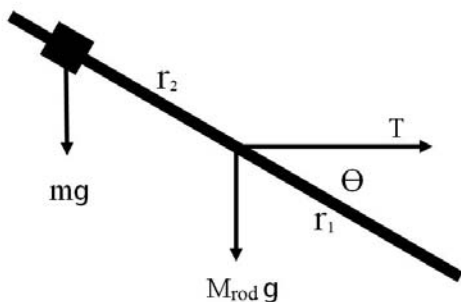


Figure 2: Free-body diagram for rod

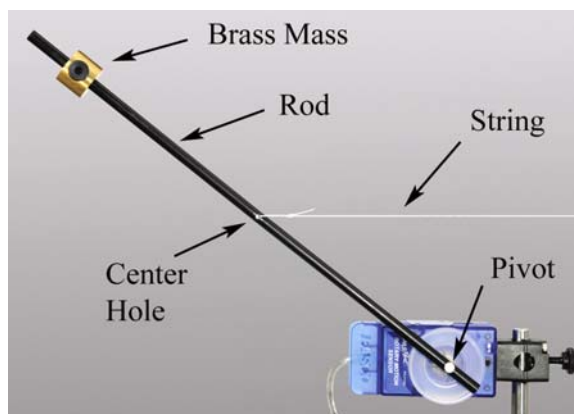


Figure 3: The rod is in static equilibrium.

- Place the brass mass somewhere near the end of the rod opposite the pivot hole. It doesn't matter where, but if you move it later, you will need to re-measure the value.
- Measure the distance r_2 , from the pivot hole out to the center of the brass mass.
- Fasten the rod to the Rotary Motion Sensor using the pulley and silver thumbscrew.
- Cut a length of string about 1 m long. Tie one end of the string to the center hole in the rod as shown in Figure 3, and tie a loop on the other end.

9. Hook the string to the Force Sensor, and adjust the position of the large base to support the black rod at an angle, as shown in Figure 1.
10. To adjust the height of the Force Sensor so that the string is level, measure the height of the string above the table, and adjust so that it is the same everywhere along the string.
11. In PASCO Capstone, set the Common Sample Rate to 20 Hz. Create two digits displays: one with the Force and one with the Angle in degrees.

Procedure

1. Unhook the string from the Force Sensor, and allow the black rod to hang vertical. Make sure there is no motion, then click on Record.
2. Lift the rod up and re-hook the string onto the Force Sensor. Click on Stop.
3. Record the string tension, T .
4. Calculate the angle, θ , shown in Figure 2. Note that this angle is not simply the angle measured by the sensor.
5. Calculate the torque caused by the string.

$$\tau_1 = T r_1 \sin\theta$$

6. Calculate the total torque in the opposite direction caused by the weight.

$$\tau_2 = (mgr_2 + M_{\text{rod}} g r_1) \cos\theta$$

7. Compare your clockwise and counter-clockwise torques with a % error. Do they cancel each other?
8. Use the other requirement for equilibrium to calculate the horizontal and vertical components of the force exerted by the pivot on the rod.
9. If the pivot exerts a force on the rod, why was this not included in the calculation of the torques?

Spring and Mass Oscillations

Equipment

1	Mass & Hanger Set	ME-8979
1	Motion Sensor	PS-2103A
1	Force Sensor	PS-2189
1	Density Set	ME-8569
1	Spring Set	ME-8999
1	Braided String	SE-8050
1	90 cm Rod	ME-8738
1	45 cm Rod	ME-8736
1	Multi-Clamp	ME-9507
1	Large Rod Base	ME-8735
Required but not included:		
1	Balance	SE-8723

Introduction

The period of oscillation, T , for a mass on a spring is given by

$$T = 2\pi \sqrt{\frac{m}{k}} \quad (1)$$

where m is the oscillating mass and k is the spring constant.

In this lab, the Motion Sensor measures the position of the oscillating mass, and the Force Sensor is used to determine the spring constant. The period of oscillation is measured, and compared to the theoretical value.

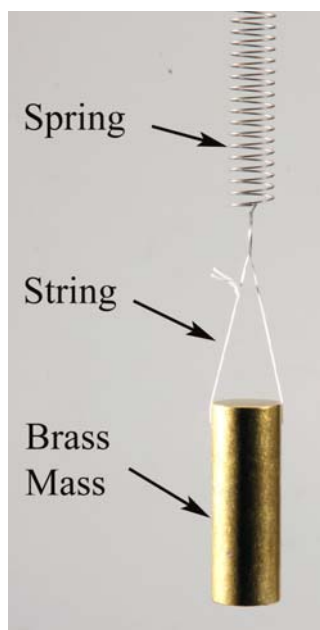
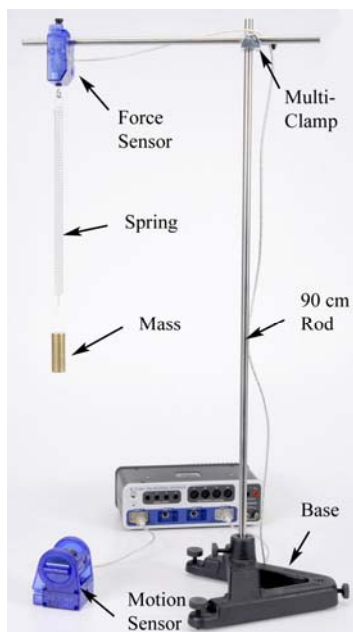


Figure 1: Spring & Mass Oscillation Figure 2: Oscillating Mass Figure 3: Spring Constant

Setup

1. Use the large base, rods, and multi-clamp to support the Force Sensor as shown in Figure 1.
2. Plug Force Sensor into port P4, and tare the sensor.
3. Position the Motion Sensor as shown and plug it into port P1.
4. In PASCO Capstone, set the Common Sample Rate to 50 Hz. Create a graph of Position vs. Time.
5. Aim the Motion Sensor upwards, towards the Force Sensor.
6. Use a balance scale to measure the mass of the brass cylinder from the Density Set.
7. Choose one of the long, stronger springs from the Spring Set. The spring with the larger spring constant should have a spot of red paint at one end. Measure the mass of the spring.
8. Tie a short piece of string through the hole in the brass mass as shown in Figure 2. Hang the mass, string, and spring assembly from the Force Sensor hook.
9. Allow the mass to oscillate and take some practice data. Adjust the Motion Sensor if necessary to get smooth continuous data.

Measuring T

1. Click on the properties (gear) icon for the Motion Sensor in the Hardware Setup window. With the mass hanging at equilibrium (not moving), click Zero Sensor Now.
2. Displace the mass from equilibrium by several centimeters, and allow it to oscillate.
3. Take around five seconds worth of data.
4. Use the coordinates tool to find the period, and record it.

Note: You can also use a sine fit to find the angular frequency, ω , and then use that to calculate the period.

5. Take data for both large and small oscillations. Is there a difference?
6. Calculate the average value of the period. Repeat several times until you get a good, solid value. Record your average.

Measuring the Spring Constant (k)

1. Remove the brass mass and replace it with a mass hanger loaded with 250 g as shown in Figure 3. Better results will be obtained if you attach a small cardboard reflector as shown in Figure 4. It is attached to the spring rather than the mass hanger since the mass hanger rotates downward slightly as more mass is added.
2. Arrange the Motion Sensor so it is directly below the target.
3. In Capstone, change the Common Sample Rate to 20 Hz. Change the Sample Mode to Keep Sample.
4. Create a graph of Force vs. Position, a Digits display of Force, and a Digits display of Position. On the Position axis of the graph, select a QuickCalc of negative Position.
5. Click Preview. Wait until the mass has stopped moving up and down (the Force number is constant) and click Keep Sample. Do not click Stop.
6. Remove 50 g and after the mass stops moving, click Keep Sample. Repeat until all 250 g has been removed. After you click Keep Sample for the case that all 250 g have been removed, click Stop.
7. On the graph, add a linear fit. From Hooke's Law, $F = kx$, so the slope of the line is the Spring Constant, k . Record the value and include the uncertainty.



Figure 4: Adding a Reflector

Analysis: Calculating T

1. Use Equation (1) to calculate the theoretical period of the mass and spring.
2. For an ideal system, the entire mass would be in the oscillating object, and the spring would have zero mass. In reality, the spring has some mass, too. But not all of the spring is moving, so how much do you include? It can be shown that one-third of the mass of the spring should be added to the mass of the oscillating object.
3. Re-calculate the period using the adjusted mass. Does it change your answer? Does it give you a better answer?
4. Compare your final theoretical value for the period to the value you measured with a % error.

Questions

1. In general, what happens to the period of a spring and mass when you increase the mass?
2. In general, what happens to the period of a spring and mass when you increase the spring constant?
3. In general, what happens to the period of a spring and mass when you increase the amplitude of the oscillation?
4. In general, what happens to the period of a spring and mass when you increase gravity?

Oscillation of a Cart and Springs

Equipment

1	PAScar Dynamics System	ME-6955
2	Compact Cart Mass	ME-6755
1	High Res Force Sensor	PS-2189
1	Rotary Motion Sensor	PS-2120A
1	Photogate	ME-9498A
1	Photogate Bracket	(in ME-8998)
1	Smart Timer Picket Fence	ME-8933
1	Spring Set	ME-8999
1	Braided String	SE-8050
1	Table Clamp	ME-9472
1	45 cm Rod	ME-8736
Required but not included:		
1	Balance	SE-8723

Introduction

The period of oscillation of the cart and spring system is measured using the Picket Fence and Photogate. The spring constant is determined using the Force Sensor and Rotary Motion to measure the displacement.

The effect on the period is investigated when changing the spring constant, amplitude of the oscillation, and the mass of the cart.



Figure 1: Cart and Spring Oscillation

The system is shown (Fig. 1) measuring the period of the oscillating cart using the Photogate and the Picket Fence. The Force Sensor and the Rotary Motion Sensor are used in a separate part of the experiment to directly measure the spring constant. Note that there are two springs: One connected to each end of the cart.

Setup

1. Set up the track as shown in Figure 2, below. Attach the Photogate before adding the endstops.
2. Plug the Photogate into Digital Input #1.
3. The Spring Set contains three each of four different springs. Start with two of the stiffer, longer springs. When new, this spring has a small dab of red paint on one end.
4. It is easier to attach the springs to the cart using a short loop of string as shown in Figure 3. The other end of the spring loops directly over the post on the endstop (see Fig. 4).
5. Place the Picket Fence in the cart as shown. Adjust the height of the Photogate so that the "Double Flag" on the top of the Picket Fence breaks the beam as the cart moves through.
6. Adjust the position of the Photogate on the track so that it is centered on the cart.

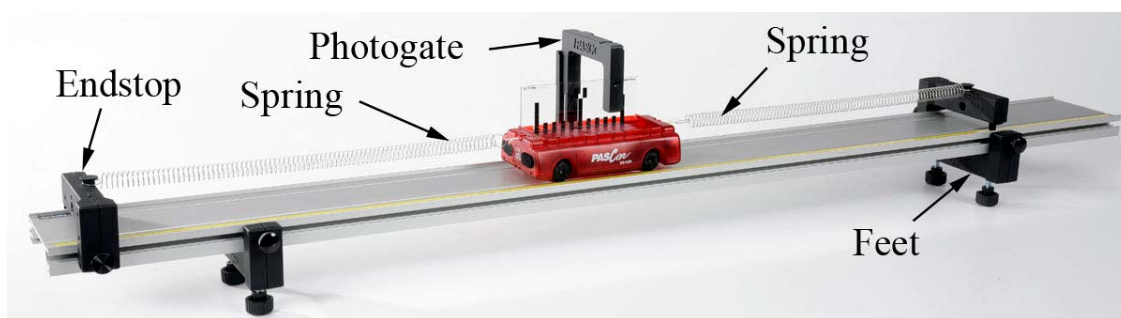


Figure 2: Cart and Track Setup

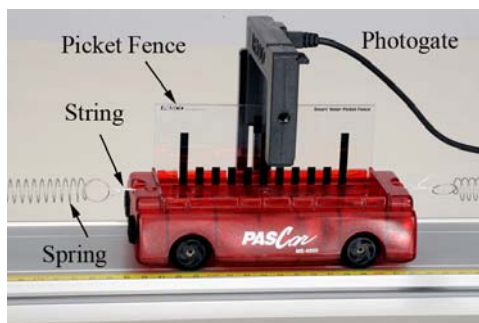


Figure 3. Attaching Springs

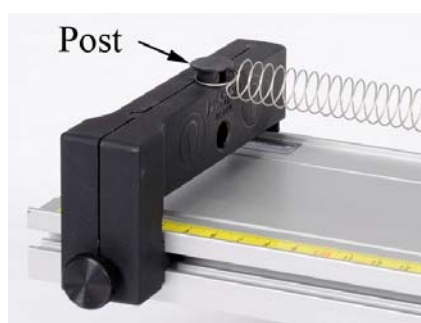


Figure 4. Endstop Post

7. In PASCO Capstone, create a custom timer for the photogate.
 - a. Open the Timer Setup at the left of the page and select Custom Timer.
 - b. Select Photogate, Ch.1.
 - c. Set up a timing sequence that consists of Photogate, Ch.1 being blocked five times, since the double-flag will block the photogate five times when one period has passed.
 - d. Specify the measurement name to be Period.
8. Create a table with one column with the Period and turn on the Mean on the statistics.

Measuring the Period of Oscillation:

1. Displace the cart from its equilibrium position by several centimeters and allow it to oscillate.
2. Click on Record to begin taking data. After each full oscillation, the measured period will be displayed in the table. After a few oscillations, click on Stop. Try another run. How much uncertainty is there in the value?
3. Displace the cart from its equilibrium position by 2 cm and record its period of oscillation. Repeat for an amplitude of 15 cm. Record your values below.
4. When you increased the amplitude of the oscillation, did the period increase, decrease, or stay about the same?
5. Incline the track by raising one end about 10 cm and adjust the Photogate so that is still centered on the cart. Measure the period of oscillation. Did the period increase, decrease, or stay about the same?
6. Put the cart back level. Move one of the endstops about 20 cm closer to the cart, so that the force exerted by the springs is now much less. Measure the period of oscillation. Did the period increase, decrease, or stay about the same?
7. Move the endstop back to its original position. Place one of the mass bars in the cart and measure the period of oscillation. Did the period increase, decrease, or stay about the same?

Procedure: Dependence of Period on Mass of Cart

1. Create a table as shown below. Both columns are User-Entered Data sets.

Table II: Vary Mass

T (s)	mass (kg)

2. Measure the mass of the Cart + Picket Fence and record the value in row 1 of Table II. Measure the Period for a 5 cm amplitude oscillation and record the value in the Table.
3. Add one of the long silver mass bars to the cart. The mass is approximately 0.25 kg, but you can use the scale to be more exact. Record the new total mass of the Cart + Picket Fence + Mass Bar in row 2.
4. Measure the Period for a 5 cm amplitude oscillation and record the value in the Table.
5. Add the second mass bar (see Fig. 5) to the cart. Note that these masses stack. Record the new mass and period in row 3.
6. Add one of the black Compact Masses (see Fig 6) and record the new mass and period in row 4.
7. Add the second Compact Mass and record the new mass and period in row 5.



Figure 5: Adding Cart Masses



Figure 6: Using Compact Cart Masses

Analysis: Period vs. Mass

1. Create a graph of T vs. mass. Can you tell by the graph what the relationship is between Period and mass? Does it look linear?
2. Click on "mass" in the horizontal axis of the graph, pick "Quick Calc" and choose an m^2 or $1/m$ graph. Do either of these choices make it more linear?
3. Return the horizontal axis to graph " m ". Use the "Quick Calc" on the vertical axis to graph T^2 . Is this linear?

Setup: Measuring the Spring Constant

1. Remove all the extra masses from the cart.
2. Attach a string to the loop at the bottom of the cart as shown in Figure 7. This string runs under the endstop and over the large pulley of the Rotary Motion Sensor (see Fig. 8) and then hooks to the Force Sensor.
3. Use the table clamp and 45 cm rod to mount the Rotary Motion Sensor as shown in Figure 8. Note that the top knob on the table clamp has been removed. The large pulley on the 3-step pulley should be on the outside. The track must be positioned so that the string coming from the cart runs straight down the track. Adjust the height so that the string does not touch either the track or the endstop.
4. Plug the Force Sensor and Rotary Motion Sensor into the PASPORT ports as shown in Figure 1.

Note that the top knob on the table clamp has been removed. This allows the Rotary Motion Sensor to be adjusted low enough. The string must run under the endstop without touching.

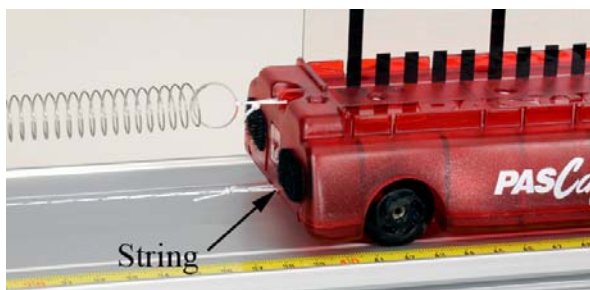


Figure 7: String Attachment for Force Sensor

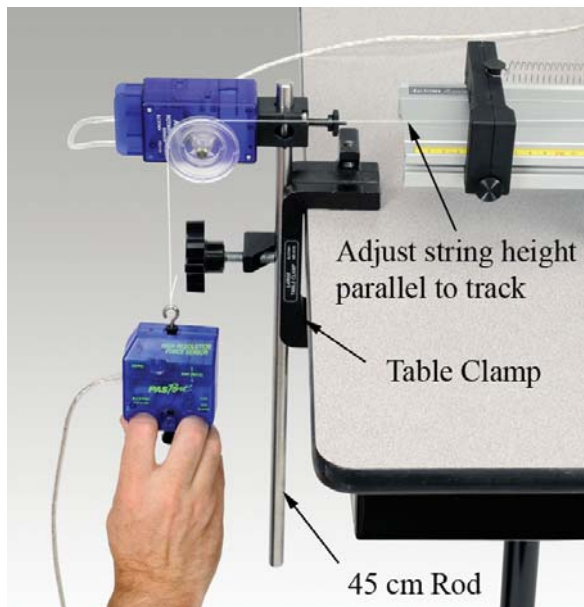


Figure 8: Measuring the Spring Constant

Procedure: Measuring the Spring Constant

When force is applied to a spring, the resulting extension or compression of the spring maintains a linear relationship with the applied force. This relationship manifests itself in Hooke's Law:

$$F = k \Delta x \quad (1)$$

where F is the applied force, Δx is the extension or compression of the spring measured from its unstretched length and k is the spring constant.

1. Use the set-up shown in Figure 8. Remove the string from the hook, and then press the zero button on the Force Sensor. Reconnect the string. Make sure the string goes over the large diameter pulley.
2. Set the Common Sample Rate to 20 Hz.
3. In Capstone, create a graph of Force vs. Position (from the Rotary Motion Sensor).
4. Create another table as shown below. Select the period T in the first column. Then click on the Set and select "Create New User-Entered Data Set" to get Set 2. In the second column, create a new User-Entered Data set called " k " with units of N/m. Also select Set 2 for this column.

Table III: Vary Spring

Set 2	Set 2
T (s)	k (N/m)

5. Click on Record to start recording data. Gently pull down on the Force Sensor. Do not extend the springs more than 20 cm. Click on Stop.
6. Since the force reading with the Force Sensor is negative for a "pull", apply a "QuickCalc" on the vertical axis to make the forces positive. If the displacement for your data is negative, you can choose a QuickCalc on the horizontal axis as well. Just click on Position in the graph and choose a "-x" QuickCalc.
7. Select a linear curve fit. You can also use the select tool to choose only a selected portion of the data.
8. What is the physical meaning of the slope? Does it have units? Enter your value for k in row 1 of Table III.

Changing the Spring Constant

Note: The mass bars are not used during this part of the experiment

1. Measure the period of the cart for a 5cm amplitude oscillation. Leave the string attached to the cart bottom loop, as you will need it for the next part. If you simply unhook the Force Sensor, the light string sliding back and forth doesn't have much effect. Enter the value in row 1 of Table III.
2. Replace one of the springs with one of the weaker, long springs.
3. Use the procedure from the last section to measure the new Spring Constant. If you do not get a different value, check your springs!
4. Measure the new period of the cart oscillation.
5. Enter values for the period and spring constant in row 2 of Table III.
6. Replace the other original spring with one of the weaker, long springs.
7. Measure the new Spring Constant and Period, and enter the values in row 3 of the Table.
8. Replace one of the weak long springs with two of the weakest short springs as shown in Figure 9. The weak short springs are the ones without the blue paint.
9. Measure the new Spring Constant and Period, and enter the values in row 4 of the Table.
10. Add the remaining weak short spring to the end of the long weak spring on the track.
11. Measure the new Spring Constant and Period, and enter the values in row 5 of the Table.

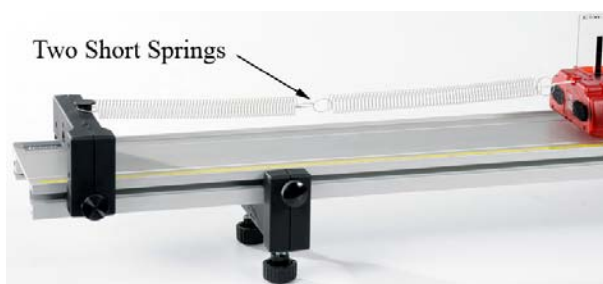


Figure 9: Using Short Springs

Analysis

1. Create a graph of T vs. k and choose Set 2. The graph shows the period data you took for five different Spring Constants. Can you tell by the graph what the relationship is between Period and mass? Does it look linear?
2. Use a "QuickCalc" on the horizontal axis to graph k^2 . Does this make it more linear?
3. Use a "QuickCalc" on the horizontal axis to graph $1/k$. Does this make it more linear?
4. Leave the horizontal axis as $1/k$. Use the "Quick Calc" on the vertical axis to graph T^2 . Is this linear?

Combined

In the first part of the lab you varied the mass of the oscillating cart, and discovered that the square of the period is directly proportional to the mass. In the second part of the lab you varied the spring constant, and discovered that the square of the period is inversely proportional to the mass. This means that the period is proportional to the square root of the mass to spring constant ratio.

$$T \propto \sqrt{\frac{m}{k}} \quad (2)$$

1. You will now combine all the data you took into one graph. From Table II (Vary Mass), copy the Period Data into column 1 of a new table as shown below. Select a new data set (Set 3) for each column. The last column is a calculation made in the Capstone calculator:

$$(m/k)^{.5} = ([\text{mass}]/[k])^{.5}$$

Table IV: Combined

Set 3	Set 3	Set 3	Set 3
T (s)	mass (kg)	k (N/m)	$(m/k)^{.5}$

2. From Table II (Vary Mass), copy the Mass Data into column 2 of Table IV.
3. What was the value of the Spring Constant for this part of the experiment? Hint: Look at the data in Table III (Vary K). Enter this value in column 3 for each of the rows.

4. Note that a (square root m/k) calculation is being automatically performed for each data set, and displayed in column 4. Check at least one of the values to confirm that it is correct.
5. Note that the units have been left off the calculation. What are they? Reduce your answer as far as possible!
6. From Table III (Vary k), copy the Period Data and paste it into the data in column 1 of Table IV below the data that is already there.
7. From Table III (Vary k), copy the Spring Constant Data and paste it into the data in column 3 of Table V.
8. What was the Cart Mass for this part of the experiment? Enter this value in column 2 for each of the new rows.
9. Create a graph of T vs. $(m/k)^{.5}$ and choose Set 3.
10. Select the linear curve fit from the graph tool palette. What is the physical meaning of the slope? Does it have units? What is the uncertainty in your value?
11. What is the accepted value for the proportionality constant for equation #2? *Hint: It is some multiple of π !*
12. Compare to the accepted value using the % error calculation.
13. Does the accepted value agree with your measured value within the uncertainty of the experiment?

Oscillation Equations of Motion

Equipment

1	Motion Sensor	PS-2103A
1	pendulum clamp	ME-9506
1	Density Set	ME-8569
1	Spring Set	ME-8999
1	Braided String	SE-8050
1	90 cm Rod	ME-8738
1	Large Rod Base	ME-8735

Introduction

The motion of an oscillating mass is measured using a Motion Sensor, and graphs are produced of position, velocity and acceleration. The relative phase of each is examined, and compared to theory.

Calculations are made for the maximum velocity and maximum acceleration during an oscillation, and compared to values measured directly off the graphed data.

Theory

For an object oscillating in simple harmonic motion, its displacement from equilibrium, x , can be written as

$$x = A \cos(\omega t) \quad (1)$$

where A is the initial amplitude and ω is the angular frequency. Note: For simplicity, we assume here that the object is released from rest.

To find the velocity, v , we take a derivative of Equation (1).

$$v = dx/dt = -\omega A \sin(\omega t) = \omega A \cos(\omega t + \pi/2) \quad (2)$$

Note the use of a trig identity to write the velocity in the form of $\cos(\omega t + \phi)$, where ϕ is the phase angle.

To find the acceleration, a , we take a derivative of Equation (2).

$$a = dv/dt = -\omega^2 A \sin(\omega t + \pi/2) = \omega^2 A \cos(\omega t + \pi) \quad (3)$$

Equation (2) shows that the maximum velocity, v_{\max} , is

$$v_{\max} = \omega A \quad (4)$$

and the maximum acceleration, a_{\max} , is

$$a_{\max} = \omega^2 A \quad (5)$$

Setup

1. Use the large base and 90 cm rod to support the pendulum clamp as shown in Figure 1.
2. Position the Motion Sensor as shown and plug it into the interface.
3. In PASCO Capstone, set the sample rate to 50 Hz. Create a graph of Position vs. Time. Change the units on the Position axis to cm.
4. Aim the Motion Sensor upwards, towards the pendulum clamp.
5. Choose one of the long, stronger springs from the Spring Set. The spring with the larger spring constant should have a spot of red paint on one end.
6. Tie a short piece of string through the hole in the brass mass as shown in Figure 2. Hang the mass, string, and spring assembly from one of the hooks on the back of the pendulum clamp.
7. Click on the properties (gear) icon for the Motion Sensor in the Hardware Setup window. With the mass hanging at equilibrium (not moving), click Zero Sensor Now.
8. Allow the mass to oscillate and take some practice data. Adjust the Motion Sensor, if necessary, to get smooth continuous data.

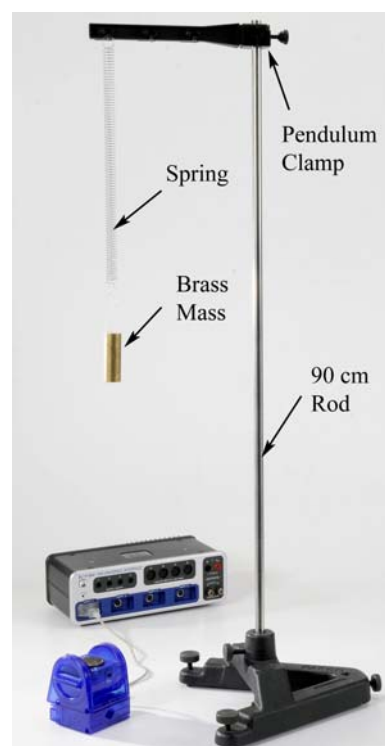


Figure 1. Simple Harmonic Motion

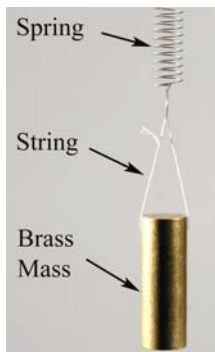


Figure 2. String

Procedure - Phase

1. Create the following calculations:
 $v = \text{smooth}(15, \text{derivative}(5, [\text{Position (m)}], [\text{Time (s)}]))$ with units of m/s
 $a = \text{smooth}(15, \text{derivative}(5, [v \text{ (m/s)}], [\text{Time (s)}]))$ with units of m/s²
2. On the graph, add a second vertical axis and put the calculation v on it. Change the units to cm/s.
3. Displace the mass from equilibrium by 10 to 20 centimeters, and allow it to oscillate. Take two or three periods worth of data. If the velocity data is not very smooth, try again. Get one good run of data.
4. Use the Coordinates tool to measure the period of the oscillation, T , and the time shift, ΔT , between the peak of position and velocity.
5. Calculate the ratio $\Delta T/T$. Is it about $1/4$? This means that the phase of the velocity is $1/4$ wavelength from the position.
6. A complete oscillation is also 360° or 2π radians. What is $1/4$ of that angle? How does this compare to the phase shown in Equation (2)?
7. Now add another vertical axis to the graph and put the calculation “ a ” on it. You can try smoothing this curve if it is not very sinusoidal. If it is too bad, take another run.
8. Use the Coordinates tool to measure the time shift, ΔT , between the peak of position and acceleration.
9. Calculate the phase shift between position and acceleration. How does this compare to the phase shown in Equation (3)?
10. Use a Sine curve fit on the position data to find the angular frequency, ω .
11. Record the amplitude, A , from the curve fit.
12. Use the Coordinates tool to measure the maximum velocity and maximum acceleration.

Analysis

1. Calculate v_{max} using Equation (4) and compare to your measured value.
2. Calculate a_{max} using Equation (5) and compare to your measured value.

Questions

1. What is the relationship between ω and the period you measured earlier?
2. Why did you need to only measure ω for the position graph?
3. When the position is at a positive maximum, the velocity is... negative maximum, zero, positive maximum?
4. When the position is at a positive maximum, the acceleration is... negative maximum, zero, positive maximum?
5. Can you answer questions 3 and 4 for when the position is at zero (equilibrium)? Why are there two answers?

Driven Oscillation of Mass and Spring

Equipment

1	Motion Sensor	PS-2103A
1	Density Set	ME-8569
1	Spring set	ME-8999
1	Braided String	SE-8050
1	Table Clamp	ME-9472
1	45 cm Rod	ME-8736
1	Large Rod Base	ME-8735
1	String Vibrator (From UI-5802)	WA-9857
1	Patch Cords (From UI-5802)	SE-9750
	Thick construction paper and tape	

Introduction

The String Vibrator is used to drive the mass and spring, and the resulting oscillation is recorded using the Motion Sensor. The driving frequency is varied to observe the response above, below and at the resonance frequency of the system. The piece of blue construction paper taped to the bottom of the oscillating mass adds damping to the system caused by the air friction drag.

Setup

1. Use two patch cords to connect the String Vibrator to Output #1 on the 850 Interface.
2. Use the table clamp and 45 cm rod to support the String Vibrator out over the edge of the table as shown in Figure 1. Note that the vibrator is positioned label side down, with the patch cords coming out the bottom.
3. Position the Motion Sensor on the floor below the String Vibrator, and plug the sensor into the interface. In PASCO Capstone, set the sample rate to 50 Hz.
4. Tie a short loop of string through the hole in the plastic cylinder from the Density Set.
5. Cut a 15 cm x 15 cm square piece of construction paper.
6. Tape the plastic cylinder to the center of the square as shown in Figure 2.
7. Select the three short, weak springs from the Spring Set. Suspend the cylinder with paper damper from the driver of the String Vibrator using the three springs in series as shown in Figure 3.
8. Adjust the height so that the paper damper is about 30 cm above the Motion Sensor.

9. Click on the properties (gear) icon for the Motion Sensor in the Hardware Setup window. With the mass hanging at equilibrium (not moving), click Zero Sensor Now. Later, if your oscillation data is not centered on zero, repeat this step.

Note: In this lab, you will vary the driving frequency to see the effect on the amplitude of the oscillation. The damping created by air friction on the blue paper fastened to the bottom of the cylinder causes the motion to settle down more quickly, making it easier to see the changes.

10. Create a graph of Position vs. Time.

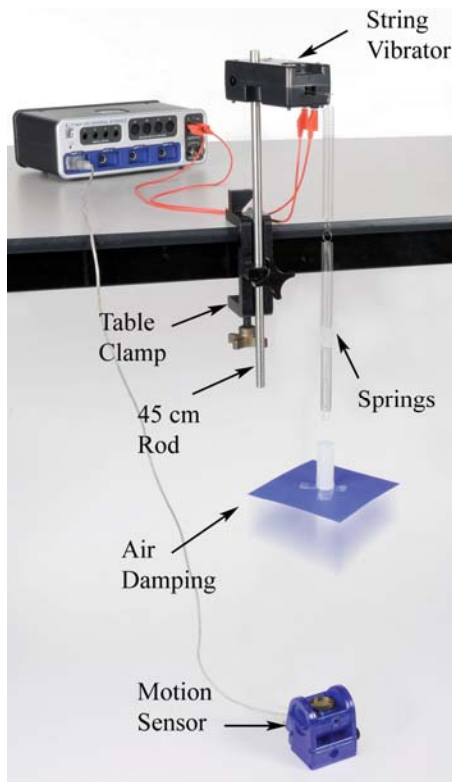


Figure 1: Driven Oscillations

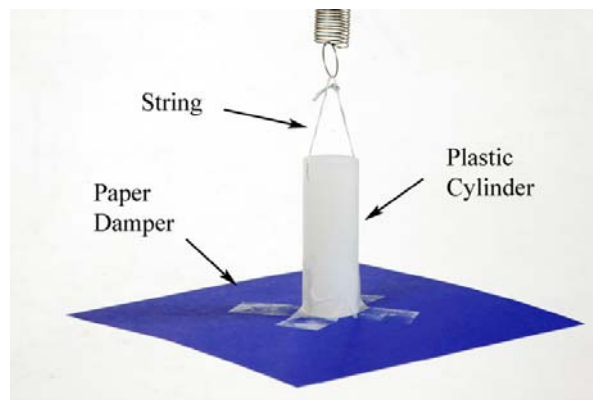


Figure 2: Adding the Damping

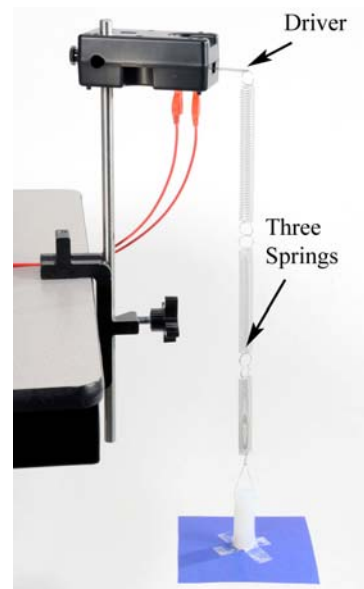


Figure 3. Three Short Weak Springs

Procedure: Resonant Frequency

1. Displace the mass from equilibrium by 15 to 20 cm, and release.
2. Immediately click on Record, and take four or five periods worth of data.
3. Select a Damped Sine from the curve fit list.
4. Record the angular frequency, ω .
5. Displace the mass again, and take another run of data. Record the frequency of this run. Calculate the average angular frequency.
6. Repeat until you get a good, solid value for the average angular frequency.

Driving Frequencies

7. Create a table as shown below. Freq, f, and A are User-Entered Data sets.

	Freq	f (Hz)	A (cm)
1	Resonance – 0.3		
2	Resonance – 0.2		
3	Resonance – 0.1		
4	Resonance – 0.05		
5	Resonance – 0.02		
6	Resonance		
7	Resonance + 0.02		
8	Resonance + 0.05		
9	Resonance + 0.1		
10	Resonance + 0.2		
11	Resonance + 0.3		
12	Resonance + 0.4		

8. Calculate the linear frequency, f, where

$$\omega = 2\pi f$$

This is the resonant frequency (in Hz) of the spring and mass system. Record this value in row 6 in the right hand column of the table.

9. Set the frequency of the signal generator to the resonant frequency, and turn the output on. Do not exceed the max voltage of 6 V! Observe the resulting oscillation, then turn off the output.

10. Subtract 0.3 from your resonant frequency and enter this value in row 1 in the right hand column of the table. Continue the process and fill out the table for the rest of the values

In the next part, you will set the signal generator to each of these frequencies, and measure the resulting amplitude using the Motion Sensor. Each time you change the frequency, you will have to wait for the oscillation to settle down. If the amplitude is fluctuating, just wait a few seconds and try another run. Give it time to settle down to a steady value. If it continues to fluctuate, just try to estimate an average value for the amplitude.

11. Set the signal generator at the first (lowest) frequency in the table, and turn on the output. You can leave the generator on, even while you change frequencies.
12. For each frequency, measure the resulting amplitude (A) with the Coordinates tool, and enter the value in the table in the third column. Turn the output off when finished.
13. Create a graph of A vs. f.

Resonance Curve

1. What determined the position where the resonance curve peaks?
2. Which way would the curve shift if you used the same springs but a larger oscillating mass?
3. What determines the height of the peak? What could you change to make it larger?
4. The String Vibrator is pushing and pulling on the spring the same at all frequencies. Why does it cause a big oscillation only near resonance? What is happening when it is far from resonance?

Physical Pendulum

Equipment

1	Rotary Motion Sensor	PS-2120A
1	Rotational Accessory	CI-6691
1	Large Rod Base	ME-8735
1	45 cm Rod	ME-8736
Required but not included:		
1	Calipers	SE-8710
1	Meter Stick	SE-8827

Introduction

The rod and disk shown, in Figure 1, oscillate as a physical pendulum. The period is measured directly by the Rotary Motion Sensor, and the values are compared to the theoretical periods calculated from the dimensions of the pendulums.



Figure 1: Setup

Theory

The period of a physical pendulum (for small oscillations) is given by

$$T = 2\pi\sqrt{I/Mgx} \quad (1)$$

where I is the rotational inertia of the pendulum of mass, M , and " x " is the distance from its center of mass to the pivot point.

For the disk used in this lab, the pivot point is at the outer rim (see Fig. 2), and thus the distance, x , is just the radius, R . Note that the rotational inertia must be calculated about the pivot point. Combining the rotational inertia of a disk about its center of mass ($I_{\text{disk}} = \frac{1}{2}MR^2$) and the Parallel Axis Theorem ($I = I_{\text{cm}} + Mx^2$) yields

$$I = \frac{3}{2}MR^2 \quad (2)$$

Combining Equations (1) and (2) gives

$$T_{\text{Disk}} = 2\pi\sqrt{3R/2g} \quad (3)$$

For the rod of length, L , the pivot point is the hole near the end (see Fig. 3), a distance " x " from the center of mass. Combining the rotational inertia of a thin rod about its center of mass ($I_{\text{rod}} = \frac{1}{12}ML^2$) with the Parallel Axis Theorem and Equation (1) yields

$$T_{Rod} = 2\pi \sqrt{\frac{\frac{1}{12}L^2 + x^2}{gx}} \quad (4)$$

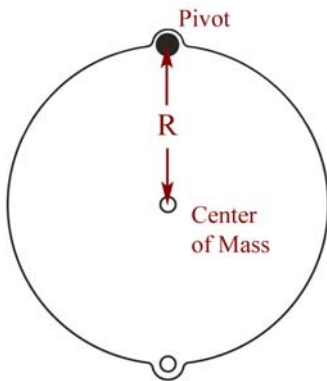


Figure 2: Disk Pivot at Edge

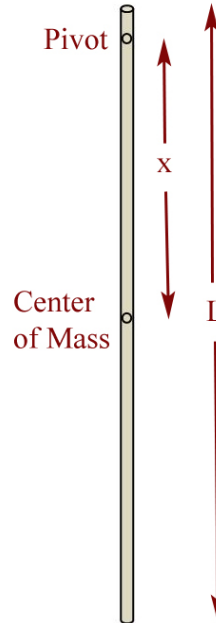


Figure 3: Rod

Note. The "ears" that stick out on the disk allow it to pivot at a radius equal to the radius of the disk: Thus $x = R$ for this disk.

For the rod, the distance x is not just $\frac{1}{2}L$, and must be measured separately. You can assume the center of mass of the rod is at the center hole, or you can try to balance it to find the position more accurately. Measurements are made on the last page, in analysis.

Setup

1. Use the base and 45 cm rod to support the Rotary Motion Sensor as shown in Figure 1.
2. Plug the sensor into the interface.
3. In PASCO Capstone, set the sample rate to 100 Hz.
4. Create a graph of Angle (in degrees) vs. Time.

Procedure

1. Attach the disk to the pulley of the Rotary Motion Sensor as shown in the inset of Figure 1.
2. With the pendulum stationary, zero the sensor.
3. Take a run of data for low amplitude ($<10^\circ$) and use the coordinates tool to measure the period.
4. Take several runs and calculate the average period.

Note: You can also use a Sine curve fit to measure the period.

5. Repeat for the rod.

Analysis

1. Use calipers to measure the diameter and calculate the radius, R , of the disk.
2. Use the meter stick to measure the total length, L , of the rod. Measure the distance, x , from the end pivot hole to the rod's center of mass.
3. Use equations (3) and (4) to calculate the theoretical periods of the disk and rod. Compare to the measured periods using percent difference and record your answers.
4. The period of a physical pendulum appears, from Equation (1), to depend on the mass of the pendulum. Why did you not have to measure the mass of the disk and rod?

Large Amplitude Pendulum

Equipment

1	Rotary Motion Sensor	PS-2120A
1	Rotational Accessory	CI-6691
1	Large Rod Base	ME-8735
1	45 cm Rod	ME-8736

Introduction

This experiment explores the oscillatory motion of a physical pendulum for both small and large amplitudes. Waveforms are examined for angular displacement, velocity and acceleration, and the dependence of the period of a pendulum on the amplitude of oscillation is investigated.

Setup

1. Use the base and 45 cm rod to support the Rotary Motion Sensor as shown in Figure 1.
2. Plug the sensor into the interface. In PASCO Capstone, set the sample rate to 50 Hz. Create a graph of Angle (in degrees) vs. Time.
3. Attach the black rod to the pulley of the Rotary Motion Sensor using the thumbscrew.
4. Place the two brass masses on the black rod. One mass should be even with the end of the rod. Position the other to leave about 3 cm of rod exposed above the mass.



Figure 1. Pendulum Oscillating at Large Angles

Procedure: Small Amplitude

1. With the pendulum stationary, zero the sensor.
2. Take a run of data with the amplitude between 10° and 20° . You only want two or three periods.
3. Rename this run "Small".
4. Does the data look sinusoidal? Try a Sine curve fit.
5. Use the Capstone calculator to create the following calculations:

$\text{vel} = \text{derivative}(15, [\text{Angle (rad)}], [\text{Time (s)}])$ with units of rad/s
 $\text{accel} = \text{derivative}(15, [\text{vel (rad/s)}], [\text{Time (s)}])$ with units of rad/s^2

6. Add two new vertical axes to the graph and put the angular velocity calculation (vel) and the angular acceleration calculation (accel) on them. Does that data look sinusoidal?

Procedure: Large Amplitude

1. Take a run of data with the amplitude greater than 160° . You only want two or three periods.
2. Rename this run "Large".
3. Does the Angle data look sinusoidal? Try a Sine curve fit.
4. Do the angular velocity and the angular acceleration data look sinusoidal?

Dependence of Period on Amplitude

1. Create a table with two columns. Create User-Entered Data sets for each column and fill the column with the initial angle (θ_0) with the values shown.
2. Take a run of data with an amplitude of approximately 5° . You want to measure the period over several oscillations, with the amplitude being 5° during the middle of the measurement. Use the Delta (coordinates) tool.
3. Record the period in the table.
4. Repeat for the other values in the table.

θ_0 ($^\circ$)	T (s)
5	
10	
20	
30	
40	
50	
70	
90	
110	
130	
150	
170	

5. Create a graph of T vs. θ_0 .
6. Textbooks usually claim that the period of a pendulum is independent of amplitude for "small angles". Looking at your data, how small does the amplitude need to be for this to be true?
7. You only took data up to 170° . In theory, what is the period for 180° ?

Variable-g Pendulum

Equipment

1	Rotary Motion Sensor	PS-2120A
1	Rotational Accessory	CI-6691
1	Acceleration Sensor	PS-2118
1	90 cm Rod	ME-8738
1	45 cm Rod	ME-8736
1	Large Rod Base	ME-8735
1	Multi-Clamp	ME-9507
Required but not included:		
1	Level	SE-8729
1	Meter Stick	SE-8827

Introduction

The black rod shown in Figure 1 acts as a pendulum, and is constrained to oscillate in a plane tilted at an angle from the vertical. This effectively reduces the acceleration due to gravity because the restoring force is decreased. The Acceleration Sensor is fastened to the Rotary Motion Sensor, and directly measures the effective "g" for the pendulum.

Theory

A physical pendulum consists of a rod of length, L , pivoted about one end. The angular frequency, ω , of the oscillation (for small amplitudes) is

$$\omega = \sqrt{3g/2L} \quad (1)$$

The angular frequency is related to the period of oscillation, T , by

$$T = \frac{2\pi}{\omega} \quad (2)$$

In this lab, you will change the effective "g" by changing the plane of oscillation of the pendulum, and measure the resulting angular frequency.

Setup

1. Connect the 90 cm rod to the base as shown in Figure 1. Use the multi-clamp to support the 45 cm rod horizontally.
2. Slide the Rotary Motion Sensor onto the horizontal rod as shown in Figure 2. Connect the sensor to port P2.
3. Fasten the metal bracket to the side of the Rotary Motion Sensor using the thumbscrew. The bracket needs to be parallel to the case as shown.
4. Attach the Acceleration Sensor to the bracket as shown in Figure 3. Connect the sensor to port P1.
5. In PASCO Capstone, set the sample rate of the Rotary Motion Sensor to 50 Hz and the sample rate of the Acceleration Sensor to 20 Hz.
6. Create a graph of Angle (in degrees) vs. Time.
7. Attach the black tube from the Rotational Accessory as shown in Figure 1.



Figure 1: The effective "g" for the pendulum is varied by changing the angle of the plane of oscillation.

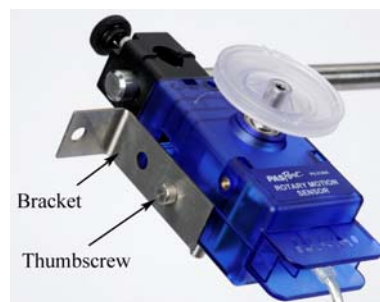


Fig. 2: Acceleration Sensor Bracket

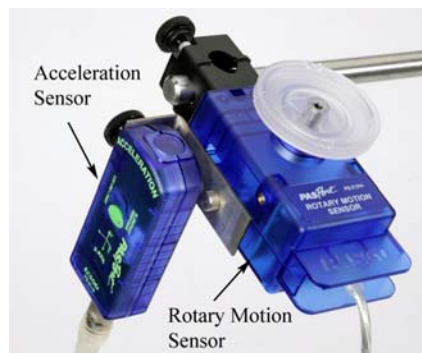


Figure 3: Acceleration Sensor

8. In the Capstone calculator, create the following calculations for the effective g (g_{eff}) and the period:

$$g_{\text{eff}} = \text{smooth}(11, \text{abs}(9.8 - [\text{Acceleration-x, Ch P2 (m/s}^2)]) \text{ with units of m/s}^2$$

$$\text{Period} = 6.28/[\omega \text{ (rad/s)}] \text{ with units of s}$$

9. Create a table as shown below. Create User-Entered Data sets called “ g ” with units of m/s^2 and “ ω ” with units of rad/s . Fill the first column with the suggested values. The third column has the calculation “Period”.

Table I: Vary “ g ”

g (m/s^2)	ω (rad/s)	Period (s)
9.8		
9.0		
8.0		
7.0		
6.0		
5.0		
4.0		
3.0		
2.0		
1.0		

10. Create a Digits display and select the calculation “ g_{eff} ”.

Procedure

- Adjust the plane of oscillation so that the pendulum is vertical. Use a level to get the case of the Rotary Motion Sensor as close to vertical as possible.
- Zero the Acceleration Sensor.
- Click on Record, and observe the effective “ g ” in the display. It should be close to 9.8 m/s^2 , but record the actual value in row 1. Click on Stop.
- Allow the pendulum to oscillate at small angles, and take 5 to 10 periods worth of data. Make sure the amplitude is less than 20° .
- Use a Damped Sine Wave curve fit, and record the angular frequency, ω , in row 1 of the table.
- Click on Record, and adjust the plane of oscillation of the pendulum until the effective “ g ” in the display is about 9.0 m/s^2 . Record the actual value in row 2 of the table, and click on Stop.

7. Take a run of data as before and record the angular frequency in the table.
8. Repeat for all the other listed values of "g". In each case, replace the suggested value with your actual value for "g" from the display.

Analysis

9. Create a graph of ω vs. "g". Is it linear? Should it be?
10. Try a QuickCalc on the vertical axis. Does graphing ω^2 give a linear relationship?
11. What is the physical significance of the slope? Hint: Look at Equation (1).
12. Using this, what is the theoretical length of the pendulum?
13. What is the actual length of the rod, measured from the end to the pivot point? How does it compare?
14. Why is "L" not the total length of the rod?

Period

15. In Table I, use Equation (2) to verify the calculation for the first row of the third column.
16. Create a graph of T vs. g. Is it linear?
17. In general, how does the period depend on gravity? Try various QuickCalcs on both axes to linearize the data.

Physical Pendulum Minimum Period

Equipment

1	Rotary Motion Sensor	PS-2120A
1	Rotational Accessory	CI-6691
1	Large Rod Base	ME-8735
1	45 cm Rod	ME-8736
Required but not included:		
1	Balance	SE-8723
1	Meter Stick	SE-8827

Introduction

The period of the physical pendulum shown in Figure 1 is measured with the lower brass mass in various positions. If you start with the mass at the bottom, and then move it up to the position shown, you find that the period has decreased, due to the fact that you have decreased the pendulum's rotational inertia. However, if you move the mass up close to the pulley, the period will be very large, due to the fact the pendulum is almost balanced by the upper fixed mass. Somewhere in between these two extremes, the period goes through a minimum value.

Setup

1. Use the base and 45 cm rod to support the Rotary Motion Sensor as shown in Figure 1. Plug in the sensor.
2. In PASCO Capstone, set the sample rate to 50 Hz. Create a graph of Angle (in degrees) vs. Time.
3. Measure the mass of the black rod, M_{rod} , and record below.
4. Measure the mass of each of the two brass masses. They should be about the same. If they are slightly different, use an average value for "m".
5. Measure the length of the black rod, L .

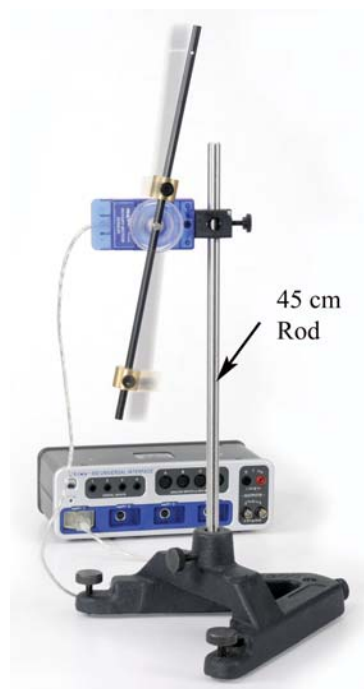


Figure 1: Minimum Period of a Pendulum

Theory

The general formula for the period of a physical pendulum is

$$T = 2\pi\sqrt{I/mgx} \quad (1)$$

For the pendulum shown here, the inertia, I , is the total inertia of the rod plus brass masses. The upper mass is fixed at r_o and the lower mass is moved to various positions, r . Both have the same mass, m . Thus

$$I = I_{\text{rod}} + mr_o^2 + mr^2 \quad (2)$$

A thin rod of mass, M_{rod} , and total length, L , rotating about center of mass, has rotational inertia

$$I_{\text{rod}} = (1/12) M_{\text{rod}} L^2 \quad (3)$$

The denominator in Equation (1) is the generic form of the restoring torque. The rod is balance at its center, so only the two masses create a torque. Note that they create opposite torques, and thus

$$"mgx" = \text{Torque} = mgr - mgr_o \quad (4)$$

Substituting Equation (2) and Equation (4) into Equation (1) yields

$$T = 2\pi\sqrt{\frac{I_{\text{rod}} + m(r^2 + r_o^2)}{mg(r - r_o)}} \quad (5)$$

To find the position, r , where the period from Equation (5) is at a minimum, take the derivative with respect to " r ", and set that expression equal to zero. Setting $dT/dr = 0$ and simplifying yields

$$mr^2 - 2mr_o r - (I_{\text{rod}} + r_o^2) = 0 \quad (6)$$

Finally, using the quadratic equation for " r " in Equation (6), and substituting that $\Delta r = r - r_o$, yields the position for minimum period is

$$\Delta r_{\text{min}} = \sqrt{2r_o^2 + I_{\text{rod}}/m} \quad (7)$$

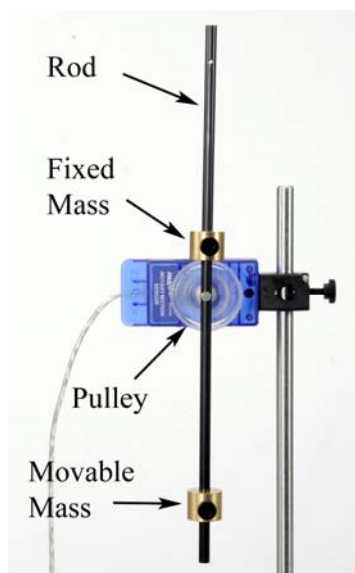


Figure 2: Physical Pendulum

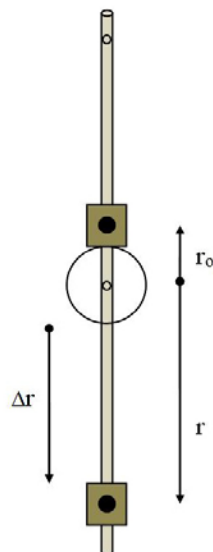
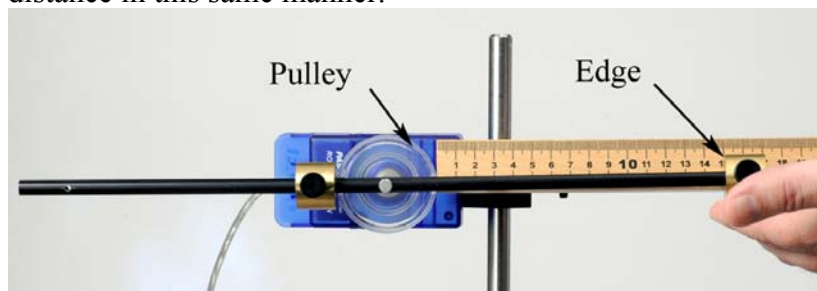


Figure 3: Mass Positions

Calculate Minimum Period

1. Place the brass masses on the black rod as shown in Figure 2. The upper mass should be up against the clear pulley, and is never changed during the lab.
2. Measure the distance r_0 as shown in Figure 3. This is the distance from the pivot point up to the center of the fixed mass.
3. Calculate the rotational inertia of the black rod using Equation (3). What are the units?
4. Use Equation (7) to calculate the theoretical position, Δr , of the movable mass for when the period is at a minimum.
5. Place the movable mass at the end of the rod, and use the meter stick, as shown in Figure 4, to adjust the length, Δr , to 15 cm. Remember that $\Delta r = r - r_0$ is the distance from the edge of the pulley out to the near edge of the mass. See Figure 3.
6. In the next section, as you move the lower mass to new positions, always measure the distance in this same manner.

Figure 4: Measuring Δr

The position, r , of the mass is from the axis of rotation out to its center of mass, as shown in Figure 3. Since this is difficult to measure exactly, we instead measure Δr , the distance from the edge of the pulley out to the near edge of the mass, as shown here. Since the theoretical position for the minimum period is written for Δr , you never have to deal with the actual distance, r .

Measuring Period

7. Re-measure the position and confirm that Δr is 15 cm.
8. Take a run of data for very small angles. The amplitude **must** be less than 5° . Record 5 to 10 periods.
9. Create a table as shown below. Create a User-Entered Data set called ω with units of rad/s. Create a calculation in Capstone and select it for the second column:

$$\text{Period} = 2\pi / [\omega \text{ (rad/s)}] \quad \text{with units of s}$$

Table I: Calculate Period

ω (rad/s)	Period (s)

Turn on the Mean in the Statistics.

10. Use a Damped Sine fit to find the angular frequency, ω , and record the value in Table I. Make sure the curve fit is set for at least four digits.
11. Take several runs. Note that the average value is being calculated, and that the period is calculated also.

Changing Δr

12. Create a table as shown below. Create a User-Entered Data set called Δr with units of cm and another set called T with units of s.
13. Enter the average Period for 15 cm in Table II.
14. Move the mass up so that Δr is 14 cm. Take several runs and find the average period, as before. Don't forget to clear out the previous values in Table I for each new position.
15. Repeat for all the Δr positions listed in Table II.

Table II: Position

Δr (cm)	T (s)
15	
14	
13	
12	
11	
10	
9	
8	
7	
6	
5	
4	

Analysis

16. Create a graph of T vs. Δr . How does your minimum value compare to the predicted?
17. You only took data every even centimeter. You can go back and take a few more runs at $1/2$ cm intervals just before and just after the minimum. Insert these new data rows in Table II.
18. Try a Polynomial curve fit on your data. Change the number of parameters to get the best fit.
19. What does the curve fit show for the position of minimum period? Compare this to the predicted value.

Archimedes' Principle

Equipment

1	Force Sensor	PS-2189
1	Density Set	ME-8569
1	Braided String	SE-8050
1	90 cm Rod	ME-8738
1	45 cm Rod	ME-8736
1	Multi-Clamp	ME-9507
1	Large Rod Base	ME-8735
Required but not included:		
1	Calipers	SE-8710
1	1000 ml Beaker	SE-7288

Introduction

Archimedes' Principle states: "When an object is submerged in a fluid, the fluid exerts an upwards buoyant force equal to the weight of the fluid displaced by the object".

In this lab, the buoyant force on an object is measured by taking the difference between the object's weight in air, and its apparent weight in water. This measured buoyant force is compared to the theoretical value calculated using the object's volume, and Archimedes' Principle.

Several objects of different shapes are examined: Some of the objects have the same density, some have the same volume, and some have the same mass. The dependence of the buoyant force on density, mass, volume and shape is explored.

Figure 1: Measuring the Buoyant Force

When an object is submerged in a fluid, the apparent weight of the object is less than the weight in air because of the upward buoyant force. Thus the buoyant force can be calculated by finding the difference between the weight of the object in air and the apparent weight of the object when it is submerged in water.



Setup

1. Use the base, rods and multi-clamp to support the Force Sensor over the beaker as shown in Figure 1.
2. Plug in the sensor. Zero the sensor.
3. Tie a piece of string onto each of the masses. Tie a loop on the other end of the string so that it can be hooked onto the sensor.
4. Put 1000 ml of water in the beaker, but don't submerge the samples yet!
5. In PASCO Capstone, set the sample rate to 500 Hz. Change the Sampling Mode to Fast Monitor.
6. Create a table as shown below. Create a User-Entered Data set called "Object" and fill in the types of objects. Create User-Entered Data sets called "W air" (Weight in air) and "W water" (Weight in water), both with units of N. The last column contains a calculation.

Table I: Buoyant Force = Weight in Air – Weight in Water

Object	W air (N)	W water (N)	Wair – Wwater (N)
Brass Cylinder			
Aluminum Cylinder			
Brass Cube			
Aluminum Cube			
Aluminum Shape			

In the Capstone calculator, create the following calculations:

Wair - Wwater = [W air (N)]-[W water (N)]	with units of N
Weight = abs(avgfilter(100,[Force (N)]))	with units of N
Buoyant Force = ρ *[Volume (cc)]*g/1000	with units of N
$\rho = 1.00$	with units of g/cm ³
g = 9.81	with units of m/s ²

7. Create a Digits display with the calculation "Weight".

Procedure: Using Weight

1. With nothing hanging on the Force Sensor, click on Monitor. Note the weight being shown in the digits display.
2. Hang the brass cylinder on the Force Sensor with the beaker moved out of the way, so that the sample hangs in air.

- Record the weight in the "W air" column of Table I.

Note that you don't need to start and stop recording. The program is in "Monitor" mode, where it continually updates the display, but doesn't actually record any data.

- Move the beaker with water under the Force Sensor, and hang the sample completely submerged as shown in Figure 1. Adjust the height if necessary.
- Record the weight in the "W water" column. Note that the buoyant force = "weight in air - weight in water" is automatically calculated in the last column.
- Repeat for the other listed samples, including the irregularly shaped aluminum piece. Always check to make sure that the weight reads zero with the sample removed, and that the sample is completely submerged but not touching the bottom when measuring in water.
- When you have made all your measurements, click on Stop.

Procedure: Using Volume

- Create a table as shown below. Select "Object" in the first column. Create a User-Entered Data set called "Volume" with units of cc. Select the calculation "Buoyant Force" in the third column.

Table II: Buoyant Force = Weight of Fluid Displaced

Object	Volume (cc)	Buoyant Force (N)
Brass Cylinder		
Aluminum Cylinder		
Brass Cube		
Aluminum Cube		
Aluminum Shape		

- Use calipers to measure the radius and height of the brass cylinder, and record your measurements.
- Calculate the volume of the cylinder and record the value in Table II.
- Note that the Buoyant Force = "weight of water displaced" is automatically calculated in the last column. Calculate the value yourself to confirm that it is correct. Pay attention to the units! Remember that the relationship between mass (m), density (ρ) and volume (V) is

$$m = \rho V$$

Hint: To calculate the weight of water displaced, you must use the density of water!

$$\rho_{\text{water}} = 1.00 \text{ g/cc}$$

Finally, remember that the buoyant force is the weight of the displaced fluid, not just the mass. You can look at the equation used in the Calculator for help.

12. Use calipers to measure the dimensions of the other samples and record their volumes in the table. To calculate the volume of the irregularly shaped object, use its weight and assume it has the same density as the other aluminum shapes.

Analysis

13. Create a table as shown below. Select "Object" in the first column, "W_{air} – W_{water}" in the second column, and "Buoyant Force" in the third column. Create a User-Entered Data set called "% Difference" in the fourth column.

Table III: Weight Method vs. Volume Method

Object	W _{air} – W _{water} (N)	Buoyant Force (N)	% Difference
Brass Cylinder			
Aluminum Cylinder			
Brass Cube			
Aluminum Cube			
Aluminum Shape			

14. Table III shows the results for the buoyant force calculated using the apparent weight (weighing method) and directly using Archimedes' Principle (volume method). What do you conclude?
15. Calculate the % difference for each sample.
16. Which other samples have approximately the same volume as the aluminum cylinder. How do their values for the buoyant force compare? Explain how this can be, even when the other sample doesn't have the same mass, density, size or shape?
17. If you re-did this experiment with the brass mass only half submerged, what would change? Would the "weight method" still give you the same answer for the buoyant force as the "volume method"? Try it!
18. The plastic cylinder that comes with the Density Set floats in water. What does it tell you about its density? What is its apparent weight when floating? What is the buoyant force acting on it while floating? What would be the buoyant force if it was completely submerged?
19. If you added salt to the water in the beaker, it would change its density. How could you use the apparent weight of the brass cylinder hanging in the salt water to find this new density? Try it!

Heat and Temperature

Equipment

1	Quad Temperature Sensor	PS-2143
1	Energy Transfer Calorimeter	ET-8499
Required but not included:		
1	Graduated Cylinder, 100-ml	
	Water (100 ml)	

Introduction

The purpose of this activity is to explore the relationship between heat and temperature by measuring the amount of temperature change in two different volumes of the same fluid, subject to the same amount of added thermal energy.

Background

Heat is defined as energy that is transferred between two or more objects by way of thermal interaction (conduction, radiation, or convection). The heat energy in an object is a representation of the TOTAL kinetic energy of ALL the particles that make up the object, and similar to mechanical energy, heat energy is a conserved quantity.

Temperature is a physical measurement of how "hot" or "cold" a substance is based on the AVERAGE kinetic energy of particles in the substance.

The amount of heat energy in an object is related to temperature, but temperature by itself cannot tell you how much thermal energy (heat) is in an object. Identical thermometers in two pots of water on a hot stove will show different temperatures even if the pots have been on the stove for the same time if the amount of water in one pot is different than the amount in the other.



Figure 1: Equipment

Setup

1. Assemble the Energy Transfer Calorimeter similar to Figure 2, using the heating resistor with two-hole rubber stopper.
2. Connect the red and black patch cords from the heating resistor to Output #1 on the 850 interface.
3. Connect the Quad Temperature sensor to any PASPORT channel on the 850 interface, and then connect a stainless steel temperature probe to port 1 on the Quad Temperature sensor.
4. Insert the stainless steel temperature probe into the second hole on the two-hole rubber stopper and gently push the probe down until it touches the bottom of the calorimeter cup.
5. In PASCO Capstone, set the sample rate to 1 Hz.
6. Create a graph of Temperature vs. Time.



Figure 2: Calorimeter Assembly

Resistor Safety

Data will be collected on the next pages, and during data collection about 1 A of current will be continuously flowing through the resistor. This current will cause the resistor to heat up which will in turn heat the water that will be placed in the calorimeter. Do not start recording data until the heating resistor is completely submerged in the water. Collecting data while the resistor is not submerged can cause it to burn up, or be dangerously hot. Do not touch the heating resistor.

Procedure: 40 ml

1. Use the graduated cylinder to measure 40 ml of water, and then lift the lid on the calorimeter and pour the measured water into the inner cup.

NOTE: Use cool (not cold) tap water, or water that has an initial temperature below 24 °C.

2. Replace the calorimeter lid with the heating resistor and stainless steel temperature probe submerged in the water in the cup.
3. Click the record button below to activate the heating resistor. Data will not be recorded until the temperature of the water in the calorimeter reaches 24 °C, and then will automatically stop after 300 seconds (5 minutes).

4. Gently swirl the water in the cup as data is recorded so the water will be heated evenly.
5. When data recording stops, pour out the warm water and set the calorimeter lid with temperature probe and heating resistor on the lab table for about a minute to cool.

Procedure: 60 ml

6. Use the graduated cylinder to measure 60 ml of water, and then pour the measured water into the inner cup in the calorimeter.

NOTE: Use cool (not cold) tap water, or water that has an initial temperature below 24 °C.

7. Replace the calorimeter lid with the heating resistor and stainless steel temperature probe submerged in the water in the cup.
8. Click the record button below to activate the heating resistor. Data will not be recorded until the temperature of the water in the calorimeter reaches 24 °C, and then will automatically stop after 300 seconds (5 minutes).
9. Gently swirl the water in the cup as data is recorded so the water will be heated evenly.

Analysis

1. Use the graph tools to determine the change in temperature for each volume of water, 40 ml and 60 ml. Record both values below.
2. How does the ΔT for 40 ml of water compare to the ΔT for 60 ml of water?
3. Did the 40 ml of water receive more, less, or the same amount of energy as the 60 ml? Why?
4. Considering your answer to the previous question, why is the final temperature of the 40 ml of water higher than the 60 ml.

Transfer of Heat by Radiation

Equipment

1	Quad Temperature Sensor	PS-2143
1	Radiation Cans	TD-8570
Required but not included:		
3	Beaker, 400-mL	
2	Beaker Tongs	
1	Hot Plate	
1	Towel or Other Insulating Material	
1 L	Water	

Optional: Aluminum Foil

Background

Heat energy is transferred in three different processes: conduction, convection, and radiation. Conduction is a thermal process in which heat energy is transferred from a hot object to a colder object through direct contact (Figure 1). Convection is a thermal process in which heat energy is transferred from one place to another through the movement of fluids (Figure 2). Radiation is a thermal process in which heat energy is converted to electromagnetic radiation (photons) which are emitted from an object's surface (Figure 3). These photons, in turn, can heat other objects similar to how the Sun heats the Earth's surface.

In this lab you will explore how heat energy is lost by a hot object and show how radiation is affected by the different surfaces of a hot object.



Figure 1: Conduction



Figure 2: Convection



Figure 3: Radiation

Temperature Calibration

1. Prepare three flexible white thermistors by inserting each one through a coffee stirrer and taping them as shown in Figure 4. You can use any plastic or wooden rod and tape the thermistor to the side of the rod, without taping over the end of the thermistor.
2. Connect the three temperature probes to the Quad Temperature Sensor using ports 1, 2, and 3 on the sensor, and then connect the Quad Temperature Sensor to the interface using a PASPORT extension cable.
3. In PASCO Capstone, open the Calibration at left.
4. Choose to calibrate all three of the temperature probes.
5. Select Two Standards.
6. Prepare an ice bath (1 liter of mostly ice and a little water) and a beaker of boiling water. Temporarily tape all three of the temperature probes together so they will be in the same place in the baths.
7. For the first calibration point, put all the probes into the ice water and gently stir them around the ice. The temperature should be 0°C .
8. For the second calibration point, put all the probes into the boiling water. The temperature should be 100°C at 1 atm of pressure.

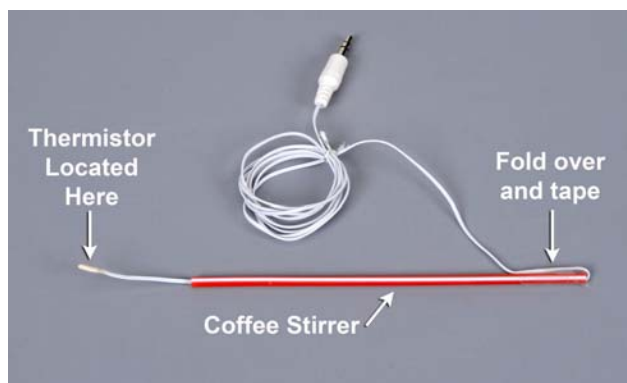


Figure 4: Preparation of Temperature Sensor

Setup

Safety:

- * Each group member should wear safety goggles while performing this experiment.
- * Always use tongs or other hot item gripping devices when handling or moving hot water containers and hot plates, including the radiation cans used in this experiment.

1. In Capstone, set the sample rate to 20 Hz. Create a Digits Display with Temperature 1. Create a graph of Temperature 1, Temperature 2, and Temperature 3.
2. Put the dry temperature sensors on the table and record room temperature. Record this value.
3. Fill each of the three 400 ml beakers with 300 mL of water and then place the beakers onto the hot plate. Set the hot plate to its highest setting and allow the water in the beakers to come to a boil.
4. Place the towel or other insulating material on the lab table (away from the hot plate), and then set the silver, black, and white radiation cans on the insulating material approximately 30 cm apart.
5. Once the water in the beakers is boiling, switch off the hot plate.
6. While one group member holds the silver can in place using another pair of tongs, fill the can the 300 mL of hot water from one of the 400-mL beakers (Figure 5).
7. In the same manner, fill the white can and the black can with 300 mL each of hot water. Then place one temperature probe in each can, letting the taped end act as a hook as shown in Figure 6. Put T1 in the silver can, T2 in the black can, and T3 in the white can. Immediately start recording.



Figure 5: Filling the Cans



Figure 6: Temperature Probe Hooked on Can

Procedure

1. Start recording.
2. While recording, constantly gently stir the water with the temperature probe. Observe the starting temperatures of the three cans. Are the starting temperatures the same? If not, which can is hotter and why is there a difference between the two starting temperatures?
3. Stop recording data after the temperature has dropped to about half-way between the starting temperature and room temperature.
4. Create a table as shown below. Create User-Entered Data sets called “Can Color”, “Can Mass” with units of g, and “Can+Water Mass” with units of g. Then create a calculation in the last column:

$$\text{Water Mass} = [\text{Can+Water Mass (g)}] - [\text{Can Mass (g)}]$$

Can Color	Can Mass (g)	Can+Water Mass (g)	Water Mass (g)
Silver			
Black			
White			
Foil			

5. After stopping, weigh each can with the water in it and record the masses in Table I. Then weigh each can without water. Be sure to use the beaker tongs when handling the hot radiation cans and beakers.

Analysis

1. Create a graph of Temperature 1 vs. Time. Then create a new plot area and select Temperature 2 on the vertical axis. Then create another new plot area and select Temperature 3 on the vertical axis.
2. Which can cooled the fastest? To answer this question, determine which of the three cans started with the coolest temperature. Use the coordinate tool and the delta tool to measure how long it took this can to cool by 15°C. Then measure how long it took for the other cans, taking the measurement from the same starting temperature of the first can and finding how long it took to cool by 15°C. It is important to compare each can between the same two temperatures.
3. When the cans were cooling, which processes were transferring heat? Which process do you think was dominant?
4. When the cans were cooling, did they cool faster at the beginning of the experiment or toward the end of the experiment? Why?

Further Study:

1. Tightly swap all three of the cans with aluminum foil and tape the foil closed.
2. Put hot water in all the cans and record the cooling as before.
3. How does the cooling compare to the cans without the foil?



Figure 7: Foil Wrapped around a Can

Conclusions

1. In general, what color can cools the fastest? Was one of the colors much faster than the others?
2. If you want something to keep warm, what kind of surface should you put on it?
3. Why are radiators on cars black?
4. Why do you wrap a potato in foil after baking it?

Specific Heat

Equipment

1	Quad Temperature Sensor	PS-2143
1	Density Set	ME-8569
1	Energy Transfer Calorimeter	ET-8499
Required but not included:		
1	Centigram Balance	
1	Hot Plate	
2	Beaker, 600 ml	
1	Graduated Cylinder, 50 ml	
1	Scissors	
1	Thread (1 meter)	
2	Paper Clip	
	Ice (500 ml)	
	Water (500 ml)	
	Paper Towels (1 roll)	
3	Coffee Stirrers	

Introduction

In this activity you will use a temperature sensor to measure the temperature change of a volume of warm water when a cold piece of metal is placed in it. Your data will be used to determine the total amount of heat transferred from the warmer water to the cold metal, which will in turn be used to determine the specific heat of the metal sample.



Figure 1: Equipment

Background

The specific heat, c , of a substance describes the amount of thermal energy (heat) that a single gram of the substance must absorb in order to change its temperature by one degree Celsius (or Kelvin).

The specific heat of water, for example, is $c_w = 4.186 \text{ J/g}^\circ\text{C}$. That is: 4.186 J of heat are needed to raise the temperature of 1g of water by 1°C . In general, we have:

$$Q = mc\Delta T \quad (1)$$

where Q is the thermal energy (heat) required to produce a temperature change ΔT in a material with a specific heat c and a mass m .

If there is no loss into the environment, when a cold metal is added to warm water, the heat gained by the metal (Q_M) must equal the heat lost by the water ($-Q_W$) and the aluminum can ($-Q_C$) and we have:

$$Q_M = -Q_W - Q_C \quad (2)$$

$$m_M c_M \Delta T_M = -m_W c_W \Delta T_W - m_C c_C \Delta T_C$$

Note that the change in temperature for the can is the same as it is for water. Solving for the specific heat of the metal gives:

$$c_M = \frac{-(m_W c_W + m_C c_C) \Delta T_W}{m_M \Delta T_M} \quad (3)$$

Setup

1. Connect the stainless steel temperature probe to port # 1 on the Quad Temperature sensor and then connect the sensor to any of the PASPORT channels on the 850 interface.
2. For this activity you will be using only the gold and silver-colored rectangular metal samples from the ME-8569 Density Set. Each of the two samples has a small hole drilled through it that will be used to attach a piece of thread to help lift the samples during data collection without touching them with your hands.
3. Run a small piece of thread (~50 cm) through the hole in each metal sample and tie the ends of the string to create a loop similar to Figure 2. Attaching a paper clip to the loop will create a small handle to help when lifting the samples.
4. Fill one 600 ml beaker with ice, and then add enough water to the ice to just cover it. Place both metal samples into the ice bath and hang the string and paper clips over the side of the beaker. Leaving the metal samples in the ice bath will eventually cool them to about 0 °C.

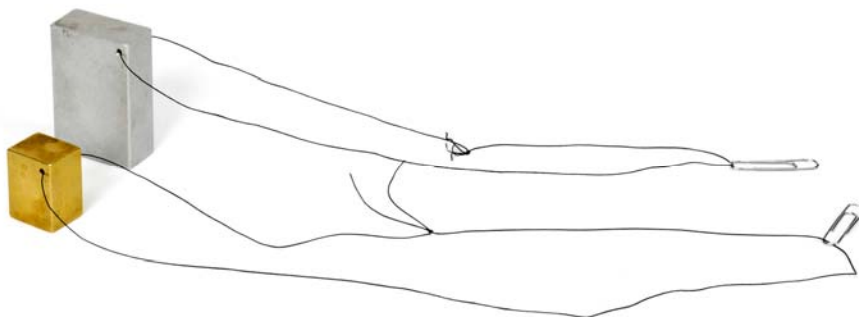


Figure 2: Metal Samples

5. Fill the other 600 ml beaker with approximately 300 ml of water and place the beaker onto the hot plate. Turn on the hot plate and set it to a medium-high heat setting.
6. In PASCO Capstone, create a Digital display and select the Temperature. Set the sample rate to 1 Hz. Change the Sampling Mode to Fast Monitor.
7. The goal is to heat the water in the beaker to approximately 60 °C, but no hotter. Monitor the temperature of the warm water by placing the temperature probe into the water and clicking the Monitor button.
8. While the water is warming, assemble the calorimeter cup with lid as in Figure 3. Lightly insert the one-hole rubber stopper that accompanies the calorimeter into the calorimeter lid.
9. When the temperature of the warm water reaches 60 °C, switch off the hot plate and click

stop in the Sampling Control Bar below (Fast Monitor Mode).



Figure 3: Calorimetry Cup



Figure 4: Calorimeter with Temperature Probe

Procedure

1. Place the temperature probe into the ice bath so that the tip of the probe is touching the gold-colored metal sample (Metal 1). Click the monitor button in the control panel to begin monitoring the temperature of Metal 1 in the digits display to the right.
2. When the temperature measurement comes to equilibrium (stops changing), click stop in the control panel, and then record the temperature value shown in the digits display.
3. Use the balance to measure the mass of the inner calorimeter cup, without its lid, to the nearest 0.01 g and record the value.
4. Use the graduated cylinder to measure 30 ml of warm ($\sim 60^\circ\text{C}$) water, and then pour the warm water into the inner calorimeter cup.
5. Measure the mass of the inner calorimeter cup with water to the nearest 0.01 g and record the value. Using the Calorimeter Mass and Cal+Water Mass values, calculate the mass of the water.
6. Put the inner cup into the outer cup of the calorimeter and put the lid on. Place the temperature probe into the warm water inside the calorimeter by inserting the probe through the one-hole stopper in the calorimeter lid. Gently swirl the water in the calorimeter for about 15 seconds to equilibrate the temperature inside the calorimeter.

7. In Capstone, change the Sampling Mode to Continuous Mode and change the sample rate to 5 Hz. Create a graph of Temperature vs. Time.
8. Click the record button in the control panel below to begin recording data, and continue to record data for about 20 seconds.

The next step must be done quickly!

9. Using the paper clip and string, remove the gold-colored metal sample from the ice water bath. DO NOT TOUCH THE METAL WITH YOUR HANDS! Using paper towels, quickly dry off the metal and then lower it into the calorimeter cup and replace the calorimeter lid making sure that the very tip of the temperature probe is submerged in the calorimeter water and not in direct contact with the metal sample.
10. Gently swirl the calorimeter cup until the temperature inside the cup comes to equilibrium. Then click stop.
11. Remove the metal sample from the calorimeter cup and completely dry it using paper towels.
12. Use the balance to measure the mass of the metal sample to the nearest 0.01 g and record the value.
13. Use the Coordinates Tool in the graph to determine the initial temperature of the water just before you added the metal sample. Record this value.
14. Use the Coordinates Tool in the graph to determine the final (equilibrium) temperature of the water once it has come to equilibrium. Record this value.

Analysis

1. Using the data you recorded and Equation 3, calculate the specific heat of Metal 1. Show your work and record your results. Be certain to use correct units. Note that the specific heat for aluminum is given below:

Metal	Specific Heat (J/g°C)	Metal	Specific Heat (J/g°C)
Silver	0.233	Tungsten	0.134
Zinc	0.387	Aluminum	0.900
Stainless Steel	0.500	Lead	0.128

2. The gold-colored Metal 1 is made of brass which has a theoretical specific heat equal to $c_{\text{brass}} = 0.380 \text{ J/g}^\circ\text{C}$. Calculate the percent error in your experimental value using the equation below. Record your result.

$$\% \text{ error} = \frac{|\text{Theoretical} - \text{Experimental}|}{\text{Theoretical}} \times 100\% \quad (4)$$

3. In your opinion, what are the three largest sources of potential error in your experimental value for c_{Metal1} , and briefly explain how these sources of error can be avoided for future trials.

Application

1. Using the same set-up and data collection procedure as you did with the brass sample, repeat this experiment using the silver-colored sample, recording all your data values into the tables next to "Metal 2".
2. Using the data and Equation 3, calculate the specific heat of Metal 2. Record your results.
3. Based on your calculated value from the previous question, and the table of common metals and their specific heat values in the Analysis section, what type of metal do you think your Metal 2 sample is?
4. Calculate the percent error in your experimental values for sample using Equation 4. Record your results.

Conclusions

1. How did the percent error in your experimental value for c_{Metal2} compare to the percent error in your experimental value for c_{Metal1} ? Why do you think the percent error was larger for one of the metal samples?
2. If both of your values for specific heat, c_{Metal1} and c_{Metal2} , are too low, how would you explain it?
3. What does the specific heat tell you about how easy it is to change the temperature of a material?
4. Why is it so important to the earth that the specific heat of water is so high? Hint: Of what is the Earth's surface mostly composed?

Electrical Equivalent of Heat

Equipment

1	Energy Transfer-Calorimeter	ET-8499
1	Quad Temperature Sensor	PS-2143
Required But Not Included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone Software	UI-5400
1	Triple-Beam Balance with Tare	SE-8707

Introduction

The purpose of this experiment is to determine the amount of electrical energy that is equivalent to a certain amount of thermal energy. This is accomplished by measuring the amount of electrical energy used in the heating resistor to heat water and the resulting thermal energy added to the water.

Also, the number of Joules in one calorie is determined.



Theory

When heat is added to a solid or a liquid, that energy goes into increasing the materials internal energy, and thus increasing its temperature. The relationship between the heat and the resulting change in temperature is given by

$$Q = mc\Delta T \quad (1)$$

Q = Heat

m = mass

c = specific heat

ΔT = change in Temperature

There are two things changing temperature in this experiment: The water and the aluminum calorimetry cup. The water and cup have different masses and specific heats, but we assume that they both have the same change in temperature.

In this experiment, heat is added to the calorimeter by the use of a heating resistor. Work is done by the students, turning the crank on an electrical generator which produces an electrical current.

The generated electrical energy is converted into heat in the resistor, increasing the temperature of the water and the cup. Historically, this has been referred to as the Electrical Equivalent of Heat.

Electrical Power is determined by the Voltage produced by the generator, and the resulting Current that is produced.

$$P = IV \quad (2)$$

I = Current through the resistor (Amps)

V = Voltage across the resistor (Volts)

P = Power (Watts = Joules/sec)

Power is the rate at which energy is generated or used: $\text{Power} = \text{Energy}/\text{time}$. Thus Energy can be calculated by

$$\text{Energy} = (\text{Power})(\text{time}) \quad (3)$$

or, in a case as with this lab where the power is not constant, Energy is the area under a Power vs. time graph.

Pre-Lab Questions

1. There are two cups in a calorimeter, separated by an insulating ring (see Figure 1). What is the purpose of having two cups?
2. Only one of the cups is used in the calculations. Which one and why?
3. Which takes less energy to raise the temperature of one gram one degree Celsius: water or aluminum?
4. Is there anything else that heats up besides the water and the cup? If so, what? Does this affect your results?
5. What is a Watt-second?

Setup



Warnings: Never apply power to the Heating Resistor unless the resistor is immersed in water. Never touch the resistor. It gets hot! Do not apply over 10 Volts.

Figure 2: Complete Set-up



Figure 1: Calorimeter

1. Plug the Quad Temperature Sensor into the interface and plug the stainless steel temperature probe into one of the ports on the Quad Temperature Sensor.
NOTE: The end of the probe goes into stopper hole. During the experiment, make sure the tip of the probe is down in the water, but not touching the heating resistor. See Figure 1.
2. Plug the leads from the heating resistor into Signal Generator #1 on the 850 Universal Interface. See Figure 2.
3. Click on Signal Generator #1 in the Hardware Setup to activate its internal Voltage-Current Sensor.
4. Open the Signal Generator panel and set Signal Generator #1 to 9 V DC. Leave the Signal Generator off; do not put it on AUTO.
5. Create a digits display with the Temperature on it.
6. Create a calculation for the power using Equation (2). The current and voltage measurements are from the Signal Generator Voltage-Current Sensor.
7. Create a graph of Temperature vs. time. Add a plot area and put Power vs. time on it.

Procedure

1. With the dry Temperature Probe lying on the table, press record to read the ambient temperature of the room. Then press STOP.
2. Measure the mass of the inner aluminum cup from the Calorimeter. Only the inner cup changes temperature and is part of the experiment. The outer (bigger) cup acts only as a

holder, and due to the air gap in between, helps to insulate the inner cup. Record the mass in the box below.

3. Prepare some water that is about 5°C below room temperature. Add about 50 g of water to the inner cup. After the cup and water have come to equilibrium and you are ready to start the experiment, you will want the temperature to be about 3°C below room temperature. This is necessary to compensate for any heat leaks between the room and the cup.
4. Measure the mass of the cup plus water, and calculate the mass of the water. Record the mass in the box below.
5. Assemble the cup, using the spacer to suspend the inner cup inside the bigger cup. Put on the lid, and insert the heating resistor stopper in the hole. Insert the temperature probe in the stopper hole, making sure that the tip is under the water.
6. Check the temperature of the water again. If the water gets too warm before you can start, you can place the cup and water in an ice bath to cool it down. Wipe off any moisture on the cup before placing it back into the outer cup. If the water is too cold, you can use the signal generator to heat it, but don't overdo it! Gently swirl the cup to stir the water and wait for equilibrium before starting the data run.
7. Start recording.
8. Turn on the Signal Generator and watch the power graph. Always stay below 10 Watts.
9. Gently swirl the calorimeter cup to mix the water during the entire recording time.
10. Watch the temperature graph until the water is above room temperature by about the same amount as it started below room temperature. Then turn off the Signal Generator but **DO NOT** stop recording.
11. Continue to record data until the temperature has reached a plateau or is decreasing. Don't forget to swirl the water!
12. Stop recording.

ANALYSIS

1. Use the Coordinates Tool and its Delta Tool on the graph to find the change in temperature, ΔT .
2. Calculate the total amount of heat, Q , added to the water and the aluminum cup. Use the proper specific heat for each. Use specific heats in units of $\text{cal/g}^\circ\text{C}$ so the heat will have units of calories. ($c_{\text{water}} = 1.00 \text{ cal/g}^\circ\text{C}$ and $c_{\text{Aluminum}} = 0.215 \text{ cal/g}^\circ\text{C}$)

$$Q = Q_{\text{Water}} + Q_{\text{Cup}}$$

$$Q = mc\Delta T$$

3. Find the area under the Power vs. time graph by selecting Area on the Statistics menu. This is the energy which was delivered to the water and the calorimeter cup.
4. Set the heat (in calories) equal to the energy delivered (in Joules). Calculate how many Joules are equivalent to one calorie. Look up the accepted value and calculate the percent difference between it and your answer.

QUESTIONS

1. In this experiment, was energy lost or gained? Explain your results using the concept of conservation of energy.
2. Was your answer larger or smaller than the accepted value? What about the experiment would cause this error?
3. Why is it necessary to start below room temperature and stop above room temperature by the same temperature difference?
4. The type of calorie (with a capital C) that you eat is actually a kilocalorie. $1 \text{ Cal} = 1000 \text{ cal}$. How many Calories did you add to the water and cup? If you expended the amount of energy that you added to the water by lifting the water instead, how far could you lift the water?

Boyle's Law

Equipment

Required:

1	Ideal Gas Law Syringe	TD-8596
1	Absolute Pressure Sensor	PS-2107
1	Quad Temperature Sensor	PS-2143

Not included, but required:

1	850 Universal Interface	UI-5000
1	PASCO Capstone	UI-5400



Figure 1: Ideal Gas Law Syringe

Introduction

In 1662, Robert Boyle discovered the relationship between the volume and the absolute pressure of a gas that is at a constant temperature. In this experiment, you will rediscover this relationship by holding the temperature of a gas constant and changing the volume of the gas, and measuring the volume and the absolute pressure.

Setup

The Ideal Gas Law Syringe allows simultaneous measurements of temperature and pressure of a gas as it is compressed. The mini stereo jack is connected to a low thermal mass thermistor built into the end of the syringe to measure temperature changes inside the syringe. The mini stereo jack plugs directly into the sensor.



Figure 2: Attaching the Sensors

The white plastic tubing coupler attaches to the pressure port of the sensor: A slight twisting motion locks the coupler onto the port. This white plastic connector can be disconnected and re-connected during the experiment to allow for different initial plunger positions. The plunger is equipped with a mechanical stop that protects the thermistor, and also allows for a quick, predetermined change in volume. Never slam the plunger down on the table. Always grip the syringe and plunger as shown to compress the air.

Procedure

1. Add a table with temperature, Absolute Pressure, and Syringe Volume (units of ml) (a new user-entered set) in PASCO Capstone. Pre-fill the Syringe Volume with the values 50 ml, 45, 40, 35, 30, 25.
2. Set the sample rate to 20 Hz and change to the Manual Sampling Mode.
3. Set up a graph of Absolute Pressure vs. Syringe Volume.
4. Disconnect the white plastic pressure coupler from the Absolute Pressure Sensor. Calibrate the Absolute Pressure Sensor using a one-point calibration in the Calibration Tool on the left of the page in PASCO Capstone.
5. Set the plunger at 50 ml, and then re-connect the coupler to the sensor.
6. Click on Preview data. Press Keep while the plunger is still at 50 ml. Then compress the plunger to 45 ml and hold it at this position. Watch the temperature on the temperature column and wait until it has dropped down to close to room temperature. Press Keep. Each time you compress the air in this sequence, wait until the temperature returns back down close to this value.
7. Compress the plunger to 40 ml and hold it at this position. Watch the temperature, and hold the plunger at 40 ml until the temperature has dropped to the value you noted in step 3. Do not release the plunger.
8. Compress the plunger to 35 ml, and wait until the temperature drops as before.
9. Repeat for 30 ml and 25 ml.
10. Stop recording data.

Analysis

1. Looking at the Pressure vs. Volume graph, try various QuickCalcs on the Volume axis to see what results in a straight line. Then do a linear curve-fit to see how well it fits.
2. How are Absolute Pressure and Volume related according to your results? Under what condition is this relationship true?
3. What physical quantities make up the slope of your straight-line graph?
4. Use the value of the slope to determine the number of moles (n) of air in the syringe. Pay attention to the units!
5. Look carefully at the graph. Why is there an offset in the axis for the volume? How do you account for this extra volume?

Further Investigations

1. Disconnect the white plastic pressure coupler from the sensor. Set the plunger at 60 cc, and then re-connect the coupler to the sensor.
2. Repeat the procedure, taking pressure and temperature data at each of the volumes (40cc, 35cc, etc.) as you did before.
3. Put this new data on the same graph. Why is this slope different? Is the volume offset **about** the same as before?

Conclusion

Write a summary of your results. What general conclusions can you draw from your results? For instance, how does the pressure of a gas change when the volume is decreased at constant temperature? What is Boyle's Law?

Absolute Zero

Equipment

Included:

1	Absolute Pressure Sensor	PS-2107
1	Quad Temperature Sensor	PS-2143
1	Absolute Zero Apparatus	TD-8595

Not included, but required:

1	850 Universal Interface	UI-5000
3	Plastic Containers (2 liters)	
	Hot Water	
	Room Temperature Water	
	Ice Water	
	Calipers	



Introduction

In this experiment, the value of absolute zero is determined in degrees Celsius by plotting Temperature vs. Absolute Pressure and finding the temperature at which the Absolute Pressure is zero.

Theory

The Ideal Gas Law relates the absolute pressure (P) and volume (V) of a gas to the absolute temperature (T) in degrees Kelvin.

$$PV = nRT \quad (1)$$

where n is the number of moles of gas, and R is the ideal gas constant.

In 1802, Joseph Gay-Lussac discovered the direct relationship between the pressure and temperature of a gas at constant volume:

$$T = cP \quad (2)$$

where, c is a constant. Solving Equation (1) for T gives the constant:

$$c = V/nR \quad (3)$$

According to Equation (2), what is the temperature of a gas when its absolute pressure is zero? We can use the fact that when the absolute pressure of the gas is zero, its temperature is zero. Although it is not possible to reach absolute zero, we can perform an experiment in which we vary the temperature of the gas at constant volume, measure the resulting absolute pressures, and

then plot absolute pressure vs. temperature (in °C). By extrapolating back to zero absolute pressure, we can find the value for absolute zero in degrees Celsius.

Since $T = T_C - T_{\text{Absolute Zero}}$, Equation (2) becomes

$$T_C = cP + T_{\text{Absolute Zero}} \quad (4)$$

At $P = 0$, the temperature T_C is equal to absolute zero.

Setup

The Absolute Zero Apparatus consists of a hollow sphere that acts as a container of constant volume as the apparatus is placed in different temperature water baths. As shown in Figure 1, plug the mini stereo jack into the temperature port to measure the temperature using the thermistor imbedded in the wall of the sphere. Connect the white plastic pressure coupling to the pressure port to measure the pressure inside the sphere.



You will need a source of hot water and a source of ice.

Pressure Sensor Calibration:

Figure 1: Connecting the Sensors

1. Create two digits displays with the Absolute Pressure on one display. The other digits should be a calculation: Open the Calculator in PASCO Capstone and make this calculation:
Abs Pressure Calibrated=[Pcal(kPa)]+[Absolute Pressure(kPa)]. Define [Pcal(kPa)] = 0.
2. With the Pressure Sensor disconnected from Absolute Zero sphere, click Monitor and compare the direct reading from the Pressure Sensor and the Calculated Pressure.
3. Subtract the Pressure Sensor Reading from atmospheric pressure (101 kPa or the reading of a barometer, if you have one). Type the result into the calculator for the constant Pcal.
4. If you have entered the correct constant for Pcal, the calculated pressure will read the calibrated pressure value. It may be necessary to calibrate the absolute pressure sensor. The sensor should read 101 kPa (14.7 psi) when you equalize it with atmospheric pressure. Set up a digits display with Absolute Pressure and record some data. If it does not read the correct value, open the Calibration tool at left and calibrate the pressure using "One Standard (1 point offset)".

Temperature Sensor Calibration:

1. Open the Calibration in PASCO Capstone.
2. Follow the calibration procedure, choosing "One Standard (1 point offset)" on calibration step 3.
3. Put the Absolute Zero Apparatus sphere into the ice bath and wait for it to come to equilibrium. See Figure 2. Once the temperature isn't changing anymore, choose to set the current value to the standard value of 0°C in calibration step 4.

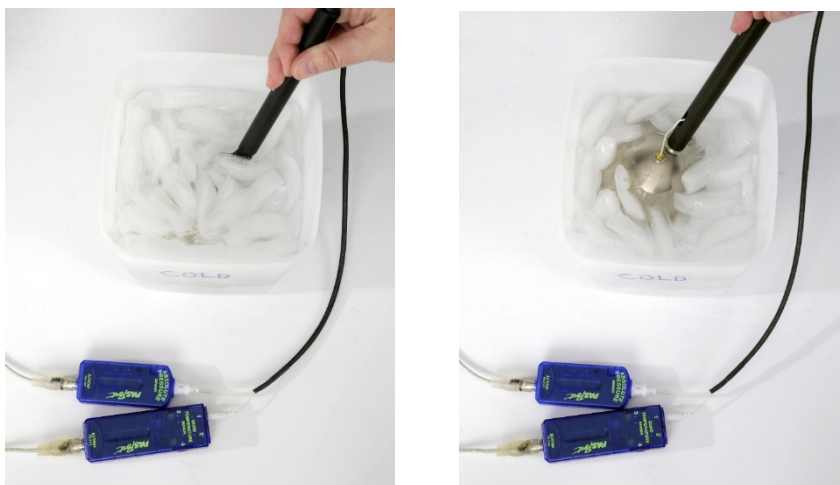


Figure 2: Be sure to completely submerge the sphere into the ice water.

Procedure

1. Set the sample rate at 10 Hz for both sensors. Set up a graph in PASCO Capstone of Temperature in $^{\circ}\text{C}$ vs. the calculated "Abs Pressure Calibrated". Create a table with Temperature and "Abs Pressure Calibrated". Select Manual Sampling from the sampling options in the Setup menu.
2. Fill one of the plastic containers with enough hot water to cover the sphere. Fill the third container with room temperature water, leaving enough room to submerge the sphere. Completely submerge the sphere in the ice water. Make sure the white plastic pressure coupler is connected to the sensor after putting the sphere in the ice water so the number of moles of gas is set while in the ice water.



Figure 3: Three Different Temperature Baths

3. Start data previewing. Completely submerge the sphere and wait for the pressure and temperature to equalize. Click on Keep to save that data pair.
4. Put the sphere into the room temperature water and completely submerge it. Don't disconnect the pressure coupler. Wait for equilibrium and then click on Keep.
5. Put the sphere into the hot water. Stir the water to get an even temperature, submerge the sphere and click on keep when the pressure and temperature equalize.
6. Click on Stop. Rename the run in the table to "Ice First".
7. Start a new run and put the sphere in the hot water and equalize the pressure by disconnecting and then reconnecting the pressure coupler while in the hot water. This makes the sphere have a different amount of gas in it. Once the pressure and temperature have come to equilibrium, press Keep.
8. Put the sphere into the room temperature water and press Keep once it has stabilized.
9. Finally, put the sphere in the ice water, wait for the readings to stabilize, and then press keep. And then press Stop. Rename this run "Hot First".
10. Repeat this procedure, equalizing the pressure in the room temperature bath first, then go to the ice water bath, and then go to a hot water bath. Rename this run "Room First".

Analysis

1. Determining Absolute Zero: By definition, the pressure of a gas is zero at absolute zero temperature. Find the temperature at which $P = 0$ for each of the three runs. You will need to fit a straight line to each run to do this. Average the results from the three runs and make an estimate of the uncertainty using the standard deviation. Round the average to the appropriate number of digits based on the value of the uncertainty.
2. Use calipers to measure the diameter of the sphere, and calculate its volume. Is this measurement more or less than the actual volume of the sphere? Why?
3. Use the Ideal Gas Law to show that a graph of Temperature vs. Pressure results in a straight line with a slope given by
$$\text{Slope} = \frac{V}{nR}$$
4. Determine the slope of this line from the Temperature vs. Pressure graph for one of your runs. Use your values to determine the number of moles (n) of air in the sphere. Pay attention to the units! Which run had the greatest number of moles of gas in the sphere?

Conclusion

Write a summary of your results. What general conclusions can you draw from your results? For instance, how does the pressure of a gas change when the temperature is decreased while the volume is held constant? How does the pressure of a gas change when the number of molecules is decreased while the volume is held constant?

Give the numerical value of Absolute Zero that you measured including the uncertainty, the accepted value, and the percent difference between them. Was the value you found lower or higher than the accepted value? Does the accepted value fall within the uncertainty of your measurement? Why or why not?

Behavior and Characteristics of Sound Waves

Equipment

1	Sound Sensor w/Extension Cable	CI-6506B
1	Open Speaker	WA-9900
2	4-mm Banana Plug Patch Cord	SE-7123
1	Tuning Fork	SE-7345
Required but not included:		
1	Musical Instrument	

Introduction

In this activity you will explore the characteristics of different sounds, the waves that produce sounds, and the fundamentals of frequency and harmonics within different sounds.

Background

We can hear many different types of sounds: the impact of a falling object, the clapping of hands, the sound of traffic, and the sounds produced by singers and other musicians are several examples. Each sound has different characteristics that make them different, but most sounds are alike in that they are produced by a vibration of some sort. Some vibrations are irregular, like a rock rolling down a hill, and some vibrations are regular, like vibration of a guitar string. We know that we can tell the difference between the sounds produced by different sources just by listening to them, but how do these differences appear in the actual sound waves themselves?



Figure 1: Devices Used to Make Different Sounds

Observing Sound Waves

Set-up

1. Connect the sound sensor to Analog Input A on the 850 using the sensor extension cord.
NOTE: You must connect the sound sensor to Analog Input A.
2. In PASCO Capstone, create an Oscilloscope Display and select Sound Intensity on the vertical axis. Change the Sampling Mode to Fast Monitor and set the sample rate to 40 kHz.

Procedure

1. Click the monitor button in the controls panel at the bottom of the screen to monitor the sound measured by the sound sensor.
2. Have two group members, one at a time, each make one different vowel sound ("EE", "OH", "AY", etc.) near the sound sensor and observe the shapes of the different sound waveforms produced. Try to carry (maintain) each sound as long as possible while group members observe.
3. Click stop when finished.
4. What were the types of sounds ("EE", "OH", "AY", etc.) and what were two similar characteristics between the two different sound waveforms seen in the oscilloscope display to the right? What caused these similarities?
5. What were two differences between the two different sound waveforms seen in the oscilloscope display to the right? What caused these differences?

Pure Tone

Background

A pure tone can be produced by different types of sound sources, such as a speaker, and is relatively pleasant to the human ear. However, pure tones have distinct waveforms and specific characteristics that are difficult for some sound sources, like a singer, to produce. In this part you will produce a pure tone using a speaker and observe the differences and similarities to the waveforms observed on the previous page.



Figure 2. Speaker Setup

Setup

1. Connect the speaker to Output Channel 1 on the 850 using the banana plug patch cords.

NOTE: You must connect the speaker to Output Channel 1.

2. Set the sound sensor and speaker on the lab bench and arrange the sensor so it faces the speaker, and is about 20 cm away, as in Figure 2.

Procedure

1. Click the monitor button to activate the speaker and simultaneously monitor the sound waveform generated by the speaker in the oscilloscope display to the right.
2. How does the pure tone waveform compare to the waveforms seen on the previous page? What are two characteristics of this waveform that are different from the waveforms observed on the previous page, and what produced these differences?
3. Click stop.

Tuning Fork

Prediction

Observe the tuning fork. When you strike the tuning fork softly with the rubber mallet a sound is produced as it vibrates. Do you think that the sound produced by the tuning fork is a pure tone? Why or why not?



Figure 3: Tuning Fork and Sound Sensor

Setup

1. Set the tuning fork on the lab bench and arrange the sensor so it faces the opening in the tuning fork box, and is about 20 cm away, as in the picture to the right.
2. Adjust the slides on each fork to the highest position.
3. Click the monitor button to begin monitoring the sound measured by the sound sensor, and then strike the tuning fork softly with the rubber mallet.
4. How does the waveform produced by the tuning fork compare to the pure tone waveform seen on the previous page? Does the tuning fork produces a pure tone?
5. Click stop.

Musical Instrument

Prediction

Your musical instrument can produce several different sounds (different notes/tones) depending on how you play it. How will the waveforms differ between different notes/tones, and will the waveforms match that of a pure tone? Explain your answers?



Figure 4: Guitar and Sound Sensor

Procedure

1. Hold the sound sensor near the instrument and then click the monitor button.
2. Play a high-pitched note/tone on the instrument and observe the waveform. Then play a low-pitched tone and observe the waveform. What is the biggest difference between the two waveforms?
3. How do both of the two waveforms compare to the waveform of a pure tone? What are some similarities and differences?
4. Click stop.

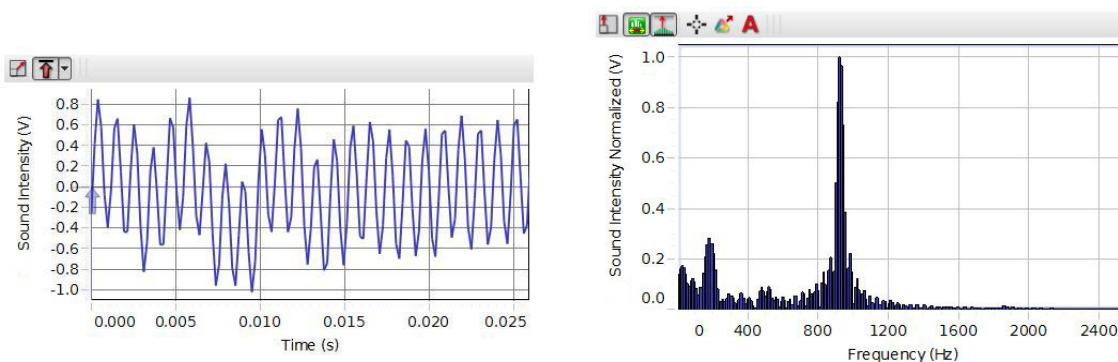
Harmonics-Instrument:

Background

Although a musical instrument can produce a sound pleasing to the human ear, it doesn't always produce a pure tone. In fact it is often the combination of different tones (different frequencies) that sounds most pleasing to the ear. Some sound sources will produce sound by vibrating at several different frequencies, all of which are an integer multiple of some fundamental (1st) frequency. This is known as harmonics.

Procedure

1. Create an FFT and select the Sound Intensity on the vertical axis.



Above are two displays: An oscilloscope that shows the sound waveform produced by the sound source, and an FFT that shows the frequency at which the sounds is emitted. When a sound is made, each spike in the graph indicates a sound being emitted at that frequency. Higher frequency means higher pitch, and lower frequency means lower pitch.

2. Set the sampling rate to 5 kHz.
3. Hold the sound sensor near the instrument and then click the monitor button.
4. Begin playing a low-pitched note/tone on the instrument and try to carry the note/tone as long as possible. Click stop while the tone is being played.
5. Observe the waveform and different frequencies that are produced by the instrument. Use the smart tool to measure the first four different frequencies and record the values.
6. Repeat the same procedure for a high-pitched tone. Use the smart tool to measure the first four different frequencies and record the value.
7. Divide each value in the High-Pitched Frequencies column by the lowest frequency in

that column. Record the results.

8. Divide each value in the Low-Pitched Frequencies column by the lowest frequency in that column. Record the results.
9. Are the calculated values approximately integer multiples of the fundamental (1st) frequency?

Harmonics-Voice

Procedure

1. Have one group member hold the sound sensor about 30 cm from her/his mouth while making the vowel sound "OH". Try to carry the sound as long as possible.
2. Click the monitor button to monitor the sound measured by the sound sensor.
3. Click stop while the sound is being carried.
4. Observe the waveform and different frequencies that are produced by the sound. Do you see harmonics within the sound? If yes, how many different harmonic frequencies do you see? If no, why do you think there aren't any harmonics?
5. What is the fundamental frequency?
6. Repeat the same procedure using the same vowel sound ("OH") but with a varying frequency from high-pitched to low-pitched. Did the number of harmonics change depending on the frequency? Explain why you think the number of harmonics did or did not change with varying frequency.
7. Using only sounds made using the mouth, repeat the same procedure and try to produce a continuous sound that has no harmonics.
8. Were you able to produce a sound without harmonics? If yes, what was the sound and why do you think it had no harmonics?

Standing Waves on a String

Equipment

1	String Vibrator	WA-9857
1	Physics String	SE-8050
1	Force Sensor	PS-2104
1	C-clamp (small)(only need one)	SE-7286
1	Patch Cords (set of 5)	SE-9750
1	Tape Measure	SE-8712A
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

Introduction

The general appearance of waves can be shown by means of standing waves in a string. This type of wave is very important because most of the vibrations of extended bodies, such as the prongs of a tuning fork or the strings of a piano, are standing waves. The purpose of this experiment is to examine how the tension required to produce a standing wave in a vibrating string of fixed length and mass density is affected by the wavelength and the frequency of the wave. This is a hands-on experiment where the student gets to feel the force required to increase the number of vibrating segments.

General Theory

Standing waves (stationary waves) are produced by the addition of two traveling waves, both of which have the same wavelength and speed, but travel in opposite directions through the same medium. Figure 1 shows such a system, where a mechanical vibrator produces a wave on a string which moves to the right and reflection from a fixed end produces a left moving wave. Where the two waves are always 180° out of phase, very little motion occurs (none if the amplitudes are the same). Such places are called nodes (see Figure 1).

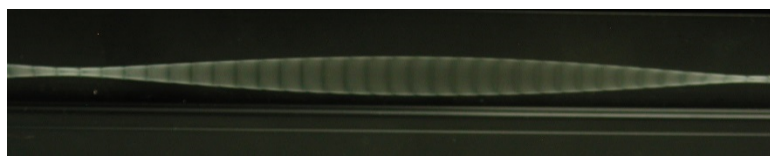


Figure 1: Standing Wave Photo

Where the two waves are in phase, the motion is maximum. These positions are called anti-nodes. Figure 2 shows a representation of a standing wave.

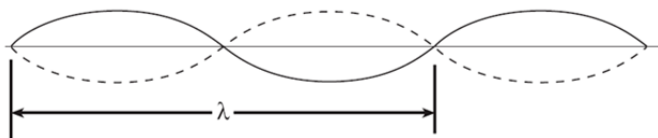


Figure 2: Standing Wave Representation

This representation shows the two extreme positions of the string.

This matches well what the eye or camera sees since the string speed is minimum at the extremes. However, don't forget that the string goes through all of the positions in between the extremes as shown by the blur in Figure 1. Note that as shown in Figure 2, the node-to-node distance is one-half of the wavelength. The necessary conditions for the production of standing waves on a stretched string fixed at both ends is the length of the string be equal to an integer number of half wavelengths so that there can be a node at each fixed end. For this experiment, one fixed end is where the string attaches to the force sensor and the other is where the string attaches to the mechanical vibrator. The end attached to the force sensor is a true node, but the end attached to the metal wand on the vibrator is not exactly a node since the wand vibrates up and down a little. Close examination (see Figure 3) shows that the true node would be a little to the left of the knot so the effective string length will be a bit longer than we measure. However, the difference does not appear to be more than a few millimeters, so is only a fraction of a percent.

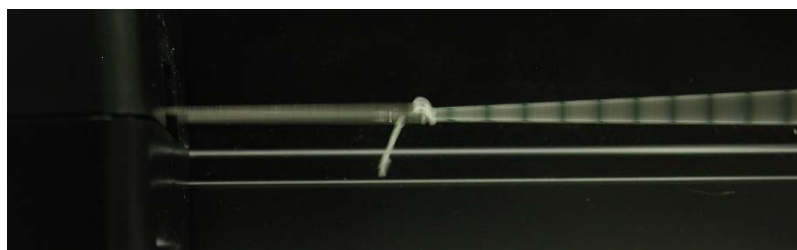


Figure 3: Vibrator ~ Node

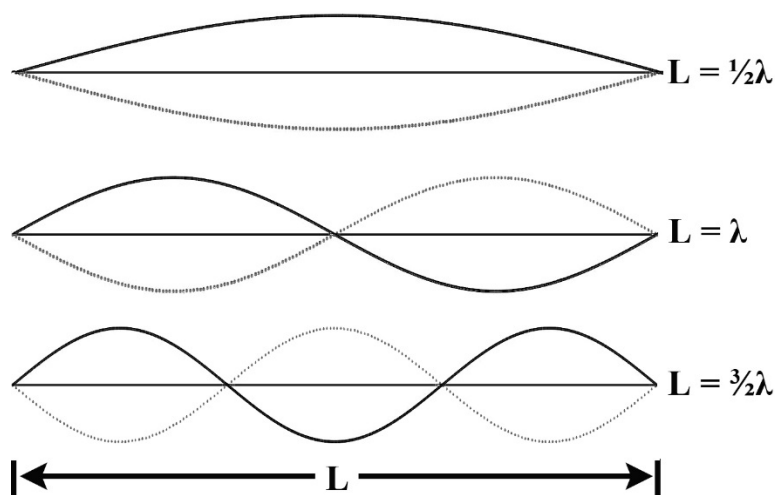


Figure 4: Modes of Vibration

Theory: Standing Waves in Strings

A stretched string has many natural modes of vibration (three examples are shown in Figure 4 above). If the string is fixed at both ends then there must be a node at each end. It may vibrate as a single segment, in which case the length (L) of the string is equal to $1/2$ the wavelength (λ) of the wave. It may also vibrate in two segments with a node at each end and one node in the middle; then the wavelength is equal to the length of the string. It may also vibrate with a larger integer number of segments. In every case, the length of the string equals some integer number of half wavelengths. If you drive a stretched string at an arbitrary frequency, you will probably not see any particular mode; many modes will be mixed together. But, if the tension and the string's length are correctly adjusted to the frequency of the driving vibrator, one vibrational mode will occur at a much greater amplitude than the other modes.

For any wave with wavelength λ and frequency f , the speed, v , is

$$v = \lambda f \quad (1)$$

The speed of a wave on a string is also related to the tension in the string, F , and the linear density (=mass/length), μ , by

$$v^2 = F/\mu = \lambda^2 f^2 \quad (2)$$

L is the length of the string and n is the number of segments. (Note that n is *not* the number of nodes). Since a segment is $1/2$ wavelength then

$$\lambda = 2L/n \quad \text{where } n = 1, 2, 3, \dots \quad (3)$$

Solving Equation 2 for the tension yields:

$$F = \mu \lambda^2 f^2 \quad (4)$$

In the first part of the experiment, we will hold λ constant by always choosing a two segment pattern so that $\lambda = L$ since $n = 2$ and vary the frequency while measuring the tension at which a two segment standing wave appears. By plotting F versus f^2 , we should see a straight line with a slope of $\mu \lambda^2$.

In the second part, we hold the frequency constant and vary the tension (Figure 4) to get standing waves with different numbers of segments, so different values of λ . Plotting F versus λ^2 should give a straight line with slope μf^2 .

String Mass Density

Each lab group will use a piece of string about one meter long. However, the mass of 1 m of string is about $\frac{1}{4}$ g which is too small for most scales to measure with much precision. Fortunately, the string is very uniform (varies by less than 1%) and not very stretchy, so we can measure the mass of a long piece and then cut it into 1 m segments that will have nearly the same mass density as average mass density of the long piece.

1. Determine the number of lab groups. Cut a piece of string that is long enough to provide each group with 1 m of string. That is, if there are five lab groups, cut a piece of string that is about 5 m long (or longer).
2. Use the tape measure to determine the length of the string to a precision of ± 1 cm.
3. Use the best available scale to determine the mass of the string. Ideally, use a digital scale with a precision of 0.01 g. To achieve this precision: 1) zero the scale; if it doesn't read exactly zero, record the value including sign, 2) add the string and record the string mass [don't forget to correct for the zero reading if it wasn't zero], 3) remove the string and verify that the zero reading hasn't changed, 4) if the zero value did change, repeat until you get consistent values. If you are using a single pan balance, the precision is 0.1 g. To achieve this precision, either zero the scale carefully or note where the equilibrium position is with nothing in the pan and use that position to achieve balance. Record the mass and calculate the mass/length.
4. The uncertainty in the "mass density" arises from the measurement of the "String mass". If the "String mass" was 2.0 g measured with a single pan balance, the precision is 0.1 g and the uncertainty would be $(0.1 \text{ g}/2.0 \text{ g}) \times 100 = 5\%$. Similarly, using a good digital scale, the numbers might be $2.00 \text{ g} \pm 0.01 \text{ g}$ and the uncertainty would be $(0.01 \text{ g}/2.00 \text{ g}) \times 100 = 0.5 \%$. However, you should not claim an uncertainty less than 1% since the string can vary by 1% in its mass density. Record your estimate for the uncertainty.
5. Cut a piece of string about 1 m long for each lab group.

Setup

1. Setup as shown in Figure 5. Clamp the String Vibrator firmly to the table. Attach two banana cables from Output 1 on the 850 Universal Interface to the Inputs on the String Vibrator. Polarity does not matter.
2. Attach the Force Sensor to any of the *PASPORT* inputs on the 850 Universal Interface.
3. Tie the 1 m string to the hook on the Force Sensor and to the vibrating blade on the String Vibrator.
4. The oscillation of the string is all in a vertical plane. It is nice to provide a dark backdrop so the student can see the pattern better. One nice solution is to use a PASCO Optics Bench (OS-8541 or OS-8508) on edge as shown in Figure 6.
5. The Standard Setup has the advantage of giving the student some direct tactile experience of how tension is related to wavelength. However, the accuracy can be improved with the Alternate Setup in Figure 6. Here the Force Sensor is attached to a steel rod (ME-8736) using the thumbscrew of the Force Sensor. The steel rod is clamped in the Large Rod Base (ME-8735) which can be moved to vary the tension. This makes it possible to control the tension and find the maximum standing wave more precisely.

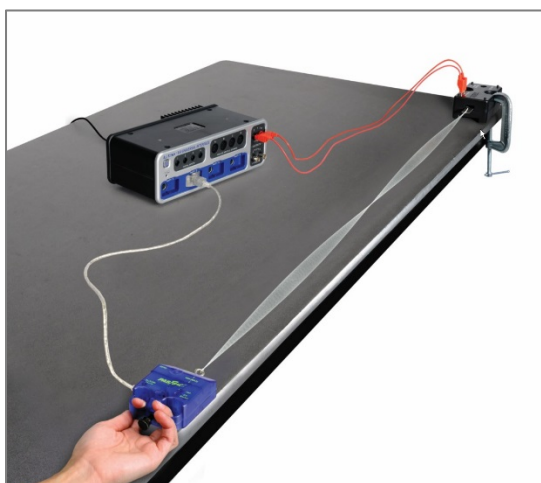


Figure 5: Standard Setup



Figure 6: Alternate Setup

6. In PASCO Capstone, create a Digits Display and select the Force. Then turn on the Statistics with the Mean selected.
7. Create a table as shown. Create User-Entered Data sets called "Frequency" with units of Hz and "Tension" with units of N.
8. Set the sample rate to 20 Hz.

Frequency (Hz)	Tension (N)
60	
85	
104	
120	
134	
147	

Constant Wavelength Procedure

1. Move the Force Sensor so the string is under tension and determine the length of the string between the knot attached to the blade on the String Vibrator and the knot attached to the hook on the Force Sensor. We will adjust for two segments (as in Figure 5) for each case, so the knot to knot distance will be the wavelength. Record your value.
2. Click on the Signal Generator at the left of the screen. Open Output 1 and set for a Sine Waveform at an Amplitude of 5 V and a frequency of 60 Hz. You may vary the Amplitude during the experiment. Increasing the Amplitude will increase the size of the standing wave. **Do Not** exceed 10 V! If the String Vibrator begins to clatter, it is being overdriven and you should decrease the Amplitude.
3. Click On to turn the String Vibrator on.
4. Adjust the tension in the string to get the string vibrating in two segments (as in Figure 5) and to maximize the amplitude of the standing wave. It is easiest to start with the tension too high and slowly decrease it.
5. When you have the maximum standing wave, click RECORD and collect data for about 10 seconds. Click STOP.
6. The force shown in the Force digits display is the average value over the 10 seconds. Ignore the minus sign. Record this value in the “Tension” column of the table in the 60 Hz row.
7. Repeat for frequencies of 85 Hz, 104 Hz, 120 Hz, 134 Hz, and 147 Hz.
8. Question: Why do we have this rather strange looking choice of frequencies? Hint: See the graph in the Analysis section.

Constant Wavelength Analysis

1. Create a graph of Tension vs. frequency. Use the QuickCalcs on the frequency axis to linearize the data.
2. Based on Equation 4, what should be the slope and y-axis intercept of a Tension vs. frequency² plot? Include an estimate of the uncertainty in the slope. The uncertainty here is due to the uncertainty in the mass density, so the percent uncertainty in the calculated slope is the same as the % uncertainty in the mass density from the String Mass Density.
3. Click on the Scale-to-Fit icon from the graph toolbar.
4. Select a Linear fit.
5. How well do the experimental slope and intercept from step 4 agree with the value you calculated for slope and intercept in step2? Discuss briefly. What does this show?

Constant Frequency Procedure

1. Create a table as shown. Create User-Entered Data sets called “# of Segments”, “String Length” with units of m, and “Tension Force” with units of N. Then open the Capstone calculator and make the calculation with units of m: $\text{Wavelength} = 2 * [\text{String Length (m)}] / [\# \text{ of segments}]$

# of Segments	String Length (m)	Wavelength (m)	Tension Force (N)
1			
2			
3			
4			
5			

2. Move the Force Sensor so the string is under tension and determine the length of the string between the knot attached to the blade on the String Vibrator and the knot attached to the hook on the Force Sensor. Enter this length in the “String Length” column of the table in each of the five rows (same value in each row).
3. Click on the Signal Generator at the left of the screen. Open Output 1 and set for a Sine Waveform at an Amplitude of 5 V and a frequency of 150 Hz. You may vary the Amplitude during the experiment. Increasing the Amplitude will increase the size of the standing wave. **Do Not** exceed 10 V! If the String Vibrator begins to clatter, it is being overdriven and you should decrease the Amplitude.
4. Click On to turn the String Vibrator on.
5. Adjust the tension in the string to get the string vibrating in one segment (nodes only at the ends) and to maximize the amplitude of the standing wave. It is easiest to start with the tension too high and slowly decrease it.
6. When you have the maximum standing wave, click RECORD and collect data for about 10 seconds. Click STOP.
7. The force shown in the Tension Force box is the average value over the 10 seconds. Ignore the minus sign. Record this value in the “Tension Force” column of the table in the first row.
8. Repeat for standing wave patterns with 2, 3, 4, and 5 segments.

Constant Frequency Analysis

1. Create a graph of Tension Force vs. Wavelength. Use the QuickCalcs on the frequency axis to linearize the data.
2. Based on Equation 4 from Standing Wave Theory, what should be the slope and y-axis intercept of the Tension vs. wavelength² plot? Include an estimate of the uncertainty in the slope. The uncertainty here is due to the uncertainty in the mass density, so the % uncertainty in the calculated slope is the same as the % uncertainty in the mass density from the String Mass Density table under the String Mass tab.
3. Click on the Scale-to-Fit icon from the graph toolbar and select a Linear Fit.
4. How well do the experimental slope and intercept from step 3 agree with the value you calculated for slope and intercept in step 2? Discuss briefly. What does this show?

Resonance in Air Columns

Equipment

1	Mini Speaker	WA-9605
1	Patch Cords (set of 5)	SE-9750
1	Resonance Air Column	WA-9606
1	Quad Temperature Sensor (only need one temperature probe)	PS-2143

Introduction

A sine wave generator drives an open speaker to create a standing sound wave in a resonance tube. The driving frequency and the length of the tube are varied to study their relationship to wavelength and the speed of the sound wave. The concepts of nodes, anti-nodes, and harmonics are investigated for both closed and open tubes.

Setup

1. In PASCO Capstone, open the Hardware Setup and click on Signal Generator#1 on the 850 Interface and select the Output Voltage/Current Sensor.
2. Click on the Signal Generator at the left of the screen and open the controls for 850 Output #1. Set the sine wave amplitude to 3 volts.
3. Place the Mini Speaker at an open end of the Resonance Air Column, as shown in Figure 1, with the housing of the Mini Speaker just inside the end of the tube. Put the piston in the other end of the Resonance Air Column.

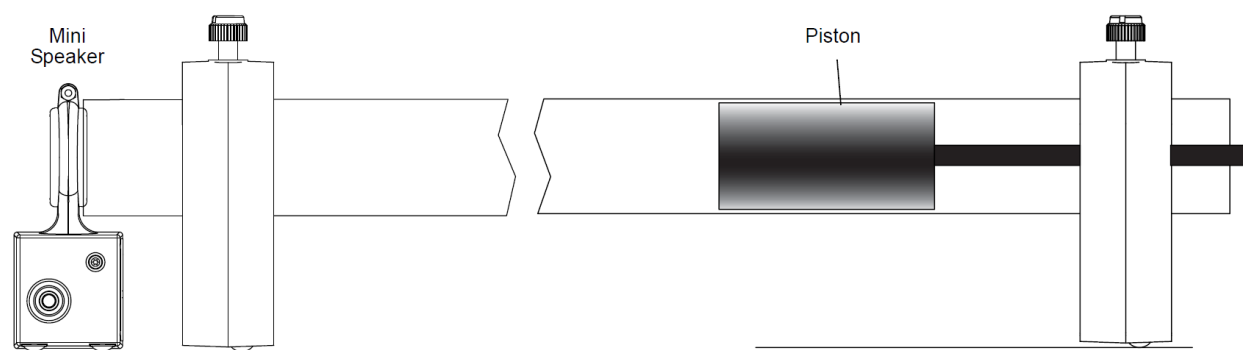




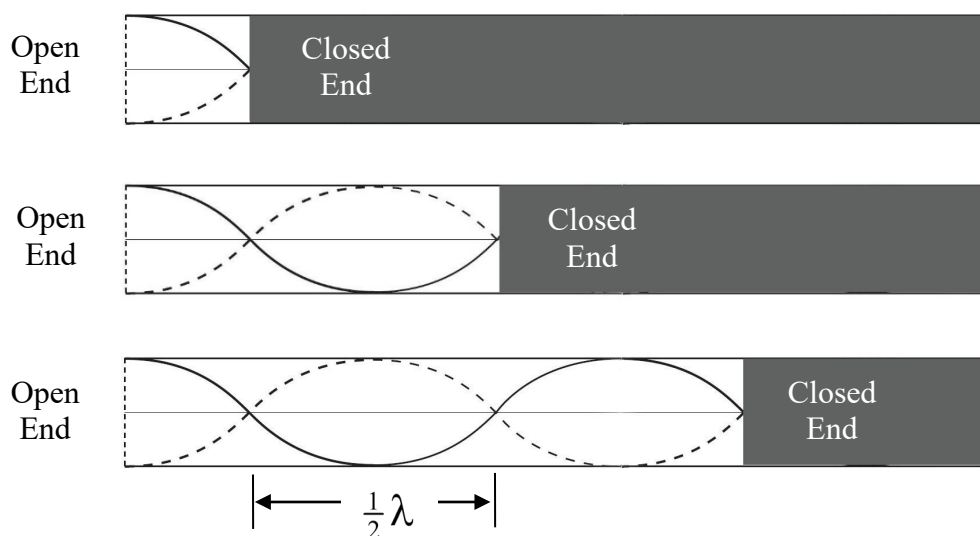
Figure 1: Equipment Setup

4. Place the Resonance Tube horizontally, as shown, with the speaker near the open end. Place the speaker at the end of the tube.
5. Connect the Quad Temperature Sensor to any of the *PASPORT* inputs on the interface and connect the temperature probe into port 1 of the sensor.
6. Create a Digits Display and select the Temperature.

Part I: Closed Tube of Variable Length

Theory

A resonating tube with one end open and the other end closed will always have a node at the closed end and an anti-node at the open end. A node represents an area where the velocity of the air is a minimum (zero), and an anti-node represents an area where the velocity of the air is a maximum. If the tube is resonating at a particular fixed frequency, the tube will resonate as shown below, where the curved lines represent the velocity profile of the air in the tube.



As the length of the active part of the tube is increased, the sound becomes loud at each successive node and quiet at the antinodes. Note that the distance between the nodes is $\frac{1}{2}\lambda$.

For all types of waves, the frequency (f) and the wavelength (λ) are related to the speed (v) of the wave as given by Equation 1.

$$v = \lambda f \quad (1)$$

Procedure

1. Slide the piston to the speaker end, so that the tube length is zero. Set the signal generator frequency for 300 Hz and the amplitude to 3 V. Turn it on.
2. Pull back the piston, increasing the tube length. The loudness of the sound will noticeably increase as you approach resonance. Move the tube in and out to pinpoint the position that gives the loudest tone. Mark this position with one of the sliders.
3. Continue to pull back the piston and find all the positions that cause a resonance. Each of these positions represents a node in the standing wave pattern.

4. Calculate the distance between the nodes, and take the average if you have more than one value. Use this distance to calculate the wavelength of the sound wave.
5. Use the frequency of the signal generator to calculate the speed of the wave.
6. Set the signal generator frequency for 400 Hz and repeat the above procedure. How does the speed of the wave compare to the previous wave at 300 Hz? Are they **about** the same?
7. The actual speed of the wave is the speed of sound in air, which is temperature dependent. This theoretical value can be calculated using

$$v = 331 \text{ m/s} + 0.6 T$$

where T is the temperature of the air in degrees Celsius. Measure the air temperature and calculate the actual speed of sound.

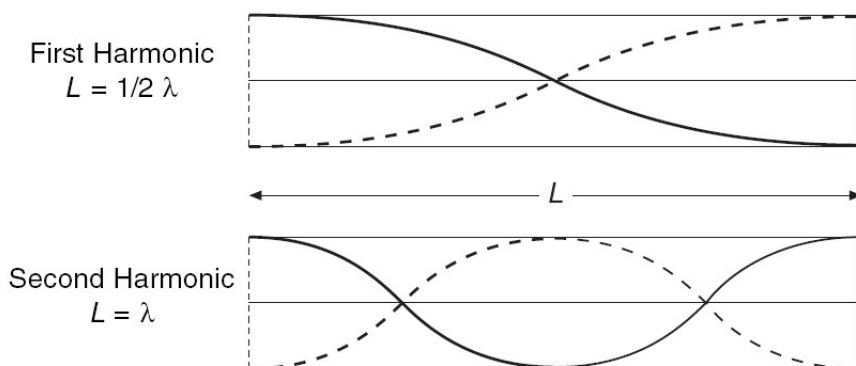
Compare your measured values for the speed of sound to the actual value. Calculate the percent deviation.

$$\% \text{ Deviation} = \frac{\text{Measured} - \text{Actual}}{\text{Actual}} \times 100\%$$

Part II: Open Tube of Fixed Length

THEORY

A resonating tube with both ends open will always have an anti-node at both ends, and at least one node in between. The number of nodes is related the wavelength and the harmonic. The first harmonic (or fundamental) has one node, the second harmonic has two, etc., as



shown here. For a tube of fixed length, at higher harmonics, the frequency is higher and the wavelength is shorter.

Procedure

1. Slide the piston all the way out, and separate it from the tube.
2. Set up the signal generator and the speaker as before. Start with the frequency at 50 Hz and amplitude 3 V. Then slowly increase the frequency. Find the frequency of the fundamental (to the nearest 1 Hz).
3. Calculate the wavelength using the frequency and the actual speed of sound you calculated in Part I. How does this compare to the length of the tube?
4. Increase the frequency of the signal generator and determine the frequency of the second and third harmonic. How do these compare to the fundamental?

Questions

1. In a pipe organ:
 - (a) Which pipes make the low notes, the long ones or the short ones?
 - (b) Which pipes sound the lower frequency, the long ones or the short ones?
 - (c) Which pipes sound the longer wavelengths, the long ones or the short ones?
2. Suppose that in this experiment the temperature of the room had been lower; what effect would this have had on the distance between nodes for each reading? Explain.
3. How would an atmosphere of helium affect the pitch of an organ pipe?

Conclusion

Summarize the differences between an open and closed tube. Also discuss:

- How the velocity, wavelength, and frequency changed as the tube length was varied.
- How the velocity, wavelength, and frequency changed for the part of the experiment in which the tube length was constant.

Speed of Sound in Air

Equipment

1	Sound Sensor	UI-5101
1	Quad Temperature Sensor	PS-2143
1	Resonance Air Column	WA-9606
1	Small A-Base	ME-8976
1	45 cm Rod	ME-8736
1	Multi Clamp	ME-9507
1	Pulley Mounting Rod	SA-9242
Required but not included:		
1	850 Universal Interface	UI-5000
1	Tape Measure (metric)	

Introduction

The purpose of this activity is to measure the speed of sound in air using a tube that is closed at one end. Use a Sound Sensor to record the initial pulse of sound and its echo. Calculate the speed of sound based on the overall distance traveled and the round-trip time.

Background

The speed of sound is different in different materials. The speed depends on the elastic modulus and the density of the material. For example, the elastic modulus of helium is about the same as the elastic modulus of air, but the density of helium is much less. Therefore, the speed of sound in helium is about three times faster than the speed in air. Sound waves travel through air much like waves travel across the surface of a lake or pond: at a fixed speed, being redirected by interactions with dissimilar objects. Much like waves on a pond are reflected off solid objects like the hull of a boat or a dock, sound waves can also be reflected or redirected.



Figure 1: Complete Setup

Setup

1. Set the resonance tube on the lab table and pull the piston back about a meter.
2. Mount the pulley mounting rod to the side of the sound sensor using the threaded socket.
3. Place the 45 cm rod vertically into the rod base, and then use the multi clamp to mount the sound sensor and pulley mounting rod at a right angle.
4. Adjust the position of the rod base and sensor so that the front of the sound sensor is just at the opening of the tube and is pointed down its length.
5. Plug in the sound sensor to Ch. A on the interface.
6. In PASCO Capstone, set the sample rate to 20 kHz. Create a graph of Sound Intensity vs. Time. Then set a measurement-base start condition: Sound Intensity is above 0.5 V and set it to pre-record for 0.01 s. Set a stop condition for the time of 0.05 s.

Procedure

1. Measure the length from the open end of the tube to the piston.
2. Click the record button below. Data will not appear in the graph until data collection is triggered by a loud sound near the sound sensor. Data collection will automatically stop after 0.05 seconds.
3. After clicking record, have a group member snap her/his fingers near the opening of the tube.



4. It should be clear in your data when the initial sound from the snap reached the sound sensor, and when the echo from the end of the tube was returned. Use the delta tool to determine the time between the initial sound and the echo. Record this time.

5. Repeat the same procedure two more times. Record the echo times.
6. Calculate the average value of your echo times. Use that average value and the path length of the sound wave to determine an experimental value for the speed of sound in air.

HINT: The path length of the sound wave is not equal to the length of the tube.

Analysis

1. The speed of sound in air is temperature dependent. This theoretical value can be calculated using

$$v = 331 \text{ m/s} + 0.6 T$$

where T is the temperature of the air in degrees Celsius. Measure the air temperature, calculate the actual speed of sound.

2. Calculate the percent error between your experimental value for the speed of sound in air and the actual value. Record your percent error in the box below.

$$\% \text{ Error} = \frac{|Actual - Experimental|}{Actual} \times 100\%$$

3. What caused the error in your experimental value for the speed of sound in air, and what could you have done differently to improve the results of this activity?

Superposition of Sound Waves

Equipment: PASCO Capstone

Background

Sound waves can be emitted from any object producing mechanical vibrations: a speaker vibrating back and forth or a vibrating tuning fork, for example. Most sound waves can be simplified and modeled using a sine curve like the ones in Figure 1. Waves with similar frequency (including sound waves) are said to be "in phase" when the troughs and crests of the waves are perfectly aligned (Figure 1-a). If the troughs and crests are not aligned, the waves are said to be "out of phase" (Figure 1-b).

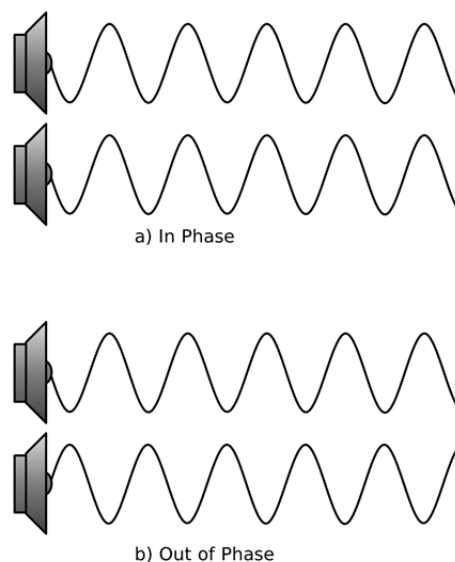


Figure 1: Sinusoidal Sound Waves

When two similar sound waves traveling through the air interact with each other, interference occurs. This interference can be constructive, making the amplitude of the resulting wave larger, or destructive, making the amplitude of the resulting wave smaller. The type of interference depends on whether the waves are in phase or out of phase.

The equation describing a sinusoidal wave is seen here in Equation 1.

$$y(t) = A\sin(\omega t + \phi) \quad (1)$$

where A is the amplitude of the wave, ω is the angular frequency of the wave ($\omega = 2\pi \times \text{frequency}$), ϕ is a phase shift ($\phi/\omega = \text{phase shift in seconds}$, and t is time in seconds).

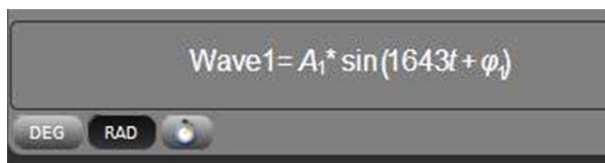
The combination of two interfering waves can be described by the simple addition of the equations describing the constituent waves, or, "superposition" of the two waves (Equation 2):

$$y_3(t) = y_1(t) + y_2(t) \quad (2)$$

$$y_3(t) = A_1\sin(\omega t + \phi_1) + A_2\sin(\omega t + \phi_2) \quad (3)$$

Procedure: Amplitude

1. Enter the following calculations into the PASCO Capstone calculator. All the calculations are unitless except where noted. Make sure the RAD button is selected.



$$\text{Wave1} = A_1 \sin(1643t + \phi_1)$$

$$A_1 = 2$$

$$\phi_1 = 10\pi$$

with units of rad

$$\text{Wave2} = A_2 \sin(1643t + \phi_2)$$

$$A_2 = 2$$

$$\phi_2 = 0$$

with units of rad

$$\text{Wave3} = \text{Wave1} + \text{Wave2}$$

$$t = \{0 \dots 0.01; 500\}$$

with units of s

2. Create a graph with the calculation Wave1 on the vertical axis and the calculation t on the horizontal axis. Then select Add Similar Measurement on the vertical axis and add Wave2 and Wave3. Click on the Data Selection button on the graph toolbar so more than one data set can be displayed at one time. Then click on the drop-down arrow and select both the Model and the Set. The graph will show two sound waves with identical characteristics (amplitude, frequency, and phase shift). The equations describing both waves (Wave1 and Wave2) can be seen in the calculator panel. Wave3 on the graph shows the resultant superposition of Wave1 and Wave2.
3. Both Wave1 and Wave2 have amplitude equal to 2. Increase the amplitude of Wave1 by changing the value for A_1 in the Calculations window from 2 to 4 (press enter after changing the value). How does the amplitude of the resultant wave change when you increase the amplitude of Wave1? What is the new amplitude of Wave3?
4. Follow the same procedure to decrease the amplitude of Wave2 (A_2) from 2 to 0.5. How does the amplitude of the resultant wave change when you decrease the amplitude of Wave2? What is the new amplitude of Wave3?
5. In your own words, describe how the amplitude of the resultant wave (Wave3) is related to its constituent waves when the constituent waves are in phase.

Procedure: Phase

1. Change the amplitude of both Wave1 and Wave2 (A_1 and A_2) to 4.
2. Increase the phase shift of Wave1 (ϕ_1) to 0.5 rad. Remember to press enter on your keyboard after changing the ϕ_1 value.
3. What happens to the Wave1 curve when its phase shift is equal to 0.5 rad? What happens to Wave3?
4. Continue to increase the phase shift of Wave1 (ϕ_1) in 0.5 rad increments, and observe Wave1 and Wave3 as you do so. Stop when you reach a phase shift of 7.
5. What happened to the Wave1 curve when its phase shift was increased? What happened to Wave3?
6. Try changing the phase shift of both waves (ϕ_1 and ϕ_2) and observe the resultant Wave3. Try both positive and negative phase shifts.
7. How does Wave3 change when both phase shifts (ϕ_1 and ϕ_2) are changed?

Analysis

1. What was the shape of the resultant Wave3 when Wave1 and Wave2 were in phase? Include the terms amplitude, frequency, and phase in your description.
2. What was the shape of the resultant Wave3 when Wave1 and Wave2 were out of phase? Include the terms amplitude, frequency, and phase in your description.
3. Adjust the phase shifts of both Wave1 and Wave2 until Wave3 experiences destructive interference (zero amplitude) and constructive interference (maximum amplitude). What is the phase difference between Wave1 and Wave2 when Wave3 experiences destructive and constructive interference?
4. Based on your response to the previous question and the trigonometric relationship between the equations for Wave1 and Wave2, can you create a generalized expression for $\phi_2 - \phi_1$ that describes when Wave3 will experience constructive and destructive interference?

Interference of Sound Waves

Equipment

1	Sound Sensor	UI-5101
1	Sensor Extension Cable	with UI-5101
1	Resonance Box Set	SE-7345
Required but not included:		
1	Metric Ruler	

Introduction

The purpose of this activity is to measure and analyze the behavior of two sounds that combine to produce beats. This activity also examines the relationship between the beat frequency and the frequencies of the two interfering sound waves.

Confirm that two sound waves of slightly different frequency will produce beats and that the beat frequency between two sound waves of slightly different frequency is the difference in their frequencies.

Background

In situations where waves with the same frequency overlap, the principle of linear superposition describes the constructive and destructive interference experienced by the resultant wave. The resultant wave amplitude changes based on the alignment of the troughs and peaks between the two constituent waves. The same theory holds true for two waves with similar phase, but different frequencies as seen in Figure 1a. Two overlapping waves with slightly different frequencies give rise to the phenomenon of beats.

A tuning fork has the property of producing a single-frequency sound wave when struck with a sharp blow. When two tuning forks with different frequencies are struck near each other, the sound waves produced by each will interfere with each other, causing the loudness of the resulting sound to rise and fall periodically: faint, then loud, then faint, then loud, and so on. These periodic variations in loudness are called beats and are the result of the superposition of the two sound waves as they travel through air as in Figure 1b.

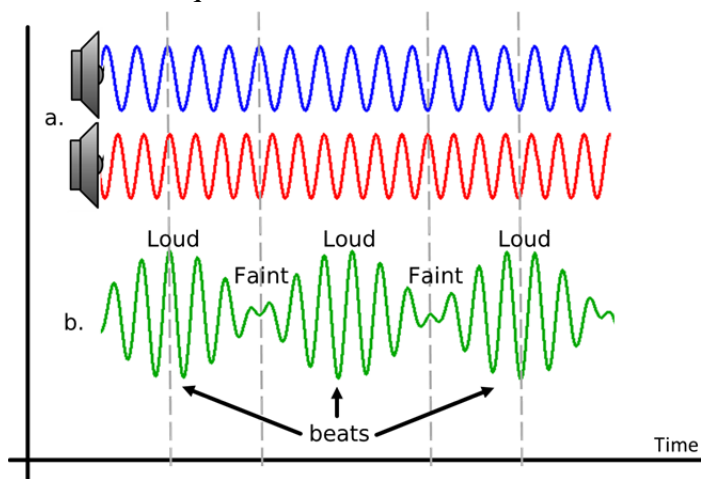


Figure 1. Interfering Sound Waves

Setup:

1. Connect the sound sensor to Analog Input A (you must connect it to the A input) on the 850 interface using the sensor extension cable.
2. In PASCO Capstone, set the sample rate to 20 kHz. Create a graph of Sound Intensity vs. Time. Open the Recording Conditions and create a Stop Condition for data collection to stop after a time of 0.3 s.
3. Place both resonance boxes next to each other lengthwise, with the openings of each facing the same direction and aligned. Be sure that the two boxes do not touch each other (Figure 2).
4. Set the sound sensor flat on the lab bench approximately 20 cm in front of the boxes with the sensing element on the sound sensor facing the openings, and aligned midway between them as in Figure 2.



Figure 2: Setup

5. Each tuning fork has two slides that will be used to adjust the output frequency from either tuning fork. When adjusting the slides, be certain to loosen the thumbscrew on each slide before attempting to move them, and always make certain that the height of both slides on each tuning fork is identical.
6. Adjust the height of both slides on one tuning fork so that the slides are 1 cm from the top of the forks.
7. Adjust the height of both slides on the other tuning fork so that the slides are 7 cm from the top of the forks.
8. Strike each tuning fork one at a time using the rubber mallet (Do not use anything other than the rubber mallet that accompanies the resonance box set to strike the tuning forks). Describe how the height of the slides on the tuning forks affects their output frequency (pitch).
9. Adjust the height of the slides on the second tuning fork from 7 cm to 3 cm, and then

strike both forks simultaneously. Describe the sound that is produced by the two forks simultaneously.

10. Repeat the previous step but this time adjust the slides on the second tuning fork to 2 cm and strike the forks simultaneously, and then again at 1.5 cm. Describe the sound as the frequency of the two forks becomes closer together?

Collect Data

1. Place your hands on both tuning forks to silence them in between the following steps.
2. Set the height of the slides on the tuning forks to 1 cm for the first tuning fork and 1.5 cm for the second tuning fork.
3. Strike the first tuning fork with the rubber mallet and then click the record button in the control panel below. Data recording will automatically stop after 0.3 s.
4. Use the coordinates/delta tool in the graph display to determine the period T of the output wave from the first tuning fork. Use this value to calculate its frequency ($f = 1/T$). Record the frequency.
5. Repeat the two previous steps for the second tuning fork. Record its frequency.
6. Strike both tuning forks with the rubber mallet and then click the record button in the control panel below. What do you notice is different about the sound wave when both forks are struck at the same time, versus one at a time?
7. Use the coordinates/delta tool in the graph display to help determine the frequency of the beats in the sound wave when both forks were struck. Record the value below. What is the relationship between the beat frequency and the frequencies of the individual sound waves (f_1 and f_2)?
8. Place your hands on both tuning forks to silence them in between the following steps.
9. Set the height of the slides on the tuning forks to 1 cm for the first tuning fork and 3 cm for the second tuning fork.
10. Repeat the collect data procedure from the previous page striking each tuning fork one at a time and recording a run of data for each. Use the coordinates/delta tool in the graph to help determine the frequency of each. Record both values.
11. Now strike both tuning forks at the same time and record another run of data. How is the shape of this wave form different from the combined wave form from the previous page?
12. Use the coordinates/delta tool in the graph display to help determine the frequency of the beats in the combined waveform. Record this beat frequency.

13. Does your relationship between beat frequency and individual wave frequency that you determined on the previous page hold true for this combined waveform? Do you think it would hold true for any combination of individual wave frequencies? Explain your answer.

Conclusions

1. Describe, in complete sentences, the relationship between beat frequency in a combined sound wave and the frequencies of the two waves that are being combined.
2. Explain how the principle of beat frequency could be used to tune two musical instruments.
3. You have seen the combined waveform of two sound waves with different frequencies. Based on your data and experience, predict how a sound waveform would appear if it were the combination of three sound waves, each with a different frequency.

Shadow and Color in Light

Equipment

1	Color Mixer	OS - 8496
1	Color Mixer Accessory Kit	OS - 8495
1	Viewing Screen	OS - 8460
1	Optics Bench	OS-8508

Introduction

When lights of two different colors are arranged so they shine on the same location on a white surface, the human eye perceives the reflection of that light as an additive mixture, because the reflected light contains wavelengths from both of the colors. Students will use the Color Mixer to learn how three colors of light - red, blue, and green - add together to create a full range of colors.

Setup

Attach the color mixer to the optics bench. Attach the viewing screen to the optics bench so it faces the color mixer. Turn up the red LED and adjust the position of the viewing screen as necessary to see the circle of red light as large as possible on the screen. The circle of red light will not be centered on the screen.

Turn the knob on the red LED fully counter-clockwise to turn off the color, and turn the knob fully clockwise to make the color as bright as possible.

Caution: The Color Mixer light-emitting diodes (LEDs) produce intense light. Do not look directly into the Color Mixer when it is turned on.



Figure 1: Adjusting the viewing screen position

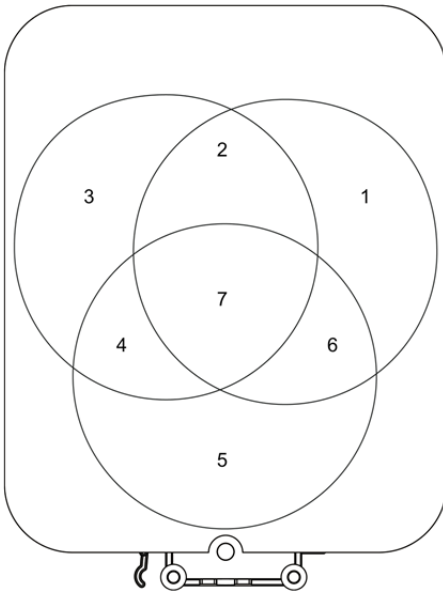
Procedure: Additive Color Mixing

1. Turn the red LED fully on with the blue and green LEDs off. What do you predict will happen as the intensity of the green LED is gradually increased?
2. Gradually increase the green LED and note the range of colors that is formed where the green and red circles of light overlap. Were your predictions accurate?
3. Now turn off the red and turn the green fully on. What do you predict will happen as the red is gradually increased in intensity?

4. Gradually increase the intensity of the red and note the colors that are formed in the overlapping segment. Were your predictions accurate?
5. Repeat the steps above for both green and red with the blue source. For each of the colors listed below, describe which colors of light were mixed to create that color. For some you will need to describe the relative intensity (low, medium, high) of each color.

Color of Light Produced	Light Color(s) Mixed
Red	
Blue	
Green	
Pink	
Yellow	
Orange	
White	
Turquoise	

6. For each of the 7 regions of overlapping circles shown in the diagram below, list the resulting colors produced by mixing the colors of light.



Region	Color of Light Produced
1	
2	
3	
4	
5	
6	
7	

Figure 2: The regions formed by overlapping circles of light

LED Emission and Filter Transmission Curves

The Color Mixer LEDs emit light whose wavelengths fall within a certain range. Although the individual color wavelengths will vary from unit to unit due to minor variations in the LEDs, the peak wavelength ranges for each color are as follows:

Color	Peak Wavelength Range
Red	620 to 630 nm
Green	520 to 535 nm
Blue	450 to 465 nm

These peak wavelength ranges are illustrated in the graph below, which is intended to give a general idea of the emission curves for each color LED in the Color Mixer.

Each filter card allows some light to pass through it. If you hold a filter card up to the sunlight and look through it, the transmitted light will reach your eye. You perceive the color corresponding to the wavelengths of light that are transmitted by the filter. For example, if you hold up filter card 1 and look through it, light between about 600 nm and 700 nm passes through the filter material and reaches the receptors in your eye, so you see red. Light of shorter wavelengths does not pass through the filter, so you do not see blue or green.

Each filter card has the characteristic transmission curve printed on the card, as shown below. The transmission curve information will be used for analysis of the behavior of the filters.

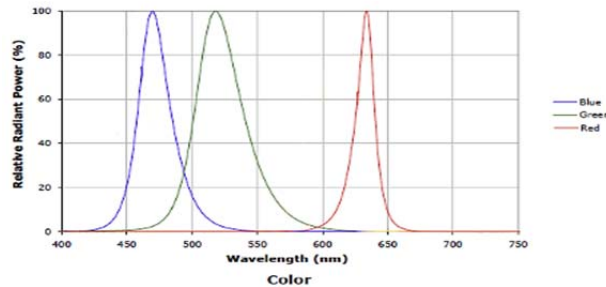


Figure 3: Emission Curves of the Color Mixer

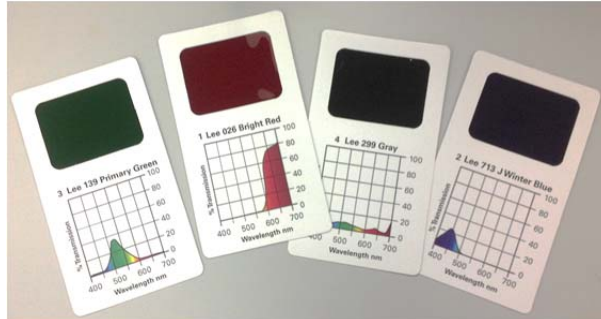


Figure 4: Filter cards, Imprinted with Transmission Curves

Procedure: Using Filters

1. Look at each of the filters that you have been given and predict what will happen to the red light from the Color Mixer when the filters 1 through 4 are placed between the red LED and the viewing screen. List your predictions in the table below.
2. Turn on only the red source and look at the screen as each of the filters is placed between the screen and the mixer. Record your observations in the table.
3. Based on what you saw with the filters and their interaction with the red light, predict what will be observed when the filters are placed in front of the blue source. Turn on the blue source and record your observations.
4. Perform the same prediction and observation activity with the green source and filters.

Filter	Predictions for Red Light	Observed Results
Card 1 – Bright Red		
Card 2 – Winter Blue		
Card 3 – Primary Green		
Card 4 – Gray		

Filter	Predictions for Blue Light	Observed Results
Card 1 – Bright Red		
Card 2 – Winter Blue		
Card 3 – Primary Green		
Card 4 – Gray		

Filter	Predictions for Green Light	Observed Results
Card 1 – Bright Red		
Card 2 – Winter Blue		
Card 3 – Primary Green		
Card 4 – Gray		

Analysis: Filters

1. Compare your observed results with your predictions for each color light. Briefly discuss any differences between predictions and observations.
2. Review the emission curves for the Color Mixer and the filter transmission curves for the red, blue and green cards. Create a graph which overlays the transmission and emission curves. Explain why the blue filter allows some of the green led light to show on the screen using the overlay graph in your explanation.
3. Explain the difference between the action of the #4 filter and the rest of the filters. How does it differ and why?
4. Based on your analysis of filters 1 through 4, which of filters 5 through 7 would behave

the most like filter 4 (gray) if it were placed between the viewing screen and the red LED?

Procedure: Absorption vs. Transmission

Using printed cards 8–11, the Color Mixer, and filter cards, students will explore the meaning of absorption and reflection of light.

Note: Ambient light in the room will make observation of some things difficult. Decrease room lighting as low as possible to enhance this lab.

1. Predict what each of the cards will look like when illuminated only by the red source.
2. Place each card (red, blue, green and white) in front of the red source and note your observations.
3. Based on what you observed with the red source, predict how the same cards will appear when illuminated by the blue and green sources.

Color Card	Predictions for Red Light	Observed Results
Card 8 – Red		
Card 9 – Blue		
Card 10 – Green		
Card 11 – White		

Color Card	Predictions for Blue Light	Observed Results
Card 8 – Red		
Card 9 – Blue		
Card 10 – Green		
Card 11 – White		

Color Card	Predictions for Green Light	Observed Results
Card 8 – Red		
Card 9 – Blue		
Card 10 – Green		
Card 11 – White		

Analysis: Absorption vs. Transmission

1. Compare your observed results with your predictions for each color light. Briefly discuss any differences between predictions and observations.
2. Did any of the cards exhibit the same brightness for all three sources? If so, which card? The relative intensity of reflection vs. wavelength is printed on the card. Create an overlay of this card's relative intensity curve with the spectral emission curves for the LEDs used in the Color Mixer. Suggest a possible explanation based on your overlay graph.

- Discuss the difference between a filter's interaction with light and an ink's interaction with light.

Procedure: Casting Shadows

- Turn on the red, green, and blue LEDs, and adjust the intensities of the lights until the whitest light possible appears on the viewing screen at the central region of overlap.
- Place a pen or a pencil as close to the screen as possible. Describe the shadow cast by the object on the viewing screen in each region of the overlapping circles on which the shadow falls.

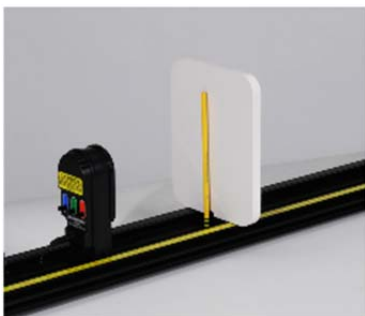


Figure 5: Pencil near Screen

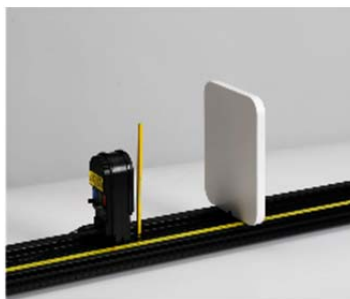


Figure 6: Pencil in Front of Color Mixer

- Turn off each LED on the Color Mixer.
- Adjust the distance of the object so that it is now about 2 cm in front of the Color Mixer.
- Turn on first the red light, then the green light, then the blue light. Observe the shadow that falls on each region of the overlapping circles.
- What color light must be blocked by the object in order to form a blue shadow? What color light must be blocked to form a red shadow?
- Develop a rule for blocking one or more colors of light to form each of the following seven colors of shadows:

Color of Shadow Produced	Light Color(s) Blocked
Red	
Blue	
Green	
Black	
Cyan	
Magenta	
Yellow	

Object and Image Distances Thin Lens

Equipment

1	Basic Optics Light Source	OS-8470
1	Optics Track	OS-8508
1	Basic Optics Viewing Screen	OS-8460
1	Convex Lens Set	OS-8456
1	Adjustable Lens Holder	OS-8474
1	Adjustable Focal Length Lens	OS-8494
Required but not included:		
1	Ruler	
	Water (15 mL)	

Introduction

The purpose of this activity is to determine the relationship between object distance and image distance for a thin convex lens. Use a light source, optics bench, lens, and viewing screen to measure object distance, image distance, and image size.



Figure 1: Equipment

Prediction

How will a convex lens change the image of an object? Explain your answer.

Background

The behavior of light through a thin lens is utilized every day in simple devices that we use. Some of these devices include magnifying glasses, telescopes, and binoculars. Even the human eye takes advantage of the lens found in its outer surface, focusing images so we can see clearly.



On a small scale, the behavior of light as it passes through a thin lens can be described using Snell's Law, the angle at which light is incident on the lens surface, and the index of refraction of the material the lens is made out of. However, using a more macroscopic scale, we can characterize this behavior using spatial measurements and simple geometry that involves the distance between the object of interest and the lens, known as "object distance", the distance between the lens and the object image, known as "image distance", and a special characteristic of the lens known as "focal length".

The goal of this lab will be to explore the behavior of light and the images it forms as it travels through a thin lens, and collect data that will help determine how image distance is related to both the object distance and focal length of a thin convex lens.

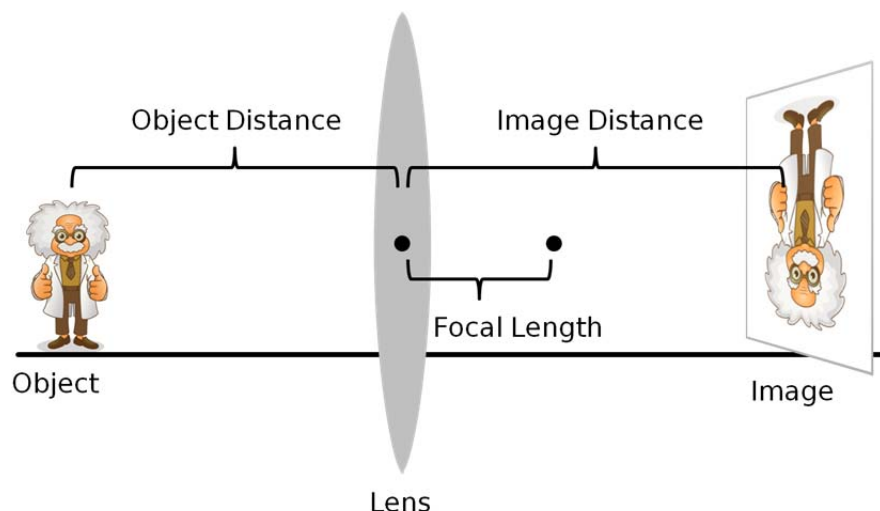


Figure 2: Image Formation from a Thin Lens

Setup

1. Mount the light source at the zero point of the optics track with the crossed-arrow pattern facing down the length of the track. Connect the power supply to the light source.
2. Assemble and fill the adjustable focal length lens with water following the fill procedure in the adjustable focal length lens manual. Try to remove as much air as possible from the lens when filling.
3. Mount the adjustable focal length lens in the adjustable lens holder, and then mount the holder with lens to the track about 20 cm in front of the light source.
4. Mount the viewing screen to the optics track anywhere on the side of the lens opposite the light source, with the flat surface facing the lens, as in Figure 3.



Explore

To produce a convex lens, press VERY slightly on the syringe. The harder you press on the syringe, the greater the curvature in the convex lens, but be careful not to press too hard as the lens will pop and water will spill out, or air may get trapped in the lens.

1. With the lens slightly convex, adjust the position of the viewing screen forward or backward until the image of the crossed-arrow pattern is in focus. When the image is in focus, the distance between the lens and the viewing screen is equal to the image distance, and the distance between the crossed-arrow pattern on the light source and the lens is equal to the object distance.
2. A convex lens with greater curvature will have a shorter focal length. How does the image distance change when you increase the curvature of the lens (decrease focal length) while keeping the object distance constant?
3. How does the **SIZE** of the image change when you decrease the focal length (constant object distance) and does its orientation change?
4. How does the behavior you see compare to your prediction on the first page?

Setup

1. Make certain the light source is at the zero point on the optics track with the crossed-arrow pattern facing down the length of the track.
2. Mount the viewing screen at the other end of the bench with the flat surface facing the light source.
3. Remove the adjustable lens holder with the adjustable lens and mount the 100-mm glass convex lens to the optics track 500 mm from the light source. Use the metric scale on the optics track and the marks at the base of the light source and lens mount (as in Figure 4) to help set this distance.

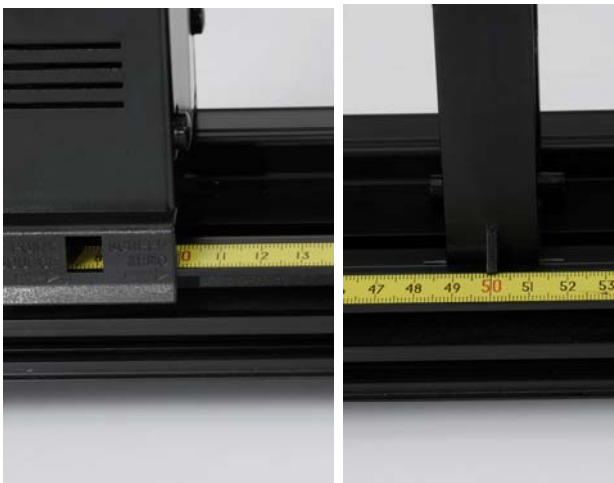


Figure 4: Track Markers

Procedure

1. In PASCO Capstone, create a table as shown below. Create User-Entered Data sets called “Object Distance”, “Image Distance”, and “Image Height”, all with units of mm.

Table I: Object and Image Distances

Object Distance (mm)	Image Distance (mm)	Image Height (mm)
500		
475		
450		
425		
400		
350		
300		
250		
200		
150		
125		
115		
110		

2. The image of the crossed-arrow target should initially appear out of focus. Adjust the position of the viewing screen forward or backward until the image of the crossed-arrow target is in focus.
3. When the image is in focus, measure the distance between the lens and the viewing screen. Record this image distance in Table I.
4. Use the ruler to measure the height of the image. Record the image height in Table I. Use negative values to indicate that the image is inverted.
5. Adjust the position of the 100-mm convex lens to the next object distance listed in Table I of 475 mm.
6. Adjust the position of the viewing screen until the image of the crossed-arrow target is in focus, and then record the image distance and height in Table I.
7. Repeat the same procedure for each object distance value in Table I. Record all values in Table I.

Analysis: Distance

1. Create a graph of Image Distance (mm) vs. Object Distance (mm).
2. What value does the image distance approach as the object distance becomes larger (approaches infinity), and what is the significance in this value?
3. What value does the object distance approach as the image distance becomes larger (approaches infinity), and what is the significance in this value?

The graph of image distance versus object distance isn't linear; however, by clicking on either axis label you can select QuickCalcs that will quickly manipulate either axis measurement by operating on it mathematically.

4. Use different QuickCalcs on both axes until the graph shows a linear relationship (you will need to rescale when applying QuickCalcs). What are the x and y variables that show a linear relationship?
5. Apply a linear fit to your data and write the $y = mx + b$ equation that describes the line below (round m to the nearest whole number). Replace y and x using the variables from your answer to the previous question.
6. What is the significance of the y and x-intercepts in your graph/equation?
7. Based on your data and the answers to the previous questions, what is the equation that relates object distance, image distance, and focal length of a thin lens?

Analysis: Magnification

Magnification is a measure of how much an image has been magnified from its original size. Mathematically, magnification is the ratio of image height to object height:

$$\text{Magnification} = \frac{\text{Image Height}}{\text{Object Height}}$$

8. In the Capstone calculator, create a calculation for the magnification (it is unitless):

$$\text{Magnification} = [\text{Image Height (mm)}]/40$$

In this calculation, the Object Height has been set to 40 mm. Use the ruler to measure the height of the object, and then enter that value into the magnification.

9. Add a column to Table I and select the Magnification calculation in that column:

Table I: Object and Image Distances

Object Distance (mm)	Image Distance (mm)	Image Height (mm)	Magnification
500			
475			

10. Create a graph of Magnification vs. Object Distance (mm) and another graph of Magnification vs. Image Distance (mm).
11. How is magnification related to object distance (proportional, inverse, etc.), and at what object distance is the magnification approximately equal to 1 (object height = image height)?
12. How is magnification related to image distance (proportional, inverse, etc.), and at what image distance is the magnification equal to 1? How does this value compare to the object distance at the same magnification?
13. Based on the responses to the previous two questions, what is the mathematical relationship that relates magnification to object and image distance?
14. What value does magnification approach as object distance approaches the focal length of the lens (100 mm)? What do you think happens to the image when the object distance is less than the focal length of the lens?

Reflection

Equipment

1	Ray Optics Kit	OS-8516
1	Basic Optics Light Source	OS-8470
Required but not included:		
1	Protractor	
1	Ruler	
1	Sheet of White Paper	
1	Pen or Pencil	

Introduction

In this activity you will experimentally confirm the Law of Reflection for a flat, concave, and convex mirror.



Figure 1: Reflection

Setup

1. Place a sheet of white paper on the lab bench, and then set the three-in-one mirror in the center of the paper.
2. Use the pen or pencil to trace the outline of the mirror on the paper and then lift the mirror off the paper. Use the ruler to measure half the length of the flat side of the outline. Make a small mark at the half-way point.
3. Use the ruler to draw a straight line from the apex opposite the flat side of the outline, through the half-way mark you just made. Extend the line several centimeters past the outline as in Figure 2. This line represents a line normal to the flat mirror surface.

4. Following the line you just drew, use the ruler to measure 1.8 cm inside the outline from the flat side of the outline. Make a small mark as in Figure 3.
5. Use the ruler to draw a straight line from the apex opposite the concave side of the outline, through the center mark you just made and then through the concave side of the outline. Extend the line several centimeters past the outline as in Figure 4. This line represents a line normal to the concave mirror surface.
6. Use the ruler to draw a straight line from the apex opposite the convex side of the outline, through the center mark and then through the convex side of the outline. Extend the line several centimeters past the outline as in Figure 4. This line represents a line normal to the convex mirror surface.

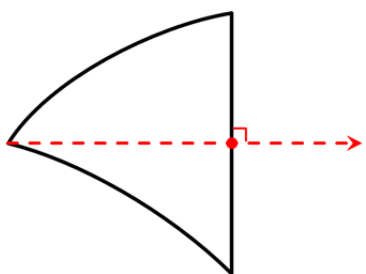


Figure 2

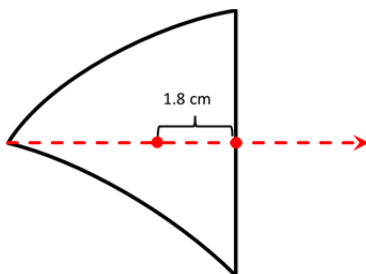


Figure 3

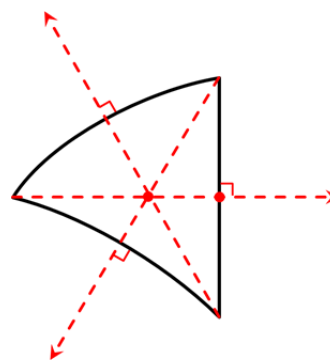
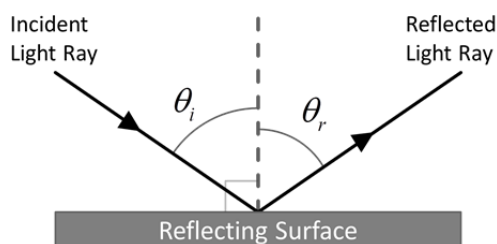


Figure 4



Background:

Figure 5: Reflected Ray

When a ray of light (incident ray) strikes a plane mirror, the light ray reflects (reflected ray) off the mirror and changes its direction of travel. The angle of incidence θ_i is the angle between a line normal to the surface and the incident ray, as in Figure 5; the angle of reflection θ_r is the angle between the normal and the reflected ray. The law of reflection states that the angle of incidence equals the angle of reflection:

$$\theta_i = \theta_r \quad (1)$$

Procedure: Flat Mirror

1. Place the three-way mirror on the paper and align it inside the outline.
2. Place the basic optics light source flat on the lab table and rotate the knob on the front of the light source to produce a single ray of light as in Figure 6.
3. Adjust the position of the light source so the single light ray hits the flat mirror at the point the normal line extends from the outline as in Figure 6.
4. Use the ruler and pen or pencil to trace the paths of the incident and reflected light rays. Label each line "Ray 1 Incident" or "Ray 1 Reflected" similar to Figure 6 to help differentiate them.
5. Lift the mirror off the paper and then use the protractor to measure the angles of both incident and reflected rays relative to the normal line. Record both values.
6. Repeat the same procedure two more times using two different incident angles. Record all data.



Figure 6: Flat Mirror Reflection

Procedure: Concave Mirror

1. Adjust the position of the light source so the single light ray now hits the concave mirror at the point the normal line extends from the outline as in Figure 7.
2. Use the ruler and pen or pencil to trace the paths of the incident and reflected light rays. Label each line "Ray 1 Incident" or "Ray 1 Reflected" similar to Figure 7 to help differentiate them.
3. Lift the mirror off the paper and then use the protractor to measure the angles of both incident and reflected rays relative to the normal line. Record both values.

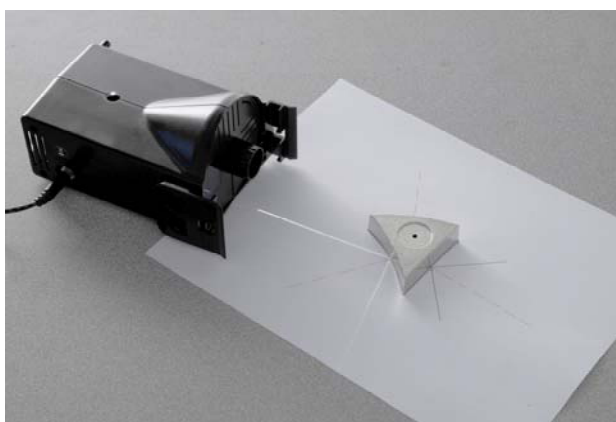


Figure 7: Concave Mirror Reflection

4. Repeat the same procedure two more times using two different incident angles. Record all data.

Procedure: Convex Mirror

1. Adjust the position of the light source so the single light ray now hits the concave mirror at the point the normal line extends from the outline as in Figure 8.
2. Use the ruler and pen or pencil to trace the paths of the incident and reflected light rays. Label each line "Ray 1 Incident" or "Ray 1 Reflected" similar to Figure 8 to help differentiate them.
3. Lift the mirror off the paper and then use the protractor to measure the angles of both incident and reflected rays relative to the normal line. Record both values.
4. Repeat the same procedure two more times using two different incident angles. Record all data.

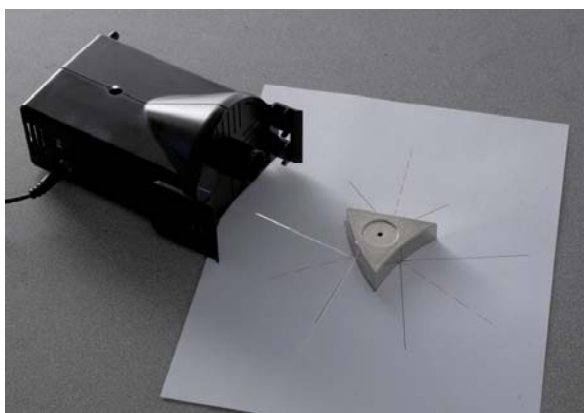


Figure 8: Convex Mirror Reflection

Analysis

1. According to the Law of Reflection, the incident angle and the reflection angle must be the same. Discuss: How well does your experiment show this? Does it matter whether the reflective surface is flat or curved? Why?
2. What are sources of experimental uncertainty for this part of the experiment?

Refraction

Equipment

1	Basic Optics Ray Table	OS-8465
1	Basic Optics Light Source	OS-8470
1	D-Shaped Acrylic Lens	w/OS-8465

Introduction

In this activity you will use Snell's Law of refraction to experimentally determine the index of refraction of a D-shaped acrylic lens.

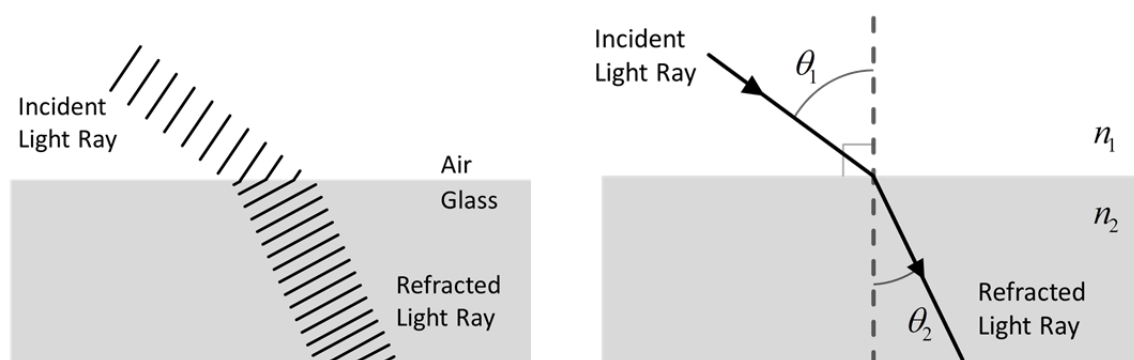


Figure 1: Refraction

Background

Refraction is the bending of the path of light when it passes from one material to another. The most common explanation of refraction includes the wave theory of light: Imagine a ray of light traveling through air. When this ray strikes the surface of a piece of glass at an angle, one side of the wave front enters the glass before the other and it slows down, while the other side continues to move at its original speed until it too reaches the glass. As a result, the light ray bends inside the glass. The amount at which a medium (like glass) can slow a light ray down is based on the medium's index of refraction n . If a medium has a high index of refraction (like glass, $n \sim 1.4$), light will travel slower through it. If a medium has an index of refraction close to 1 (like air, $n \sim 1$) light will travel faster through it.

In addition to the different indexes of refraction, the angle at which a light ray bends when traveling from one medium to another is also affected by the angle at which the original light ray is incident. The relationship is described by a simple equation known as Snell's Law (Equation 1). Where n_1 is the index of refraction of the first (incident) medium, n_2 is the index of refraction of the second medium, and θ_1 and θ_2 are the incident and refracted angles respectively.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (1)$$

Setup

1. Place the basic optics light source flat on the lab table and rotate the knob on the front of the light source to produce a single ray of light as in Figure 2.
2. Place the basic optics ray table on the lab bench just in front of the light source, such that the light ray passes through the center of the ray table.
3. Rotate the top of the ray optics table so that light ray is aligned with the 0° mark on the tabletop.
4. Place the D-shaped acrylic lens in the center of the table (frosted side down), and adjust its position so it fits within the lens outline on the tabletop.

Important Note

With the equipment set up you should see the light ray passing through the lens. If you adjust the angle at which the light is incident on the flat front of the D-shaped lens you will see the light ray change direction due to refraction within the glass.

You may also notice that the direction of the light ray does not change when it leaves the glass, even though $n_1 \neq n_2$. Explain why this happens?

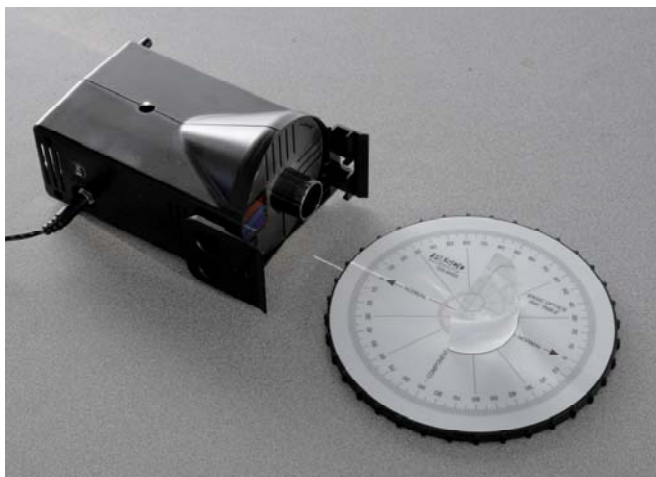


Figure 2: Setup

Procedure

1. In PASCO Capstone, create a table as shown below. Create User-Entered Data sets for both columns. Fill in the values shown in the first column.

Table I: Refractive Angles for D-Shaped Lens

Incident Angle θ_1 ($^\circ$)	Refraction Angle θ_2 ($^\circ$)
0	
5	
10	
15	
20	
25	
30	
35	
40	
45	
50	
55	
60	
65	
70	
75	

2. Set the incident angle to 0° by rotating the top of the basic optics ray table. Make certain that the light ray hits the flat surface of the lens at its center.
3. Observe the refracted ray of light and record the refraction angle in Table I.
4. Repeat the same procedure for each incident angle in Table I. Record all measurements into Table I and make certain that the light ray hits the flat surface of the lens at its center for all measurements.



Figure 3: Measuring the Refraction Angle

Analysis

1. In the Capstone calculator, create the following equations (both are unitless):

$$\sin \theta_1 = \sin([\text{Incident Angle}, \theta_1 (^{\circ})])$$
$$\sin \theta_2 = \sin([\text{Refraction Angle}, \theta_2 (^{\circ})])$$

2. Create a graph of $\sin \theta_1$ versus $\sin \theta_2$ for your data. Turn off the connected lines in the graph properties.
3. Use a curve fit to help determine a value for the index of refraction for the acrylic lens (n_2). Assume that the index of refraction for air (n_1) is 1. Record the experimental value.
4. If acrylic glass has a theoretical index of refraction of 1.49, what is the percent error on your experimental value?

$$\% \text{ Error} = \frac{|\text{Actual} - \text{Experimental}|}{\text{Actual}} \times 100\%$$

5. What caused error in your measurements and how could these have been avoided?

Dispersion

Equipment

1	Ray Optics Kit	OS-8516
1	Basic Optics Light Source	OS-8470
Required but not included:		
1	Protractor	
1	Ruler	
1	Sheet of White Paper	
1	Pen or Pencil	

Introduction

In this activity you will observe dispersion through an acrylic rhomboid and calculate the different indices of refraction for different color light.



Figure 1: Dispersion from a Prism

Theory

Ordinary white light is a combination of waves with wavelengths extending over the visible spectrum (from red to violet). The speed of light in a vacuum is the same for all colors of light, but the speed in a material is different for different wavelengths. Therefore, the index of refraction of a material depends on the wavelength (color) of the light that passes through the material, and is a property of the incident light as well as a property of the material. If a beam of light contains more than one color of light, each color will refract by a different amount and each color will come out of the material traveling in a different direction. This is called dispersion: the separation of a beam of light into its component colors by refraction. When ordinary white light passes through a material, the dispersion is observed as a rainbow that comes out the other end.

Setup

1. Place a sheet of white paper on the lab bench, and then set the acrylic rhomboid (frosted side down) near the top-left corner of the paper. Adjust the orientation of the rhomboid to match that in Figure 2.
2. Use the pen or pencil to trace the outline of the rhomboid on the paper and then lift the rhomboid off the paper.

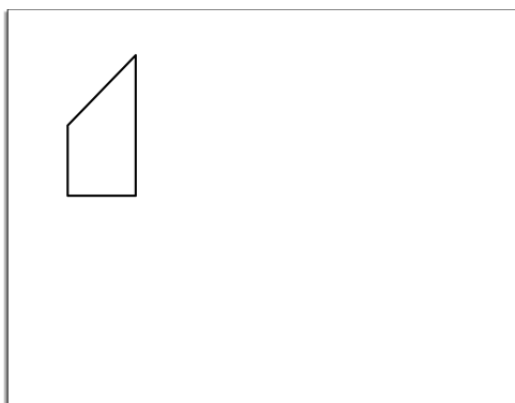


Figure 2: Rhomboid on Paper

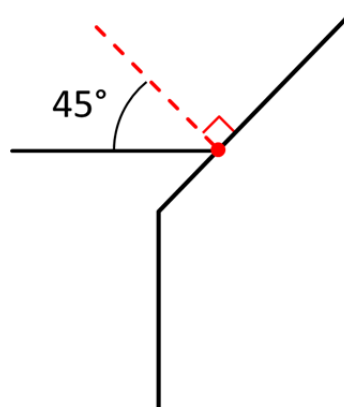


Figure 3: Rhomboid with Lines

3. Choose a point (any point) along the angled side of the outline, and then use the protractor to draw a normal line at that point similar to Figure 3.
4. At the same point, draw a 45° line relative to normal that extends outward from the outline similar to Figure 3.
5. Place the rhomboid back on the paper (frosted side down) and adjust its position so that it sits within the outline.
6. Place the basic optics light source flat on the lab table and rotate the knob on the front of the light source to produce a single ray of light as in Figure 4. Adjust the position of the light source so that the light ray is incident on the angled side of the rhomboid and aligned with the 45° line drawn on your paper.

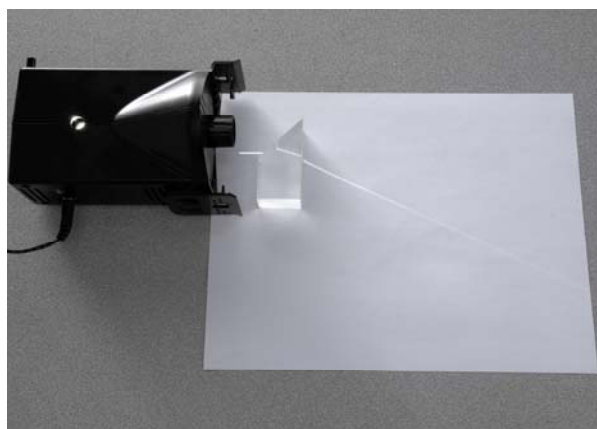


Figure 4: Single Ray of Light

Procedure

1. Observe the refracted light ray as it passes through the rhomboid and travels down the length of the paper. What colors can you see in the dispersed light (you may need to darken the room to see some colors better)?
2. The surface of the rhomboid at which the light ray leaves is called the "dispersion interface". Use the pen or pencil to carefully mark on the outline where the light ray exits the dispersion interface.
3. Follow the dispersed ray of light as far down the paper as possible without going off. At this point, carefully make a small mark where the blue light and red light reach the end of the paper. Similar to Figure 5.
4. Remove the rhomboid from the paper and use the ruler to draw a line between the point at which the incident ray hit the rhomboid and where it exited at the dispersion interface.
5. Use the ruler to draw a line connecting the point at which the light ray exited the dispersion interface and each color mark (red and blue) at the end of the paper. Label each line "red" or "blue" to differentiate them.
6. Finally, use the protractor to draw a line normal to the dispersion interface at the point from which the light ray exited, that bisects the dispersion interface, as in Figure 6.

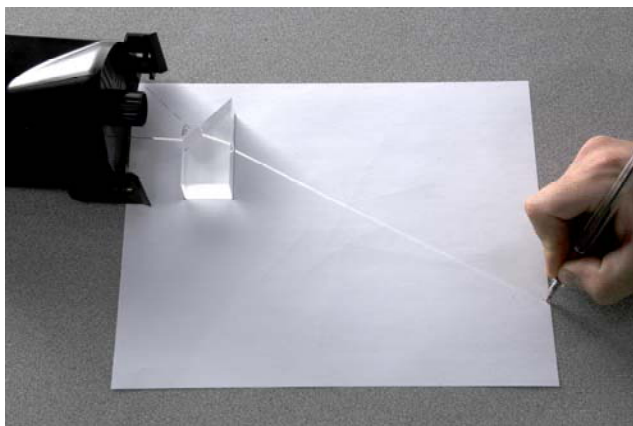


Figure 5: Marking the Paper

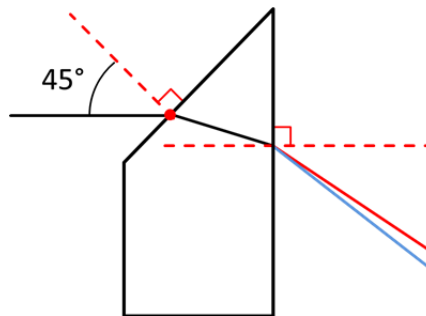


Figure 6: Dispersion Lines

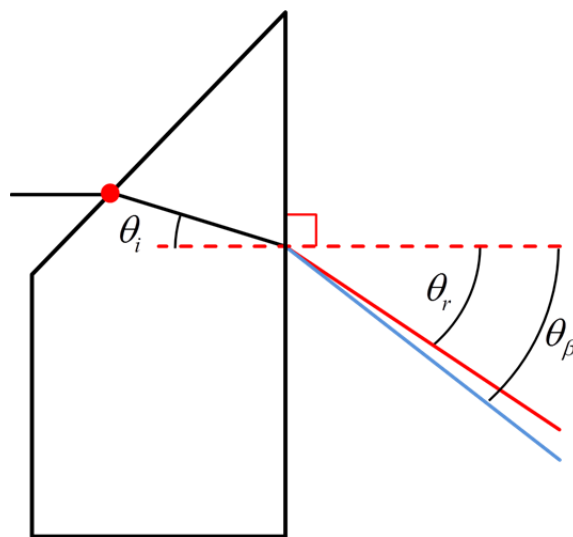


Figure 7: Dispersion Angles

Analysis

1. Use the protractor to measure the incident angle at the dispersion interface θ_i , as well as the dispersion angles θ_r for red light and θ_β for blue light as seen in Figure 7. Record all angles in degrees.
2. Based on the two different dispersion angles between red light and blue light, which color traveled faster in the acrylic rhomboid? How do you know?
3. Use Snell's Law to calculate the index of refraction for the two different colors of light (n_r for red and n_β for blue) in the acrylic rhomboid. Assume that the light ray basically remains a single white light ray (does not disperse much) as it travels through the rhomboid, and the index of refraction for air is 1.
4. Given the definition of index of refraction, and your values from the previous question, calculate the speed of each color light (v_r for red and v_β for blue) in the acrylic rhomboid. Record the results below.
5. In your own words, describe in a sentence or two the relationship between wavelength of light and the speed at which it travels through a medium (like acrylic).

Focal Length of a Concave Mirror

Equipment

1	Light Source, Basic Optics	OS-8517
1	Concave/Convex Mirror	OS-8457
1	Concave Mirror Accessory	OS-8532
1	Optics Bench, Basic Optics	OS-8518

Introduction

The purpose of this activity is to measure the focal length of a concave mirror. Use a light source, concave mirror, and half screen accessory on an optics bench to measure the focal length of the concave mirror.



Background

Concave and convex mirrors are examples of spherical mirrors. Spherical mirrors can be thought of as a portion of a sphere which was sliced away and then silvered on one of the sides to form a reflecting surface. Concave mirrors are silvered on the inside of the sphere and convex mirrors are silvered on the outside of the sphere.

If a concave mirror is thought of as being a slice of a sphere, then there would be a line passing through the center of the sphere and attaching to the mirror in the exact center of the mirror. This line is known as the principal axis. The point in the center of the sphere from which the mirror was sliced is known as the center of curvature and is denoted by the letter C in the diagram. The point on the mirror's surface where the principal axis meets the mirror is known as the vertex and is denoted by the letter A in the diagram. The vertex is the geometric center of the mirror. Midway between the vertex and the center of curvature is a point known as the focal point; the focal point is denoted by letter F in the diagram. The distance from the vertex to the center of curvature is known as the radius of curvature (abbreviated by "R"). The radius of curvature is the radius of the sphere from which the mirror was cut. Finally, the distance from the mirror to the focal point is known as the focal length (abbreviated by "f").

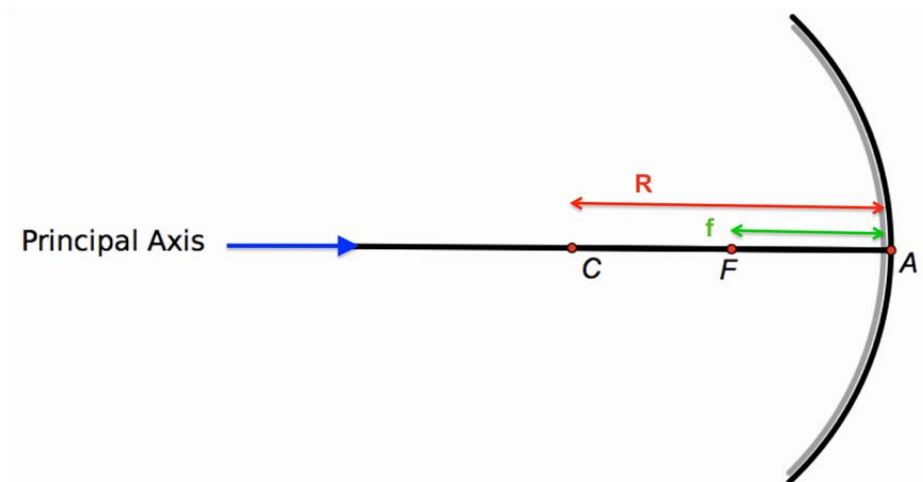


Figure 1: Concave Mirror

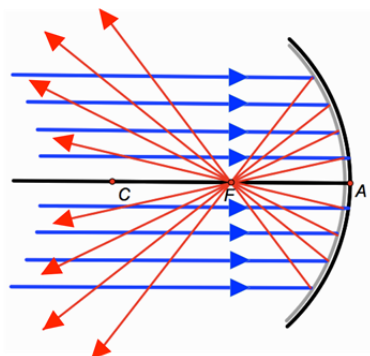


Figure 2: Focal point of the Concave Mirror

The focal point is the point in space at which light incident towards the mirror and travelling parallel to the principal axis will meet after reflection. The diagram at the right depicts this principal. In fact, if some light from the Sun was collected by a concave mirror, then it would converge at the focal point. Because the Sun is such a large distance from the Earth, any light rays from the Sun which strike the mirror will essentially be travelling parallel to the principal axis. As such, this light should reflect through the focal point.

The image formed by the light rays as they converge at the focal point of a concave mirror can appear on a card placed at the focal point. Because this image can form on a physical object, the image is known as a real image. This is in contrast to the other type of spherical mirror (a convex mirror) in which the light rays appear to converge at a point behind the mirror. Such images cannot be formed on a physical object, and are known as virtual images.

For any spherical mirror, the focal length f is related to the radius of curvature R of the mirror by:

$$f = \frac{1}{2} R$$

where R is always a positive value for a concave mirror.

Setup

1. Mount the Light Source at one end of the Optics Bench. Place the Concave Mirror at the other end of the Optics Bench.
2. Position the Light Source so the crossed arrow target is aimed at the Concave Mirror and the concave surface of the mirror faces the light source.
3. Place the Half-Screen a few centimeters in front of the Concave Mirror (between the mirror and the Light Source).



Procedure

1. Move the Half-Screen closer to or further from the Concave Mirror until the reflected image of the crossed arrow target on the white screen is focused.
2. Measure the distance between the position indicators on the Half-Screen and the Concave Mirror. Record the distance.



Figure 4: Crossed Arrow Target Image Focused on White Screen

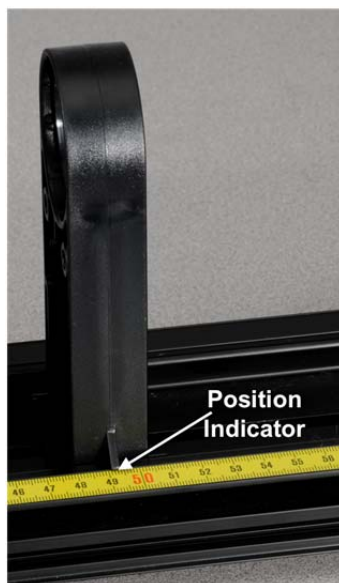


Figure 5: Position Indicator on Concave Mirror

Analysis

1. The focal length of the Concave Mirror is printed below the mirror. How does the measured distance compare to the focal length of the Concave Mirror?
2. How might you determine the focal length more accurately?
3. What is the orientation of the image of the crossed arrow target compared to the target itself?
4. How does the size of the image of the crossed arrow target compare to the target itself?

The Telescope and the Microscope

Equipment

Qty	Items	Part Number
1	Basic Optics Light Source	OS-8470
1	Optics Track	OS-8508
1	Basic Optics Viewing Screen	OS-8460
1	Geometric Lens Set	OS-8456
1	Accessory Lens Set	OS-8519
Required but not Included		
1	Metric ruler	
	Rubber bands	
1	Scissors	
	Tape	

Introduction

The telescope and the microscope are two important optical devices that use two lenses. In each device a primary lens (the *objective*) forms a real image and a secondary lens (the *eyepiece*) is used as a magnifier to make an enlarged virtual image. The purpose of this activity is to construct a simple telescope and a simple microscope and to measure their magnifications. Biconvex (convergent) thin lenses of focal lengths +100 mm and +200 mm will be used as the primary and eyepiece lenses. A viewing screen covered with a reference grid on an optics bench will be used to make measurements.

Theory

The Images Formed by Thin Lenses:

All the lenses used in this activity are thin compared to the other distances involved. Under these condition, the Thin Lens Formula can be used:

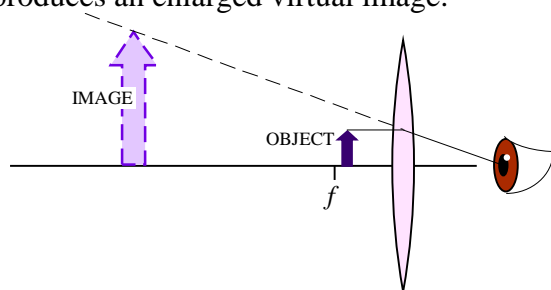
$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \quad [\text{Eq. 1 — The thin lens formula.}]$$

Here f is focal length, d_o is the distance between the object and the lens, and d_i is the distance between the image and the lens. The image formed by a thin lens can be described by its orientation (upright or inverted) and by its magnification (enlarged or reduced, compared to the original object). Both descriptors can be determined by taking the ratio of d_i to d_o :

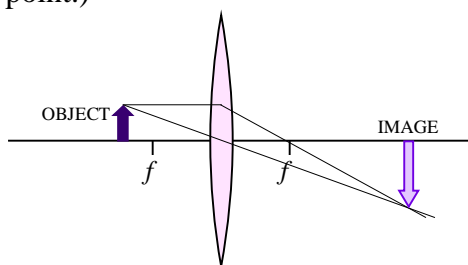
$$m = \frac{-d_i}{d_o} \quad [\text{Eq. 2 — The magnification.}]$$

The distance d_i is taken as negative if the image appears on the same side of the lens as the object (virtual image). Then, if m is positive, the image is upright. If m is negative, the image is inverted.

When an object is placed closer to a biconvex (convergent) lens than the focal length, the lens works as a magnifier and produces an enlarged virtual image.



When an object is placed farther from a biconvex (convergent) lens than the focal length, the lens produces an inverted, real image. (The image could be reduced or enlarged, depending how close the object is to the focal point.)



When two thin lenses are used, we analyze the distances by taking the image from one lens as the object for the second. The observer views an image that is “an image of an image.” The overall magnification, M , of the two-lens system is the product of the individual magnifications of each lens:

$$M = m_1 m_2 = \left(\frac{-d_{i1}}{d_{o1}} \right) \left(\frac{-d_{i2}}{d_{o2}} \right)$$

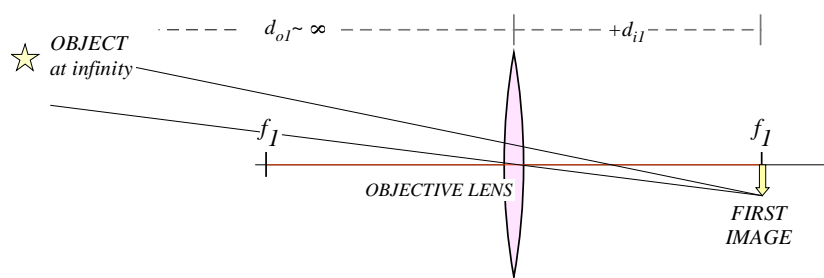
[Eq. 3 — The total magnification of a two-lens system.]

The Refractive Astronomical Telescope:

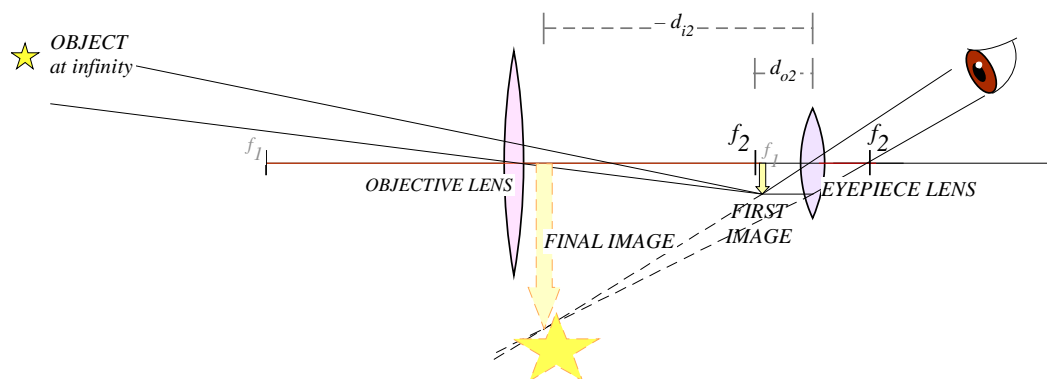
An astronomical telescope is used to view large objects that are at large distances from the lenses. A *refractive telescope* uses lenses and the principle is very simple: the objective lens produces a first real image of a very far away object. From the thin lens equation, notice that if the distance to the object is very large ($d_o \rightarrow \infty$), then,

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \approx \frac{1}{d_i},$$

and the image forms coincident with the objective's focal point. The eyepiece then is placed close to that first image, so that the first image falls within the eyepiece's focal length and is thus magnified. The closer the first image is to the eyepiece's focal point, the longer the distance to the final image. Astronomical telescopes are usually built so that the first image forms exactly at the focal point of the eyepiece lens. In this case, the separation between the lenses is exactly $d = f_1 + f_2$, which is the length of the telescope tube.



(a) The OBJECTIVE lens forms the first image.



(b) The EYEPIECE lens greatly magnifies the first image.

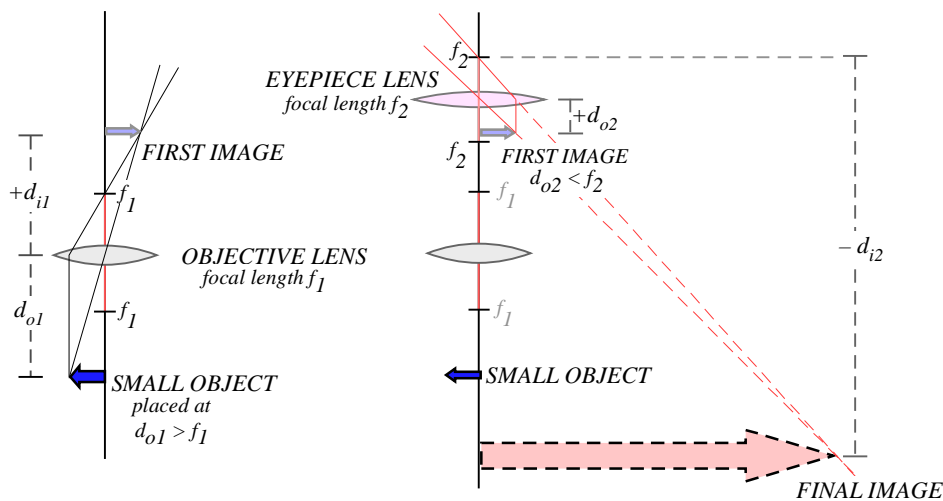
The magnification of an astronomical telescope with the object at infinity, and with f_1 and f_2 both coincident with the first image, is defined as the ratio of the focal length of the objective to that of the eyepiece:

$$M = \frac{-f_1}{f_2}$$

[Eq. 4 — The magnification of a telescope with object at infinity.]

The Compound Microscope

A compound microscope is used to view small objects that are very close to the lenses. A microscope is useful when the magnification required is more than what can be obtained with a single magnifier lens. The principle is very simple: the objective lens produces a first real image of the object, by having the object be just beyond its focal length. The eyepiece will then be placed very close to that first image, so that the first image falls within the eyepiece's focal length and is thus greatly enlarged.



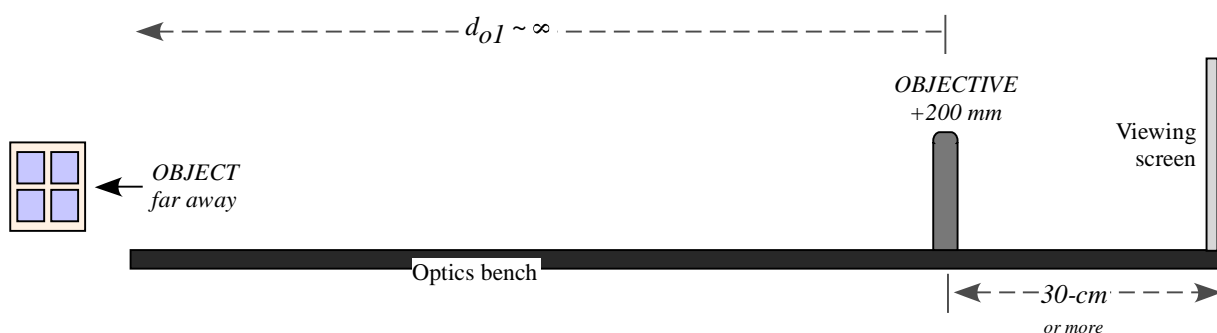
(a) The **OBJECTIVE** lens forms the first image. This image is real, inverted and reduced.

(b) The **EYEPIECE** lens forms the final image using the first image as its object. This final image is virtual and greatly enlarged.

Procedure A

The Astronomical Telescope: Looking at a Far Away Object

1. Set the optics bench on a table so that one end points to an open window or open door or a lamp at the opposite end of the classroom. Dim the lights inside the classroom.
2. Mount the +200 mm lens on the opposite side of the bench, at least 30-cm away from the end. (This space is needed to install the eyepiece later.) Install the viewing screen at the end of the track.



3. Move the viewing screen towards the lens until a sharp image of the object is seen. According to the theory, if the object is infinitely far away, then the first image forms at the focal point of the objective lens. (Does this hold true? Is the image forming about 20-cm from the lens?) Make fine adjustments around the focal point until the image is very sharp.
4. Make a note of the exact positions along the track of the objective lens and the first image in the Data Table.
5. Write a description of this first image in the Data Table: Is it inverted or upright? Is it enlarged or reduced? Is it real or virtual?
6. Mount the +100 mm eyepiece 10 centimeters behind the first image. This should make the separation between the lenses 30-cm (that's the telescope's lengths: $f_1 + f_2$), plus or minus any small adjustment made in step 3.
7. Remove the viewing screen, but keep track of the position of the first image. It is useful to mark the position with a piece of tape on the side of the track.
8. With only one eye open, look through the eyepiece directly toward the object. Move the eyepiece forward or backwards a little bit, as needed, until you comfortably see a very sharp, enlarged image of the object. You should not be squinting or forcing your eye into focus. Move the eyepiece until the image comes into focus without any strain on your eyes.
9. Record the position of the eyepiece in the Data Table.
10. Visually estimate the magnification of this telescope: position yourself where you can see both the image and the object comfortably. Hold a ruler a fixed distance near your eyes and measure the apparent height of both the image and the object. You may need to open and close your eyes in turns, and focus on the ruler to do this, but as best as you can keep your eyes and the ruler in the same position. Record the estimates in the data table.

Analysis A

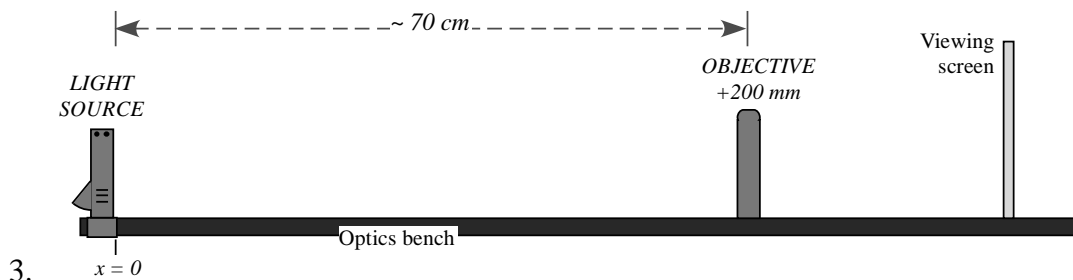
The Astronomical Telescope: Looking at a Far Away Object

1. Use the recorded positions to determine the following distances:
 - Distance from the objective lens to the first image, d_{i1} .
 - Distance from the first image to the eyepiece lens, d_{o2} .
2. Use the thin-lens formula (Eq. 1) to calculate the distance from the eyepiece to the final image, d_{i2} .
3. Calculate the magnification of the second image, $m_2 = -d_{i2}/d_{o2}$.
4. Calculate the theoretical magnification, ...

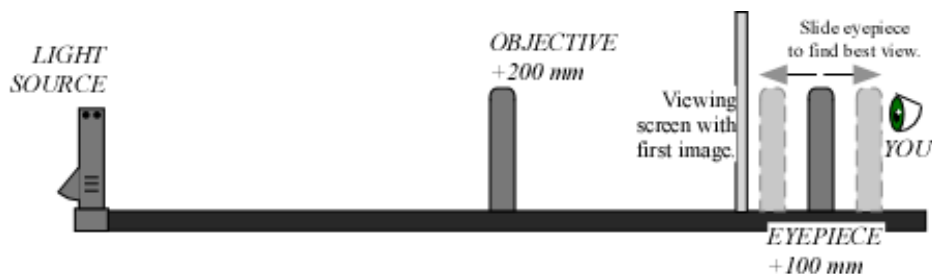
Procedure B: The Astronomical Telescope: Looking at a Nearby Object

In this part of the experiment the telescope arrangement will be used to examine an object that is a finite distance from the lenses. It will no longer be assumed that $d_{o1} \rightarrow \infty$.

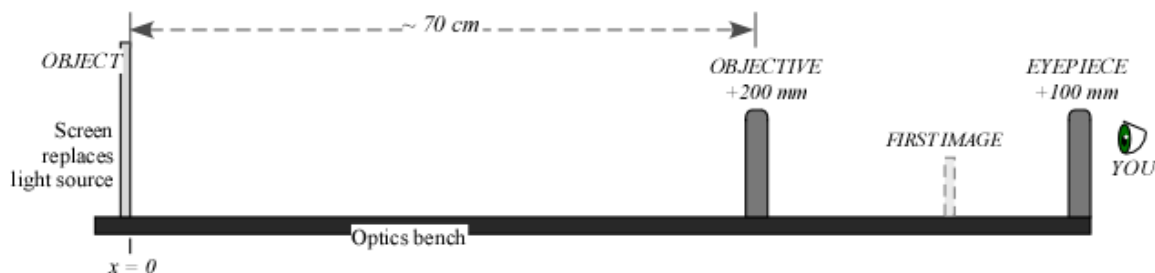
1. Install the Light Source so that its front edge (the side with the crossed-arrows) is at the $x = 0$ mark on the track. Turn the light source on.
2. Place the +200-mm lens about 70 cm away from the light source and place the viewing screen behind the lens, as illustrated.



3. Move the viewing screen forward or backward until a sharp image of the crossed-arrows is seen. This is the first image. Record the position of the objective and the first image in the Data Table.
4. Write a description of this first image in the Data Table: Is it inverted or upright? Is it enlarged or reduced? Is it real or virtual?
5. Install the +100 mm lens (the eyepiece) directly behind the viewing screen.
6. With your eye close to the +100-mm eyepiece, look through the lens as you move it back away from the viewing screen. Stop when you are comfortably seeing a sharp and enlarged image of the back of the viewing screen. (You are using this lens as you would a magnifier glass, so adjust forward-and-backward until you get the best possible view of a magnified screen holder.)



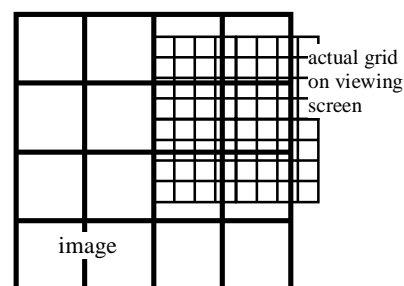
8. Remove the viewing screen, but remember the location of the first image. It helps to mark the location with a piece of tape on the side of the track.
9. Tape a copy of the grid (see the last page) onto the viewing screen.
10. Replace the light source with the viewing screen. The first image is now an image of the grid.



11. *Check for and Eliminate the Parallax.* Parallax is an apparent shifting of the image with respect to the background due to the motion of the observer. It happens when the image is not in same plane as the object (grid pattern).

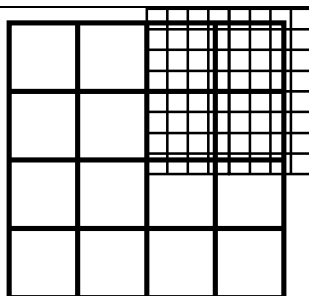
Check to see if your image shows parallax:

- Open both eyes and look through the lens at the image with one eye while looking ‘around the edge’ of the lens at the grid pattern with the other eye. You should see the image-grid on top on a dimmer, smaller grid, as illustrated.
- You may also see that the lines tend to curve near the edges of the lens, which is not shown in the illustrations.
- Move your head up and down or side to side and observe how (or if) the image moves with respect to the grid.

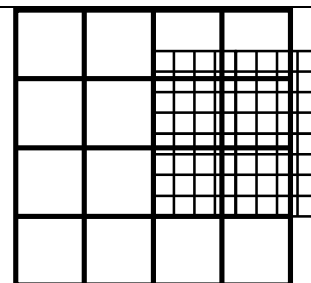


Parallax — the image appears to freely float in all directions above the actual grid.

If there is parallax, the image-grid will change position with respect to the smaller grid as you move your head.



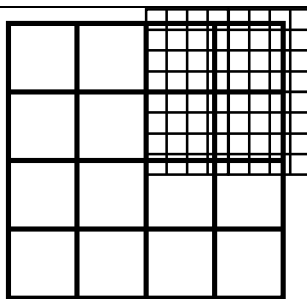
(a) The view with both eyes open.



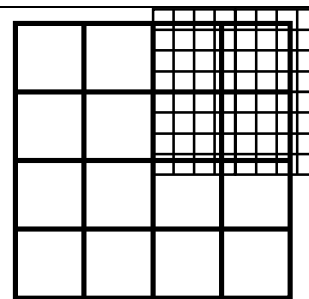
(b) Move your head and the image displaces with respect to the grid.

NO parallax — the relative position of the image and the grid stay fixed for any position of the observer.

If there is *NO parallax*, then as you move your head the position of the image with respect to the background will not change. They will appear to be stuck together.

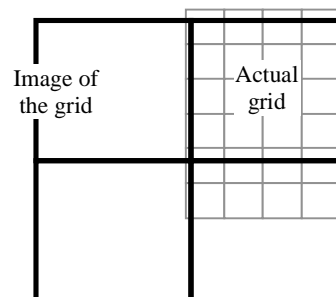


(a) The view with both eyes open.



(b) The view from any position of your head is the same.

12. If you found that your image shows parallax, move the eyepiece lens until the image lines do not shift relative to the object lines when you move your head.
13. At this point record the position of the eyepiece in the Data Table.
14. Visually estimate the total magnification of this telescope by counting the number of squares in the grid pattern that lie inside of one square of the image. Record the estimate in the data page.



In this example there are about 4 grid squares inside 1 image square.

15.

Analysis B

The Astronomical Telescope: Looking at a Nearby Object

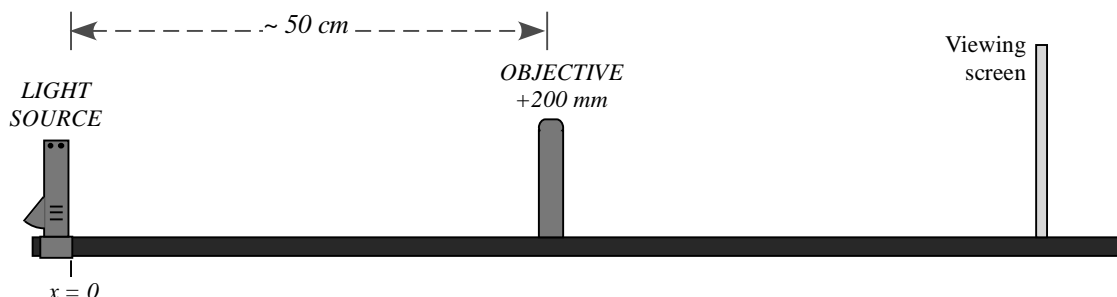
1. Use the recorded positions to determine the following distances:
 - Distance from object to objective lens, d_{o1} .
 - Distance from objective lens to the first image, d_{i1} .
 - Distance from the first image to the eyepiece lens, d_{o2} .
2. Use the thin-lens formula (Eq. 1) to calculate the distance from the eyepiece to the final image, d_{i2} .
3. Calculate the magnification of the images, m_1 and m_2 .
4. Calculate the total magnification of the telescope, M .

Procedure C

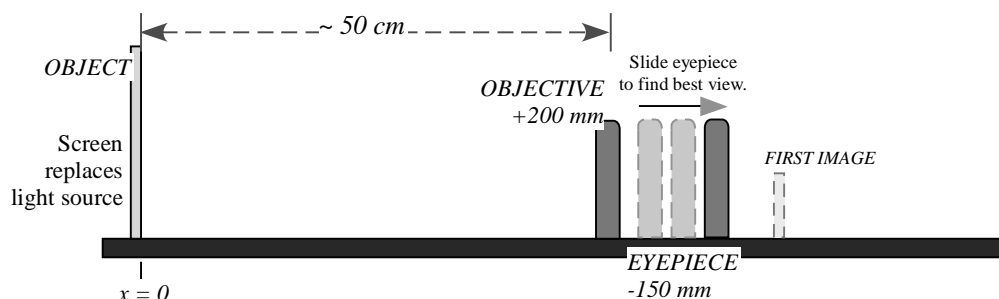
The Galileian Telescope: Using a Negative Eyepiece

The famous telescope built by Galileo near 1609 used a diverging convex lens as the eyepiece. In this part of the experiment this design will be compared to the astronomical telescope built in the previous activities, in which a convergent lens was used as the eyepiece.

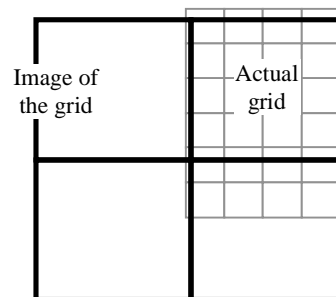
1. Install the Light Source so that its front edge (the side with the crossed-arrows) is at the $x = 0$ mark on the track. Turn the light source on.
2. Place the +200-mm lens about 50 cm away from the light source and place the viewing screen behind the lens, as illustrated.



3. Move the viewing screen forward or backward until a sharp image of the crossed-arrows is seen. This is the first image. Record the position of the object (the light source), the objective lens and the first image in the Data Table.
4. Write a description of this first image in the Data Table: Is it inverted or upright? Is it enlarged or reduced? Is it real or virtual?
5. Remove the viewing screen, but remember the location of the first image. It helps to mark the location with a piece of tape on the side of the track.
6. Tape a copy of the grid (see the last page) onto the viewing screen.
7. Replace the light source with the viewing screen. The first image is now an image of the grid.
8. Install the divergent -150-mm lens directly behind the objective lens. This will be the eyepiece.
9. Look through the eyepiece at the grid. Slide the eyepiece back (away from the objective) to find the best enlarged image of the grid. (Should not be blurry.)



10. *Check for and eliminate the parallax.* Go to Procedure B, step 10, for instructions on how to do this.
11. After removing the parallax (if any), record the position of the eyepiece in the Data Table. Notice that the eyepiece is between the objective and the first image. This is different from what happened when using a converging (positive) eyepiece.
12. Visually estimate the total magnification of this telescope by counting the number of squares in the grid pattern that lie inside of one square of the image. Record the estimate in the data page.



In this example there are about 4 grid squares inside 1 image square.

Analysis C

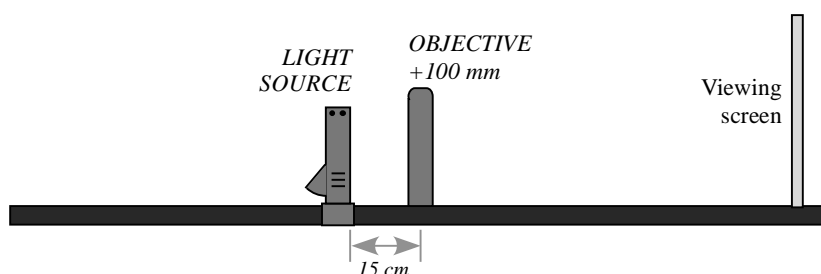
The Galilean Telescope: Using a Negative Eyepiece

1. Use the recorded positions to determine the following distances:
 - Distance from object to objective lens, d_{o1} .
 - Distance from objective lens to the first image, d_{i1} .
 - Distance from the first image to the eyepiece lens, d_{o2} .
2. The convention for using the thin lens equation requires that when both lenses end up on the same side of the first image, the “second object distance” be taken as negative. Add a negative sign to the distance d_{o2} and use it as such in any calculation.
3. Use the thin-lens formula (Eq. 1) to calculate the distance from the eyepiece to the final image, d_{i2} .
4. Calculate the magnification of the images, m_1 and m_2 .
5. Calculate the total magnification of this telescope, M .

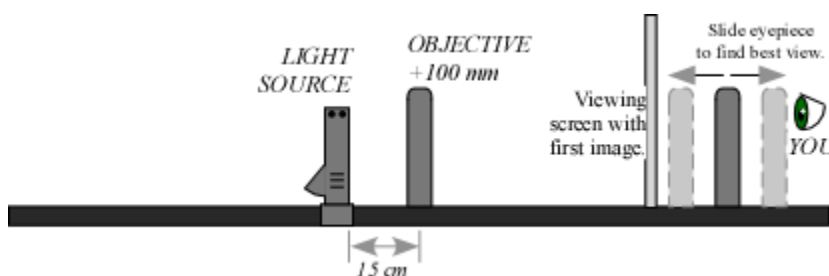
Procedure D

The Compound Microscope: Looking at a Nearby but Very Small Object

1. Mount the +100-mm lens about the middle of the track. In this part of the experiment, the +100-mm lens will be the objective.
2. Install the Light Source 15-cm behind the +100-mm lens, with the crossed-arrows facing the lens. Install the viewing screen on the other side of the lens, as illustrated.



3. Move the viewing screen towards the lens until a sharp image of the crossed-arrows is seen. This is the location of the first image.
4. Make a note of the exact positions along the track of the object (the light source), the objective lens and the first image in the Data Table.
5. Write a description of this first image in the Data Table: Is it inverted or upright? Is it enlarged or reduced? Is it real or virtual?
6. Mount the +200-mm lens directly behind the viewing screen. In this experiment, the +200-mm lens will be the eyepiece.
7. With your eye very close to the +200-mm lens, look through the +200-mm lens as you move it back away from the viewing screen. Stop when you are comfortably seeing a sharp and enlarged image of the back of the viewing screen. (You are just using this lens as you would a magnifier glass, so adjust forward-and-backward until you get the best possible view of a magnified screen holder.)



8. Remove the viewing screen, but remember the location of the first image. It is useful to mark this location with a piece of tape on the side of the track.
9. Remove the light source. It is no longer needed.
10. Use a rubber band to hold a copy of the grid (see last page) against the viewing screen. The rubber band is used instead of tape so that you can still move the grid and adjust its position later on.

11. Place the screen with the grid in the exact same position where the light source used to be. The grid has a very small message written in the middle of it. This will be the very small object we want to see through the microscope.
12. Look through the +200-mm lens (the eyepiece) and move your head around to find the image of the small message. You may need to move this lens just slightly to focus it. Move the grid, if needed, to center the message in your field of view. Can you read the message?
13. Record the position of the eyepiece lens (the +200-mm) in the Data Table.

Analysis D

The Compound Microscope: Looking at a Nearby but Very Small Object

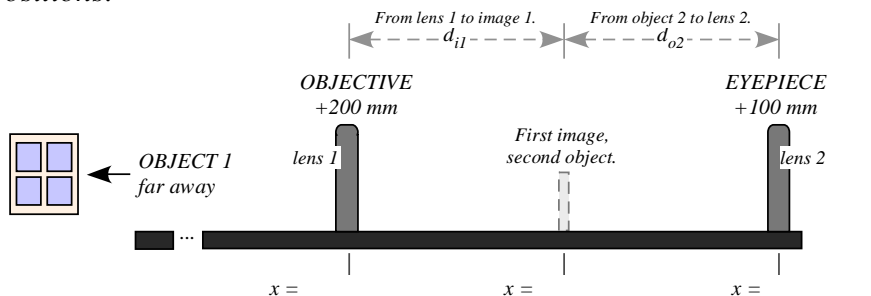
1. Use the recorded positions to determine the following distances:
 - Distance from object to objective lens, d_{o1} .
 - Distance from objective lens to the first image, d_{i1} .
 - Distance from the first image to the eyepiece lens, d_{o2} .
2. Use the thin-lens formula (Eq. 1) to calculate the distance from the eyepiece to the final image, d_{i2} .
3. Calculate the magnification of the images, m_1 and m_2 .
4. Calculate the total magnification of the microscope, M .

Lab Report: The Telescope and the Microscope

Name: _____

DATA TABLE PROCEDURE A: The Astronomical Telescope: Looking at a Far Away Object

Summary of Positions:



Visual Description of the First Image:

Orientation: _____

Magnification: _____

Type: _____

Summary of Distances:

FIRST IMAGE: $d_{o1} \rightarrow \infty$

$d_{i1} = \underline{\hspace{2cm}}$ cm

FINAL IMAGE:

$d_{o2} = \underline{\hspace{2cm}}$ cm

$d_{i2} = \underline{\hspace{2cm}}$ cm

(calculated)

$$\rightarrow m_2 = \frac{-d_{o2}}{d_{i2}} =$$

Visual Estimate of the Total Magnification:

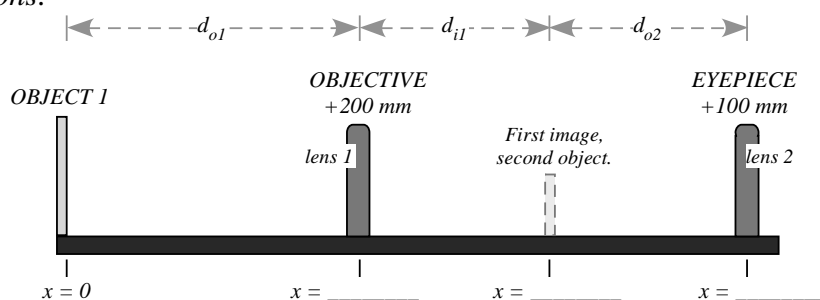
$$\left. \begin{array}{l} \text{Apparent height of image } h_i = \underline{\hspace{2cm}} \\ \text{Apparent height of object } h_o = \underline{\hspace{2cm}} \end{array} \right\} M_{\text{visual}} = \frac{-h_i}{h_o} =$$

Theoretical Total Magnification:

$$\left. \begin{array}{l} \text{Objective focal length } f_1 = \underline{\hspace{2cm}} \\ \text{Eyepiece focal length } f_2 = \underline{\hspace{2cm}} \end{array} \right\} M = \frac{-f_1}{f_2} =$$

DATA TABLE PROCEDURE B: The Astronomical Telescope: Looking at a Nearby Object

Summary of Positions:



Visual Description of the
First Image:

Orientation: _____

Magnification: _____

Type: _____

Summary of
Distances:

FIRST IMAGE:
$$\left. \begin{array}{l} d_{o1} = \text{_____ cm} \\ d_{i1} = \text{_____ cm} \end{array} \right\} \rightarrow m_1 = \frac{-d_{i1}}{d_{o1}} =$$

FINAL IMAGE:
$$\left. \begin{array}{l} d_{o2} = \text{_____ cm} \\ d_{i2} = \text{_____ cm} \\ \text{(calculated)} \end{array} \right\} \rightarrow m_2 = \frac{-d_{o2}}{d_{i2}} =$$

Visual Estimate of the Total Magnification:

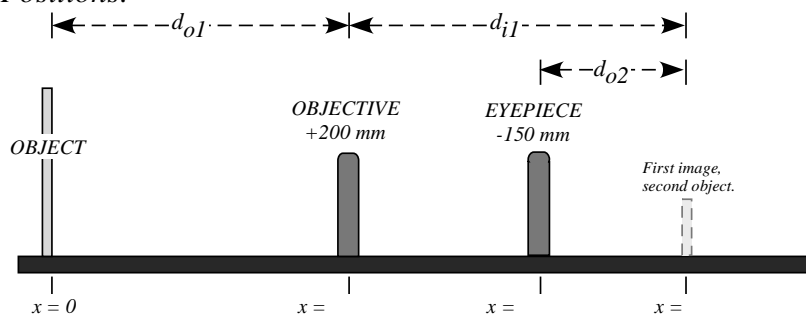
There are $n_o =$ _____ squares of the object,
inside $n_i =$ _____ squares of the image.
$$\left. \right\} M_{\text{visual}} = \frac{-n_o}{n_i} =$$

Theoretical Total Magnification:

$$M = m_1 m_2 =$$

DATA TABLE PROCEDURE C: The Galilean Telescope: Using a Negative Eyepiece

Summary of Positions:



Visual Description of the
First Image:

Orientation: _____

Magnification: _____

Type: _____

Summary
of
Distances:

FIRST IMAGE: $\left. \begin{array}{l} d_{o1} = \underline{\hspace{2cm}} \text{ cm} \\ d_{i1} = \underline{\hspace{2cm}} \text{ cm} \end{array} \right\} \rightarrow m_1 = \frac{-d_{i1}}{d_{o1}} =$

FINAL IMAGE: $\left. \begin{array}{l} d_{o2} = \underline{\hspace{2cm}} \text{ cm} \\ d_{i2} = \underline{\hspace{2cm}} \text{ cm} \\ \text{(calculated)} \end{array} \right\} \rightarrow m_2 = \frac{-d_{o2}}{d_{i2}} =$

Visual Estimate of the Total Magnification:

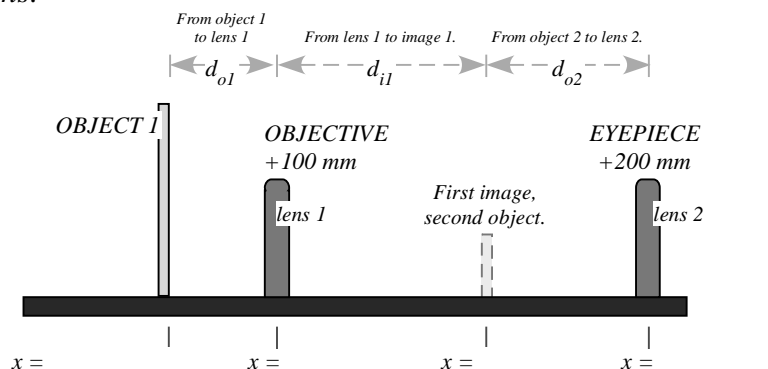
There are $n_o = \underline{\hspace{2cm}}$ squares of the object,
inside $n_i = \underline{\hspace{2cm}}$ squares of the image. $\left. \vphantom{\begin{array}{l} n_o \\ n_i \end{array}} \right\} M_{\text{visual}} = \frac{n_o}{n_i} =$

Theoretical Total Magnification:

$$M = m_1 m_2 =$$

DATA TABLE PROCEDURE D: The Compound Microscope: Looking at a Nearby but Very Small Object

Summary of Positions:



Visual Description of the First Image:

Orientation: _____

Magnification: _____

Type: _____

Summary of Distances:

FIRST IMAGE: $\left. \begin{array}{l} d_{ol} = \text{_____ cm} \\ d_{il} = \text{_____ cm} \end{array} \right\} \rightarrow m_1 = \frac{-d_{il}}{d_{ol}} =$

FINAL IMAGE: $\left. \begin{array}{l} d_{o2} = \text{_____ cm} \\ d_{i2} = \text{_____ cm} \\ \text{(calculated)} \end{array} \right\} \rightarrow m_2 = \frac{-d_{o2}}{d_{i2}} =$

Total Magnification:

$$M = m_1 m_2 =$$

What is the message?

QUESTIONS for PROCEDURES A, B and C: Telescopes

1. It should have been immediately obvious that when you look through the astronomical telescope (procedures A and B) the image is upside down. Discuss: Is this a big problem when making astronomical observations?
2. In contrast: What is the orientation of the final image in the Galilean telescope?
3. Is the final image from a telescope real or virtual? How can you tell?
4. How good were your visual estimates of the total magnification of the telescopes, as compared to the theoretically expected values? Discuss what makes the visual estimates hard to measure in each case.
5. According to Eq. 3, the total magnification of a two lens system is $M = m_1 m_2$. Go to Procedure A: use the theoretical magnification and the calculated value for m_2 , to calculate what must have been the magnification of the first image, m_1 . Does the value of matches your visual observations? Discuss.

6. Use your calculation of m_1 (question 4) and Eq. 2 to determine the distance from the objective to the object, d_{o1} (the one we assumed was infinite). Discuss: does the calculated distance seem realistic, given the actual object you were looking at? Why yes or why not? Was it reasonable, then, to assume that $d_{o1} \rightarrow \infty$?
7. In general, which type of telescope would require a longer tube-length, an astronomical telescope or a Galilean telescope? Why?

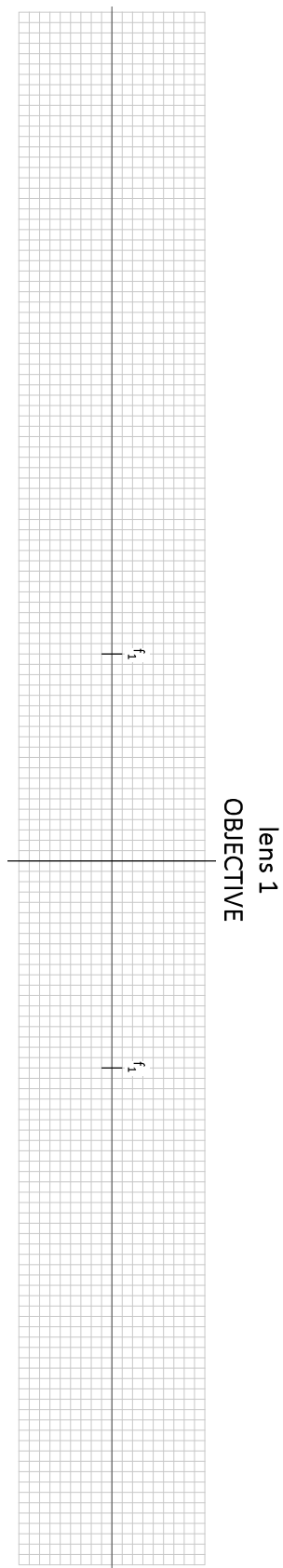
QUESTIONS for PROCEDURE D: The Compound Microscope

1. Is the final image of the microscope upright or upside down?
2. Is the final image of the microscope real or virtual? How can you tell?

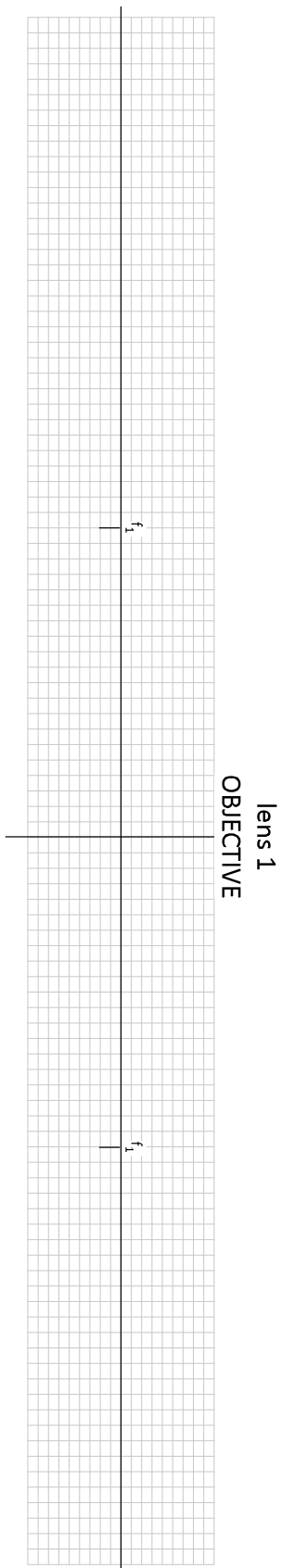
RAY DIAGRAMS

Use the grids provided in the next pages to trace principal ray diagrams for Procedures B, C and D.

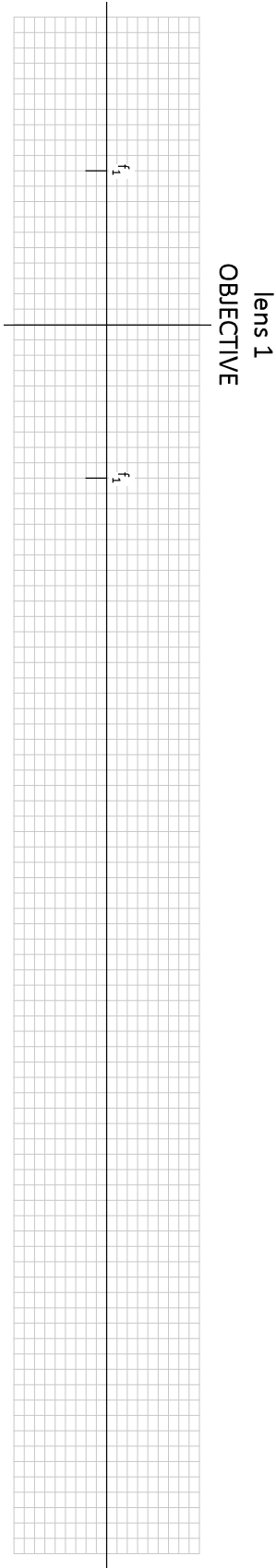
PROCEDURE B: The Astronomical Telescope: Looking at a Nearby Object



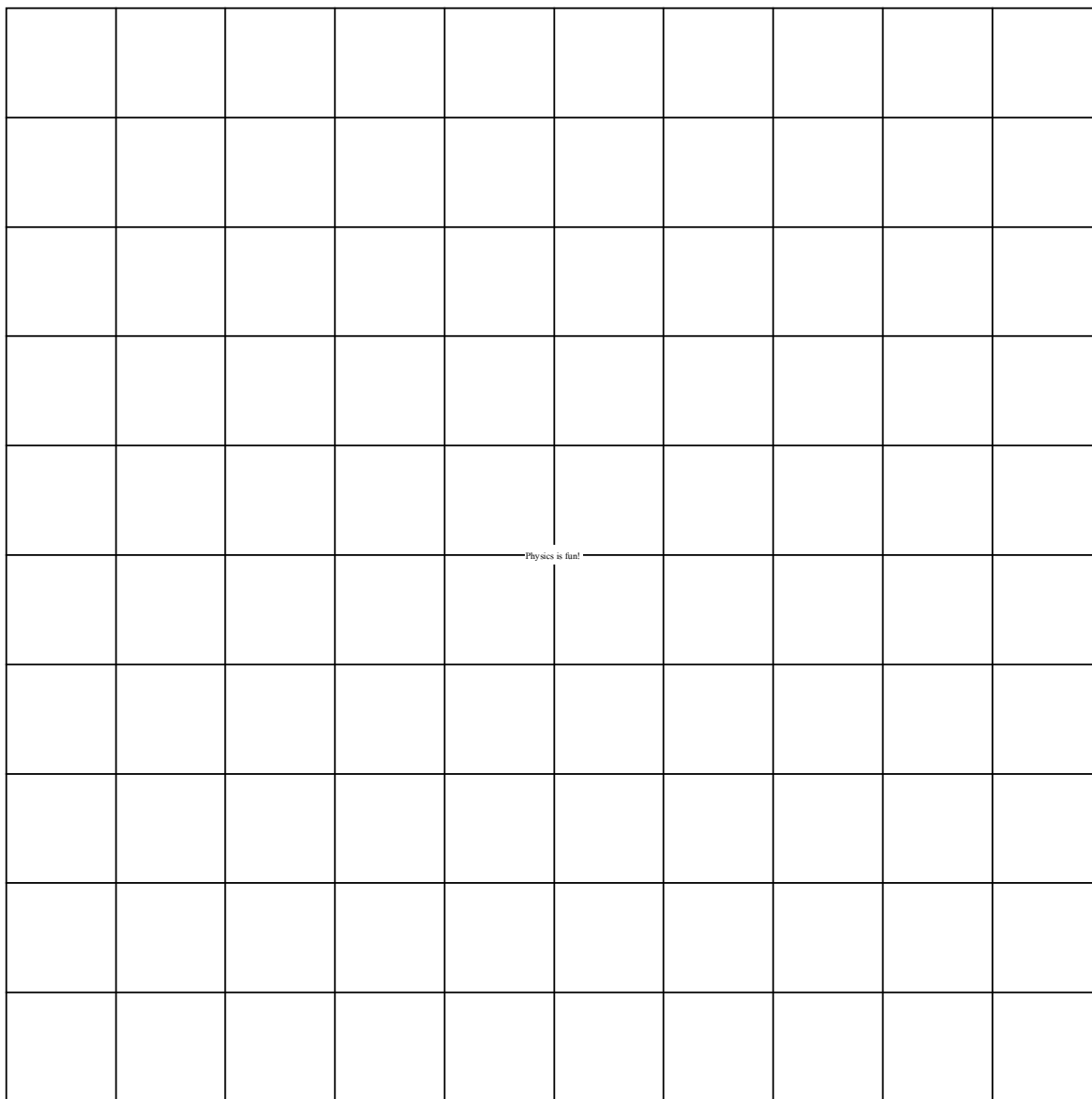
PROCEDURE C: The Galilean Telescope: Using a Negative Eyepiece



PROCEDURE D: The Compound Microscope



GRID PATTERN
Copy and attach to the Viewing Screen



Variation of Light Intensity

Equipment

1	High Sensitivity Light Sensor	PS-2176
1	Sensor Extension Cable	
1	Large Rod base	ME-8735
1	Rod, Stainless Steel, 45 cm	ME-8736
1	Multi Clamp	ME-9507
	Required but not included:	
1	Flashlight (or other DC light source)	
1	Incandescent Light Source (AC)	
1	Fluorescent Light Source (AC)	

Introduction

The purpose of this activity is to compare the variation in intensity of light from different light sources. Students will use a light sensor to record and compare incandescent versus fluorescent light sources, as well as light from AC versus DC sources.



Background

Electric light bulbs are powered by a voltage at a frequency of 60 Hz (or 50 Hz in some countries). The maximum amplitude of the voltage, and thus a maximum brightness from the bulb, occurs twice per cycle because an electric bulb is energized when the voltage increases, regardless of the polarity of the voltage. An electric bulb energized by alternating current will have maximum intensity 120 (or 100) times per second, as well as a minimum intensity (zero) 120 (or 100) times per second.

Fluorescent lights blink on and off at a particular frequency. Light from incandescent bulbs powered by alternating current fluctuates at well. The light intensity from a light bulb powered by direct current should not vary.

In this experiment you will use a High Sensitivity Light Sensor to measure the intensity of light from bulbs powered by AC and DC sources, monitoring the light intensity in an oscilloscope display and noting any variations in the intensity.

Using the Light Sensor

The High Sensitivity Light Sensor has three range settings. To select a range, press one of the buttons on the sensor. The button of the selected range is illuminated. Select a lower range to measure lower light levels with higher resolution. Select a higher range to measure brighter light.

Try the following to become more familiar with the Light Sensor:

1. Connect the light sensor via the sensor extension cable to the 850 interface.
2. Position the Light Sensor on the table so the aperture on the sensor is below an overhead light. Press the button on the sensor for the lowest range (candle icon).
3. Create a Digits Display and select Light Intensity.
4. Change the Sampling Mode to Fast Monitor. Set the sample rate to 1 kHz. Start monitoring data.
5. Switch the Light Sensor to the middle range setting and observe the value of Light Intensity in the Digits display.
6. Switch to the highest range setting and observe the value of Light Intensity in the Digits display.
7. Cover the Light Sensor aperture and observe the value of the value of Light Intensity.
8. Return the range to the middle setting. Pick up the sensor. Observe the value of Light Intensity as you move the Light Sensor closer to the overhead light source. Observe what happens when you move the Light Sensor farther from the light source.
9. Click "Stop" to stop monitoring data.



Figure 1: Aperture of Light Sensor Pointed at Overhead Light

Procedure: Incandescent AC

1. Change the Sampling Mode to Continuous. Create an FFT Display with Light Intensity on the vertical axis. Set the Sample Rate to 500 Hz.
2. Open the Recording Conditions and set a Start Condition on the measurement Light Intensity when it rises above 5. Then set a Stop Condition for Time-based so recording will stop after 3 seconds.
3. Place the Light Sensor on the table so the aperture faces the AC incandescent lightsource, as shown in Figure 2.
4. Position the Light Sensor approximately 0.5 m from the light source.
5. Turn off the room lights.
6. Begin recording data. Turn on the light source. Data will not appear in the FFT Display until you turn on the light source, and will automatically stop recording after 3 seconds. Turn off the light source.
7. Use the Scale Axis tool in the FFT Display to rescale the axes as necessary so you can see the frequency of the peak light intensity. You can also adjust the scale of each axis by dragging the numbers on the axis up, down, left, or right.
8. Use the Coordinates tool to measure the frequency of the peak light intensity. Record this value.



Figure 2: Setup of Incandescent AC Light Source

9. Create a graph of Light Intensity vs. Time. Set the sample rate to 1 kHz.
10. Turn on the light source.
11. Begin recording data. Data recording will automatically stop recording after 3 seconds. Turn off the light source.
12. Determine the number of times per second the light intensity fluctuates. One way to do this is to count the number of complete cycles that occur within a 0.1-second time period, and multiply by 10. Record this value.

Procedure: Fluorescent AC

1. Replace the incandescent light source with the fluorescent light source.
2. Begin recording data. Turn on the light source. Data will not appear in the FFT Display until you turn on the light source, and will automatically stop recording after 3 seconds. Turn off the light source.
3. Use the Scale Axis tool in the FFT Display to rescale the axes as necessary so you can see the frequency of the peak light intensity. You can also adjust the scale of each axis by dragging the numbers on the axis up, down, left, or right.
4. Use the Show Coordinates tool to measure the frequency of the peak light intensity. Record this value.
5. Turn on the light source.
6. Using the Light Intensity vs. Time graph, begin recording data. Data recording will automatically stop recording after 3 seconds. Turn off the light source.
7. Determine the number of times per second the light intensity fluctuates. Record this value.

Procedure: Incandescent DC

1. Replace the fluorescent light source with the incandescent DC light source.
2. Turn on the light source.
3. Begin recording data. Data will automatically stop recording after 3 seconds. Turn off the light source.
4. Use the Scale Axis tool in the FFT Display to rescale the axes as necessary so you can see the frequency of the peak light intensity. You can also adjust the scale of each axis by dragging the numbers on the axis up, down, left, or right.
5. Use the Show Coordinates tool to measure the frequency of the peak light intensity. Record this value.
6. Turn on the light source.
7. Using the Light Intensity vs. Time graph, begin recording data. Data recording will automatically stop recording after 3 seconds. Turn off the light source.
8. Determine the number of times per second the light intensity fluctuates. Record this value.

Analysis & Conclusions

1. How do the frequency of light intensity variation for the fluorescent AC bulb and the incandescent AC bulb compare to the accepted value for AC frequency?
2. How does the fluctuation of an incandescent bulb run on 60 Hz (or 50 Hz) AC differ from the fluorescent bulb?
3. How does the fluctuation of a light bulb run on 60 Hz (or 50 Hz) AC differ from the incandescent bulb powered by DC?

Light Intensity vs. Distance

Equipment

1	120 cm Optics Bench	OS-8508
1	Basic Optics Light Source	OS-8470
1	Aperture Bracket	OS-8534B
1	Large Table Clamp	ME-9472
1	45 cm Steel Rod	ME-8736
1	20 g hooked mass (Hooked Mass Set)	SE-8759
1	Thread	
1	High Sensitivity Light Sensor	PS-2176
1	Rotary Motion Sensor	PS-2120A
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

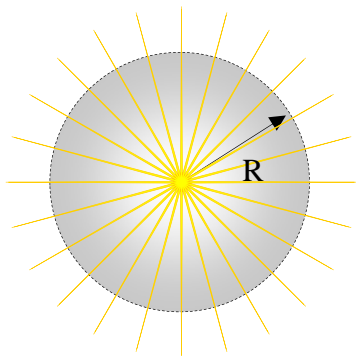
Introduction

The relative light intensity versus distance from a point light source is plotted. As the Light Sensor is moved by hand, the string attached to the Light Sensor that passes over the Rotary Motion Sensor pulley to a hanging mass causes the pulley to rotate, measuring the position. The experiment is repeated with an extended source.

This experiment needs to be done in a room with low light levels, but not totally dark.

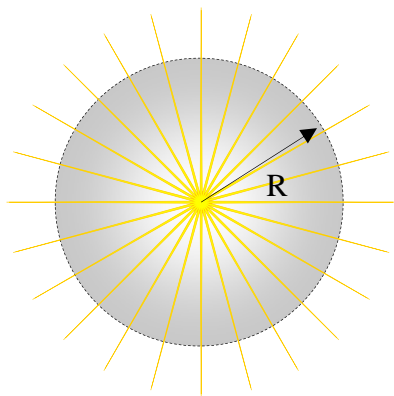
Various curves are fitted to the data to see which fits better.

This laboratory could also be used to model the Coulomb interaction, showing how an effect, whether lines of force or virtual particles, would be decreased as it is spread over an increasing area.



Theory

If light spreads out in all directions, as it does from a point light source, the intensity at a certain distance from the source depends on the area over which the light is spread. For a sphere of radius r , what is the equation for the surface area?



$$A = \underline{\hspace{2cm}}$$

Intensity is calculated by taking the power output of the bulb divided by the area over which the light is spread:

$$I = P/A \quad (1)$$

Where I is the intensity, P is the power and A is the area.

Put the surface area of a sphere into the intensity equation. How should the intensity of a point source depend on distance?

$$I = \underline{\hspace{2cm}} \quad (2)$$

Setup

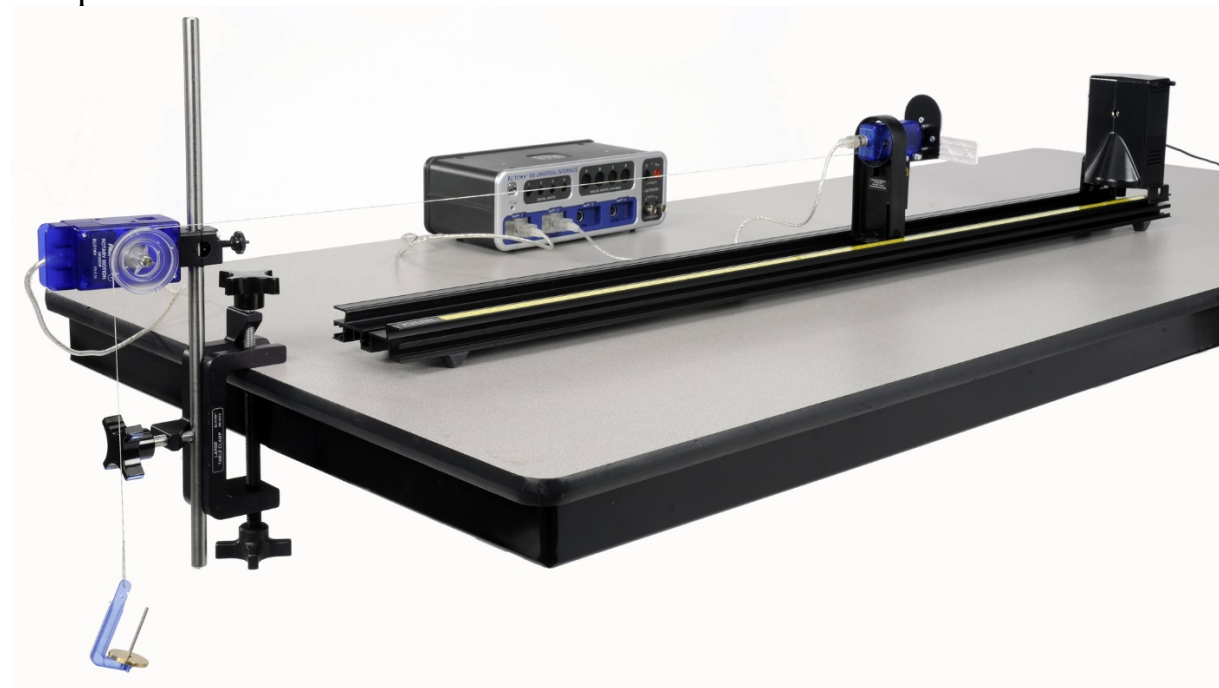


Figure 1: Complete Setup

1. Set up the equipment as shown in Figure 1. The thread is attached to the Aperture Bracket by tying the string through the hole as shown in Figure 2 and passes over the large pulley on the Rotary Motion Sensor to a hanging 10 g mass. The thread must be long enough so the white Aperture Disk can be 15 cm from the point source, but should not hit the floor when the Aperture Bracket is moved back as far as possible on the track. The thread should be horizontal and aligned parallel with the track but need not be centered on the Aperture Bracket. The Rotary Motion Sensor should be set so the thread is aligned with the pulley groove and does not pull sideways on the pulley.

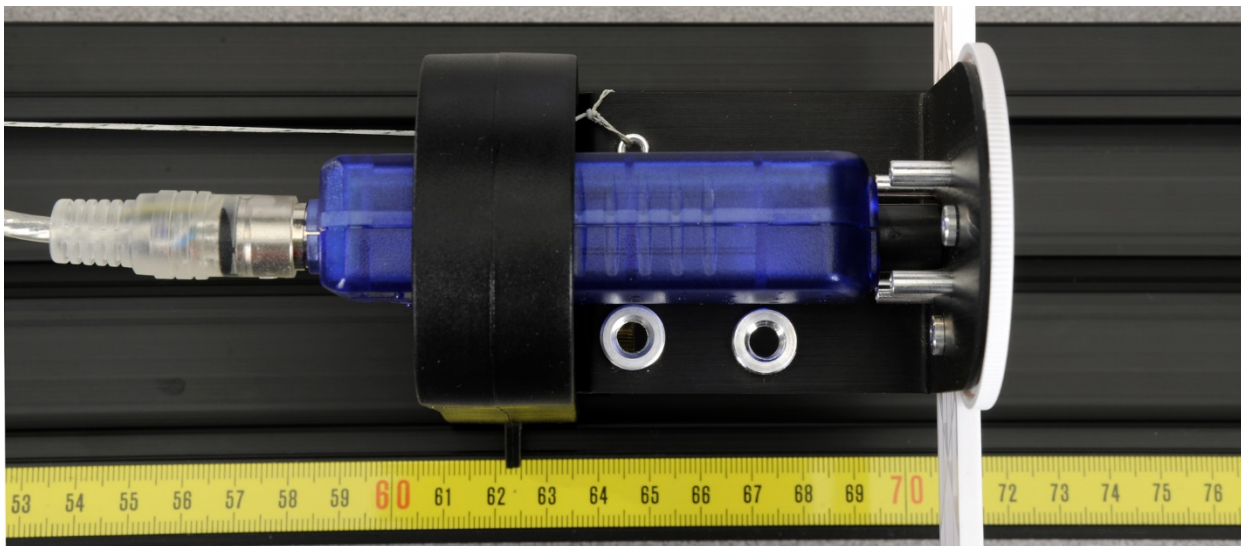


Figure 2: Tying the String to the Light Bracket

2. Attach the High Sensitivity Light Sensor to the Aperture Bracket using the screw.
3. Plug the Rotary Motion Sensor and the Light Sensor into the 850 Universal Interface.
4. In PASCO Capstone, set the Common sample rate to 10 Hz.
5. Create a digits display and select the Relative Intensity.

Procedure A: Sensitivity of the Light Sensor

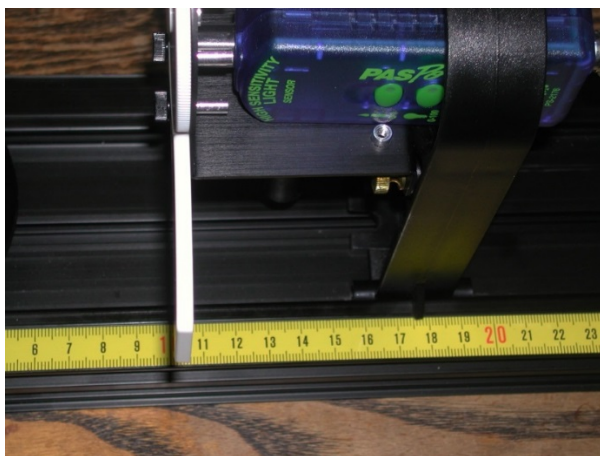


Figure 2: Positioning the Light Sensor

The sensitivity of the Light Sensor must be adjusted so it does not max out and so it is not set so low that the signal is poor.

1. Set the Basic Optics Light Source so the point light source is at 0.0 cm. The center of the point light source is indicated by the edge of the notch in the bottom of the light source bracket (see arrow on the bottom of the bracket). Set the front of the Light Sensor mask 10 cm from the center of the point light source. Note that you must sight down the front of the Light Sensor mask to see where it lines up with the track measuring tape (see Figure 2). Alternately, you can use the position indicator foot on the holder, the leading edge of which is 7.5 cm behind the front of the sensor mask. In the photo, the leading edge of the foot is at 17.5 cm.
2. Rotate the aperture bracket to the white circle.
3. Press the RECORD button and monitor the Intensity at 10 cm in digits display. Press the middle (0-100) button on the High Sensitivity Light Sensor. Apply power to the Point Light Source. The Intensity in the box at the right should be around 60%. If it is more than 90%, try starting further away from the source. If you start at a position different from 10 cm, record the value of your initial position. Unplug the Point Light Source. Click STOP. Click Delete Last Run.

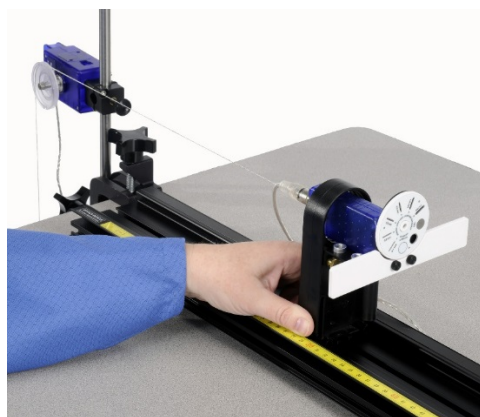


Figure 3: Moving the Light Sensor

Procedure B: Calibration Run

1. Open the calculator in Capstone and create the following calculations:

Abs position=abs([position])	Units of m
$I = [A]/(\text{abs}([position]) + [B])^D + [C]$	Units of %
A = 1	Units of m^2
B = 0.1	Units of m
C = 0	Units of %
D = 2	Unitless

2. Create a graph of Relative Intensity vs. Abs position. Note that Relative Intensity is graphed versus the absolute value of the position (Abs. position) measured by the Rotary Motion Sensor since the measured value may be plus or minus depending on the set-up. Also notice that 0 is where the sensor is when you click RECORD.
3. Turn off most of the room lights. With the point source off, we want the Relativity Intensity levels to not vary by more than a few percent as the Light Sensor is moved down the track. To check this (with the point source off), start with the Light Sensor 10 cm from the center of the light bulb, click RECORD and then slowly move the sensor away from the light source until the 10 g mass strikes the floor. Note that you should keep your hand and body behind the screen (see photo) to avoid reflecting light onto the screen. Click STOP. Click on the Scale-to-Fit button on the top left of the toolbar above the graph. If the variation is more than 0.2 %, click the Delete Last Run button, turn all of the room lights off and repeat the run. Click on the Data Summary button on the left side of the page. Click on any place that it says Run #1 and re-label it Calibrate Run. Click Data Summary again to close it.

Procedure C: Point Source/Extended Source Runs

1. Apply power to the Point Light Source.
2. With the Light Sensor 10 cm (or at the distance from Procedure A, part 3 where the Relative Intensity drops below 90%) from the center of the light bulb, click on RECORD. Hold the back of the Light Sensor holder and move the Light Sensor slowly away from the light source until the 10 g mass strikes the floor. As you do this, the thread will rotate the Rotary Motion Sensor, recording the distance the Light Sensor is from the bulb. Click STOP. Click Data Summary and re-label this as Point Source Run.
3. Reverse the Light Source so the target screen is now at 1.0 cm and facing the sensor.
4. With the Light Sensor at the same starting position as in part 2, click on RECORD. Hold the back of the Light Sensor holder and move the Light Sensor slowly away from the light source until the 10 g mass strikes the floor. Click STOP. As in part 1 above, click Data Summary and re-label this as Extended Source Run.

Analysis: Point Source

1. Select the Point Source Run using the Data Selector if it isn't already selected. Click on the Scale-to-Fit button so the graph fills the page. The scales on the left side and the right side must be the same. If they are not, move the hand icon over any number on the right side and drag up or down to match the scale on the left.
2. Examine Intensity calculation in the Calculator:

$$I = \{ A / (\text{abs}[\text{position}] + B)^D \} + C$$

The absolute value of position is taken since we want a positive distance, but the Rotary Motion Sensor may give negative values depending on how it is hooked up. Nominal values for A, B, C, & D are given. You need to choose better values for A, B, C, & D to improve the agreement between the measured Relative Intensity and the Theory intensity (I). To do this consider the following questions:

- a. What is the physical meaning of C? What value should you use and why?
- b. What is the physical meaning of B? Hint: when you started the measurement, the computer read your position as zero, but was it?
- c. Based on the equation you developed in the Theory section, what should D be?
- d. What should A be?

Analysis: Extended Source

1. In the calculator, create the following equations:

$I2 = [A2] / (\text{abs}([position]) + [B2])^{[D2]} + [C2]$	Units of %
$A2 = 1$	Units of m^2
$B2 = 0.1$	Units of m
$C2 = 01$	Units of %
$D2 = 2$	Unitless

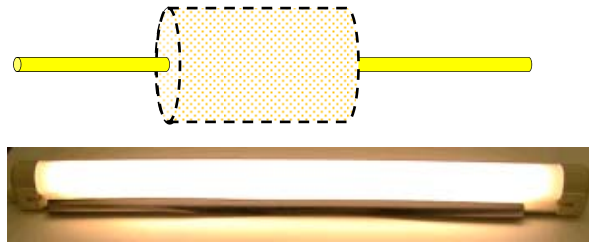
2. Select the Extended Source Run using the Data Selector if it isn't already selected. Click on the Scale-to-Fit button so the graph fills the page. The scales on the left side and the right side must be the same. If they are not, move the hand icon over any number on the right side and when the parallel plate icon appears click and drag up or down to match the scale on the left.
3. Examine calculation for the theoretical values for the Intensity ($I2$) as a function of position.

$$I2 = \{ A2 / (\text{abs}[position] + B2)^{D2} \} + C2$$
4. Note that the above equation is exactly the same as in the Analysis Point Source section except A becomes A2, B becomes B2, and so on. Set the values of A2, B2, C2, & D2 equal to the values of A, B, C, & D. Adjust the value of A2 so the curves have the same value at absolute position = 0. How well does your data fit the $1/r^2$ theory curve?
5. Now set $D2 = 1$. You will also need to increase A2 by a factor of 10 since at position = 0, you are now dividing by 0.1 instead of 0.1^2 .
6. Although the fit is not perfect, it should be reasonably close for the first 0.2 m from the source. That is, the intensity falls off like $1/r$ rather than $1/r^2$. Why does the $1/r$ fit fail as the distance becomes greater than 0.2 m?

Questions

1. How well did the theory I match the measured I? What does this show?
2. If $D = 1$, would it be possible to pick A, B, & C to make the theory I match the measured I? Try it!
3. If $D = 3$, would it be possible to pick A, B, & C to make the theory I match the measured I? Try it!

4. Suppose you repeated this experiment with a long fluorescent bulb and the Light Sensor is moved away from the bulb along an axis perpendicular to the light bulb and near its center. Would you expect the light intensity for this line of light to depend on distance in the same way as it does for a point light source? Why or why not? What dependence on distance would you expect?



5. Why do you think the extended source intensity dropped off like $1/r$ when the sensor was close to the source?

Polarization

Equipment

1	Polarization Analyzer	OS-8533A
1	Basic Optics Bench (60 cm)	OS-8541
1	Red Diode Laser	OS-8525A
1	High Sensitivity Light Sensor	PS-2176
1	Rotary Motion Sensor	PS-2120
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	UI-5400

Introduction

Laser light (peak wavelength = 650 nm) is passed through two polarizers. As the second polarizer (the analyzer) is rotated by hand, the relative light intensity is recorded as a function of the angle between the axes of polarization of the two polarizers. The angle is obtained using a Rotary Motion Sensor that is coupled to the polarizer with a drive belt. The plot of light intensity versus angle can be fitted to the square of the cosine of the angle allowing us to verify the Law of Malus.

As part of the two polarizer experiment, we demonstrate that the diode laser is 100% polarized. We use this to simulate a three polarizer system. The non-rotating polarizer is set perpendicular to the laser polarization so transmission is minimized. The analyzer is then placed between the laser and the fixed polarizer and the student finds that some of the beam is now transmitted. This allows a striking verification of the vector nature of the electric field. This experiment can be performed with the room lights on.

Theory

A polarizer only allows light which is vibrating in a particular plane to pass through it. This plane forms the "axis" of polarization. Unpolarized light vibrates in all planes perpendicular to the direction of propagation. If unpolarized light is incident upon an "ideal" polarizer, only half of the light intensity will be transmitted through the polarizer.

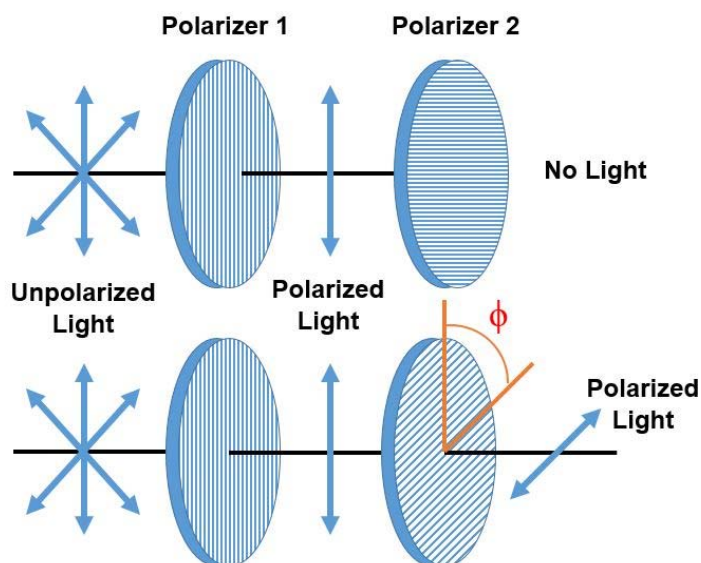


Figure 1: Light Transmitted through Two Polarizers

The transmitted light is polarized in one plane. If this polarized light is incident upon a second polarizer, the axis of which is oriented such that it is perpendicular to the plane of polarization of the incident light, no light will be transmitted through the second polarizer. See Figure 1. However, if the second polarizer is oriented at an angle not perpendicular to the axis of the first polarizer, there will be some component of the electric field of the polarized light that lies in the same direction as the axis of the second polarizer, and thus some light will be transmitted through the second polarizer.

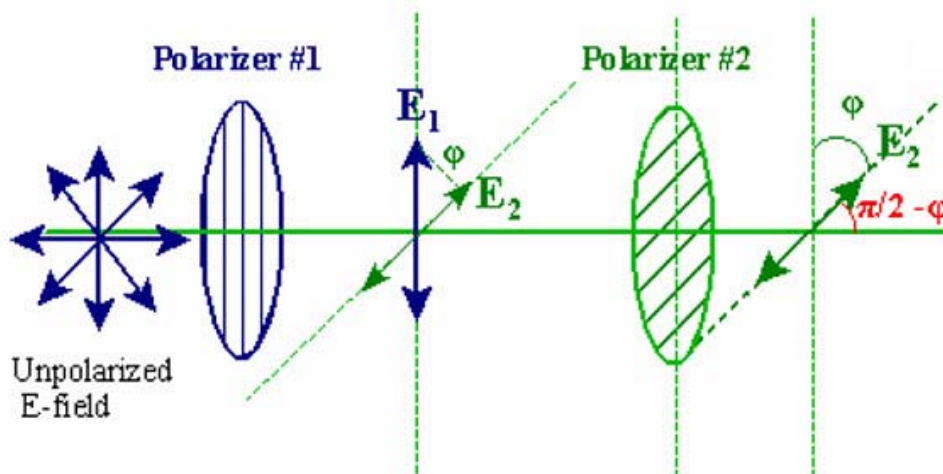


Figure 2: Component of the Electric Field

If the polarized electric field is called E_1 after it passes through the first polarizer, the component, E_2 , after the field passes through the second polarizer which is at an angle ϕ with respect to the first polarizer is $E_1 \cos \phi$ (see Figure 2). Since the intensity of the light varies as the square of the electric field, the light intensity transmitted through the second filter is given by

$$I_2 = I_1 \cos^2 \phi \quad (1)$$

Theory for Three Polarizers

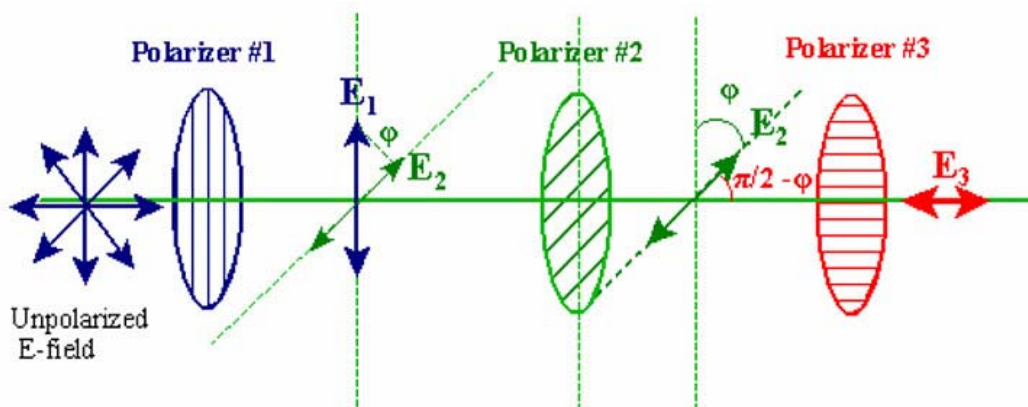


Figure 3: Electric Field Transmitted through Three Polarizers

Unpolarized light passes through 3 polarizers (see Figure 3). The first and last polarizers are oriented at 90° with respect each other. The second polarizer has its polarization axis rotated an

angle ϕ from the first polarizer. Therefore, the third polarizer is rotated an angle $(\pi/2 - \phi)$ from the second polarizer. The intensity after passing through the first polarizer is I_1 and the intensity after passing through the second polarizer, I_2 , is given by

$$I_2 = I_1 \cos^2 \phi$$

The intensity after the third polarizer, I_3 , is given by

$$I_3 = I_2 \cos^2 (\pi/2 - \phi) = I_1 \cos^2 \phi \cos^2 (\pi/2 - \phi) = I_1 \cos^2 \phi \sin^2 \phi \quad (2)$$

since $\cos (\pi/2 - \phi) = \sin \phi$.

Using the trigonometric identity, $\sin 2\phi = 2\cos\phi \sin\phi$, gives:

$$I_3 = (I_1/4)\sin^2 2\phi \quad (3)$$

So we predict that the maximum intensity will be four times smaller than the max intensity for the two polarizer case and that intensity will run through its full cycle in $\pi/2$ radians rather than π radians as was the case with two polarizers. This does assume that the polarizers are ideal and transmit 100% of the light aligned with their optical axis and 0% of the light perpendicular to their optical axis. This is not true for real polarizers and we expect that the intensity will not quite go to zero. It also means that the max intensity decreases when more polarizers are inserted in the beam even though all the optical axes are aligned with the beam. This does not affect our results since both the two and three polarizer experiments insert two polarizers in the beam.

Setup



Figure 4: Equipment Separated to Show Components

1. Mount the aperture disk on the aperture bracket holder.

2. Mount the Light Sensor on the Aperture Bracket with the attachment thumbscrew (not the 6 cm rod) and plug the Light Sensor into a PASPORT input on the 850 Universal Interface. Click the low sensitivity (0-10,000) button on the side of the Light Sensor.
3. Rotate the aperture disk so the open aperture is in front of the light sensor (see Figure 5).



Figure 5: The Aperture Disk

4. Remove the black rod attachment adaptor from the Rotary Motion Sensor (RMS) using the attached tool. Make sure the pulley on the RMS is mounted so the large pulley is toward the body of the RMS. Using the two mounting screws stored on the Polarization Analyzer bracket, mount the Rotary Motion Sensor on the polarizer bracket so the pulley is toward the bracket. Connect the large pulley on the Rotary Motion Sensor to the polarizer pulley with the plastic belt stored on the polarization bracket (see Figure 6).
5. Plug the Rotary Motion Sensor into a *PASPORT* input on the 850 Universal Interface.

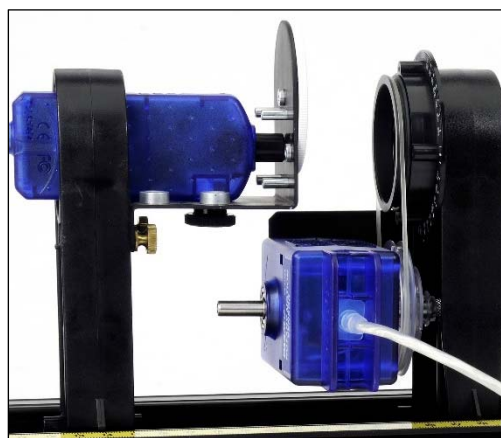
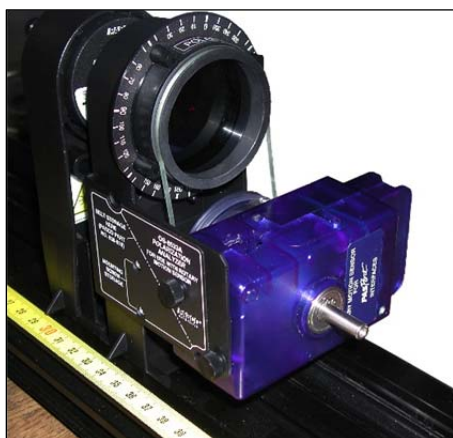


Figure 6: Rotary Motion Sensor Connected to Polarizer with Belt

6. In PASCO Capstone, set the Common Sample Rate to 100 Hz.
7. Create a graph of Relative Intensity vs. Time.
8. Push all the components on the Optics Track as close together as possible. See Figure 7. The aperture disk on the light sensor should not touch the Polarization Analyzer.

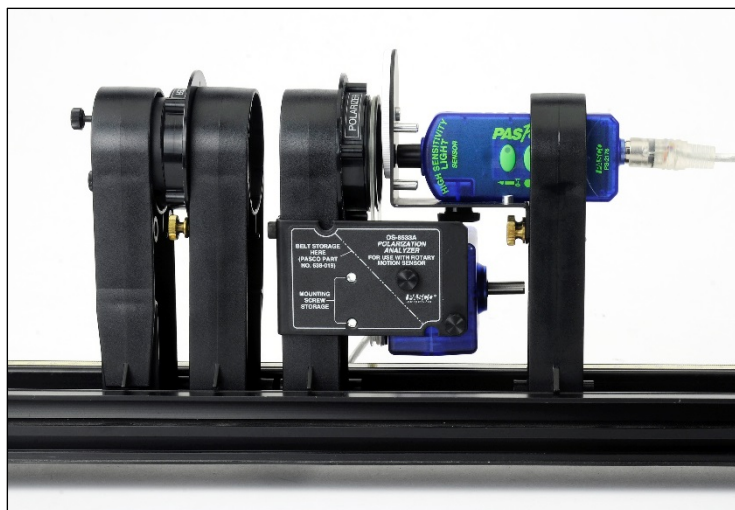


Figure 7: Setup with Components in Position for Experiment

Initial Procedure for Two Polarizers

To align the polarizers to allow the amount of light that passes through to be maximum:

1. Since the laser light is already polarized, the first polarizer must be aligned with the laser's axis of polarization. First remove the holder with the Polarization Analyzer and Rotary Motion Sensor from the track. Slide all the components on the track close together. Click RECORD and then rotate the polarizer that does not have the Rotary Motion Sensor through a full 360 degrees. Click STOP. Click the Scale-to-Fit button on the toolbar above the graph so the graph fills the page. Note that the transmitted intensity drops almost to zero (should be less than 0.5%) twice during the rotation. This proves that the diode laser is 100% (or nearly) polarized. The two maximums will probably not be equally high due to the fact that the polarizer is not quite ideal. Click RECORD and rotate the polarizer until the light intensity on the graph is at its maximum (the higher of the two maximums). Click STOP. Lock the polarizer in place with the brass bolts.
2. On the Sampling toolbar, click on the arrow next to the Delete Last Run button and choose Delete All Runs.
3. To allow the maximum intensity of light through both polarizers, replace the holder with the polarizer and Rotary Motion Sensor on the track, press RECORD, and then rotate polarizer that does have the Rotary Motion Sensor until the light intensity on the graph is at its maximum (see Figure 4 under the Setup A tab). Click STOP.
4. Delete the last run.

Procedure

1. Create a calculation that makes the angle positive regardless of which direction you rotate the analyzing polarizer:

Analyzer Angle = $\text{abs}([\text{Angle (rad)}])$ with units of rad

2. Create a graph of Relative Intensity vs. Analyzer Angle.
3. Note the angle that is at the top of the Polarization Analyzer (should be either 0 or 180 degrees).
4. Click RECORD and slowly rotate the polarizer 360 degrees (one revolution). Stop when the Relative Intensity is at a max. Then click STOP. Try to move slowly and steadily through the peak points. You may move faster between the peak points.
5. Click on the Data Summary button on the left of the screen. Click on this run and re-label it "2 Polar". Click Data Summary to close it.

Analysis for 2 Polarizers

1. If the graph does not fill the page, click the Scale-to-Fit tool at the upper left.
2. Click and drag the vertical axis to stretch out the curve so it is easier to see the minimum.
3. Click on the Smart Cursor from the graph toolbar. Position the cross-hairs directly above the minimums and read the angle at each of the minimums. How much has the angle changed going from minimum to minimum to minimum? Why?

Curve Fit for Two Polarizers

1. Equation 1 from the theory indicates that the intensity is dependent on the square of the cosine of the angle. On the graph, select a Cosine Squared fit.
2. How well does the theory work?

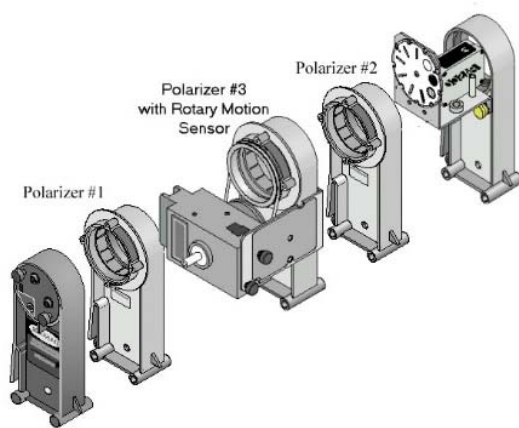
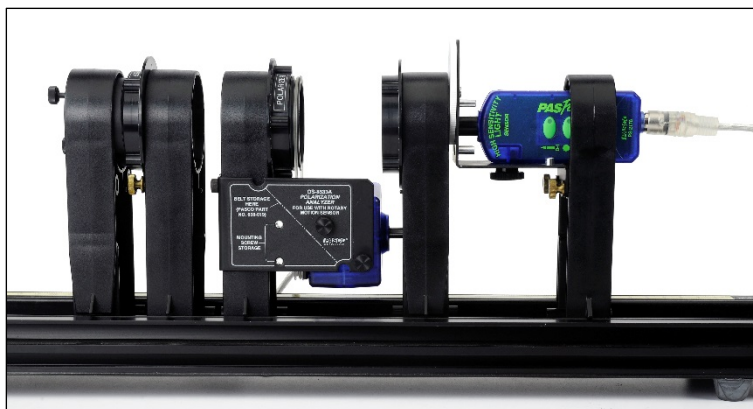


Figure 8: Three Polarizer Setup

Optional: Procedure for 3 Polarizers

1. Now repeat the experiment with 3 polarizers. If you do not have a third polarizer, borrow one from another lab group. Add the third polarizer between the light sensor and the Polarization Analyzer. See Fig. 8.
2. Remove the Polarization Analyzer.
3. Click RECORD and rotate the polarizer closest to the light sensor until the Relative Intensity is minimum. Click STOP. Tighten the brass bolt on that polarizer. Now the two polarizers are at right angles to each other. Click Delete Last Data Run (Caution: Don't delete "2 Polar"!!)
4. Place the Polarization Analyzer back on the track. Click RECORD and again adjust the Polarization Analyzer for minimum. Click STOP. Click Delete Last Data Run (Caution: Don't delete "2 Polar"!!)
5. Note the angle that is at the top of the Polarization Analyzer.
6. Click RECORD and slowly rotate the polarizer which has the Rotary Motion Sensor through 360 degrees (one revolution) in a either direction. Stop when the Relative

Intensity is at a minimum. Then click STOP. Try to move slowly and steadily through the turning points. You may move faster between the turning points.

7. Click on the Data Summary button on the left of the screen. Re-label this run “3 Polar”. Click Data Summary to close it.

Analysis for 3 Polarizers

1. Click on Run Select icon to display more than one set of data and then on the black triangle to select “2 Polar” and “3 Polar”.
2. Why are there twice as many cycles of “3 Polar” as “2 Polar”?
3. Equation 3 from Theory predicts that the “3 Polar” maximums should be $\frac{1}{4}$ as high as the “2 Polar” maximums. Does this check out correctly? Remember that the polarizers are not ideal.
4. What is the angle between the middle polarizer and the first polarizer (the laser polarization axis) to get the maximum transmission through all 3 polarizers?
5. What is the angle between the middle polarizer and the first polarizer to get the minimum transmission through all 3 polarizers?

Curve Fit for Three Polarizers

1. On the graph, select a User Defined Fit and enter in $y = D * (\sin(B * \phi))^2 + K$.
2. If the sine squared fit does not find a good fit initially, try changing the value of B and update the fit.
3. How well does the theory work? What is the value of B? Does it match the theory?

Brewster's Angle

Equipment

1	Basic Optics Light Source	OS-8470
1	Basic Optics Ray Table	OS-8465
1	Polarizer	OS-8533A

Background

When unpolarized light is incident on a transparent dielectric surface, most of the light is refracted through the transparent medium, but some light is also reflected, as in Figure 1. The amount of light reflected is dependent on the angle of incidence and the polarization of the incoming light.

In this experiment you will explore how the intensity and polarization of light changes when reflected from the surface of a transparent medium, and then compare your experimental results to a theoretical value known as Brewster's Angle.

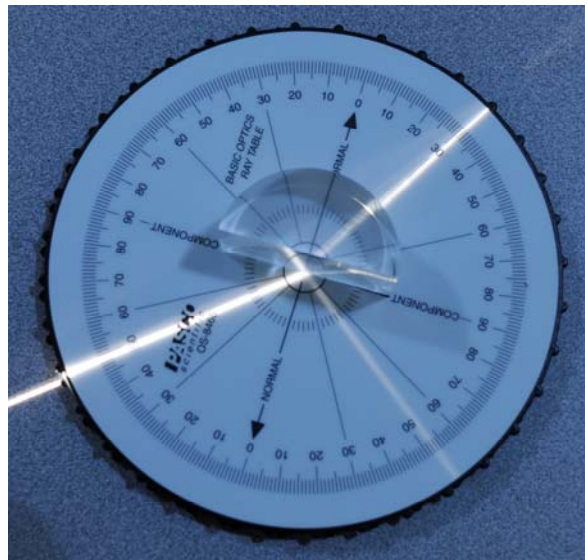


Figure 1: Light Being Reflected and Refracted

Setup

1. Set the Ray table on the lab bench, and place the clear acrylic D-shaped lens within the outline on the top of the ray table.
2. Connect the light source to power, and then adjust the dial on the front of it so that only one ray of light is emitted.
3. Turn off all the lights in the classroom.
4. Place the light source on the lab bench so that the front of it is as close to the ray table as possible without touching it, and the ray of light is incident on the center of the flat side of the D-shaped lens (similar to Figure 2).
5. Making sure to keep the light ray incident on the center of the flat side of the D-shaped lens, adjust the incident angle of the light ray to 25° .
6. Assuming all of the light that is incident on the D-shaped lens is either refracted or reflected, about what percentage of the incident light appears to be reflected?
7. Is the incident light ray polarized? If not, what could you do to make it polarized?
8. Increase the incident angle to several larger angles. What happens to the apparent percentage of incident light that is reflected as the incident angle increases?
9. Adjust the incident angle back to 25° .



Figure 2: Ray Table Setup

Collect Data

1. Close one eye and look down the path of the reflected light ray (as in Figure 3) observing the intensity of the reflected ray on the surface of the ray table.

NOTE: Your head should be near the plane of the lab table, and you may need to adjust the position of your head side-to-side to best see the reflected light ray.

2. Place the polarizer disk in front of your open eye and slowly rotate the disk one full revolution. What happens to the intensity of the reflected ray observed on the surface of the ray table as you rotate the polarizer disk?

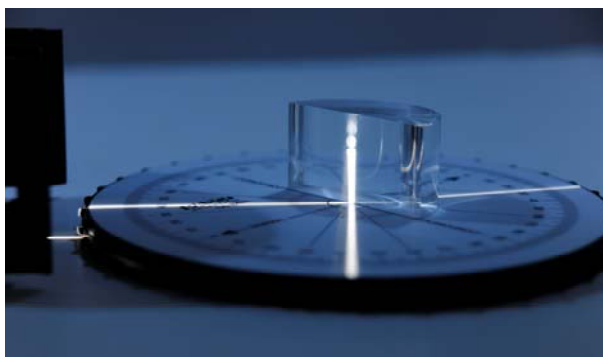


Figure 3: Viewing the Reflected Light

- Adjust the incident angle to 40° and repeat the previous steps. What happens to the intensity of the reflected ray observed on the surface of the ray table as you rotate the polarizer disk?
- What happened to the polarization of the reflected light ray when the incident angle was increased? How does the polarizer disk indicate the polarization of the reflected light ray?
- Observe the reflected light ray using the polarizer disk for each incident angle between 45° and 75° , using 5° increments. Be sure to rotate the polarizer disk one full revolution for each incident angle and pay close attention to the intensity of the reflected light ray.
- Describe your observations of the reflected light ray at increasing incident angles. What changed as incident angle increased, and what stayed the same?
- Use the polarizer disk and ray table to determine the incident angle and polarizer orientation (rotation) that allows none of the reflected light ray to be seen. Record the incident angle.

Theory

As you have observed, when unpolarized light reflects off a nonconducting surface like the acrylic D-shaped lens, it is partially polarized parallel to the plane of the reflective surface depending on the incident angle of the incoming light. As you have also seen, there is a specific incident angle at which the reflected light is 100% polarized. This angle is called Brewster's angle, and it occurs when the reflected ray and the refracted ray are 90° apart.

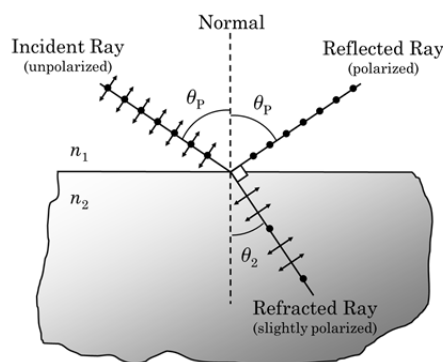


Figure 4: Brewster's Angle

To determine the mathematical relationship that describes Brewster's angle we can start by using Snell's Law:

$$n_1 \sin \theta_p = n_2 \sin \theta_2 \quad (1)$$

Because $\theta_1 + \theta_2 = 90^\circ$ or $\theta_2 = 90^\circ - \theta_p$, an important substitution can be made into Equation 1:

$$n_1 \sin \theta_p = n_2 \sin (90^\circ - \theta_p) \quad (2)$$

Substituting $\sin (90^\circ - \theta_p) = \cos \theta_p$ back into Equation 2 gives:

$$n_1 \sin \theta_p = n_2 \cos \theta_p$$

Therefore $\tan \theta_p = n_2/n_1 \quad (3)$

Equation 3 describes the relationship between both indices of refraction, n_1 and n_2 , and Brewster's angle θ_p .

Analysis

1. Calculate the theoretical value for Brewster's angle using the D-shaped acrylic lens. Assume that the index of refraction of air is 1 and index of refraction for the acrylic lens is 1.49.
2. How does your experimental value for Brewster's angle from the Collect Data page compare to the theoretical? What is the percent error?

$$\tan \theta_p = \frac{n_2}{n_1}$$

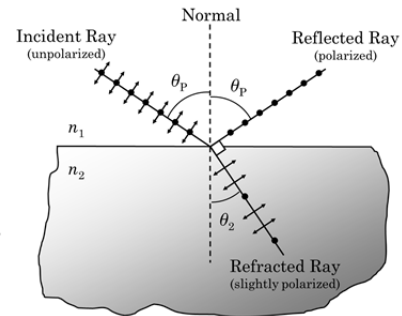


Figure 5: Brewster's Angle Equation

$$\%error = \frac{|\text{Theoretical} - \text{Experimental}|}{\text{Theoretical}} \times 100\%$$

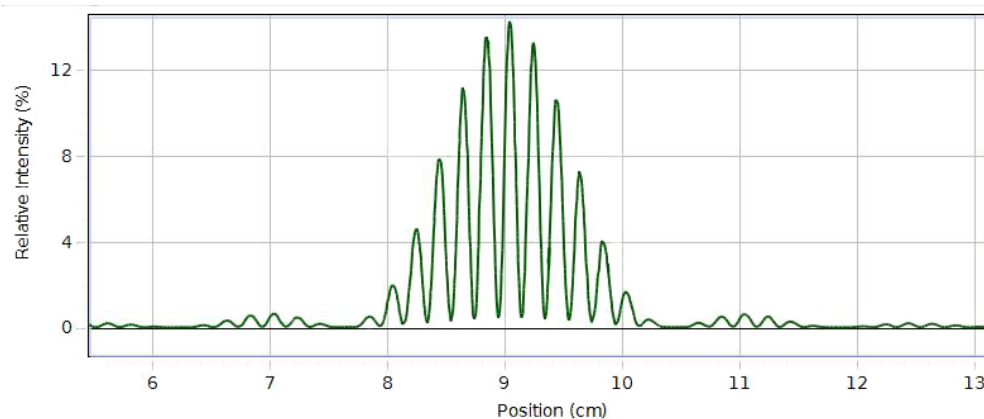
Interference and Diffraction of Light

Equipment

1	Basic Optics Track, 1.2 m	OS-8508
1	High Precision Diffraction Slits	OS-8453
1	Red Diode Laser	OS-8525A
1	Green Diode Laser	OS-8458
1	Aperture Bracket	OS-8534B
1	Linear Translator	OS-8535
1	High Sensitivity Light Sensor	PS-2176
1	Rotary Motion Sensor	PS-2120

Introduction

The distances between the central maximum and the diffraction minima for a single slit are measured by scanning the laser pattern with a light sensor and plotting light intensity versus distance. Also, the distance between interference maxima for two or more slits is measured. These measurements are compared to theoretical values. Differences and similarities between interference and diffraction patterns are examined, including the effect of changing the wavelength of the light.



Double Slit Interference Pattern

Single Slit Theory

When diffraction of light occurs as it passes through a slit, the angle to the minima (dark spot) in the diffraction pattern is given by

$$a \sin \theta = m\lambda \quad (m=1,2,3, \dots) \quad (1)$$

where "a" is the slit width, θ is the angle from the center of the pattern to a minimum, λ is the wavelength of the light, and m is the order ($m = 1$ for the first minimum, 2 for the second minimum, ...counting from the center out).

In Figure 1, the laser light pattern is shown just below the computer intensity versus position graph. The angle θ is measured from the center of the single slit to the first minimum, so m equals one for the situation shown in the diagram. Notice that the central spot in the interference pattern is twice as wide as the other spots since $m=0$ is not a minimum.

Since θ is a very small angle, $\sin\theta \sim \tan\theta = x_m/L$, where x_m is the distance from the center of central maximum to the m^{th} minimum on either side of the central maximum and L is the distance from the slit to the screen.

$$\sin \theta \approx \tan \theta = x_m/L \quad (2)$$

It is easier to measure the distance ($\Delta x = 2x_m$) from the m^{th} minimum on one side to the m^{th} minimum on the other side than to try to judge the center of the pattern. Equation (2) becomes

$$\sin \theta \approx \tan \theta = \Delta x / 2L \quad (3)$$

Our accuracy will be improved by making (Δx) as large as possible. The slit width is not known very well. The uncertainty in the width is ± 0.005 mm. That is a 25% uncertainty for the 0.020 mm slit. So instead of using the slit width to calculate a value for the laser wavelength, we use the known wavelength of the laser to calculate a more accurate value for the slit width.

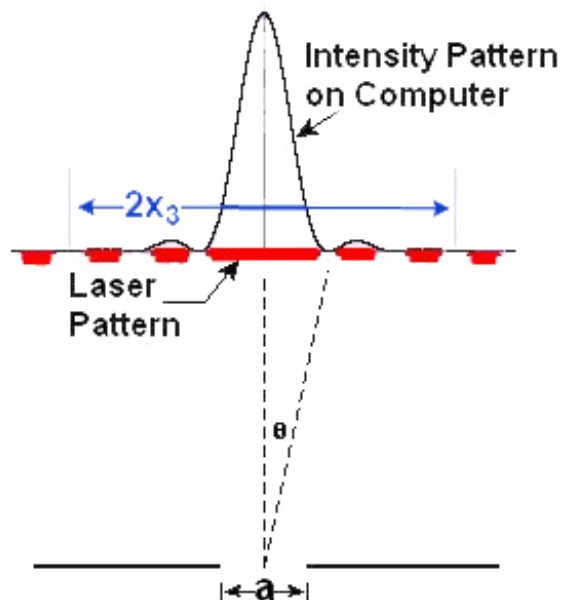


Figure 1: Single Slit Diffraction

Double Slit Theory

When interference of light occurs as it passes through two slits, the angle from the central maximum (bright spot) to the side maxima in the interference pattern is given by

$$d \sin \theta = n\lambda \quad (n=0,1,2,3, \dots) \quad (4)$$

where "d" is the slit separation, θ is the angle from the center of the pattern to the n^{th} maximum, λ is the wavelength of the light, and n is the order (0 for the central maximum, 1 for the first side maximum, 2 for the second side maximum ...counting from the center out).

In Figure 2, the laser light pattern is shown just below the computer intensity versus position graph. The angle theta is measured from the midway between the double slit to the second side maximum, so n equals two for the situation shown in the diagram.

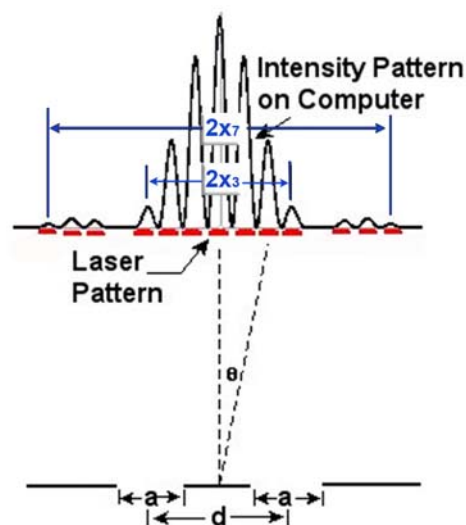


Figure 2: Double Slit Interference

As before, theta is a small angle and Equation (3) still holds:

$$\sin \theta \approx \tan \theta = \Delta x / 2L \quad (3)$$

where $\Delta x = 2x_n$ is the distance from the n^{th} side maximum on one side to the n^{th} side maximum on the other side of the central maximum and L is the distance from the slits to the screen. Since it is more accurate to measure from the n^{th} maximum on one side to the n^{th} maximum on the other side, we will measure $2x_n$.

Note that the single slit diffraction pattern is also present in the double slit pattern. It is responsible for the broad minima that occur (see Figure 2). This means we must be careful when counting n in the double slit pattern since a double slit maximum can be suppressed by a single slit minimum.

Pre-Lab Questions

1. For a single slit, as the slit width is increased, what happens to the pattern? Does the angle to the first diffraction minimum increase or decrease or stay the same?
2. For a double slit, as the slit width is increased, what happens to the pattern? Does the angle to the first diffraction minimum increase or decrease or stay the same? Does the angle to the first interference maximum increase or decrease or stay the same?
3. For a double slit, as the slit separation is increased, what happens to the pattern? Does the angle to the first diffraction minimum increase or decrease or stay the same? Does the angle to the first interference maximum increase or decrease or stay the same?
4. For a double slit, as the wavelength is decreased, what happens to the pattern? Does the angle to the first interference maximum increase or decrease or stay the same?

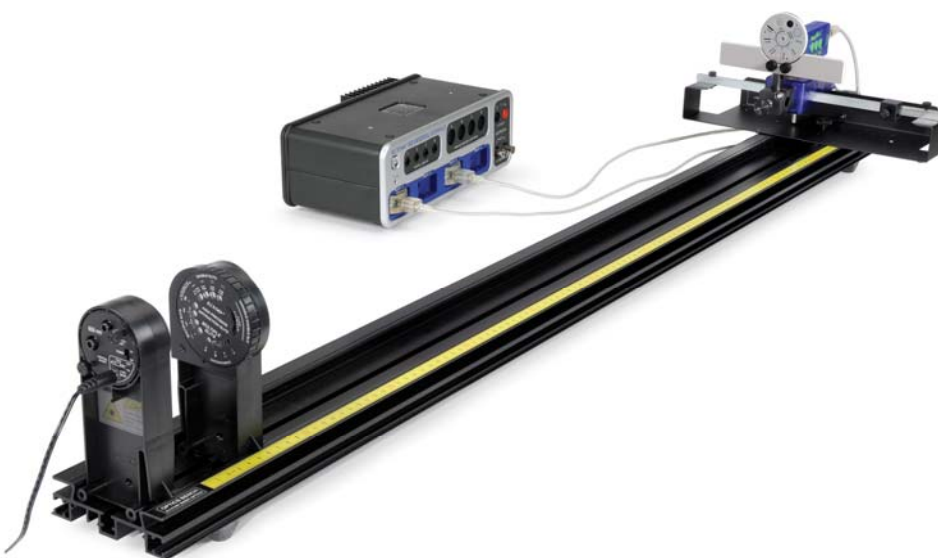


Figure 3: Complete System

Setup

1. Mount the laser on the end of the optics bench. Mount the High Precision Single Slit disk to the optics bench with the printed side toward the laser as shown. Turn on the laser.
CAUTION: Never shine the laser beam directly into anybody's eye! To select the desired slits, just rotate the disk until it clicks into place with the 0.02 mm aperture slit illuminated by the laser.
2. Mount the Rotary Motion Sensor on the rack of the Linear Translator and mount the Linear Translator to the end of the optics track (see Figure 4). Arrange things so the black stop block on the linear translator arm is on the left side as viewed from the laser and all the way against the bracket. Mount the Light Sensor to the Aperture Bracket (set on slit #6) with the 3 cm black rod. Mount the black rod in the Rotary Motion Sensor rod clamp. The Light Sensor should be aligned with the bracket so it points parallel to the optics track.
3. Move the light sensor until you can see the beam somewhere on the white screen. Use the adjustment screws on the laser (see Figure 5) to adjust the position of the laser beam from left-to-right and up-and-down to make the pattern on the white screen as bright as possible. Once this position is set, it is not necessary to make any further adjustments of the laser beam when viewing any of the slits on the disk. When you rotate the disk to a new slit, the laser beam will be already aligned. Since the slits click into place, you can easily change from one slit to the next, even in the dark.

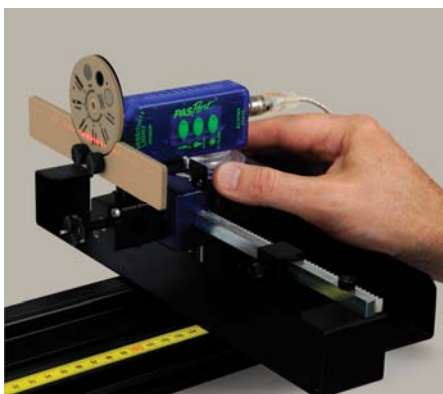


Figure 4: Mounting the Light Source



Figure 5: Aligning the Laser

4. Move the Light Sensor up or down until the light pattern is centered on the slits shown in Figure 6. Use slit #6.

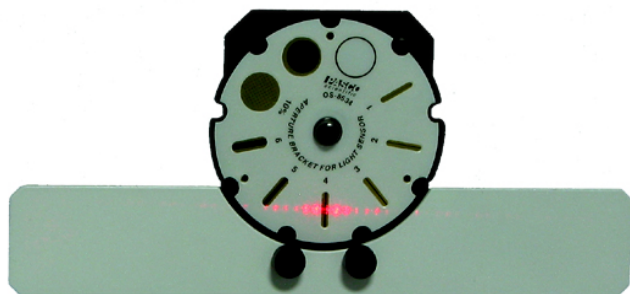


Figure 6: Aligning the Light Sensor Vertically

5. Set the Light Sensor for maximum sensitivity by pressing the 0-1 button. If the Light Intensity goes too high (it will flat line at 100% on the graph), turn the sensitivity down by pressing the (0-100) button on the Light sensor.
6. Plug the Rotary Motion Sensor and the Light Sensor into the *PASPORT* inputs on the 850 Universal Interface.
7. Click open the Hardware Setup button at the left of the screen. Click on the Rotary Motion Sensor icon. To the right of where it says Rotary Motion Sensor at the bottom of the Hardware Setup panel, click on the Gear icon. In the Linear accessory line, click on the white triangle and select Rack & Pinion. Click OK. Click the Hardware Setup button to close the screen.
8. In Capstone, set the Common Sensor Sample Rate to 25 Hz. Create a graph of Relative Intensity vs. Distance.
9. Create a table as shown below.

Table I: Measurement Summary

Label	a (mm)	d (mm)	m	n	Δx (m)	Calculated Slit Width (mm)	Calculated λ (nm)	λ %Difference (%)
0.02 mm	0.020	0.00						
0.04 mm	0.040	0.00						
0.04a-0.25d Run	0.040	0.25						
0.04a-0.25d Run	0.040	0.25						
0.04a-0.50d Run	0.040	0.50						
0.04a-0.50d Run	0.040	0.50						
0.04a-0.25d Green Run	0.040	0.25						

Single Slit Procedure

1. Measure the distance between the slits (front of Slit Disk) and the screen. You can use the scale on the track, but it is easier and more accurate to use a meter stick. Record the wavelength of the laser (printed on its back).
2. Turn out the room lights.

3. Observe the pattern on the screen as you rotate the Single Slit to each of its four positions (0.16, 0.08, 0.04, 0.02 mm). How does the pattern change as you decrease the slit width? Answer Question 1 in the Conclusions section. Set the disk to the 0.02 mm slit.
4. Move the Light Sensor so the Rotary Motion Sensor (RMS) is against the black stop block on the linear translator arm. If the positions are all negative when you start taking data, click on the Hardware Setup and click on the properties gear for the Rotary Motion Sensor and check "Change Sign".
5. Click on the RECORD button. Then slowly turn the RMS pulley to scan the pattern. Hold the rear of the RMS down against the linear translator bracket so it does not wobble up and down as it moves. Click on STOP when you have finished the scan. If you make a mistake, simply delete the run using the Delete Last Run button at bottom of screen and do the scan again. If the intensity maxes out (100%), change the gain setting on the light sensor and repeat the run. Click on Data Summary at the left of the screen. Double-click on Run #1 and re-label it "0.02 mm". Click Data Summary to close it.
6. Repeat for the 0.04 mm slit. Press the 0-100 button on the Light Sensor. Label the run "0.04 mm".

Single Slit Analysis

1. Select the 0.02 mm Run. Click the Scale-to-Fit button on the graph toolbar. Ignore the noise on the central maximum. It mostly arises because the beam from the solid state laser is not very well collimated resulting in the horizontal spread of the beam. This means different parts of the beam from the laser strike the slit at slightly different angles (from the left or right of the beam instead of the center of the beam), resulting in slightly different path lengths to the screen and some additional interference in the pattern. It does not affect the positions of the minimums.
2. We need to expand the vertical scale to see the minimums more clearly. Click and drag the vertical scale to expand the scale. Continue until you can clearly see the 1st minimums (nearest the central max).
3. Click on the Coordinate Tool from the graph toolbar. Drag the crosshairs to the 1st minimum on the left. Right-click on the Coordinate Tool and select Show Delta. Drag the delta to the 1st minimum on the right. Record the delta position in the " Δx " column of the table under the Data tab. Note: If the delta value does not have 3 significant figures, right-click on the Coordinate Tool and go to its properties and change the number of significant figures to 3.
4. Solve Equation (1) for the slit width and substitute Equation (3) into Equation (1). Calculate the slit width and enter it into the table.
5. Repeat steps 1-4 for the 0.04 mm Run. Your accuracy will be improved by using minimums further from the center if you can see them clearly. Record the "m" value in the table to reflect the minimum you actually measured. You must use the same minimum on each side of the center!

Double Slit Procedure

1. Note where the index foot is on the bottom of the Single Slit holder with respect to the yellow scale on the Optics Bench. Replace the Single Slit holder with the Double Slit holder so the index foot is in the same position. The distance to the screen should be the same as it was for the single slit experiment.
2. Change to slit #2 on the Light Sensor bracket and push the 0-100 button. Turn out the room lights.
3. Observe the pattern on the screen as you rotate the Double Slit to each of its four positions ($a = 0.04 \text{ mm}$ & $d = 0.25 \text{ mm}$, etc.). How does the pattern change? Can you see the single slit diffraction pattern? Answer Question 2 in the Conclusions section. Set the disk to the $a = 0.04 \text{ mm}$ and $d = 0.25 \text{ mm}$ position.
4. Move the Light Sensor so the Rotary Motion Sensor (RMS) is against the black stop block on the linear translator arm. Set the Light Sensor for max sensitivity (0-100).
5. Click on the RECORD button.
6. Then slowly turn the RMS pulley to scan the pattern. Hold the rear of the RMS down against the linear translator bracket so it does not wobble up and down as it moves. Click on STOP when you have finished the scan. If the intensity maxes out (100%), change the gain setting on the light sensor and repeat the run. Click on Data Summary at the left of the screen. Double-click on the current Run #1 and re-label it: "0.04a-0.25d". Click Data Summary closed.
7. Repeat for the 0.04 mm wide slit with slit separation 0.50 mm. Set the Light Sensor bracket to slit #1 and press the 0-100 button. Label the run "0.04a-0.50d".

Double Slit Analysis

1. Select the 0.04a-0.25d Run. Click the Scale-to-Fit button.
2. Click on the Coordinate Tool (graph toolbar). Right-click in the center of the crosshairs and select tool properties. Then increase the number of significant figures to 4. We actually want 4 decimal places which means 4 significant figures when the positions is greater than 0.1 meters.
3. We need to expand the horizontal scale to see the maxima more clearly. The pattern should look like the example on the Intro page.
4. Under the central diffraction pattern, select a maximum that is far to the left of the central max as possible. For example, the $n=5$ max. (Recall that the central max is $n=0$.) Drag the crosshairs to the 5th maximum on the left. Right-click on the Coordinate Tool and select Show Delta. Drag the delta to the 5th maximum on the right. Record the delta position in the

“ Δx ” column of the table under the Data tab. If the number of your max was different from 5, enter your value in “n” column.

5. Your precision will be improved if you can use a larger value of n. We need to expand the vertical scale to see the maximums more clearly. Click and drag the vertical axis upward. Continue until the peak with the cursor on it is near the top of the graph.
6. Recall that you know the n value for the peak the cursor is on and for the corresponding peak on the other side of center. Count n values out as far as you can (you can generally tell how many 2 slit peaks were suppressed by the single slit diffraction pattern). Enter your values in the table under the data tab in the second 0.04a-0.25d Run line. Don't forget to change the “n” value in the table to match the value you used.
7. Solve Equation (4) for the wavelength and substitute Equation (3) into Equation (4). Calculate the wavelength and enter it into the table.

Double Slit with Green Laser

1. Note where the index foot is on the bottom of the red laser with respect to the yellow scale on the Optics Bench. Replace the red laser with the green laser so the index foot is in the same position. The distance from the slits to the screen should be the same as it was before.
2. Align the green laser beam in the same manner as you did before for the red laser.
3. Turn out the room lights.
4. Set the disk to the $a = 0.04$ mm and $d = 0.25$ mm position.
5. Move the Light Sensor so the Rotary Motion Sensor (RMS) is against the black stop block on the linear translator arm. Set the Light Sensor for max sensitivity (0-100) and the Light Sensor slit to #2.
6. Click on the RECORD button.
7. Then slowly turn the RMS pulley to scan the pattern. Hold the rear of the RMS down against the linear translator bracket so it does not wobble up and down as it moves. Click on STOP when you have finished the scan. If the intensity maxes out (100%), change the gain setting on the light sensor and repeat the run. Click on Data Summary at the left of the screen. Double-click on the current run and re-label it: 0.04a-0.25d Green. Click Data Summary closed.

Double Slit with Green Laser Analysis

1. Select the 0.04a-0.25d Green Run. Click the Scale-to-Fit button.
2. Click on the Coordinate Tool (graph toolbar). Right-click in the center of the crosshairs and select tool properties. Then increase the number of significant figures to 4. We actually want 4 decimal places which means 4 significant figures when the positions is greater than 0.1 meters.
3. We need to expand the horizontal scale to see the maxima more clearly. The pattern should look like the example on the Intro page.
4. Under the central diffraction pattern, select a maximum that is far to the left of the central max as possible. For example, the $n=5$ max. (Recall that the central max is $n=0$.) Drag the crosshairs to the 5th maximum on the left. Right-click on the Coordinate Tool and select Show Delta. Drag the delta to the 5th maximum on the right. Record the delta position in the " Δx " column of the table under the Data tab. If the number of your max was different from 5, enter your value in " n " column.
5. Your precision will be improved if you can use a larger value of n . We need to expand the vertical scale to see the maximums more clearly. Click and drag the vertical axis upward. Continue until the peak with the cursor on it is near the top of the graph.
6. Recall that you know the n value for the peak the cursor is on and for the corresponding peak on the other side of center. Count n values out as far as you can (you can generally tell how many 2 slit peaks were suppressed by the single slit diffraction pattern). Enter your values in the table under the data tab in the second 0.04a-0.25d Green Run line. Don't forget to change the " n " value in the table to match the value you used. Calculate the wavelength as you did for the red laser and enter it into the Data table.

Single Slit Comparison to Double Slit

1. Select the 0.04 mm run and the 0.04a-0.25d run on the graph.
2. How are these patterns similar?
3. How are these patterns different?

Comparison of Double Slits Having Different Slit Separations

1. Select the 0.04a-0.25d run and the 0.04a-0.50d run on the graph.
2. How are these patterns similar?
3. How are these patterns different?

Comparison of Red and Green Wavelengths

1. Select the 0.04a-0.25d run and the 0.04a-0.25d Green run on the graph. You may want to change the colors of these runs to Red and Green in the Data Summary.
2. Which wavelength is longer: Red or Green?
3. How are these patterns similar?
4. How are these patterns different?
5. Do Equations (1) and (4) predict these differences?

Conclusions

1. Using your eyes, how does the single slit pattern change as you increase the slit size?
2. Using your eyes, how does the double slit pattern change as you increase the slit separation?
3. How does the Single Slit Diffraction change as you vary the slit width (a)? Does this agree with your answer to Question 1 above?
4. How does the Double Slit pattern change as you vary the slit separation (d)? Does this agree with your observations from Question 2 above?
5. How does the Double Slit pattern change as you vary the wavelength? Does this agree with your answer to the pre-lab question?

Electrostatic Charges

Equipment

1	Basic Electrometer	ES-9078
1	Charge Producers and Proof Plane	ES-9057C
1	Faraday Ice Pail and Shield	ES-9042A
1	Conductive Spheres, 13 cm	ES-9059C
1	Conductive Shapes	ES-9061
1	Electrostatics Voltage Source	ES-9077
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	UI-5400

Introduction

The purpose of part A of this activity is to compare and contrast the results of three different methods of charging: (1) rubbing two objects together; (2) touching a charged object to a neutral one (charging by contact); and (3) grounding a neutral object while it is polarized (charging by induction).

Part A will also demonstrate the law of conservation of charge.

The purpose of part B of this activity is to investigate how charge distributes on the outer surfaces of a spherical conductor and on the outer surface of a non-spherical conductor. The charge distribution inside the spherical conductor will also be examined.

Theory A

Electric Charges

Electric charge is a fundamental property of nature. It comes in two types, called positive and negative. Positive charge is the type of charge carried by protons. Negative charge is the type of charge carried by electrons. As nearly as can be measured (better than 1 part in 10^{30}), the magnitude of the charge on an electron is the same as the magnitude of the charge on a proton. Atoms normally have the same number of protons and electrons and this balance of charges makes them electrically neutral. Most objects are found in this neutral state. For an object to be positively charged, it has to have more protons than electrons. For an object to be negatively charged, it has to have more electrons than protons, disturbing the neutral charge balance.

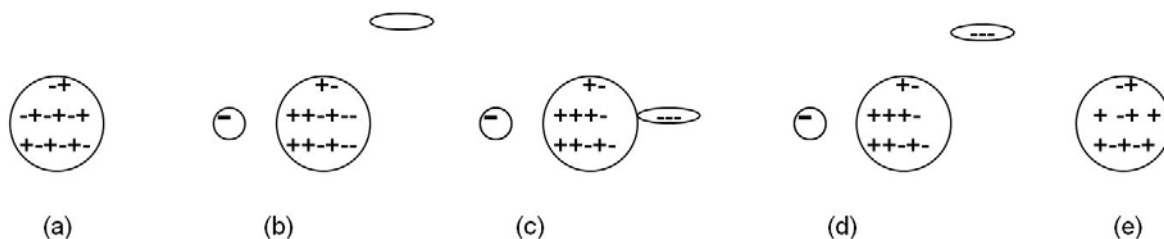
Forces between Charges

Opposite charges always attract. Like charges tend to repel. At an elemental level, like charges always repel (electrons repel electrons, protons repel protons), but for macroscopic objects, non-symmetric charge distribution can result in an overall attraction between two objects that carry the same type of overall charge (positive or negative). Non-symmetrical charge distribution always results in an attraction between a charged object and an electrically neutral (overall)

object.

Charging: all charging processes involve the transfer of electrons from one object to another. In order for an object to become positively charged, it must lose some of its electrons. In order for an object to become negatively charged, it must acquire more electrons.

1. *Charging by rubbing:* When two initially neutral non-conducting objects are rubbed together, one of them will generally bind electrons more strongly than the other and take electrons from the other. The law of conservation of charge requires that the total amount of electrons be conserved. That is, electrons only move from one object to another, but no new electrons are created, nor do they disappear. Overall, the two objects when considered together still have zero net charge.
2. *Charging by contact:* When a charged object is touched to a neutral (or less charged) object, repulsive forces between the like charges result in some of the charge transferring to the less charged object so the like charges will be further apart. This effect is much larger for conducting objects.
3. *Charging by induction:* The protons and electrons inside any object respond to electric forces of attraction or repulsion. When an object is placed near a charged object, the charged object will exert opposite forces on the protons and the electrons inside the other object, forcing them to move apart from each other. One side of the object will become more positive than it was initially. The other side will become more negative, as electrons migrate internally. This condition is called **polarization**, a word that refers to the object having “poles,” or opposite sides with different electrical states, even though the object as a whole may still neutral. If a conductor is touched to the polarized object, some of the charge will transfer to the conductor. If the conductor is then removed, the object now carries a net charge different from its initial charge. For example, consider the sequence in Figure 1. Figure 1a shows an isolated neutral conductor. In Figure 1b, a negatively charged object has been placed near the neutral conductor, which is now polarized. Another conductor (elliptical) is shown but is not yet involved. In Figure 1c, the elliptical conductor touches the polarized conductor and some of negative charge transfers to the elliptical conductor due to repulsive from the negative charged object. In Figure 1d, the elliptical conductor is removed, taking some negative charge with it and leaving a net positive charge on the round conductor. In Figure 1e the negatively charged object has been removed. The charge on the round conductor re-distributes, but the overall charge on the conductor is now positive. Note that we have ignored polarization of the elliptical conductor.



Setup A

1. Connect the Electrometer to the Faraday Ice Pail as shown in Figure 2. Connect the alligator clip with the red band to the inner conductor and the ground (black alligator) to the outside conductor. The Electrometer is a device that can measure the voltage difference between small charges without affecting the charges. The “ice pail” is the inner conducting mesh cylinder and is called an ice pail for historical reasons. When a charge Q is placed inside the inner cylinder, the cylinder becomes polarized with a charge almost (exact if there wasn't an open top) equal to Q moving to the outside of the inner cylinder. The voltage between the inner and outer cylinders is directly proportional to charge on the outside of the inner conductor, so this gives a way to directly measure the change inside the “ice pail.”



Figure 2: Charging Setup

2. Turn on the Electrometer and set the Range to 10V.
3. Ground the Ice Pail touching a finger to both the inner and out cylinder at the same time. Then remove the finger from the inner cylinder and then the finger from the outer cylinder. The word “grounding” is used to mean removing all (really just most of) the excess charge. We generally do this by touching the system with a conductor that is much larger than the system, in this case our bodies.
4. Press the “ZERO” button on the Electrometer. This forces the Electrometer to read zero even if there is a charge on the Ice Pail. This is OK since we really are only interested in changes in the charge.
5. You may need to redo the grounding and/or zeroing of the Ice Pail during the experiment. It is very easy to transfer charge to the ice pail by touching it or even getting too close to it with a charged object. It may even acquire a charge sitting on the table for a while. To see how sensitive the system is, stick a finger down the axis of the inner cylinder (without touching the cylinder.) Now rub your fingers through your hair, or on your shirt, or shuffle your shoes on the floor and try sticking your finger back into the Ice Pail. See any difference? What happens if you touch the Ice Pail? What's the moral about where you put your hands during the experiment? Redo the grounding of the Ice Pail.
6. Change the Range on the Electrometer to 100V. Press the Zero button again.

- One at a time, insert the disks on the Charge Producer wands (one with a dark plastic disk and the other with a white leather disk) into the inner basket. Where are your hands? If the disks are uncharged, the needle in the electrometer will stay at zero. If the needle moves, then there is residual charge in the wands. To remove the residual charge, touch the charge producers to the outer basket of the grounded ice pail. Sometimes if residual charge is hard to remove, you can breathe on the disks. The moisture from your breath will remove the charges. It is difficult to remove all the charge since the disks are non-conducting. If you see a voltage change of less than one volt, that is good enough.

Procedure A1: Charging by Rubbing Objects Together

- Ground the ice pail, zero the electrometer and make sure there is no charge on the charge producing wands (see step 7 under Setup A).
- Hold one wand in each hand and lower them into the lower half of the inner basket, without letting them touch each other or the walls of the basket. Since there is no net charge in either wand, the needle in the monitor should not move and still read nearly zero. Press the Zero button on the Electrometer. Record the “initial” reading in row 1 of Table I.

Table I: Electrometer Voltages

	Reading	Run 1 (V)	Run 2 (V)	Run 3 (V)
1	Initial			
2	After rub			
3	After separation			
4	Dark out			
5	Both in			
6	White out			
7	Final			
8	Both out			
9	Sum			

- Do all of the following steps as rapidly as possible to minimize charge migration to the surroundings.
- While inside the basket, briskly rub the two charge producers together and observe the needle in the monitor. Record the “after rubbing” reading in row 2 of Table I.
- Stop rubbing. Still inside the basket, separate the wands and observe the needle in the monitor. Record the “after separation” reading in row 3 of Table I.

6. Take the dark wand out of the basket. Record the “dark out” reading in row 4 of Table I.
7. Insert the dark wand into the basket with the white wand (not touching). Record the “both in” reading in row 5 of Table I.
8. Remove the white wand. Record the “white out” reading in row 6 of Table I.
9. Insert the white wand into the basket with the dark wand. Record the “final” reading in row 7 of Table I.
10. Remove both wands. Record the “both out” reading in row 8 of Table I.
11. Rub the two wands together and then remove the charge from the white one by touching it to the outside mesh cylinder. Ground the Ice Pail with your finger and zero the Electrometer. Repeat steps 2-10.
12. Rub the two wands together and then remove the charge from the black one. Ground the Ice Pail and zero the Electrometer. Repeat steps 2-10.

Analysis A1

1. What can you immediately conclude about the charges on the white wand and the dark wand based on the signs of the voltages in Run 1?
2. Note that lines 3, 5, and 7 are exactly the same system so should have the same voltage. Any difference implies that there has been some charge lost or gained. In addition, line 8 should be zero unless some charge has transferred. Looking at these should allow you to estimate the uncertainties in the experiment and decide if numbers agree within the uncertainties.
3. Recall that the voltage is directly proportional to the charge. Thus if a voltage of 8 V implies 8 units of charge, a voltage of 12 V implies 12 units of charge.
4. What do lines 1-3 imply?
5. Add line 4 to line 6 (don't forget the sign). Enter the sum on line 9.
6. Compare line 1 to line 9. What does this imply?

Procedure A2: Charging by Contact

1. Ground the ice pail and zero the electrometer. Record the "zero" reading in line 1 of Table II.
2. Briskly rub the white and dark charge producers together to charge them.
3. Insert the white charge producer into the inner basket of the ice pail. Record the “initial”

voltage on the electrometer in line 2 of Table II.

4. Let the white disk on the charge producer touch the wall of the basket. Record the “after touch” voltage on the electrometer in line 3 of Table II.
5. Remove the white disk. Record the “disk out” voltage on the electrometer in line 4 of Table II.
6. Repeat steps 1-5 using the dark charging disk.

Procedure A3: Charging by Induction

1. Ground the ice pail and zero the electrometer. Record the "zero" reading in line 1 of the Charge by Table II.

Table II: Charge by Contact/Induction

	State	White Disk Contact (V)	Dark Disk Contact (V)	White Disk Induction (V)	Dark Disk Induction (V)
1	Zero				
2	Initial				
3	After touch				
4	Disk out				

2. Rub the wands together to charge them.
3. Without letting the wand touch the ice pail, insert the white wand into the lower half of the inner basket. Record the “initial” voltage on the electrometer in line 2 of Table II.
4. While the charge producer is inside the basket, momentarily ground the ice pail by bridging between the outer and the inner cylinder with your finger and then removing your finger. Record the “after touch” voltage on the electrometer in line 3 of Table II.
5. Remove the wand from the ice pail. Record the “wand out” voltage on the electrometer in line 4 of Table II.
6. Repeat steps 1-5 using the dark charge producer.

Analysis A2/A3

1. What can you conclude from the data in the 2nd and 3rd columns (contact data) in the table?
2. Explain what is happening when you induce a charge on the inner mesh cylinder. That is, explain the data in columns 3 & 4 of the table. Why does the sign change?

Theory B

Charge Distribution on a Conducting Surface: charge will tend to concentrate at places on a conductor where the surface is more sharply curved. This happens because charges do not interact as strongly with other charges that are “over the horizon” since the electric field lines cannot pass through a conductor.

Charge inside a Spherical Conducting Shell: if the force between two point charges obeys an *inverse square law* (i.e. falls off like $1/r^2$), then all the charge on a conducting spherical shell must lie on the outside of the shell and the inside of the shell must be uncharged. Although we check this crudely here, it is possible to verify this with great precision and it is currently known that the exponent is 2 to within better than 1 part in 10^{30} !

Procedure B1: Measuring the Charge at Different Locations on the Outer Surface of a Spherical Conductor

1. Plug in the Electrostatics Voltage Source and turn it on. Attach a black lead from the Common (Com) jack to a convenient ground like a water pipe or the silver outside connectors of the #2 or #3 outputs on the 850 Universal Interface. Attach the red lead to the +3000 V terminal and leave the spade connector on one end of the red lead unattached. P.S. you cannot get shocked by this power supply since it can only produce a tiny current.
2. Ground the ice pail (the inner cylindrical wire mesh) with your finger as before. Turn on the Electrometer, set it to the 30V range, and zero the electrometer.
3. The “proof plane” is the metal disk (silver looking) on one of the black wands. It is used for sampling charge on a conductor by touching it to the surface of the conductor. The amount of charge that transfers to the proof plane is proportional to the surface charge density at the point of contact. Make sure there is no charge in the proof plane by inserting it into the inner mesh cylinder. The electrometer should read zero. If there is charge on the proof plane ground it by touching it to any ground or the outer mesh cylinder.
4. Place the spherical conductor (no hole) well away from other objects (including people) to prevent polarization effects. Nothing should be closer to the sphere than the base on which it sits. The Faraday Ice Pail should also be well away from the sphere. You should perform the following steps as rapidly as possible to prevent significant discharge of the sphere through the air.
5. Briefly touch the free end of the red lead (the spade lug) to the spherical conductor (without a hole). This will charge the conductor to an electric potential of 3000V.
6. Touch the sphere at point A (see Figure 3) with the proof plane keeping your hands far away

as possible.

7. Put the proof plane in the inner cylinder of the “ice pail” and record the voltage from the electrometer on Figure 3 at point A. Do not ground the proof plane so the total charge on the sphere and proof plane remains constant.
8. Repeat for points B & C.

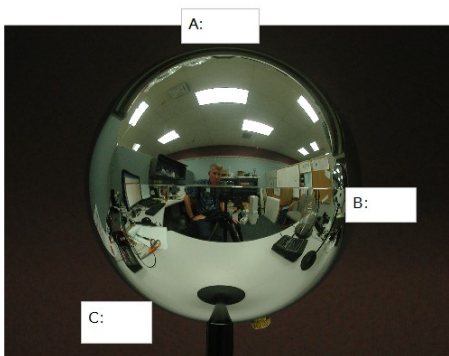


Figure 3: Charge Distribution on a Sphere

Analysis B1:

Recall that the voltages recorded on Figure 3 are not the voltages on the sphere (the sphere is at a uniform 3000 V). They are the voltages between the inner and outer mesh cylinders with the proof plane inside the inner cylinder, which is directly proportional to the charge on the proof plane. What can you conclude about the distribution of charge on the sphere?

Procedure B2: Charging the Spherical Conductor to Different Potentials.

1. Same setup as in Procedure B1.
2. Ground the ice pail. Set the electrometer to the 10 V range and zero the electrometer. Make sure there is no charge in the proof plane. The electrometer should read zero. Repeat this anytime the electrometer does not read zero with nothing in the ice pail.
3. With one end of the red lead in the +1000 V terminal of the Electrostatics Voltage Source, touch the other end briefly to the surface of the conducting sphere.
4. Touch the top of the sphere with the proof plane.

- Without letting it touch the basket, insert the proof plane into the lower half of the inner basket of the ice pail. Record the electrometer voltage in the second column of Table III.

Table III: Voltage vs. Charge on a Sphere

Sphere Potential (V)	Electrometer Reading (V)
1000	
2000	
3000	

- Ground the proof plane. Make sure there is no residual charge in the proof plane before continuing.
- Repeat the measurement for the +2000 V and +3000 V outputs (still on the 10 V range). If the reading is 9.9 V, you have exceeded the range. In that case, change the electrometer to the 30 V range, ground the ice pail, zero the electrometer and proceed.

Analysis B2

Recall that the electrometer voltages are the voltages between the inner and outer mesh cylinders with the proof plane inside the inner cylinder, which is directly proportional to the charge on the proof plane. What can you conclude about the charge on the sphere vs the electric potential (voltage) of the sphere?

Procedure B3: Measuring the Charge on the Outer Surface of a Non-Spherical Conductor

- Same setup as Procedure B1 except replace the sphere with the non-spherical conductor. Use the +3000 V terminal on the Voltage Source. Electrometer on the 30 V range.
- Ground the ice pail, zero the electrometer and make sure there is no charge in the proof plane. The electrometer should read zero.
- Briefly connect the oblong-shaped conductor to the +3000V outlet of the Electrostatics Voltage Source.
- Touch the large-radius end (point A on Figure 4) of the oblong shaped conductor with the proof plane.

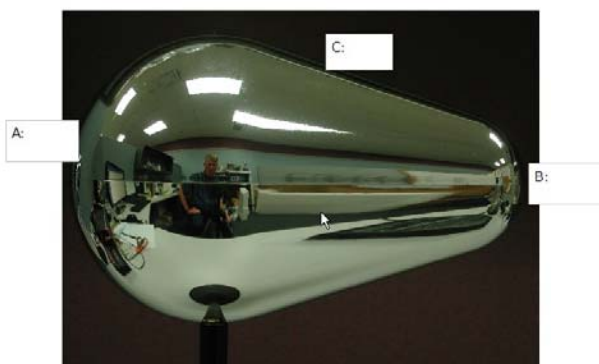


Figure 4: Non-spherical Charge Distribution

5. Without letting it touch the basket, insert the proof plane into the lower half of the inner basket of the ice pail. Record the reading from the electrometer on Figure 4 at point A.
6. Repeat the process at points B & C. Do not ground the proof plane so the total charge remains constant.

Analysis B3

What can you conclude about the distribution of charge on a non-spherical conductor?

Procedure B4: Measuring the Charge on the Inner Surface of a Spherical Conductor

1. Same setup as Procedure B3 except replace the oblong conductor with the sphere with a hole on top.
2. Ground the ice pail, zero the electrometer and make sure there is no charge on the proof-plane wand. You need to make a decision here. You may use either the disk end of the proof plane or the ball end. The ball end was designed for this experiment. However, it picks up a smaller amount of charge than the disk does, so requires you to operate on the 3 V range of the electrometer. The problem is that it is very easy to charge the non-conducting parts of the wand and on the 3 V range these charges have a large impact, and it is very difficult to discharge them. If you can successfully ground the ball end so that the electrometer remains near zero when the uncharged ball is inserted in the inner cylinder, then the ball works fine. I prefer using the disk with the electrometer on the 30 V range. Little charges on the handle are then not so important. However, considerable care is required to insert the disk into the hole without touching the sphere, and there is a risk of charge transfer even if the disk just comes close to the edge of the hole without touching.
3. Briefly touch the end of the red lead (attached to the +3000 V terminal) to the conducting sphere.
4. Keeping the proof plane as far as possible from the edges of the hole, insert the uncharged proof plane into the charged sphere and touch the inner wall near the bottom. Remove the proof plane from the hole. If the proof plane touches the edge, start over.

- Without letting it touch the basket, insert the proof plane into the lower half of the inner basket of the ice pail. Record the electrometer reading in the first line of Table IV.

Table IV: Sphere Voltages

	Sphere with Hole	Electrometer Voltage (V)
1	Inside	
2	Inside near hole	
3	Outside	
4	Inside again	
5	Outside again	

- Keeping the proof plane as far as possible from the edges of the hole, insert the uncharged proof plane into the charged sphere and touch the inner wall near the hole. Be careful that the wand does not touch the edge of the hole or you will put a charge on the wand. Remove the proof plane from the hole. If the proof plane touches the edge, start over.
- Without letting it touch the basket, insert the proof plane into the lower half of the inner basket of the ice pail. Record the electrometer reading in the second line of Table IV.
- Touch the proof plane to the outside of the sphere (anywhere) and repeat step 7, recording the value from the electrometer on line 3.
- Without grounding it, insert the proof plane in the hole and touch the inner wall near the bottom. Repeat step 7, recording the value on line 4.
- Touch the proof plane to the outside of the sphere (anywhere) and repeat step 7, recording the value from the electrometer on line 5. If lines 3 and 5 are nearly equal and around 10 V, your data is probably OK. Variations of ± 1 V are probably not significant.

Analysis B4

- What does the data in the table tell you about the distribution of charge on a hollow spherical shell?
- Explain what happened in line 4 of Table IV.

Lab Report: Electrostatic Charges

Name: _____

Note: The answers to the fill-in-the-blanks questions are about the registers polarity of the electrometer. Answer 'Positive,' 'Negative,' or 'Zero.'

OBSERVATIONS PROCEDURE A: Charging by Rubbing Objects Together

While rubbing the two charge producers together inside the basket:

The charge detected is _____.

After rubbing, with wands still in the basket, but not touching:

The charge detected is _____.

After removing the dark wand from the basket:

The charge detected on the white wand alone is _____.

The charge detected on the dark wand alone is _____.

QUESTIONS PROCEDURE A:

1. While the two wands were being rubbed against each other, what was their overall net charge?
2. After the rubbing process, what was the net overall charge of the two wands?

3. What is the evidence that the rubbing process gave each wand an electric charge?

4. What is the polarity of the white charge producer after rubbing it with the dark one? Did the white wand gain or did it lose electrons during the rubbing process? Where did the electrons go (or come from)?

5. What is the polarity of the dark charge producer after rubbing with the white one? Did the dark wand gain or did it lose electrons during the rubbing process? Where did the electrons go (or come from)?

6. Explain how this experiment demonstrates the law of conservation of charge.

**OBSERVATIONS PROCEDURE B:
Charging by Contact**

After placing the white charge producer the inner basket:

The charge detected is _____.

After letting the charge producer touch the wall of the basket:

The charge detected is _____.

After inserting the dark charge producer into the inner basket and letting it touch the basket:

The charge detected is _____.

QUESTIONS PROCEDURE B:

1. Before the white wand touched the basket, what was the polarity of the white wand? What was the state of the basket?
2. After the white wand touched the basket, what was the polarity of the basket? Did the basket gain or lose electrons during the contact with the white wand? Where did the electrons go (or come from)?
3. After the dark wand touched the basket, what was the polarity of the basket? Did the basket gain or lose electrons during the contact with the dark wand? Where did the electrons go (or come from)?
4. When a charged object touches an initially neutral object, the neutral object acquires a charge. How does the polarity acquired by the initially neutral object compare to the polarity of the charged object that touched it?

**OBSERVATIONS PROCEDURE C:
Charging by Induction**

Without letting the wand touch the ice pail:

The polarity of the charge on the white wand is _____.

After grounding the ice pail and removing the wand:

The polarity of the charge on the pail is _____.

Repetition with the dark charge producer:

The polarity of the charge on the dark wand is _____.

After the, the polarity of the charge on the pail is _____.

QUESTIONS PROCEDURE C:

1. At the end of the process, how does the charge acquired by the pail compare to the polarity of the charge on the wand that was used?
2. When using the white wand: Did the ice pail gain or lose electrons during the charging by induction process? Where did the electrons go (or come from)?
3. When using the dark wand: Did the ice pail gain or lose electrons during the charging by induction process? Where did the electrons go (or come from)?

Electric Field Plotting

Equipment

1	Field Mapper Kit	PK-9023
	Replacement Supplies:	
	Conductive Ink Pen	PK-9031B
	Conductive Paper w grid	PK-9025
	Conductive Paper (no grid)	PK-9026
1	Voltage Sensor	UI-5100
1	Short Patch Cords	SE-7123
	Required but not included:	
1	PASCO Capstone	
1	850 Universal Interface	UI-5000

Introduction

The purpose of this qualitative activity is to introduce the students to the concept of a field and to make the idea of the electric field more concrete by examining a number of examples. A number of rules about the electric field are verified. At the end of the activity, the student should be able to sketch the electric field around a simple charge distribution.

The idea of equipotential surfaces is also developed, but the lab is designed to be done before the concept of electric potential is introduced.

Theory

The electric field is way to visualize the interaction between charged objects. It is assumed that the electric field permeates the space around a charged object and is responsible for the force that the object exerts on other charges. The electric field (strength) is defined as the force per unit charge on a vanishingly small test charge q .

$$E = F/q \quad (1)$$

Note that this is a vector relationship where E and F must lie in the same (or opposite if q is negative) direction.

To help visualize the field we use the concept of electric field lines where, by convention, the lines begin on positive charges and terminate on negative charges. These lines must satisfy two conditions. First, E must be tangent to the lines at all places. Second, the magnitude of E is directly proportional to the density of the lines. This second requirement is only true in a three dimensional space. The patterns in this activity will be essential two dimensional (due to the conductive paper), but it will still be true that where the lines are close together, the field is strong.

There are a number of rules about the field lines that help draw them for the static case:

1. The lines should have the same symmetry as does the charge distribution.
2. The number of lines from a charge q should be proportional to q . Note: Due to the way the power supply works, the charge due to the positive terminal is equal and opposite to the charge due to the negative terminal.
3. Near a point charge, the point charge dominates (due to $1/r^2$) and the field is that of an isolated point charge (fully symmetric).
4. The lines cannot stop in space. They begin on a $+$ charge and end on a $-$ charge. (Otherwise the force does not fall off as $1/r^2$.)
5. Field lines cannot cross (otherwise violate conservation of energy.)
6. Field lines cannot pass through a conductor (otherwise charge moves.)
7. Field lines must be perpendicular to the surface of a conductor (otherwise charge moves.)
8. The lines must be perpendicular to any equipotential surface (see below.)

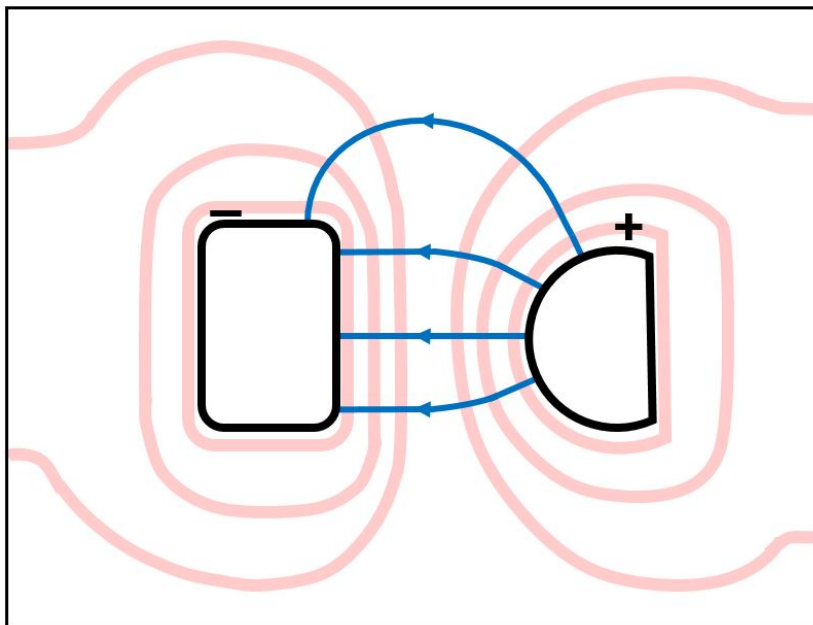


Figure 1: Equipotential Lines in Pink; E-field Lines in Blue with Arrows

An equipotential surface is a surface upon which no work is required to move a charge on that surface. How can we move a charge in a region where there is a force on it due to the electric field and yet do no work? The answer lies in the fact that the work, W , done is the scalar product of force, F , and displacement, d , so depends on the angle.

$$W = Fd \cos \theta$$

If θ is 90° , the work done is zero. For example, a satellite in a circular orbit around the Earth does no work against gravity so does not need any additional energy (i.e. firing its engine) to orbit. So an equipotential surface must be perpendicular to the force and thus an equipotential surface must be perpendicular to the electric field (strength) and field lines (see Figure 1). The electric field is difficult to measure directly, but it is very easy to find the equipotential surfaces using a voltmeter (we'll see how a voltmeter works later in the course). For example, all the points where the voltage is 4 volts form an equipotential surface. In the case of our two dimensional pattern, the equipotential "surfaces" will be lines.

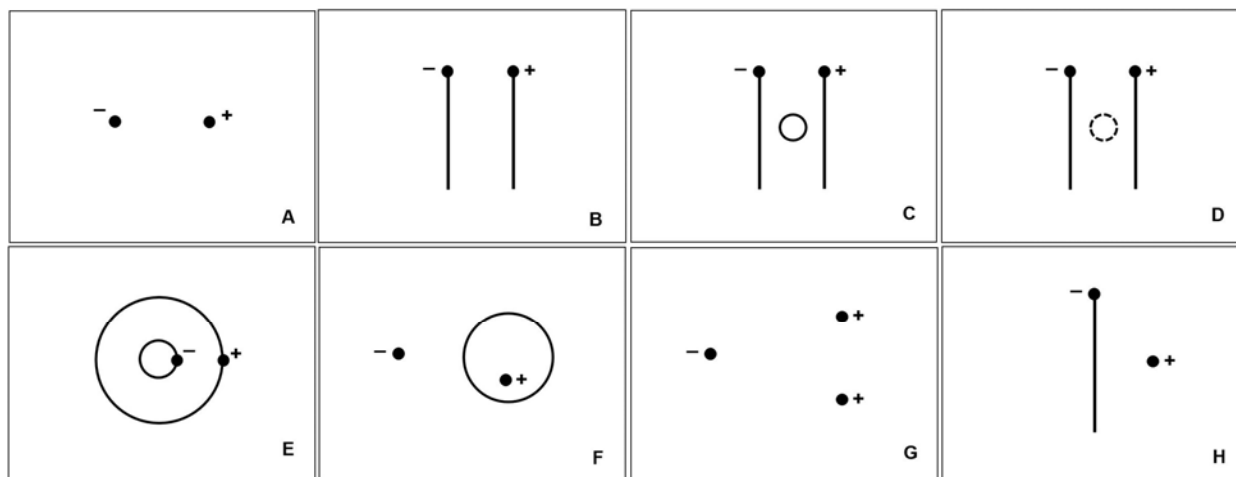


Figure 2: Electrode Patterns: The dots represent the position of pins to which the power supply leads are attached.

Setup

1. Prepare the desired patterns using the conductive pen and conductive paper. The patterns must dry completely before use or being stacked. Some suggested patterns are shown in Figure 2. The letters are for reference only and should not be drawn on the paper. The + and - are to show where to connect the electrodes and should not be drawn on the paper. The circles in patterns C and F are free floating and should not be connected to the power supply. The only pattern using three electrodes is G where an extra wire is required to connect to the second positive electrode. The primary region of interest in G is around the two positive charges. The dashed line in pattern D is a hole cut in the paper to simulate an insulator in the field. Patterns B, C, E, and F are very interesting and should not be skipped.
2. Attach the conductive paper with the pattern on it to the cork board with push pins at the four corners. The paper is not very conductive, but must carry a little current for the voltage sensor to work. The fact that the paper carries a small current actually affects the electric field somewhat and near the edges of the paper the affects may be noticeable.

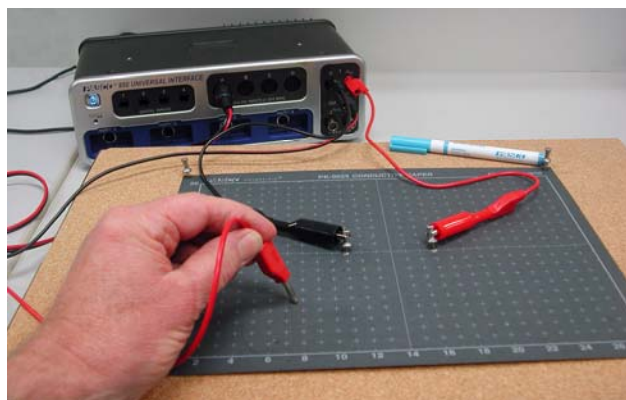


Figure 3: Setup

3. Attach a red patch cord to the red terminal of Output 1 (attach a second red for pattern G). Attach a black patch cord to the black terminal. Attach an alligator clip to the other end of each patch cord and clip each to a silver push pin (see Figure 3). Insert the push pins into the appropriate electrodes on the pattern drawn on the conductive paper. *It is important that you do not bump the electrode push pins during the experiment* since doing so may change the voltages on the paper. This is not a disaster since the shapes of the equipotential surfaces will not be affected, but it is frustrating to be tracing a 4.0 V surface that suddenly becomes a 3.0 V surface.
4. Click on Signal Generator at the left of the screen. Set Output 1 for a 15 V DC signal and click Auto so it will turn on any time you click Record. Click the Signal generator again to close it.
5. Insert the Voltage Sensor in Channel A on the 850 Universal Interface. Attach the black lead to the black terminal on Output 1 of the 850. Leave the sample rate at the default rate of 20 Hz. Create a Digits display with the Voltage (Ch. A) selected.

Procedure

1. Check for good connections by first clicking Record and touching the red lead of the voltage sensor to the paper near (not touching) the negative electrode. The voltage reading (upper right of screen) should be 2-3 V. It is not zero since there is a fair amount of contact resistance between the electrode and the paper. If the voltage is much above 3 V, try moving the push pin to another spot in the electrode. Check near the positive electrode. The value should be at least 12 V. For any of the lines or circles of conductive ink, check to make sure the voltage is the same everywhere on the circle or line. If it isn't, there must be breaks in the line and you should get a new pattern.
2. Trace the 4.0 V equipotential. To do this locate a place on the paper near the negative electrode where the voltage is 4.0 V. Try to keep the probe at the same angle (see Figure 4 for example) and use the same pressure for each reading (the voltage is pressure sensitive). When you find a 4.0 V spot apply more pressure and rotate the probe to make a small depression in the paper (some depressions show in Figure 4). Then locate more 4.0 V spots to make a surface (actually a line) surrounding the negative electrode. *Hint:*

near a point electrode, the 4.0 V equipotential should be roughly circular. For other electrodes, the 4.0 V equipotential should roughly be roughly parallel to the electrode. Important Hint: this is not a very precise experiment. 4.0 V means roughly within a few tenths of a volt. Do not waste time trying to find the exact spot! The values will change by several tenths of a volt (or more if you bump the electrodes). This process is meant to be quick and dirty.

3. Pick nine more voltages so you trace a total of ten equipotential surfaces spaced out across the page. Keep track of what voltages you use for each.
4. When you have ten equipotential lines, click Stop.

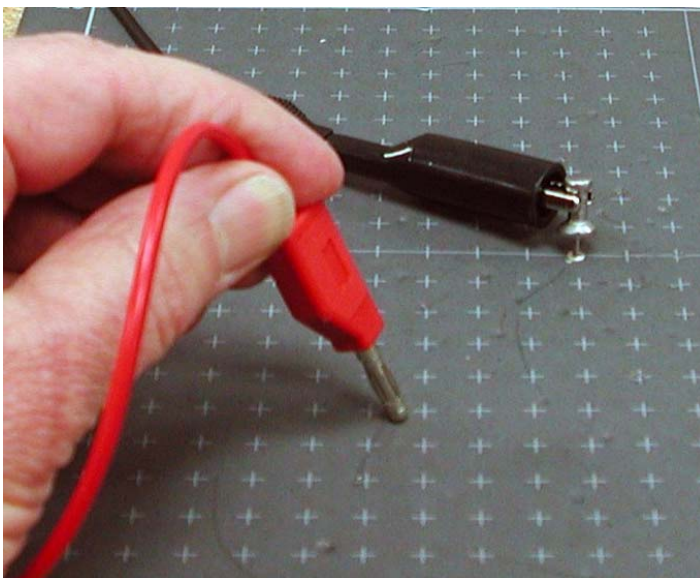


Figure 4: Probe Position

Analysis

1. Copy the pattern you made onto a sheet of white paper by sliding the white paper under the black paper and securing the white paper with a couple of push pins. Then push a push pin through each of the dimples in the black paper. It is easiest to follow the equipotential lines you used. Don't worry if in some places they are so close that you lose track of which line is which. Also use the push pin to make the positions of the electrodes.
2. Smooth fit equipotential lines to your data points. Draw smooth curves even if they don't go exactly through each data point.
3. Now use rules 2, 3, 4, and 8 from Theory to sketch the electric field lines. See Figure 1. Remember that the electric field is a vector field and you should draw an arrow on each line, directed from the positive charge to the negative charge. Hint: If there are any point charges in the field, start at the point charges, drawing eight symmetric lines, and then keep the lines perpendicular to the equipotential surfaces as you draw them in (see Figure 1).

4. Note: The odd-shaped curve that shows in the 5.0 V line (and others) is due to the edge of the conducting paper. The system is not quite static since some current is required for the voltage sensor to function. The E field lines show the path that charge (current) follows. Current cannot flow from the conducting paper into the air, so the field lines must either run parallel to the edge or avoid it. Places to the left and right of the pattern show an almost constant voltage, so in these places the electric field must be nearly zero (why?). At the top and bottom of the pattern, the E field lines run parallel to the edge and the equipotential lines must be perpendicular to the edge. This modification of the field is produced by surface charge on the edge of the paper.

Conclusions

Discuss any interesting points about your pattern. As appropriate, answer each of the questions below. It is interesting to note that pattern A is the attractive dipole and G is the repulsive dipole that show in most textbooks. Pattern B is a parallel plate capacitor (what is special about it?) and pattern E is a coaxial cable (where is it used in your house and why?)

1. Does your pattern have the same symmetry as the charge distribution?
2. Do the field lines cross each other?
3. Are the field lines perpendicular to the surface of any conductor?
4. Where in the pattern is the field strongest/weakest? Note that where the equipotential surfaces are close together, the electric field must be strong (why?)
5. What is the distribution of charge like on any conductor in your pattern? Remember that charge begins on positives and ends on negatives. Where more lines begin/end there is more charge. Also remember that your conductors have some thickness, so really have two surfaces. Is the charge the same on both? It helps to put a + where each line begins and a – where each line terminates.
6. Is there any evidence of charge polarization?

Ohm's Law

Equipment

1	AC/DC Electronics Laboratory	EM-8656
1	Short Patch Cords (set of 8)	SE-7123
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

Introduction

The purpose of this experiment is to verify Ohm's Law for commercially manufactured resistors and to examine the limits of validity for Ohm's Law. The behavior of resistors, a diode, and a light bulb are examined.

Theory

In metals and some other materials (in particular, commercially manufactured resistors), one finds experimentally that the voltage drop, V , across the material is directly proportional to the current, I , through the material (provided the temperature remains relatively constant):

$$V \propto I$$

which is referred to as Ohm's Law. It is convenient to define a proportionality constant called the resistance (unit: Ohm [Ω] = V/A) such that

$$V = IR. \quad (1)$$

A resistor generally means a device that obeys Ohm's Law (many devices do not) and has a resistance R .



Figure 1: Ohm's Law Setup



Figure 2: Resistor Color Code

Setup

1. Setup the circuit shown in Figure 1 using the $330\ \Omega$ (orange-orange-brown-gold) resistor between the spring clips. The gold band on the resistor means it is accurate to within 5% ($330 \pm 17\ \Omega$). If an ohmmeter is available, use it to check the resistance. This will give you a value that is accurate within a few %.
2. In PASCO Capstone, open the Hardware Setup and click on Signal Generator #1 on the 850 Universal Interface and select the Output Voltage Current Sensor.
3. Click open the Signal Generator at the left of the screen. Set Output 1 for a Triangle Waveform with a Frequency of 0.1 Hz and an amplitude of 2.5 V. Click Auto. Click the Signal Generator again to close the panel.
4. Set the sample rate for the Output Voltage Current Sensor to 50 Hz.
5. Create a graph of Output Voltage vs. Output Current.

Procedure

1. Click RECORD. Collect data for about 10 seconds (one full cycle) and then click STOP. The graph (Output Voltage vs Output Current) should show a straight line (with some noise.)
2. Click on Data Summary at the left of the page. Double click on any Run #1 and re-label it "330 Run". Click Data Summary again to close it.
3. Replace the $330\ \Omega$ resistor with a $560\ \Omega$ (green-blue-brown-gold) resistor. As before, check it with an ohmmeter if one is available.
4. Click RECORD. Collect data for about 10 seconds and then click STOP. Re-label this run "560 Run"
5. Remove the $560\ \Omega$ resistor and attach light bulb to the input terminals using the long white wires as jumpers as shown in Figure 3.

6. Click RECORD. Collect data for about 30 seconds and then click STOP. There should be a funny kink in the graph. Observe what the bulb is doing as the kink occurs. Answer Question 5 in Conclusions. Re-label this run as “Light Bulb”.
7. Remove the white jumper wires and place a diode in the clips as in Figure 4. Note that the diode looks like a small black resistor with one grey end. Arrange the diode so the grey end is “up” toward the red lead from the 850 Interface.
8. Click open the Signal Generator and reduce the voltage to 1.0 V.
9. Click RECORD. Collect data for about 10 seconds and then click STOP. Re-label this run as “diode up”.
10. Reverse the diode so the grey end is “down” toward the black lead.
11. Click RECORD. Collect data for about 10 seconds and then click STOP. Re-label this run as “diode down”.

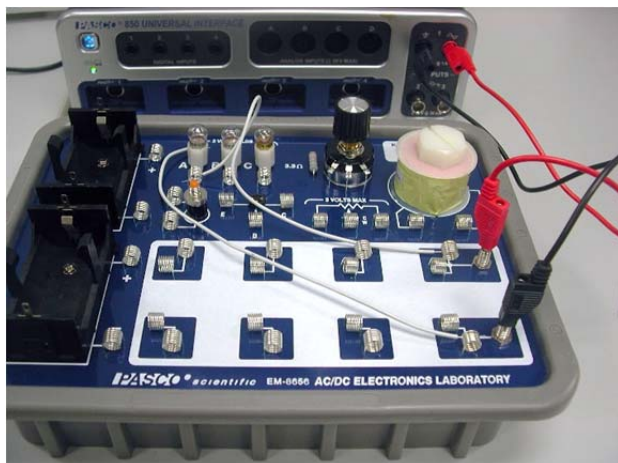


Figure 3: Light Bulb Setup



Figure 4: Diode “up” Setup

Analysis: Ohm's Law for a Resistor

Random noise generated in the 850 Universal Interface limits the precision of the current reading to about ± 0.1 mA. In addition there is a zero error in the current reading of up to 5 mA. This affects the intercepts but does not change the slope of the line.

1. Click once on the multicolored Run Select icon in the graph toolbar to show more than one data set. Then click on the black triangle by the Run Select icon and select the “330 Run” and the “560 Run”. Both should show on the graph.
2. Click on the Scale-to-Fit icon on the graph toolbar.
3. Select the “330 Run” data by clicking on it in the legend box or by clicking the “330 Run” data on the graph.
4. Click on the black triangle by the Curve Fit icon on the graph toolbar and select Linear.

5. Repeat for the “560 Run” data. You may need to drag one of the Linear boxes to see both of them at the same time.
6. Answer Questions 1-4 in the Conclusions section.

Analysis: Light Bulb

1. Click on the black triangle by the Run Select icon and select the “Light Bulb” run.
2. Click on the Scale-to-Fit icon.
3. Answer Question 6-8 in the Conclusions section.
4. To help answer Question 8, hook up the lamp again as in Figure 2. Click open Signal Generator and set output 1 for a Frequency of 0.01 Hz and an Amplitude of 2.5 V. Click Auto. Click RECORD and let it run for one full cycle (100 s). You should see both this run and the “Light Bulb” run on the graph. If not, use the Run Select icon to select both. Is the answer to Question 8 more clear now? Re-label this run “lamp slow”.
5. Wait a minute! Tungsten is a metal and the metals are supposed to obey Ohm’s Law. What is going on? Turn off “Light Bulb” so only “lamp slow” is displayed on the graph. Click on the Selection icon and drag the Selection box handles to select the data where voltage is between -0.1 V and +0.1 V and current is between -0.05 A and +0.05 A. Click the Scale-to-Fit icon. Click on the black triangle by the Curve Fit icon and select Linear. Answer Question 9 in the Conclusions section.

Analysis: Diode

1. Click on the black triangle by the Run Select icon and select the “diode up”, and “diode down” runs. Both curves should show at the same time.
2. Click on the Scale-to-Fit icon.
3. Click on the Selection icon. Drag the handles on the Selection box to include the data between +/- 1 V and +/- 0.05 A.
4. Click the Scale-to-Fit icon. Click the Remove Active Element icon.
5. Click the black triangle by the Run Selection icon and select “330 Run” in addition to the “diode up”, and “diode down” runs. Note that all three curves have the same x-intercept (where $V = 0$). The current is zero here, but probably does not read zero due to the zero error in the current sensor. Assume the current is actually zero at this point and answer Questions 10-12 in the conclusions.

Ohm's Law Conclusions

1. Why do the lines formed by the data have some width?
2. Why do the "330 Run" line and the "560 Run" line cross on the $V = 0$ axis?
3. How well do the resistors obey Ohm's Law? Explain fully how you know!
4. What is the physical meaning of the slope of the Linear Fit to the data on the Ohm's Law graph? Hint: what are the units of the slope?
5. What is the bulb doing during the kink in the curve?
6. What evidence is there that the light bulb does not obey Ohm's Law?
7. Why doesn't the light bulb obey Ohm's Law?
8. Why are there two curves? That is, why are there two values of current for each voltage near the kink? And why is there a kink?
9. Is there any region where the light bulb obeys Ohm's Law? Why?
10. Does the diode obey Ohm's Law? How do you know?
11. Does the diode conduct in both directions? Explain fully.
12. When does the diode conduct?

Series Parallel Circuits

Equipment

1	AC/DC Electronics Laboratory	EM-8656
1	Short Patch Cords (set of 8)	SE-7123
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

Introduction

Series/Parallel circuits are reduced to an equivalent resistance and that resistance is verified by measuring the total current and total voltage.

In a second stand-alone experiment, the behavior of lamps in series, parallel, and series/parallel is qualitatively examined.

Theory

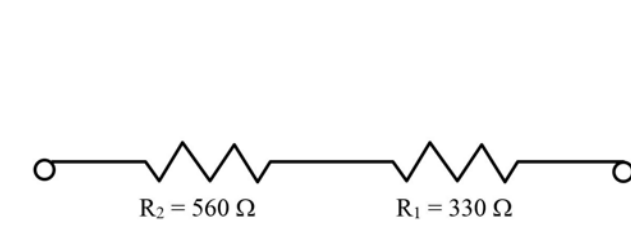
A resistor generally means a device that obeys Ohm's Law (many devices do not) and has a resistance R . Two (or more) resistors can be connected in series (as in Figure 1), or in parallel (as in Figure 2). Resistors could also be connected in a series/parallel circuit as shown in Figures 3 and 4. An equivalent resistor is a single resistor that could replace a more complex circuit and produce the same total current when the same total voltage is applied. For a series circuit, the resistances are additive:

$$R_{eq} = R_1 + R_2 \quad (2)$$

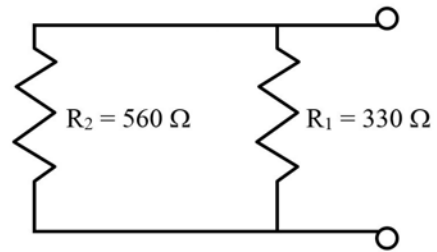
where R_{eq} is the equivalent resistance. For a parallel circuit, the resistances add as reciprocals

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} \quad (3)$$

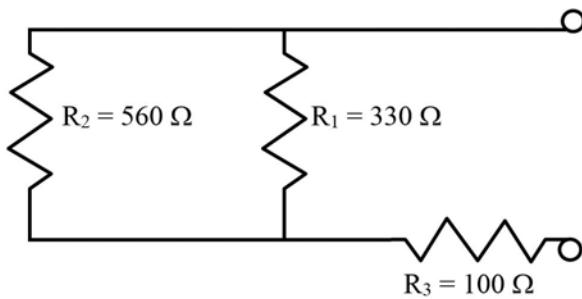
A more complex circuit like that in Circuit Diagram 3 can be handled by noting that R_1 and R_2 are in parallel and can be reduced to an equivalent resistance using Equation 3. That equivalent resistance is then in series with R_3 and can be treated using Equation 2 to find the equivalent resistance of the entire series/parallel circuit. Circuit Diagram 4 can be handled in a similar manner.



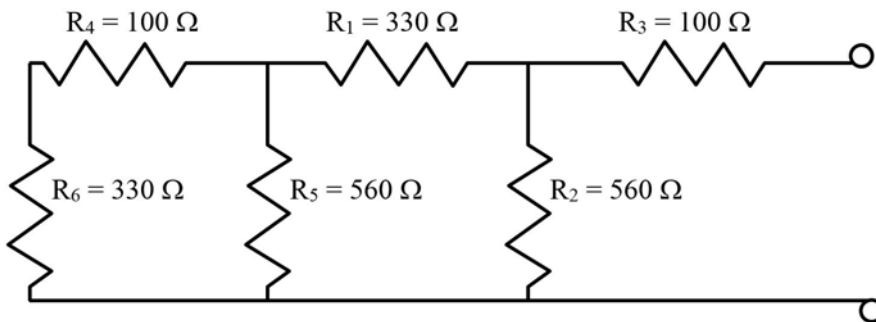
Circuit Diagram 1: Series



Circuit Diagram 2: Parallel



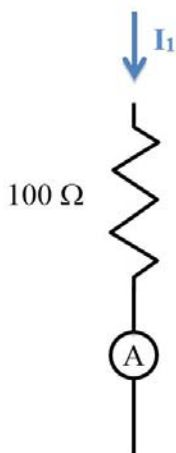
Circuit Diagram 3: Simple Series Parallel



Circuit Diagram 4: Complex Series Parallel

Resistor Calibration

Locate two $100\ \Omega$ ($\pm 5\%$) (brown-black-brown-gold) resistors, two $330\ \Omega$ (orange-orange-brown-gold) resistors, and two $560\ \Omega$ (green-blue-brown-gold) resistors. Label different positions on a piece of paper R_1 , R_2 , R_3 , R_4 , R_5 , R_6 . Put the $100\ \Omega$ resistors at R_3 and R_4 , the $330\ \Omega$ resistors at R_1 and R_6 places, and the $560\ \Omega$ resistors at R_2 and R_5 places. After we measure the resistances, it will be important to keep them straight. Construct the circuit shown in Figure 1. One of the $100\ \Omega$ resistors is connected between the two springs. The 850 Universal Interface measures the voltage between the red and black wires and the current flowing through the wires.



Circuit Diagram 5: Calibration Circuit

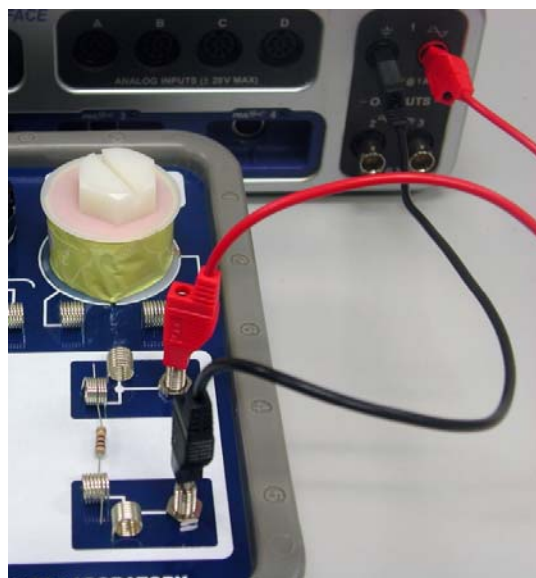


Figure 1: Ammeter Calibration

The color codes on the resistors only have a precision of $\pm 5\%$. This can be improved to about $\pm 1\%$ using the calibration circuit.

1. In PASCO Capstone, open the Hardware Setup and click on Signal Generator #1 on the 850 Universal Interface and select the Output Voltage Current sensor.
2. Set the sample rate for the Output Voltage Current sensor to 50 Hz.
3. Create a graph of Output Voltage vs. Output Current.
4. Click open the Signal Generator at the left of the page. Set Waveform for a Triangle wave at 10 Hz and Amplitude for 10 V. Click Auto. Click Signal Generator to close the panel.
5. Click Record. Click Stop after a few seconds.
6. On the graph, select a linear fit.
7. The slope of the line is the measured resistance. Record the value of the resistance.
8. Repeat for each of the six resistors. Make sure you keep track of which resistor is which.

Equivalent Resistance

Using the calibrated values for the resistors, calculate the equivalent resistance for each of the four circuit diagrams shown in the Theory Section. Record these equivalent resistances.

Calibrate Procedure

The internal ammeter operates by measuring the voltage drop across a small resistor ($\sim 0.1 \Omega$). Since the sensitivity is about 0.1 mA, this means the 850 Universal Interface must measure voltages of 0.01 mV. Noise can result in significant zero error. By averaging over several seconds we can achieve a precision of 0.1 to 0.2 mA, but with systematic errors that can approach 5 milliamps. We can correct for this with a brief calibration procedure.

1. Make sure the 100Ω resistor with the actual resistance closest to 100Ω is back in the calibration circuit (see Figure 1).
2. Create a calculation in Capstone:

$$i_{\text{avg}} = \text{avg}([\text{Output Current (mA)}]) \quad \text{with units of mA}$$
3. Create a Digits display and select the calculation “ i_{avg} ”.
4. Create a table as shown below. In the first column, create a User-Entered Data Set called “Theory Current” with units of mA. Fill the column with the values shown which are calculated ($\text{Theory Current} = V/100\Omega$ where V is 0 to 7V) assuming the resistance is exactly 100Ω . If your value is different, correct the first column. In the second column, create a User-Entered Data Set called “A Current” with units of mA. In the third column create a calculation:

$$A_{\text{correct}} = -[A_{\text{Current (mA)}}] + [i_{\text{avg (mA)}}] \quad \text{with units of mA}$$

Table I: Ammeter Calibration Data

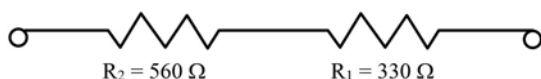
Theory Current (mA)	A Current (mA)	A correct (mA)
0		
10		
20		
30		
40		
50		
60		
70		

5. Click open the Signal Generator at the left of the screen. Set 850 Output 1 for a DC Waveform and a DC Voltage of 0 V. Click the On button.
6. Click Record.

7. Wait several seconds until the measured current stops varying as the average becomes well defined. Click Stop.
8. Enter the value in the second column of the first row Table I.
9. Click Delete Last Run at the bottom of the screen.
10. In the Signal Generator panel, increase the voltage by 1 V and repeat. Then repeat, increasing the voltage by 1 V each time until 7 V is reached. Enter the values in the appropriate line in Table I.

Setup

Construct the circuit shown in the Circuit Diagram 1 and Figure 3.



Circuit Diagram 1: Series

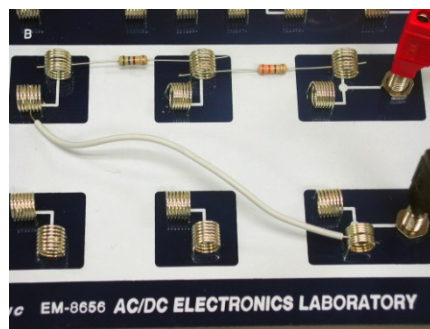
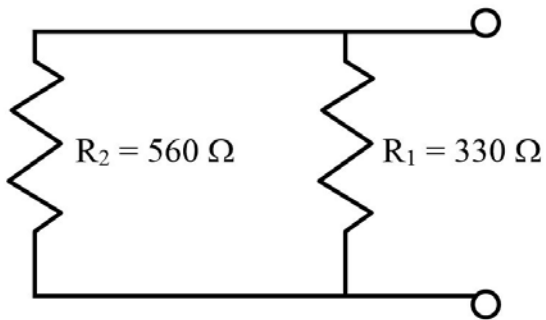


Figure 3: Series Circuit

Procedure

1. Click open the Signal Generator. Select Output 1 DC Waveform at 15 V. Click Auto. Click the Signal Generator again to close the panel.
2. Click Record. After the values stop varying, click Stop.
3. Correct the Total Current by adding the correction for that current from Table I. Use the corrected value for total current and the total voltage to calculate the Equivalent Resistance.
4. Repeat for each of the circuits shown on the next page.

Circuits



Circuit Diagram 2

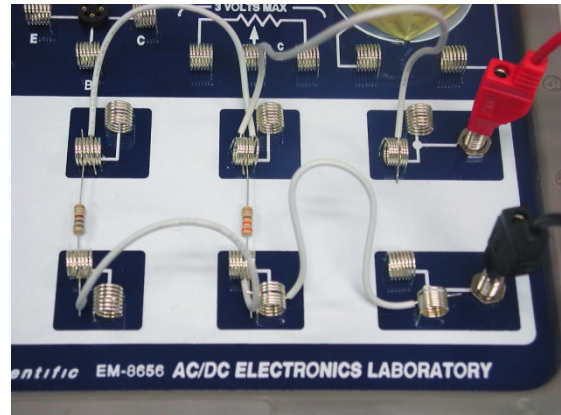
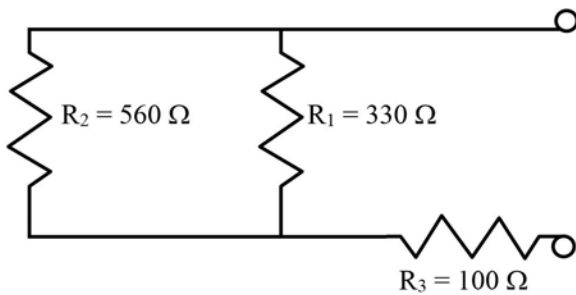


Figure 4: Parallel Circuit



Circuit Diagram 3

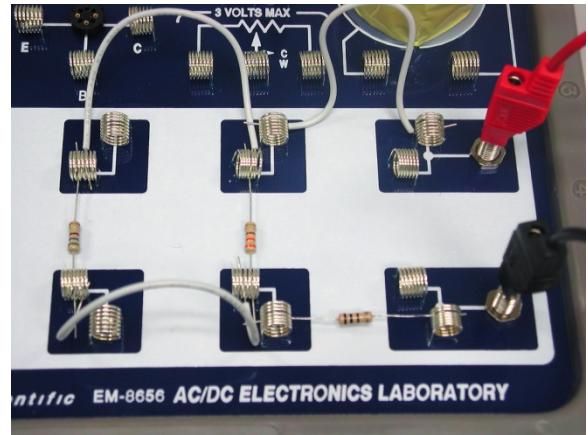
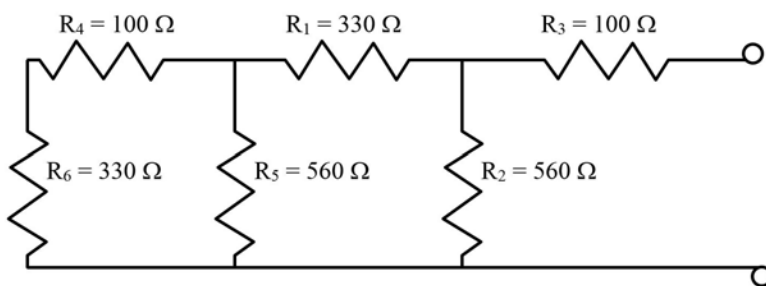
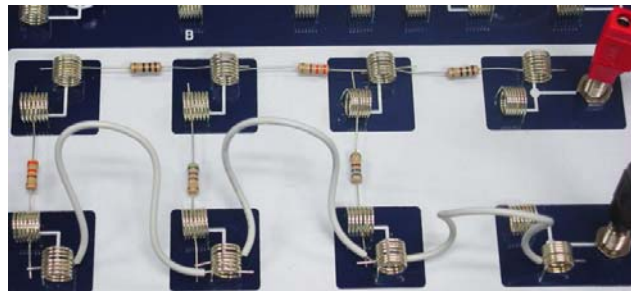


Figure 5: Simple Series Parallel



Circuit Diagram 4

Figure 6: Complex Series Parallel



Conclusions

How well did the experiment work? What does it show?

Lamp Setups

Setup as in Figure 7 with only lamp A in the circuit.



Figure 7: Single Lamp



Figure 8: Lamps A&B in Series

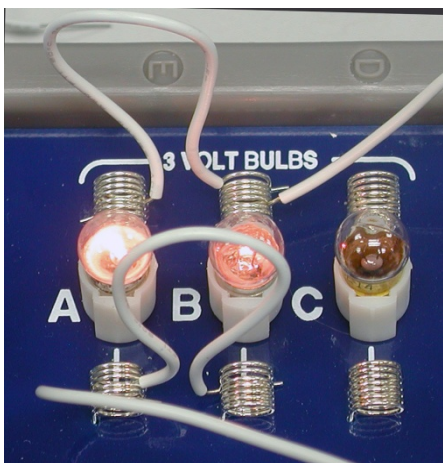


Figure 9: Lamps A&B in Parallel

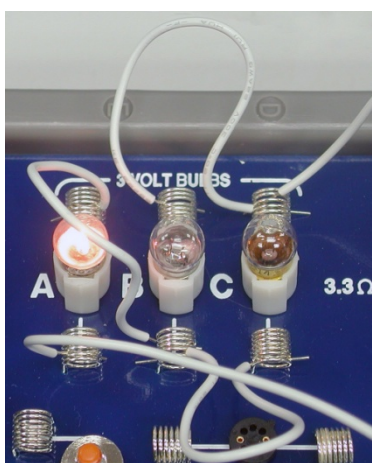


Figure 10: Series Parallel Lamps

Lamp Procedure

1. Click open the Signal Generator at the left of the page. Set Waveform for a Triangle wave at 10 Hz and Amplitude for 2.5 V. Click On.
2. Click Record. Click Stop after a few seconds. Click the Signal Generator Off.
3. Select a linear fit on the graph of Output Voltage vs. Output Current. The data will not quite be linear since the bulb resistance changes as it heats and cools.
4. The slope of the line is the measured resistance of the bulb at its operating temperature. Record the value to the nearest 0.1 Ω for bulb A.
5. Repeat for the other two bulbs.
6. Put bulbs A and B in series as shown in Figure 8 and repeat. Answer question 1 in the Lamp Conclusions Section.
7. Put bulbs A and B in parallel as shown in Figure 9 and repeat. Answer question 2 in the Lamp Conclusions Section.
8. Put bulb A in series with bulbs B and C which are in parallel as shown in Figure 10 and repeat. Answer question 3 in the Lamp Conclusions Section.

Lamp Conclusions

1. How does the brightness of two bulbs in series compare to a single bulb? Why?
2. How does the brightness of two bulbs in parallel compare to a single bulb? Why?
3. Why is one bulb brighter? Why do two bulbs not glow?
4. Using the formulas from Theory, calculate the equivalent resistances for the two and three bulb circuits.
5. Why does the measured value of resistance for the series circuit not agree with the calculated value?
6. Why does the measured value of resistance for the parallel circuit agree with the calculated value?
7. Why does the measured value of resistance for the series/parallel circuit not agree with the calculated value? Why is it roughly the same as for bulb A alone?

Kirchhoff's Circuit Laws

Equipment

1	Resistive/Capacitive/Inductive Network	UI-5210
1	AC/DC Electronics Laboratory	EM-8656
3	Voltage Sensors	UI-5100
2	Current Probe	PS-2184
1	Short Patch Cords (set of 8)	SE-7123
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

Introduction

Kirchhoff's Laws form the basis of all circuit analysis. Here we verify the laws for a resistive circuit using a DC input and for a time varying RC circuit. The DC portion and the RC portion of the lab are each stand-alone labs.

Theory

Kirchhoff's Rules (sometimes called laws) state:

1. Junction Rule: the total current flowing into any point is zero at all times where we use the convention that current into a point is positive and current out of the point is negative.

$$\Sigma I = 0 \quad (1)$$

2. Loop Rule: the sum of the voltage drops around any closed loop must equal zero where the drop is negative if the voltage decreases and positive if the voltage increases in the direction that one goes around the loop.

$$\Sigma V = 0 \quad (2)$$

We will apply Kirchhoff's rules to the "Y" circuit shown in Figure 1. V_o will be the supply voltage from Output 1 of the 850 Universal Interface. V_c will be produced by the voltage divider setup shown in Figure 2. We will not attempt to calculate V_c , but will measure it directly. To solve for the three unknown currents, we need three equations. Applying Equation 1 at point A in the circuit:

$$I_1 + I_2 - I_3 = 0 \quad (3)$$

where we take current flowing in as positive and current out as negative. Applying Equation 2 around loops 1 and 2 yields:

$$R_1 I_1 + R_3 I_3 - V_C = 0 \quad (4)$$

$$-R_2 I_2 - R_3 I_3 + V_o = 0 \quad (5)$$

where the voltage is negative if we go from high voltage to low (with the current arrow across a resistor).

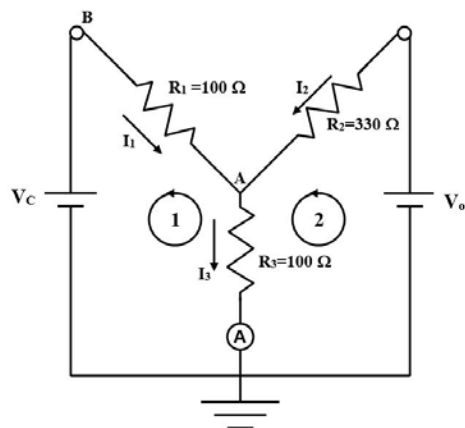


Figure 1: "Y" Circuit

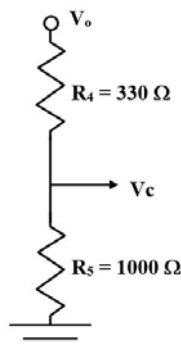


Figure 2: Voltage Divider

Resistor Calibration

1. In PASCO Capstone, open the Hardware Setup and click on Signal Generator #1 on the 850 Universal Interface and select the Output Voltage Current sensor.
2. Plug in a Voltage sensor to Channel A on the interface.
3. Open the Data Summary and click on the Properties gear button for the Voltage Sensor Ch. A. Set the Gain to 1000x.
4. If the Current Probe is not visible in the Data Summary under the Voltage Sensor (Ch. A), click on the eye (visibility) icon next to the Voltage Sensor (Ch. A) and select the Current Probe.
5. Create a graph of Output Voltage vs. Current Probe (Ch. A). Create another graph of Output Voltage vs. Output Current.
6. On the Sampling Control Bar at the bottom of the Capstone page, set the Common Sample Rate to 50 Hz.
7. Construct the circuit shown in Figures 3 through 5. A $100\ \Omega$ ($\pm 5\%$) (brown-black-brown-gold) resistor is connected in series with a Current Probe (the A with a circle around it [for ammeter] on the circuit diagram). A Voltage sensor is attached to the Current Probe as shown and then to Ch. A on the 850 Universal Interface. It is important to observe polarity by connecting red to red and black to black where possible. There is a second ammeter built into the 850 Output 1.

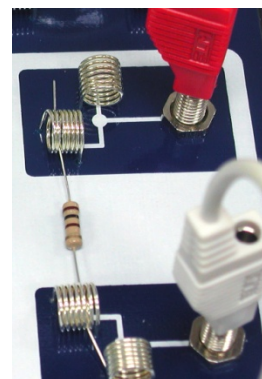
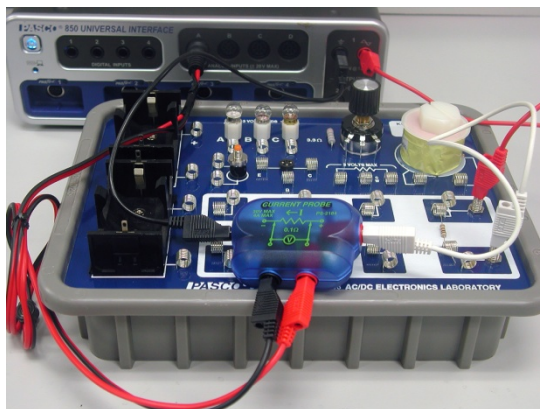
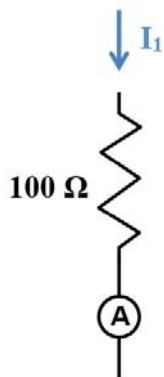


Fig. 3: Calibration Circuit Figure 4: Ammeter Calibration

Figure 5: 100 Ω Resistor

The color codes on the resistors only have a precision of $\pm 5\%$. This can be improved to about $\pm 1\%$ using the calibration circuit.

1. Click open the Signal Generator at the left of the page. Set Waveform to Triangle at 10 Hz and an amplitude of 10 V. Click Auto. Click Signal Generator to close the panel.
2. Click Record. After about 2 seconds, click Stop.
3. For each graph, select a Linear fit.
4. The slope of each line is the measured resistance. Record the slopes and average the two values.
5. Repeat for another 100 Ω and a 330 Ω (orange-orange-brown-gold) resistor. Make sure you keep track of which 100 Ω resistor is R_1 and which is R_3 .

Ammeter Calibration

The Current Probes work by measuring the voltage drop across a small resistor (0.1 Ω for the Current Probes). Since the sensitivity is about 0.1 mA, this means the 850 Universal Interface must measure voltages of 0.01 mV. Noise can result in significant zero error. By averaging over several seconds we can achieve a precision of 0.1-0.2 mA, but with systematic errors that can approach 1 milliamp. We can correct for this with a brief calibration procedure.

1. Make sure the 100 Ω resistor is back in the calibration circuit (see Figure 4).
2. Click open the Signal Generator at the left of the screen. Set 850 Output 1 for a DC Waveform and a DC Voltage of 0 V. Click the On button.
3. Create a Digits display with Current Probe (Ch.A). Select units of mA and in the Statistics, turn on the Mean.
4. Click Record.

- Wait several seconds until the measured mean current stops varying as the average becomes well defined. Click Stop.
- Create a table as shown below. In the first column, create a User-Entered Data Set called "Theory Current" with units of mA. In the second column, create a User-Entered Data Set called "A Current" with units of mA. In the third column, create a calculation called "A Correct" with units of mA:

$$A \text{ correct} = -[A \text{ Current (mA)}] + [\text{Theory Current (mA)}]$$

Table I: Ammeter Calibration Data

Theory Current (mA)	A Current (mA)	A correct (mA)
0.0		
10.0		
20.0		
30.0		
40.0		
50.0		
60.0		
70.0		

- Enter the value in the second column of the first row of Table I.
- Click Delete Last Run at the bottom of the screen.
- In the Signal Generator panel, increase the voltage by 1 V and repeat. Then repeat, increasing the voltage by 1 V each time until 7 V is reached. Enter the values in the appropriate line. Turn Signal Generator off.
- The Theory Current in column 1 is calculated assuming that the resistance is exactly 100 Ω . If your value is different, correct the first column by calculating $I = V/R$ using your exact R.

DC Setup

Construct the circuit shown in the Figure 6:

- First attach the resistors as shown in Figure 7. Note that the "Y" is on the left and the voltage divider (see Figure 2 on the Theory page) is the two resistors on the right. R_1 is the 100 Ω resistor on the upper left.
- R_2 is the 330 Ω resistor at top center.
- R_3 is the 100 Ω resistor running from top to bottom.
- The voltage divider will supply V_c to point B on the left end of R_1 . Attach a 330 W resistor from top to bottom as shown and a 1 k Ω resistor (brown-black-red-gold) at the

bottom right. A white jumper wire connects the upper left (left end of R_1) to the lower right (center of the voltage divider providing V_c). A white jumper wire also connects the right end of R_2 to the upper right spring where V_o will be applied. Another jumper connects the lower left spring to the left end of the $1000\ \Omega$ resistor.

5. Three more jumper wires have one end attached to springs as shown. *Note: it is important to use the jumper wires to attach to the board and not connect to the springs directly with alligator clips since it is rather easy to pull the springs loose from the circuit board.*

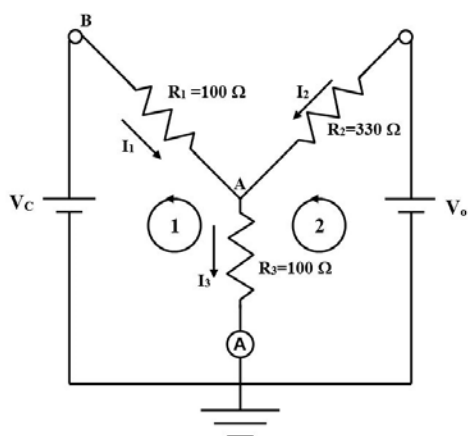


Figure 6: “Y” Circuit

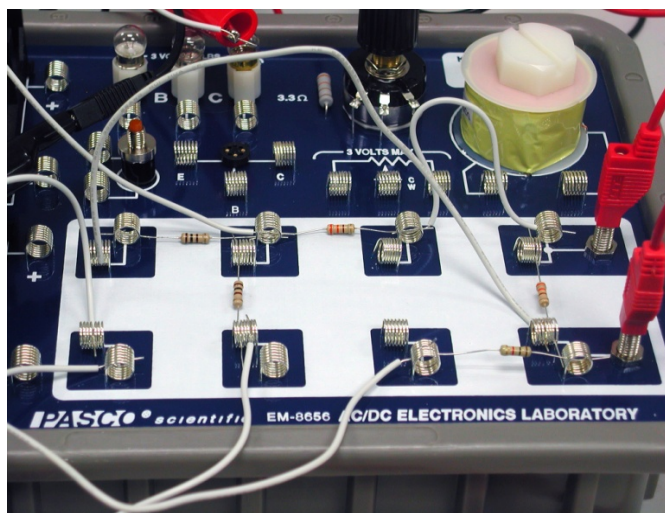


Figure 7: Resistor Setup

6. Attach the ammeter by clipping the red end of the ammeter to the white wire attached to the bottom of the $100\ \Omega$ resistor (R_3) as shown in Figure 8. The black side of the ammeter attaches to the white wire coming from the lower left spring. The black wire from Output 1 on the 850 also attaches to this point (ground).
7. Plug Voltage sensors into Channels B and C on the 850. The black leads from both are attached to the black side of Output 1 on the 850. The red side of Output 1 is attached to the upper banana input (V_o) on the circuit board as shown in Figure 9. The red lead from Analog input C is attached to the lower banana input (V_c) on the circuit board. The red lead from Analog input B is attached to the white wire coming from the junction point A between the three resistors. It will measure V_a .

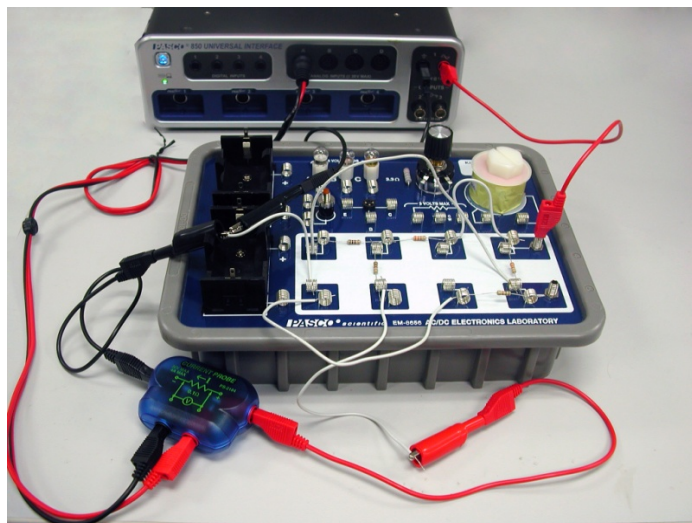


Figure 8: Hooking Up the Ammeter

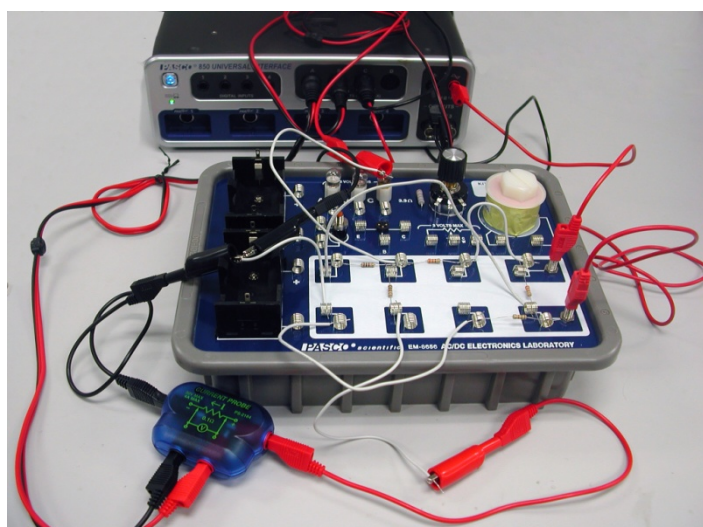


Figure 9: Connecting the Voltage Probes

DC Current Procedure

1. Click open the Signal Generator at the left of the screen. Set 850 Output 1 for a DC Waveform and a DC Voltage of 15 V. Click the Auto button.
2. Open the Calculator and create two calculations, both with units of A:

$$I1 \text{ cal} = ([\text{Output Voltage, Ch O1 (V)}] - [\text{Voltage, Ch B (V)}]) / [R2 - 330 (\Omega)]$$

$$I2 \text{ cal} = ([\text{Voltage, Ch C (V)}] - [\text{Voltage, Ch B (V)}]) / [R1 - 100 (\Omega)]$$
3. Create Digits displays for V(Ch. B), V(Ch. C), Output Voltage, Current Probe (Ch. A), I1 cal, and I2 cal. For the Current Probe Digits, choose the Mean on the statistics.
4. Click Record.

- Wait several seconds until the measured current stops varying as the average from the Current Probe becomes well defined. Click Stop.
- Record the voltage and current values from all the Digits displays.

Note: Although the total current, I_3 , is measured directly, I_1 and I_2 are calculated from the measured voltage drops using $\Delta V/R = I$. Although it would be nice to measure them directly, shifting the ammeter ground introduces error of a few mA which decreases the precision of the experiment since the current values are quite small. This really is not a limitation on the results since this is what the ammeter does as well. It measures the voltage drop across a $0.1\ \Omega$ precision resistor. We have just made our own ammeters by replacing the $0.1\ \Omega$ resistor with the known values for the resistors in the circuit.

DC Analysis

- Apply the correction from the Current Correction graph to i_A ave to get a corrected value for I_3 and record it.
- Using Equations 3-5 from Theory, calculate values for I_1 , I_2 , and I_3 . These three equations may be solved simultaneously, or you may solve them using a 3×4 augmented matrix.
- Calculate the theory values that you should expect for the three currents and the percent difference from measured and record them.

Conclusion

How well did your values check out?

RC Setup

Construct the circuit shown in the Circuit Diagram (Figure 10) with reference to Figures 11 and 12:

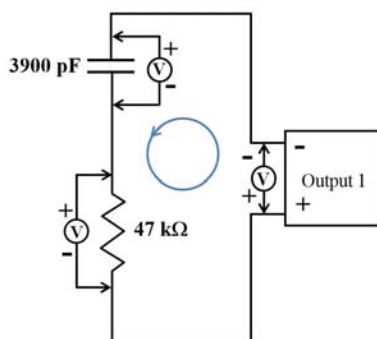


Fig. 10: Circuit Diagram

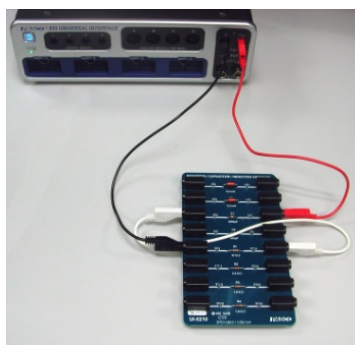


Figure 11: RC Series

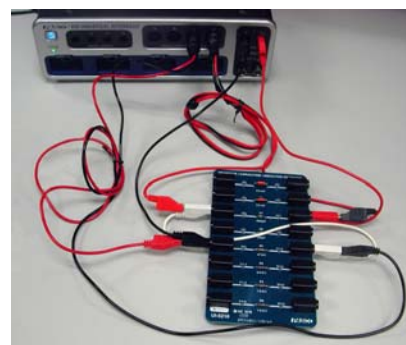


Figure 12: Adding the Sensors

- First construct the series circuit shown in Figure 11 using the 3900 pF capacitor and the 47 kΩ resistor. Note the polarities, with the red lead from the 850 Output 1 attached to

the right side of the capacitor and the left side of the capacitor attached to the right side of the resistor.

2. Now add the Voltage Sensors as shown in Figure 12. The polarities must match that shown in Circuit Diagram (Fig. 10) with the red leads on the left ends of the resistor and capacitor. The Voltage Sensor across the resistor must attach to Channel C and the Voltage Sensor across the Capacitor must attach to Channel D.
3. Create an Oscilloscope display with both the voltages from Channel C and D on the same vertical axis and time on the horizontal axis.
4. Set the sample rate for Voltage Ch. C and Ch. D at 500 kHz. Change Sampling Mode to Fast Monitor Mode.

RC Procedure

1. Click open the Signal Generator. It should be set for a Square Waveform at 1000 Hz and 10 V. Click On.
2. Click Monitor at the lower left of the screen. The oscilloscope should record one cycle and stop. If any of the vertical jumps in the square wave fall exactly on one of the vertical time lines (0.0002 s, etc.), click monitor again.
3. Click Off on the Signal Generator and click on the Signal Generator button to close the Signal Generator panel.
4. The pattern on the oscilloscope screen shows the input voltage (V0), the voltage across the resistor (VR), and the voltage across the capacitor (VC). Why the voltages vary will be dealt with later in the course. Here we are only interested in verifying that Kirchhoff's Loop rule holds at any instant of time.

RC Analysis

1. Create a table as shown below.

Table II: RC Voltages

Time in millisecc. (ms)	V0 (V)	VR (V)	VC (V)	V loop (V)
0.200				
0.400				
0.602				
0.800				
1.000				

Create the User-Entered Data sets called "Time in millisecc" with units of ms; "V0" with units of V; "VR" with units of V; and VC with units of V. In the last column, create a calculation with units of V:

$$V_{\text{loop}} = [V0 \text{ (V)}] + [VR \text{ (V)}] + [VC \text{ (V)}]$$

2. Click on the Coordinate tool on the oscilloscope toolbar (crosshairs). We want 5 significant figures in the coordinates box. If that is not the case, right click on the center of the cross-hairs on the oscilloscope and select Tool Properties and increase the significant figures to 5.
3. Move the cross-hairs up the 0.2 ms (0.0002 s) line and record the values for V_0 , V_R , and V_C to three decimal places in the Table II. Try to get the value for time in the coordinates box as close to 2.00×10^{-4} s as possible (the last two digits will always be zero). You should be able to get within 0.02×10^{-4} s always and generally exactly on 2.00×10^{-4} s. If you can't get it exactly on, try to take all three data points at the same time.
4. Repeat for 0.4 ms, 0.6 ms, 0.8 ms, and 1.0 ms.

RC Conclusions

Considering the sum voltages in the 5th column of the RC Voltages table under the RC Analysis tab, what can you conclude about Kirchhoff's Loop Rule for time varying circuits?

Capacitance

Equipment

1	Basic Electrometer	ES-9078
1	Basic Variable Capacitor	ES-9079
1	Electrostatics Voltage Source	ES-9077
1	Short Patch Cords (set of 8)	SE-7123

Required but not included:

1	850 Universal Interface	UI-5000
1	PASCO Capstone	
	Paper	

Introduction

The purpose of this experiment is to investigate how the capacitance of a parallel-plate capacitor varies when the plate separation is changed and to qualitatively see the effect of introducing a dielectric material between the plates. A computer model of the system will be developed and the student will observe some of the power of computer modeling.

Theory

A capacitor is used to store charge. A capacitor can be made with any two conductors kept insulated from each other. If the conductors are connected to a potential difference, V , as in for example the opposite terminals of a battery, then the two conductors are charged with equal but opposite amount of charge Q , which is then referred to as the “charge in the capacitor.” The actual net charge on the capacitor is zero. The capacitance of the device is defined as the amount of charge Q stored in each conductor after a potential difference V is applied:

$$C = Q/V$$

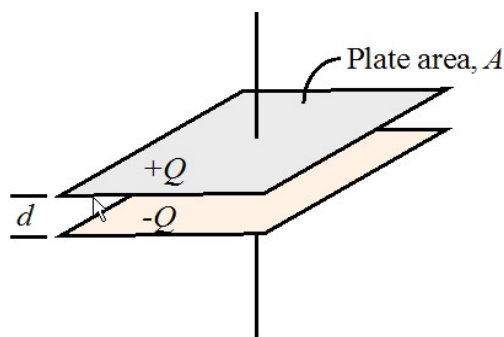
Rearranging gives:

$$V = Q/C \quad (1)$$

The simplest form of a capacitor consists of two parallel conducting plates, each with area A , separated by a distance d . The charge is uniformly distributed on the surface of the plates. The capacitance of the parallel-plate capacitor is given by:

$$C = \kappa \epsilon_0 A/d$$

Where κ is the dielectric constant of the insulating material between the plates ($\kappa = 1$ for a vacuum; other values are measured experimentally and can be found in tables), and ϵ_0 is the



permittivity constant, of universal value $\epsilon_0 = 8.85 \times 10^{-12}$ F/m. The SI unit of capacitance is the Farad (F).

The system we use is more complex. In addition to the two moveable parallel plates, the connecting wires and the electrometer also have some capacitance. This capacitance is roughly equal to the capacitance of the moveable plates when the plates are 1 cm apart and cannot be ignored. Including this gives:

$$C = \kappa \epsilon_0 A/d + C_{\text{sys}} \quad (2)$$

where C_{sys} is the capacitance of the rest of the system. Substitution of Equation 2 into Equation 1 yields:

$$V = Q/(\kappa \epsilon_0 A/d + C_{\text{sys}}) \quad (3)$$

Any material placed between the plates of a capacitor will increase its capacitance by a factor κ called the dielectric constant where:

$$C = \kappa C_0 \quad (4)$$

with C_0 being the capacitance when there is a vacuum between the plates of the capacitor. Dielectric materials are non-conductive. Any dielectric material can be used to keep the plates in a capacitor insulated from each other (preventing them from touching and discharging). To three significant figures, $\kappa = 1.00$ for air. For all materials, $\kappa > 1$. If the charge on a capacitor is kept constant while a dielectric is inserted between the plates, Equations 1 & 4 yield:

$$Q = CV = C_0 V_0 = C/(\kappa \epsilon_0 V_0) \quad \text{so} \quad V = V_0/\kappa$$

Where V_0 is the voltage before inserting the dielectric and V is the voltage after insertion. Since $\kappa > 1$ always, we have

$$V < V_0 \quad (5)$$

Setup



Figure 1: Setup



Figure 2: Indicator Foot

1. Move the Variable Capacitor plates so they are about 2 mm apart. Use the adjustment screws on the back of the moveable plate to make the plates parallel. Easiest way to do this is to look directly down from above the plates and adjust the horizontal adjust until the gap looks uniform, then look at the gap from the side and even with the center of the plates and adjust the vertical screw. May need to repeat the process a few times.
2. Position the movable plate so the leading edge of the indicator foot (see Fig. 3) is at the 0.2 cm position. The gap between the two plates should be 0.2 mm all the way around. Check it with a ruler. If the gap varies repeat step 1. If the gap is not 0.2 mm, release the holding screw on the non-moving plate and move it until the gap is 0.2 mm and then tighten the screw back down.
3. Attach the twin lead (red & black) connector to the Signal Input jack on the Basic Electrometer. Route the wires as far away from where your hand and your body will be as possible. The charges in this experiment all small so static discharge will foul things up. Also, people are conducting plates and have a significant amount of capacitance. *You can foul things up just by being close.* It is best to make the fixed plate ground by attaching the black wire's spade lug to it. Attach the red spade lug to the terminal on the moving plate. The wire must be free to move when the plate moves.
4. If you have a black banana/banana wire (not included) attach it as shown from the common (com) terminal on the Electrostatic Voltage Source to the ground terminal on the Electrometer. Alternately, use the provided banana/spade wire and connect the spade lead to the terminal on the fixed plate where the other ground lead is already attached. Attach the red banana/spade lead to the +30V terminal and leave the spade end free. Plug in the transformer and apply power to the Electrostatic Voltage Source. Shift the switch on the back to the On position. The green Power On light should glow.
5. Use the supplied adaptor cable to attach from the Signal Output on the Electrometer to the A Analog Input on the 850 Universal Interface. It is important that it be the A input!

6. In PASCO Capstone, create a table and create a user-entered data set called Separation with units of cm. Enter the values shown in Table I. Select the Voltage measurement in the second column.

Table I: Air Gap Capacitor

Separation (cm)	Voltage (V)
8.0	
7.0	
6.0	
5.0	
4.0	
3.0	
2.0	
1.5	
1.0	
0.5	
0.3	

7. Create a graph of Voltage vs. Separation.

Procedure A: The Effect of the Plate Separation

1. Set the capacitor plates 0.3 cm apart by setting the movable plate so leading edge of its indicator foot is at the 0.3 cm mark.
2. Turn on the electrometer and set the range button to the 100 V scale.
3. Remove any charge from the capacitor by momentarily touching both plates at the same time with your hand.
4. Zero the electrometer by pressing the 'ZERO' button until the needle goes to zero.
5. Momentarily connect a cable from the +30V outlet in the voltage source to the stud on the back of the movable capacitor plate. This will charge the capacitor. Remove the charging cable.
6. Read the following steps. They need to be performed quickly since the charge will slowly escape from the electrometer, especially if the humidity is high. One person should run the computer while one moves the capacitor plate. Everyone else should stay back. Everyone should try to be in the same position for each reading. Anybody who is close is a significant part of the system and can make the readings change.

7. Slide the movable plate so it is at 8.0 cm (leading edge of the indicator foot). Once the plate is in position, the person moving the plate should move away 50 cm or so and try to be in the same position for each measurement.
8. In Capstone, click the PREVIEW button at the lower left to begin collecting data. Colored numbers will appear in first row of the table. The person doing the computer should click the Keep Sample (red checkmark in the lower left) button. The number in the first row will turn black and the colored number will move to the second row. The person at the computer should read the next separation (7 cm) out loud and wait.
9. Move the plate to 7.0 cm and repeat the process until 0.3 cm.
10. Click the STOP button to end the data collection.
11. Examine the graph. If it looks like a smooth curve, you are done. If not, repeat the process until you get a nice looking run.

Analysis A

$$V = Q/(\kappa \epsilon_0 A/d + C_{\text{sys}}) \quad (3)$$

Examination of Equation 3 from Theory A show that if $C_{\text{sys}} = 0$, then V is directly proportional to d and the Voltage vs. Separation graph on the Data page should be a straight line. This is clearly not the case. To verify Equation 3 for the case where C_{sys} is not zero, we need to know Q and C_{sys} . We determine these by fitting the math model (Equation 3) to the data.

First we note that

$$\kappa \epsilon_0 A = (1.00) * (8.85 \times 10^{-12} \text{ F/m}) (2.46 \times 10^{-2} \text{ m}^2) = 2.18 \times 10^{-13} \text{ Fm} = 2.18 \times 10^{-11} \text{ F cm}.$$

So the parallel plate capacitance when $d = 1 \text{ cm}$ is $C_{1.0} = 2.18 \times 10^{-11} \text{ F}$. Note that this value is entered in line 2 of the Calculator.

When d is small (0.3 cm) the first term in the denominator dominates and

$$Q \sim V_{0.3} (\kappa \epsilon_0 A)/d = (30 \text{ V}) * (2.18 \times 10^{-11} \text{ F cm}) / (0.3 \text{ cm}) = 2.2 \times 10^{-9} \text{ C}.$$

This value is entered as an initial guess for the value of Q in line 1 of the calculator. Q is constant so when d becomes large, C_{sys} dominates in the denominator and we have:


$$C_{\text{sys}} \sim Q/V_8 \sim 2.2 \times 10^{-9} \text{ C} / 80 \text{ V} = 2.7 \times 10^{-11} \text{ F}$$

Where V_8 is the voltage when $d = 8 \text{ cm}$. This is taken as the initial guess for C_{sys} ($=C_1$) on line 3 of the calculator.

Note that C_{sys} is about equal to $C_{1.0}$ at 1.0 cm. At 0.3 cm, $C_{0.3} = 7 \times 10^{-11} \text{ F}$ so $C_{0.3} \sim 3 C_{\text{sys}}$ and the approximation above is decent but not great. At 8 cm $C_8 = 2.7 \times 10^{-12} \text{ F} = C_{\text{sys}} / 10$, so the approximation is good, but not perfect.

1. In the Calculator, create the following calculations:

$Q = 3.0 \times 10^{-9}$	Units of C
$\kappa \epsilon_0 A = 2.18 \times 10^{-11}$	Units of (F cm)
$C_1 = 3.6 \times 10^{-11}$	Units of F
$V \text{ model} = [Q]/([\kappa \epsilon_0 A]/[\text{Separation}] + [C_1])$	Units of V

2. Use the Data Display button () to select your best run.
3. Adjust the values for Q on line 1 of the Calculator and for C_1 on line 2 to make the model match the experimental curve as well as possible.
4. Answer the first four questions on the conclusions page.

Procedure B: The Effect of a Dielectric between the Plates

1. In PASCO Capstone, create a table and create a user-entered data set called Paper Position with no units. Enter the values shown in Table II. Select the Voltage measurement in the second column.

Table II: Paper Dielectric

	Paper Position	Voltage (V)
1	out	
2	in	
3	out	
4	in	
5	out	
6	in	
7	out	
8	in	
9	out	

2. You will use paper as the dielectric to be inserted between the plates. Get a stack of paper about 1 cm thick.
3. Position the movable plate of the capacitor at 8 cm.
4. Turn on the electrometer and set the range button to the 100 V scale.
5. Remove any charge from the capacitor by momentarily touching both plates at the same time with your hand.

6. Zero the electrometer by pressing the 'ZERO' button. The needle must be at zero.
7. Momentarily connect a cable from the +30V outlet in the voltage source to the stud on the back of the movable capacitor plate. This will charge the capacitor. Remove the charging cable.
8. Click on the PREVIEW button.
9. One student holds the stack of paper directly above the gap between the capacitor plates so that the long side of the paper is vertical. Hold the paper with one hand and keep the other hand on the metal connector attached to the signal input of the Electrometer so that there is no static charge on the student holding the paper. Press the Keep Sample button to record the voltage when the paper is not between the plates.
10. Lower the paper between the two plates until it touches the base. Do not let the paper touch either plate! Keep your hand as far above the plates as possible. Press the Keep Sample button to record the voltage when the paper is between the plates.
11. Pull the paper back above the plates and repeat steps 8 and 9 several times.
12. Click the STOP button to stop monitoring the data.
13. If the final voltage with the paper out is much different from the initial paper out value, you probably touched the plates and should repeat the experiment.

Conclusions

1. What happened to the voltage as the plates got closer together (d decreasing)?
2. What were your best fit values for the charge Q and C_{sys} ?
3. How well did your model fit the data? Try to explain any discrepancy. Hint: What approximations are made when deriving the parallel plate capacitance ($C = \kappa \epsilon_0 A/d$) from Gauss' Law?
4. Briefly discuss the value of computer modeling.
5. Examine Table II. Does the data agree with Equation 5? What does a dielectric do?

RC Circuit

Equipment

Included:

1	Resistor/Capacitor/Inductor Network	UI-5210
1	Voltage Sensor	UI-5100
1	Short Patch Cord Set	SE-7123
Not included, but required:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

Introduction

The manner by which the voltage on a capacitor decreases is studied. The half-life for the decay is measured directly and also calculated using the capacitive time constant.

Theory

Capacitors are circuit devices that can store charge. The capacitance (size) of the capacitor is a measure of how much charge it can hold for a given voltage.

$$Q = CV_C \quad (1)$$

where C is the capacitance in Farads, Q is the charge in Coulombs, and V_C is the voltage across the capacitor in Volts.

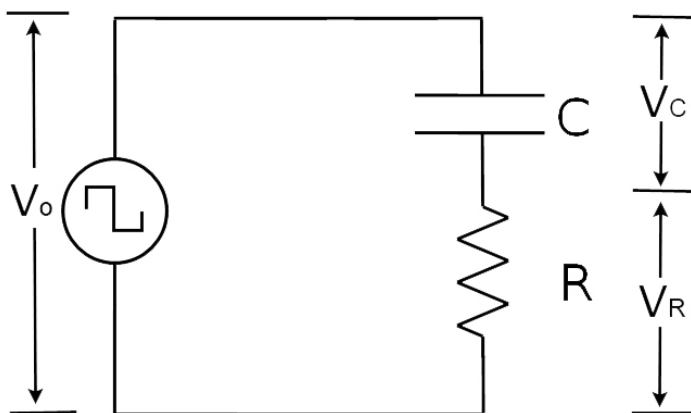


Figure 1: RC Circuit Voltages

To determine how the charge on a capacitor decays in time, use Kirchhoff's Loop Rule for Figure 1:

$$V_o = V_C + V_R \quad (2)$$

Solving Equation (1) for the voltage across the capacitor gives

$$V_C = Q/C \quad (3)$$

The voltage across the resistor is given by Ohm's Law:

$$V_R = IR \quad (4)$$

Therefore,

$$V_o = Q/C + IR \quad (5)$$

Since the applied voltage, V_o , is zero when the capacitor is discharging, Equation (5) reduces to

$$Q/C + IR = 0 \quad (6)$$

Since the current is

$$I = \frac{dQ}{dt} \quad (7)$$

Equation (6) becomes the differential equation

$$\frac{dQ}{dt} + \left(\frac{1}{RC}\right)Q = 0 \quad (8)$$

Solving Equation (8) for Q gives

$$Q = Q_{\max} e^{-\left(\frac{t}{RC}\right)} \quad (9)$$

Plugging Q into Equation (2) gives the voltage across the capacitor as a function of time

$$V(t) = V_o e^{-\left(\frac{t}{RC}\right)} \quad (10)$$

where $V_o = Q_{\max}/C$. The rate that voltage across a capacitor (and the charge stored in the capacitor) decreases depends on the resistance and capacitance that are in the circuit. If a capacitor is charged to an initial voltage, V_o , and is allowed to discharge through a resistor, R , the voltage, V , across the capacitor will decrease exponentially.

The half-life, $t_{1/2}$ is defined to be the time that it takes for the voltage to decrease by half:

$$V(t_{1/2}) = V_o/2 = V_o e^{-t_{1/2}/RC} \quad (11)$$

Solving for the half-life gives $t_{1/2} = RC \ln 2$. (12)

The product RC is called the capacitive time constant and has the units of seconds.

Pre-lab Questions

1. Show that the capacitive time constant RC has units of seconds.
2. If the capacitance in the circuit is doubled, how is the half-life affected?
3. If the resistance in the circuit is doubled, how is the half-life affected?
4. If the charging voltage in the circuit is doubled, how is the half-life affected?
5. To plot the equation $V(t) = V_0 e^{-t/RC}$ so the graph results in a straight line, what quantity do you have to plot vs. time? What is the expression for the slope of this straight line?

Setup

1. Construct the circuit shown in Figure 2. The voltage source is Signal Generator #1 on the 850 Universal Interface. $C = 3900 \text{ pF}$ and $R = 47 \text{ k}\Omega$.

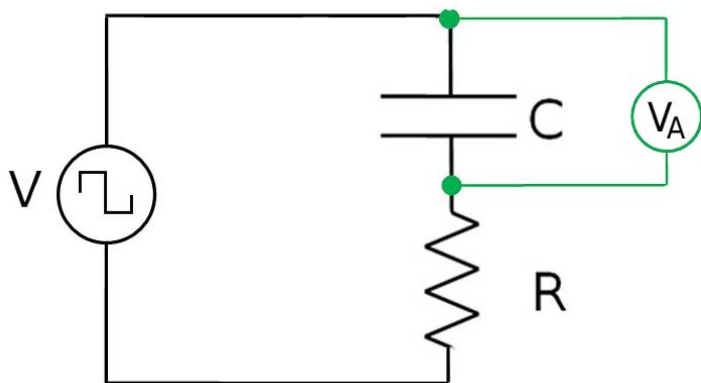


Figure 2: RC Circuit Diagram

2. Click on Signal Generator #1 to connect the internal Output Voltage-Current Sensor. Set the signal generator to a 350 Hz positive square wave with 4 V amplitude. Set the signal generator on Auto.
3. Plug the Voltage Sensor into Channel A. Connect the Voltage Sensor across the capacitor.

Procedure

1. Set up an oscilloscope display with the Voltage Ch.A and the Output Voltage on the same axis. Select the Fast Monitor Mode. Click Monitor and adjust the scale on the oscilloscope so there is a complete cycle, so the capacitor fully charges and discharges.

2. Increase the number of points (using the tool on the scope toolbar) to the maximum allowed. Then take a snapshot of both voltages shown. Rename the snapshots "3900pF".

Analysis

1. Create a graph with Voltage Ch.A and the Output Voltage vs. time. Select the voltages for the 3900 pF run on the graph.
2. Using the Coordinates Tool, measure the time it takes for the voltage to decay to half of its maximum. This time is the half-life. It may be necessary to reduce the snap-to-pixel distance to 1 in the properties of the Coordinates Tool (right click on the tool to access the properties).
3. Measure the time it takes for the voltage to decay to one-quarter of its maximum. This is two half-lives. Then divide this time by two to find the half-life.
4. Measure the time it takes for the voltage to decay to one-eighth of its maximum. This is three half-lives. Then divide this time by three to find the half-life. Take the average of the three measured values of the half-life. Estimate the precision of the measurement and state it as {half-life \pm precision}.
5. Calculate the theoretical half-life given by Equation (12) and compare it to the measured value using a percent difference.

Linearize the Data

1. Create a calculation $x = \ln(V/V_0)$ and plot it versus time. Also plot the voltage across the capacitor in the same plot area. This will help you identify where the capacitor is discharging.
2. In the graph, choose the 3900 pF run. Select the part of the $\ln(V/V_0)$ plot where the capacitor is discharging and fit it to a straight line.
3. Use the slope of the line to find the half-life. To determine how the slope is related to the half-life, solve Equation (10) for $\ln(V/V_0)$.
4. Does this value agree with the value found from the previous analysis?

Increase the Voltage

Increase the voltage amplitude to 8 V. Keep the circuit components the same. Repeat the procedure and analysis.

Decrease the Capacitance

Replace the 3900 pF capacitor with a 560 pF capacitor and repeat the procedure and analysis. The frequency of the signal generator should be changed to 1800 Hz. Return the output voltage to 4 V.

Conclusions

1. Summarize how changing the voltage and capacitance changes the half-life.
2. Include the values found for the half-lives and the % differences. Does the theoretical value lie within the range of precision of your measurements? Explain what causes the differences.
3. Did your answers to the Pre-Lab Questions agree with the results?

Phase Relationships in an LRC Circuit

Equipment

1	Resistor/Capacitor/Inductor Network	UI-5210
4	Voltage Sensors	UI-5100
1	BNC-to-Banana Cord for 850 Output	UI-5119
1	Patch Cords (Set of 5)	SE-7123

Introduction

The phase differences between the output voltage, the voltage across the inductor, the voltage across the capacitor, and the voltage across the resistor will be examined at resonant frequency, and the half-power frequencies above and below resonance.

Analysis verifies that the voltage lags the current in a capacitor by 90° , and voltage leads current by 90° in an inductor, and that by using phasor math one can understand how the internal resistance of the components prevents the angles from being exactly 90° . Phasor math is also used to show that the maximum voltages add correctly only if one uses phasor math. The instantaneous voltages are also added to show that Kirchhoff's Loop Theorem is correct for this circuit. The formulas for the reactance are also verified.

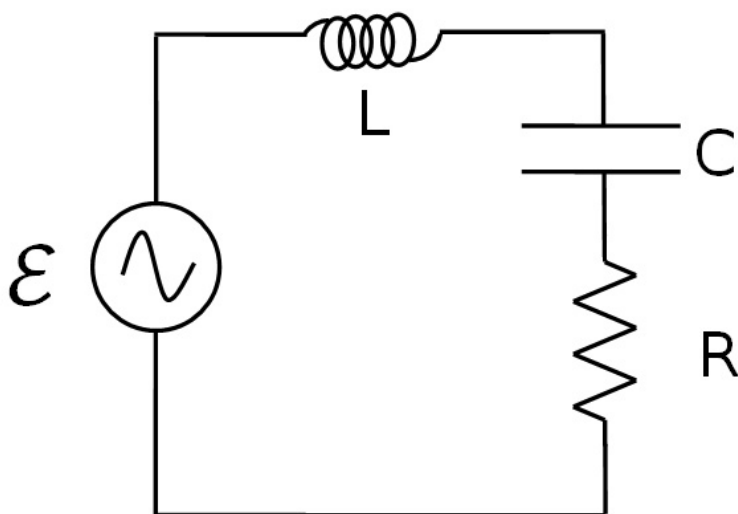


Figure 1: LRC Series Circuit Diagram

Theory

An inductor, a capacitor, and a resistor are connected in series with a sine wave generator. Since it is a series circuit, the current will be common to all the components and given by

$$I = I_{\max} \cos(\omega t) \quad (1)$$

The voltage across the resistor will be in phase with the current, but the voltage across the inductor leads the current by 90° and the voltage across the capacitor lags by 90° . Adding the three EMF voltages, \mathcal{E} , results in a total voltage that varies sinusoidally, but has a phase shift ϕ with respect to the current and is given by

$$\mathcal{E} = \mathcal{E}_{\max} \cos(\omega t + \phi) \quad (2)$$

The three components obey the AC analogs of Ohm's Law: $V_R = IR$, $V_{L \max} = I_{\max} X_L$, $V_{C \max} = I_{\max} X_C$, where X_L and X_C are the AC analogs of resistance called the inductive reactance and the capacitive reactance. Since the voltage across the resistor is in phase with the current, the phase of the current can be measured by measuring the phase of the voltage across the resistor. The capacitive reactance and the inductive reactance are given by:

$$X_C = \frac{1}{\omega C} \quad (3)$$

$$X_L = \omega L \quad (4)$$

In terms of the measured variables:

$$\frac{V_C}{V_R} = \frac{1}{\omega CR} \quad (5)$$

$$\frac{V_L}{V_R} = \frac{\omega L}{R} \quad (6)$$

At resonance, $X_L = X_C$ and $\phi=0$. Setting Equation 3 equal to Equation 4 yields the resonant angular frequency:

$$\omega_{\text{res}} = \frac{1}{\sqrt{LC}} \quad (7)$$

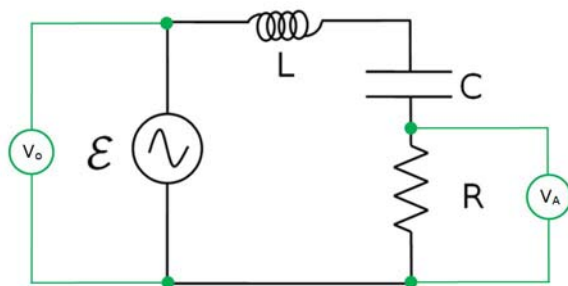


Figure 2: LRC Series Circuit

Phasors

A convenient way to summarize the information on the Theory page is to use phasors. Recall that circuit current is in phase with V_{R0} . At resonance, $V_C = V_L$ and they cancel each other. So the total voltage (\mathcal{E}_{\max}) equals the voltage across the resistor (V_{R0}) and the phase shift is zero. Below resonance (the case shown), $V_C > V_L$, the capacitor dominates, total voltage lags total current and the phase shift is negative. Above resonance the inductor dominates.

The magnitudes of the phasors are related through phasor math where \mathcal{E}_{\max} is the sum of the other three as indicated in Figure 3 where the phasors are added like vectors.

Measuring the Phase Angle:

We will measure the time Δt by which a signal leads or lags the circuit current (actually V_R). Since 360° of phase shift is equivalent to one cycle, we have:

$$\phi = 360^\circ (\Delta t/T) = 360^\circ (\Delta t) f \quad (8)$$

where T is the period and f is the frequency.

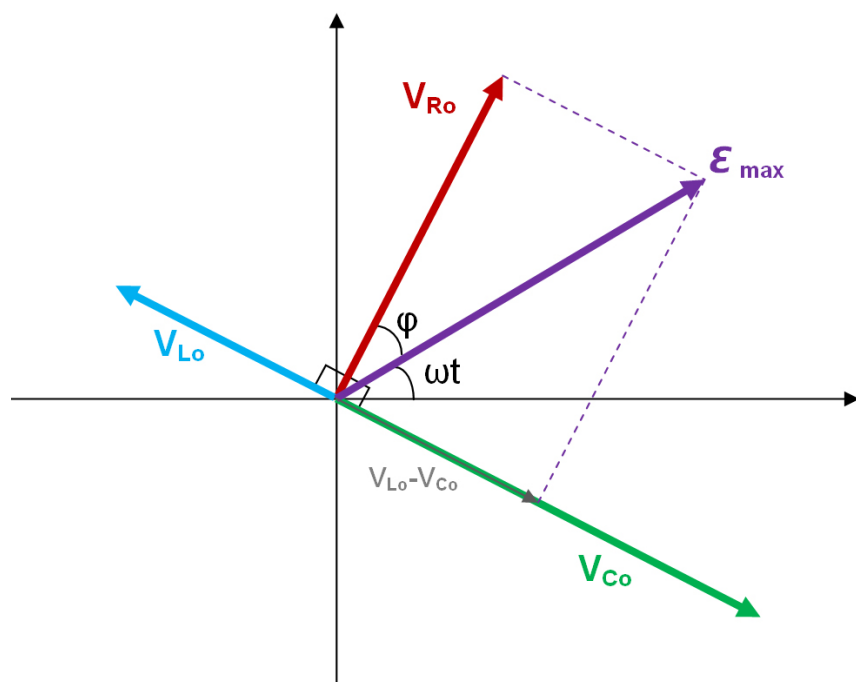


Figure 3: Phasors

Setup

1. Construct the circuit shown at right using the following values (see Figure 4):

$$\begin{aligned}L &= 6.8 \text{ mH} \\C &= 3900 \text{ pF} \\R &= 1.0 \text{ k}\Omega\end{aligned}$$

Connect to Output #2 on the 850 Universal Interface using the BNC to banana cord. Note that it is important to connect the left hand side of the inductor to the right hand side of the capacitor and the left hand side of the capacitor to the right hand side of the resistor as shown. A voltage sensor is connected to the D analog input on the 850 Universal Interface and connected so that it measures the total voltage ($V_D = V_o$) as shown in Figure 4.

2. Now connect the other three voltage sensors as shown in Figure 6. Input A is connected across the resistor. Input B is connected across the inductor. Input C is connected across the capacitor. Note that the black side of each voltage sensor is attached on the left side of the circuit board.

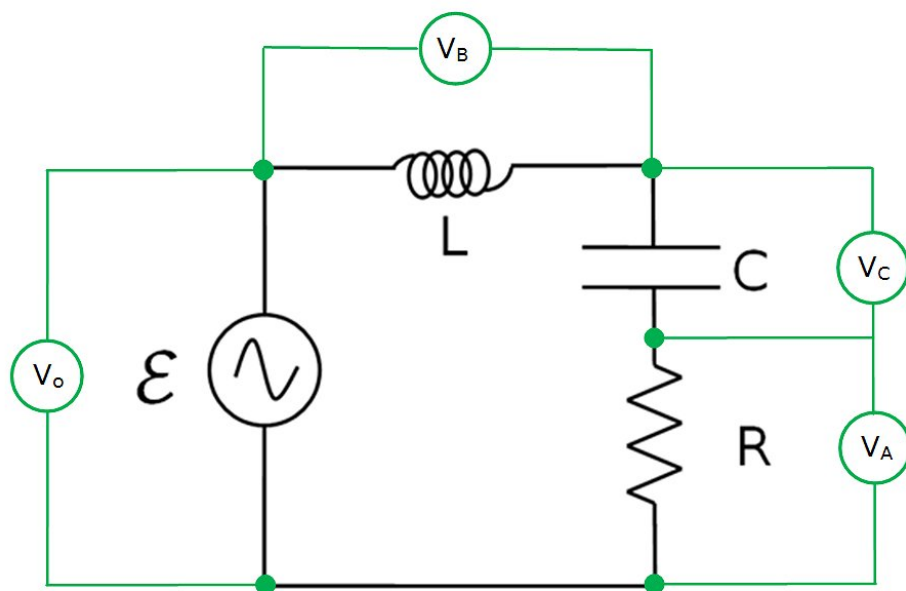


Figure 4: Circuit Diagram with Voltage Sensors

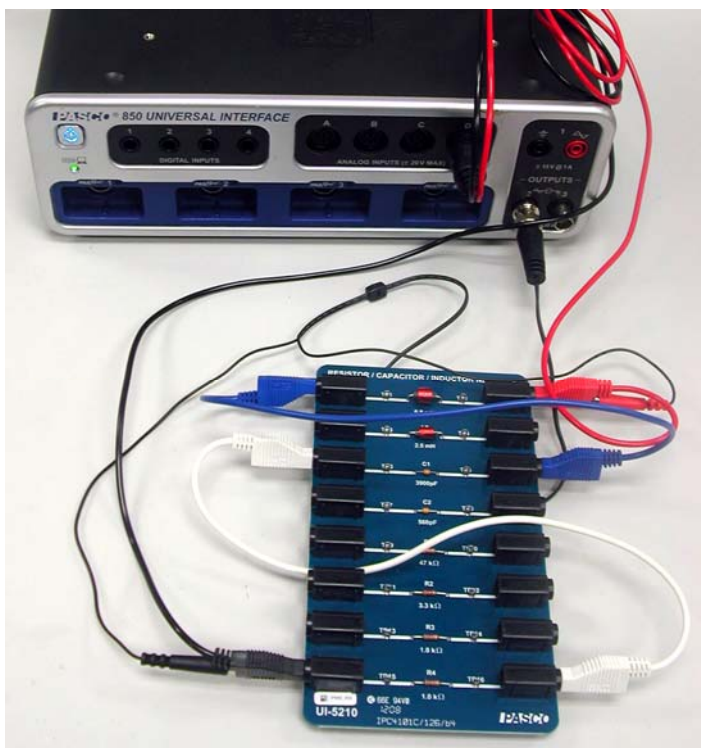


Figure 5: LRC Circuit without Sensors

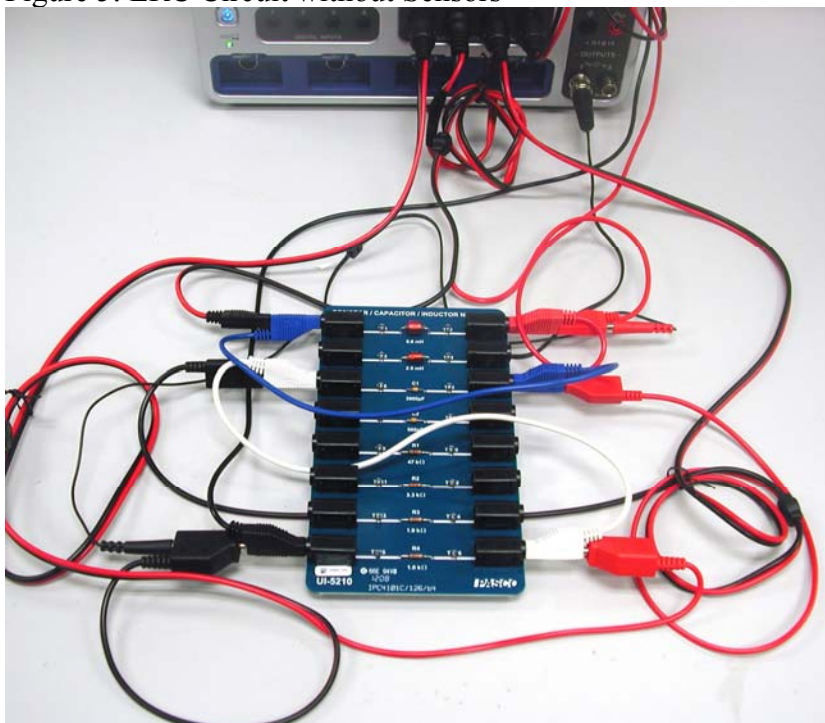


Figure 6: Circuit with Sensors

Procedure

1. In PASCO Capstone, create an Oscilloscope display and put the voltage measurements from all four voltage sensors on a single vertical axis of the oscilloscope. You do this by adding similar measurements on the measurement selector on the axis. Set the time units to μs .
2. Set the sample rate to 1 MHz and set the Sampling Mode to Fast Monitor.
3. Click open the Signal Generator. Signal Generator #2 should be set to a frequency of 30,000 Hz and an amplitude of 6 V. Also, the Auto button should be selected.
4. Click Monitor. If the scope trace is rolling left or right, click the trigger button in the scope toolbar. Adjust the vertical scale so the signals are as large as possible without going off screen. Adjust the horizontal scale so you see about two cycles.
5. Adjust the Signal Generator Frequency (to the nearest 100 Hz) to make the phase $\phi=0$ by making $V_D (=V_o)$ and $V_A (=V_R)$ cross the $V=0$ axis at the same point. Adjust the Signal Generator Amplitude so that the maximum V_R voltage is exactly 6 V. Click Stop. $V_R < V_o$ because the coil has a resistance of $\sim 60 \Omega$. Record the frequency for resonance in Table I as shown in step 6.
6. Create Table I as shown below:

System	frequency (Hz)	$\Delta t V_L$ (μs)	$\Delta t V_C$ (μs)	$\Delta t V_o$ (μs)	ϕ_L (deg)	ϕ_C (deg)	ϕ_{TOTAL} (deg)
Resonance							
Below Res.							
Above Res.							

The first five columns are all user-entered data sets. The last three columns are calculations:

$$\phi_L = 360 * [\Delta t V_L \text{ (s)}] * [\text{frequency (Hz)}]$$

$$\phi_C = 360 * [\Delta t V_C \text{ (s)}] * [\text{frequency (Hz)}]$$

$$\phi_{\text{TOTAL}} = 360 * [\Delta t V_o \text{ (s)}] * [\text{frequency (Hz)}]$$

7. Click Data Summary to open it. Highlight all four data sets in the scope Legend box. Click the Create a data set in the scope toolbar. Monitor Run Snapshots should appear for each voltage in the Data Summary box. Re-label each of the four as "Resonance". Click Data Summary closed.

8. Click Monitor. Adjust the Signal Generator Frequency below resonance to a point where $V_R = 4\text{ V}$. Adjust the horizontal scale for two cycles. Click Stop. Repeat step 7 above; this time re-label as "Below Res". Record the frequency in Table I.
9. Repeat for the $V_R = 4\text{ V}$ above resonance. The signal will be a little jagged since at 1 MHz there are only about 20 points per cycle.

Phase Analysis

1. Create a graph and put the voltage measurements from all four voltage sensors on a single vertical axis. You do this by adding similar measurements on the measurement selector on the axis. On the horizontal axis, set the time units to μs .
2. Select the four "Resonance" data sets. Expand the horizontal scale so about 1 cycle shows. The vertical scale should be set so that the range is from -0.5 V to 2.5 V . This will make the $V=0$ crossings easy to see.
3. The Coordinate tool should show 3 significant figures, have the delta tool turned on, and the Snap to Pixels disabled by setting the "snap distance" = 1. If not, right click on the Coordinate tool and adjust Tool Properties.
4. To find the phase shift of a voltage, use the delta tool on the coordinates tool to measure the difference in time between the first two points where the two signal cross the x axis ($V=0$) with a negative slope. First, position the delta tool on the first place this happens for V_R (V,A). Now position the cross-hairs on the V_L crossing of $V=0$. Record this phase shift time (Δt_{VL}) in Table I (with any sign). Leave the delta tool on the V_R crossing and use the cross-hairs to measure the times for V_C and V_o . The phase shifts are calculated using Equation 8.
5. Repeat for the "Below Res" and "Above Res" data.

Voltage Analysis

1. Select the four "resonance" data sets.
2. The Coordinate tool should show 3 significant figures and the Snap to Pixels disabled by setting the "snap distance" = 1. If not, right click on the Coordinate tool and adjust Tool Properties.
3. Use the Coordinate tool to determine the maximum voltages: V_R , V_L , V_C , V_o and enter them in the Table II as shown in Step 4.

4. Create Table II as shown below:

System	frequency (Hz)	V _R (V)	V _L (V)	V _C (V)	V _o (V)	V _L /V _R	V _C /V _R	V _L /V _R Theory	V _C /V _R Theory
Resonance									
Below Res.									
Above Res.									

The first two columns are identical to the ones in Table I. The next four columns are user-entered data sets and the last four columns are calculations:

$$V_L/V_R = [V_L (V)]/[V_R (V)]$$

$$V_C/V_R = [V_C (V)]/[V_R (V)]$$

$$V_L/V_R \text{ theory} = 2\pi[\text{frequency (Hz)}][L (H)]/[R (\Omega)]$$

$$V_C/V_R \text{ theory} = 1/(2\pi[\text{frequency (Hz)}][C (F)][R (\Omega)])$$

$$[L] = 0.0068 \text{ H}$$

$$[C] = 3.9\text{e-}9 \text{ F}$$

$$[R] = 1000 \Omega$$

5. Select the four "below res" data sets and repeat.
6. Select the four "above res" data sets and repeat.

Conclusions

1. Using Equation 7, calculate the resonant angular frequency and the resonant frequency and compare to experiment.
2. Examine these equations in the Calculator:

$$V_L/V_R = [V_L (V)]/[V_R (V)]$$

$$V_C/V_R = [V_C (V)]/[V_R (V)]$$

$$V_L/V_R \text{ theory} = 2\pi[\text{frequency (Hz)}][L (H)]/[R (\Omega)]$$

$$V_C/V_R \text{ theory} = 1/(2\pi[\text{frequency (Hz)}][C (F)][R (\Omega)])$$

Do the first two equations represent Equations 5&6? What do the V_C/V_R , V_C/V_R theory, V_L/V_R , and V_L/V_R theory ratios imply about Equations 3 & 4?

3. Does $X_C = X_L$ at resonance (when $\phi=0$)? How do you know?

4. Which reactance (X_C or X_L) is larger above resonance? Below resonance? How do you know?
5. Considering the total phase shift, " ϕ_{TOTAL} ", does the circuit behave more like a capacitor or more like an inductor below resonance? How do you know? Considering the voltages, why is this true?
6. We expected that the voltage across the capacitor should lag current by 90° and the voltage across the inductor should lead by 90° . While this is approximately true, your data should show both shifts to be less than 90° . This occurs because each component has some small internal resistance (heating the component) that behaves like a series resistor (and is frequency dependent). As shown in Figure 7, the voltage across the inductor is then the phasor sum of the current times the inductive reactance and the current times the internal resistance r_L . This results in a phase angle less than 90° . Use Figure 7 to calculate r_L for the resonance case. Draw a similar diagram for the capacitor and use it to calculate r_C at resonance.
7. At resonance the total voltage is dropped across the total resistance $= R + r_L + r_C$ since the internal resistance may be treated as being in series. Use the values you found in step 6 to calculate the value you would expect to measure across R and compare to what you actually observed at resonance.

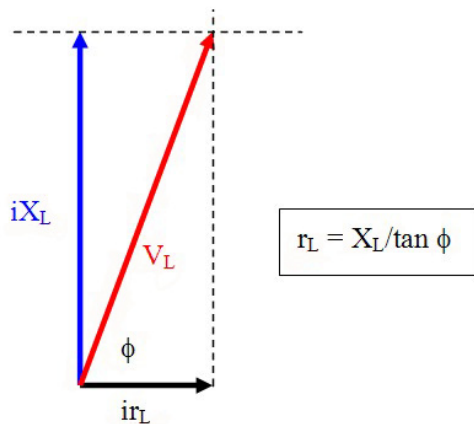


Figure 7: Effect of Inductor Resistance

Phasor Analysis

1. Do the voltages at a given frequency obey scalar math? That is, does $V_R + V_C + V_L = V_o$? For any of the three cases?
2. Does the phasor math implied by Figure 3 give the correct answer? That is, is V_o the phasor sum of V_R , V_C , & V_L ? Before trying this, recall that the V_R values are too small since they do not include the voltage drops across the internal resistances of the capacitor and inductor. We really want $V_R + V_{rL} + V_{rC} = [(R + r_L + r_C)/R]V_R$. We can get the value of the resistance ratio (in the square brackets) by noting that for the resonance case the $V_o = V_R + V_{rL} + V_{rC}$, so $[(R + r_L + r_C)/R] = (V_o / V_R)_{\text{res}}$. Use the resonance data to find the ratio and then correct the value of V_R for the other two cases. Note that this isn't quite correct since the internal resistances are frequency dependent and the V_r 's do affect V_L and V_C a little, but it is a good first approximation.
3. Using the corrected values for V_R verify that phasor math gives the correct value for V_o within a reasonable uncertainty for both the below and above resonance cases.
4. On the graph, select the four "Below Res" cases. Pick any vertical line (for example 10 μ s) and use the Coordinate tool to measure the voltage for each of the four voltages at that instant. Enter the values in line 4 of Table II including sign. Do these values obey scalar math? Do you see why scalar math fails for the max values used in step 1 above?

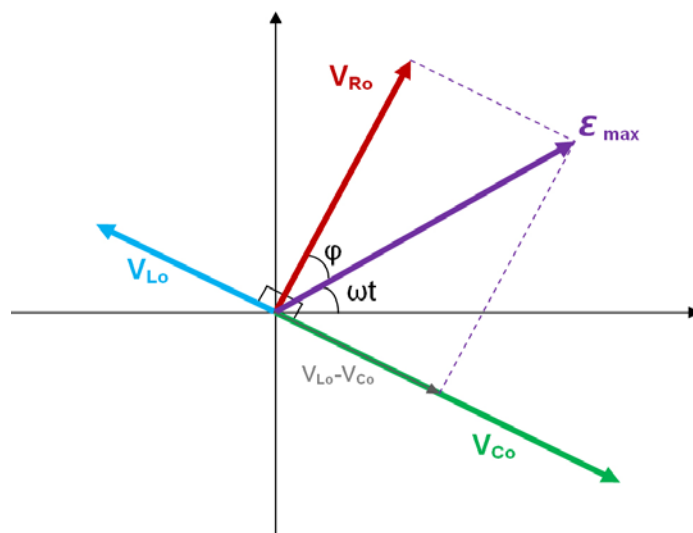


Figure 3: Phasors

LRC Circuit Resonance

Equipment

1	Resistor/Capacitor/Inductor Network	UI-5210
2	Voltage Sensor	UI-5100
1	BNC-to-Banana Cord for 850 Output	UI-5119
1	Patch Cords (Set of 5)	SE-7123

Introduction

The current through a series LRC circuit is examined as a function of applied frequency and the effects of changing the values of the resistance, inductance, and capacitance are observed. The phase difference between the applied voltage and the current is measured below resonance, at resonance, and above resonance.

Theory

An inductor, a capacitor, and a resistor are connected in series with a sine wave generator. Since it is a series circuit, the current will be common to all the components and given by

$$I = I_{\max} \cos(\omega t) \quad (1)$$

The voltage across the resistor will be in phase with the current, but the voltage across the inductor leads the current by 90° and the voltage across the capacitor lags by 90° . Adding the three EMF voltages, \mathcal{E} , results in a total voltage that varies sinusoidally, but has a phase shift ϕ with respect to the current and is given by

$$\mathcal{E} = \mathcal{E}_{\max} \cos(\omega t + \phi) \quad (2)$$

The three components obey the AC analogs of Ohm's Law: $V_R = IR$, $V_{L \max} = I_{\max} X_L$, $V_{C \max} = I_{\max} X_C$, where X_L and X_C are the AC analogs of resistance called the inductive reactance and the capacitive reactance. The capacitive reactance and the inductive reactance are given by:

$$X_C = \frac{1}{\omega C} \quad (3)$$

$$X_L = \omega L \quad (4)$$

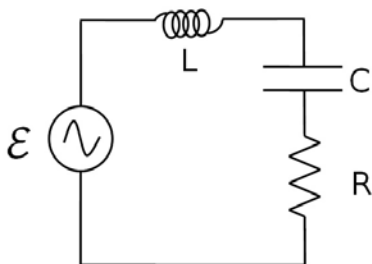
The maximum current and total voltage are then related by

$$\mathcal{E}_{max} = I_{max} Z \quad (5)$$

where Z is called the impedance and is the AC analog of resistance for the entire circuit. The phase shift is related to the other variables by

$$\tan \phi = \frac{(X_L - X_C)}{R} \quad (6)$$

Since the voltage across the resistor is in phase with the current, the phase of the current can be measured by measuring the phase of the voltage across the resistor.



The impedance Z is given by

$$Z = \sqrt{R^2 + (X_C^2 - X_L^2)} \quad (7)$$

At resonance, the current is maximum and thus the impedance is at its minimum. The minimum impedance (Equation 7) occurs when $X_L = X_C$, yielding $Z = R$. Setting Equation 3 equal to Equation 4 yields the resonant frequency:

$$\omega_{res} L = \frac{1}{\omega_{res} C} \quad (8)$$

$$\omega_{res} = \frac{1}{\sqrt{LC}} \quad (9)$$

Setup

1. Connect the BNC-to-Banana cord to the #2 Signal Generator and connect the red cord to one end of the 2.5 mH inductor on the circuit board. Connect the other end of the inductor to the 560 pF capacitor in series and the 1.0 k Ω in series. Then connect the black cord to the open end of the resistor.
2. Connect a Voltage Sensor to Channel A on the 850 interface and attach the leads across the resistor, making sure the black cable from the voltage sensor is connected to the grounded side of the resistor.
3. Connect a Voltage Sensor to Channel B on the 850 interface and attach the leads across the leads of the Output #2 cable, making sure the black cable from the voltage sensor is connected to the black side of the signal generator.
4. Open the Signal Generator 850 Output 2 and choose the Sine Wave at a frequency of 10,000 Hz and an amplitude of 7 V. Leave the output on AUTO.

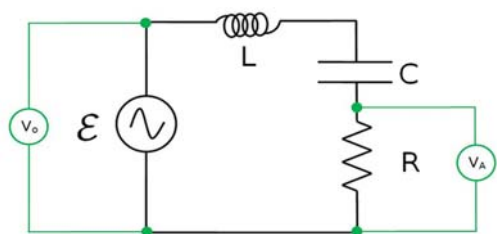


Figure 1: Series LRC Circuit

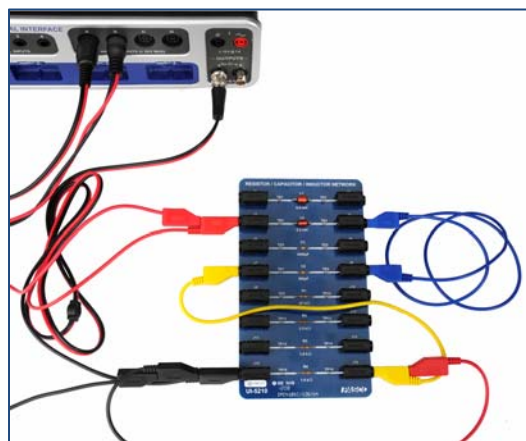
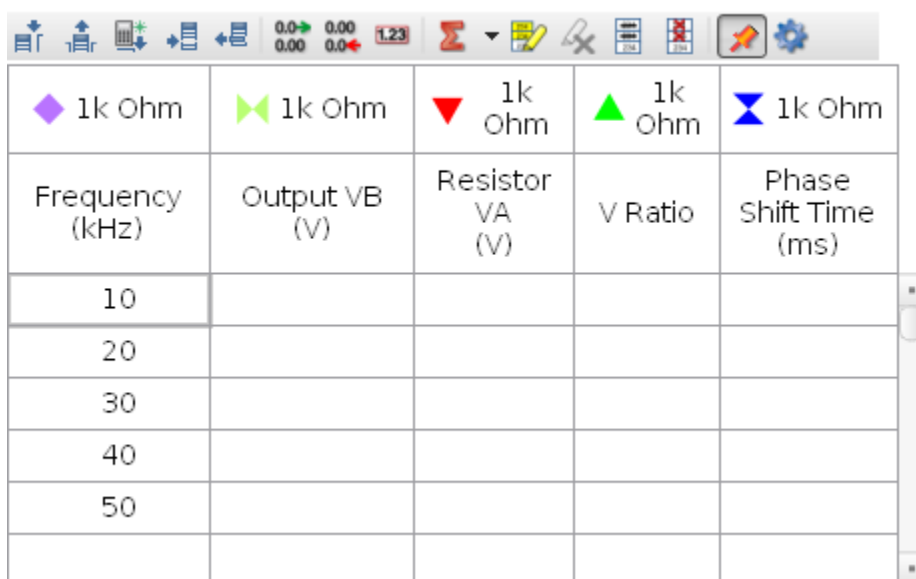


Figure 2: LRC Circuit with Sensors

5. Create a table as shown below.

Table I: Data for Resonance Curve



Frequency (kHz)	Output VB (V)	Resistor VA (V)	V Ratio	Phase Shift Time (ms)
10	0.00	0.00	1.23	0.00
20				
30				
40				
50				

The first three columns and the last column are User-Entered data sets. The fourth column is a calculation:

$$V \text{ Ratio} = [\text{Resistor VA (V)}] / [\text{Output VB (V)}]$$

In the table shown, the first set has been renamed “1 k Ohm”.

6. Create a graph of V Ratio vs. Frequency in kHz.
7. Create an oscilloscope with both voltages on the same axis (this is done by choosing similar measurement in the measurement selector on the axis). Select ms for the units of time on the horizontal axis.
8. Set the common sample rate to 10 MHz.

Procedure: Plotting the Resonance Curve

In this part of the lab, you will vary the frequency of the applied voltage and record the response (current) of the circuit. The response is measured by measuring the voltage across the resistor since the current is in phase with this voltage and it is proportional to it.

One further complication is that you must divide the resistance voltage by the output voltage (of the 850) to account for any changes in the output voltage. This works because if the output voltage doubles, then the resistance voltage also doubles and the ratio V_R/V_o remains constant. This is faster than trying to adjust the output voltage each time to keep it constant.

1. Begin with the signal generator set on 10 kHz. Record this frequency in Table I. Click on Monitor. If the trace is rolling left or right, click the trigger on the oscilloscope. Adjust the horizontal scale on the scope so about three cycles show.
2. Stop monitoring and use the coordinates tool to measure the amplitude of each of the voltages and type the results in Table I. The coordinate tool should show three significant figures for voltage, the snap to pixel distance should be 1 (snap disabled) and the delta tool should be on. If not, right click on the tool and change tool properties. Increase the vertical scale to make the signal (especially V_A) you are measuring as large as possible. Always measure the positive peak. Set the coordinate tool so the horizontal line is tangent to the peaks. Leave the vertical scale expanded until after step 3. That will make it easier to measure the phase shift.
3. To find the phase shift between the two voltages, use the delta tool on the coordinates tool to measure the difference in time between the first two points where the two signal cross the x axis ($V=0$) with a negative slope. First position the delta tool on the first place this happens and then spread the horizontal scale so that less than one cycle shows so that you can see the x axis crossings more clearly. Record this phase shift in time in Table I in column 5. Then click the Scale to Fit icon and decrease the horizontal scale so about three cycles are visible. The cross-hairs should always be on V_B and the delta tool on V_A so that the sign of the phase shift time given by the delta tool will be correct. When current (in phase with $V_A = V_R$) is to the left of V_B (= total voltage), then total voltage lags current (negative phase shift) since total voltage shows up later in time.
4. Increase the frequency of the output by 10 kHz and repeat the measurements.
5. Continue to increase the frequency in steps of 10 kHz up to 250 kHz. Above 250 kHz continue by 25 kHz steps up to 500 kHz (why is this OK? Hint: examine Figure 2).
6. To find the resonance peak more precisely, we need more data near the peak (see Figure 2). We want readings at 5 kHz intervals for the region within 20 kHz of the peak. For example, if the peak is at 140 kHz, we would like to add points at: 125 kHz, 135 kHz, 145 kHz, & 155 kHz. To do this, on the Table I, click and drag to highlight the 130 kHz row. From the graph toolbar, click on insert empty cells above. Then add a run at 125 kHz. Repeat for each desired data point.

7. Exchange the 1 k Ω resistor for the 3.3 k Ω resistor and repeat the entire procedure. In Table I, click the header where the set name is and create a new data set called “3.3 k Ohm”.

Analysis of the Resonance Curve

1. Display the runs for both of the resistors on the graph.
2. Measure the height of the peak for each curve and the frequency of each peak. You might want to expand the horizontal scale. Record them in the box below.
3. Measure the width of the curve at half the max height for each resistor. As before, you should set the snap to pixel distance to 1 for the coordinate tool.

Questions

1. How do the height and width of the curves change when you increase the resistance?
2. Calculate the theoretical resonant frequencies and compare them to the measured values with a percent difference. Remember that the frequency of the signal generator is f which is related to the theoretical frequency by

$$f_{res} = \frac{\omega_{res}}{2\pi}$$

$$\omega_{res} = \frac{1}{\sqrt{LC}}$$

3. Does the resistance change the resonant frequency? How does the resistance of the inductor affect the results?
4. Why don't the peaks equal one at the resonant frequency?
5. Why isn't the resonant curve symmetrical about the resonant frequency?

Procedure: Phase Difference

The current is in phase with the voltage across the resistor so we can know the phase of the current by measuring the phase of the resistor voltage.

The phase difference between the resistor voltage and the output voltage is the amount (in radians) that resistor voltage peak is shifted from the output voltage peak. If the peaks are shifted by one wavelength, that would correspond to one cycle or 2π radians. One cycle corresponds to one period (T). So, to determine the amount of shift, we measure the amount of time the peaks are shifted (Δt) and calculate the ratio $\Delta t/T$ to find what percentage of a full cycle they are shifted. Thus the phase difference, ϕ , is equal to this percentage times 2π radians.

$$\varphi = \frac{\Delta t}{T} \times 2\pi \quad (10)$$

Since the frequency $f = 1/T$,

$$\varphi = 2\pi f \Delta t \quad (11)$$

1. Create a calculation:

$$\text{"Phase Shift"} = 2\pi * [\text{Frequency (kHz)}] * [\text{Phase Shift Time (ms)}]$$

2. Create a graph of "Phase Shift" vs. frequency in kHz.

Questions

1. What should the phase shift be at resonance? How well do your two runs agree with this?
2. As the frequency goes to zero, to what value does the phase shift go? Look at your graph and at the theoretical equation and consider the limit as the frequency goes to zero.

$$\tan \varphi = \frac{(X_L - X_C)}{R} \quad (7)$$

where

$$\omega_{res} L = \frac{1}{\omega_{res} C} \quad (8)$$

and

$$\omega_{res} = \frac{1}{\sqrt{LC}} \quad (9)$$

3. As the frequency goes to infinity, to what value does the phase shift go? Look at your graph and at the theoretical equation and consider the limit as the frequency goes to infinity.
4. Does the current lead or lag behind the applied voltage below the resonant frequency?
5. Which is larger above the resonant frequency: the capacitive reactance or the inductive reactance?
6. How does changing resistance affect the phase vs. frequency graph?

Computer Model

1. Create a calculation:

$$\frac{V_R}{V} = \frac{R}{\sqrt{(R+r)^2 + (\omega L - \frac{1}{\omega C})^2}}$$

$$V_R/V = [R]/\text{sqrt}([R]+[r])^2+([\omega]*[L]-(1/([\omega]*[C])))^2)$$

2. Verify that the above equation corresponds to the voltage ratio, $(V_R/V) = R/Z$, using Equation (7), except that the total resistance is $R+r$, where r is the resistance of the coil.
3. Vary the values of r , L , and C to fit the curve as well as possible for frequencies below 200 kHz (see Step 4 below). Answer the following questions:
 - a. What does r affect?
 - b. What does C affect?
 - c. What does L affect?
4. The fit at high frequency is not perfect because the coil resistance (loss due to heating) is frequency dependent and increases with frequency. At 500 kHz the measured value of V_R/V is about 30% low implying $r \sim 5000 \Omega$. This seems high and there may something else going on.
5. Once we have a functioning model we can use it to examine the system. For example, instead of doing the 3300 Ohm experiment, we could just use the model. Try it by changing R to 3300 Ohm. Wow, that's a lot easier!

General Properties of Diodes

Equipment

1	AC/DC Electronics Laboratory	EM-8656
2	Voltage Sensors	UI-5100
1	Short Patch Cords (set of 8)	SE-7123
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

Introduction

The purpose of this experiment is to investigate the characteristic curves (I vs. V) of various types of diodes and to determine their “turn-on” voltages.

Theory

A diode (or p-n junction rectifier) is an electronic device which allows current to flow in only one direction. As can be seen in the characteristic curve of the diode in Figure 1, when the voltage drop across the diode is negative (called reverse bias), no current flows (except for a very small reverse current). When the voltage becomes positive, no current flows until a “turn on” voltage is exceeded (for the case shown at about 0.5 V). From then on a very small increase in voltage results in a very large increase in current. Note that here we have defined positive voltage to be that which causes current flow. In terms of a circuit diagram an arrow is used to indicate a diode as in Figure 2, and current flows only in the direction of the arrow. So current would flow if the red side of V_A was positive with respect to the black side by more than about 0.5 V. From Figure 1 it is clear that the “turn on” voltage is somewhat arbitrary and we take it to be the voltage where the current exceeds 2.0 mA.

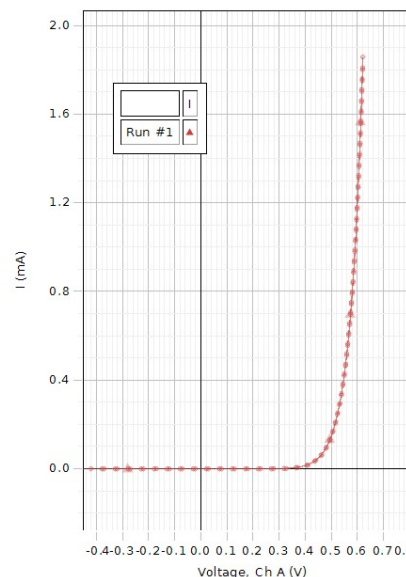


Figure 1: Characteristic Curve

A light-emitting diode emits light as current passes through the diode. A bicolor LED (here yellow green) is actually two diodes in parallel but in opposite directions so the yellow allows current flow in one direction and the green allows current flow in the opposite direction. A bicolor LED is an example of a Zener diode. The Zener diode has a “turn on” voltage for both positive and negative voltages (for a Zener the “turn on” voltage is called the “breakdown voltage”) This is useful in circuits since the voltage across the Zener remains constant independent of the current providing it is above the “breakdown voltage”.

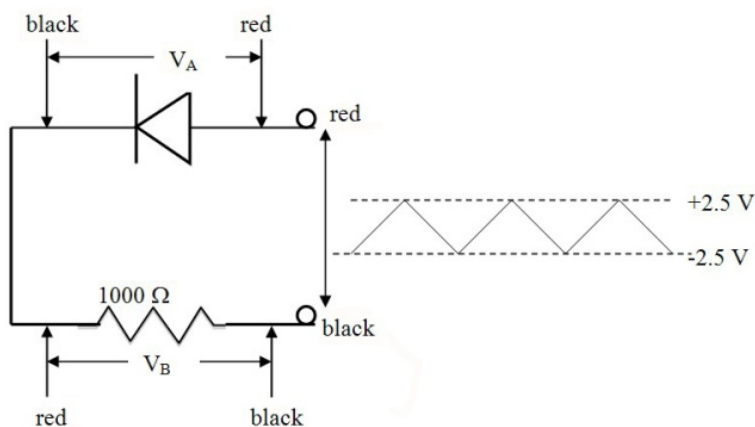


Figure 2: Diode Circuit

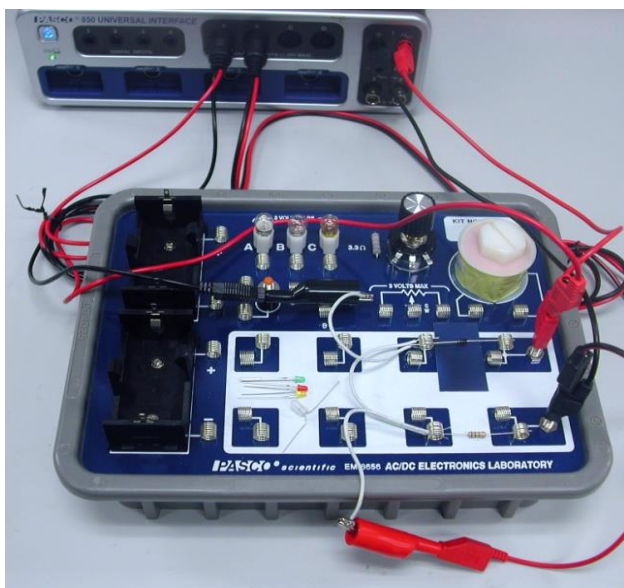


Figure 3: Setup

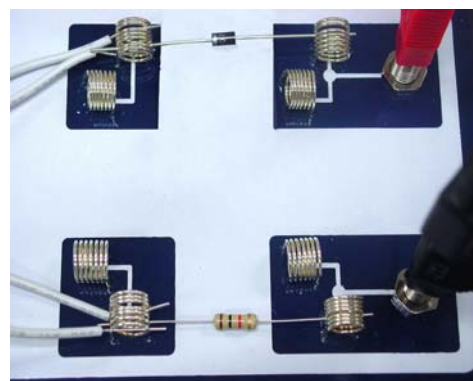


Figure 4: Close-up of Diode Setup

Setup

1. Setup the circuit shown in Figures 2, 3 & 4 using the $1000\ \Omega$ (brown-black-red-gold) resistor between the spring clips. The gold band on the resistor means it is accurate to within 5% ($1000 \pm 50\ \Omega$), but it is probably much better. The gray band (cathode end) on the diode should be to the left away from the positive (red) terminal.
2. Attach patch cords from Output 1 on the interface the banana jacks on the Electronics Laboratory circuit board. Observe the polarity shown so the red patch cord attaches to the jack by the right end of the diode.

3. Attach a Voltage Sensor to Analog Input A on the interface. Its red end should attach to the red patch cord from Output 1. Attach an alligator clip to the black end, clip it to a white wire and attach the white wire to a spring clip at the left end of the diode. *Caution: if you attach the alligator clip directly to the spring clip, you will tend to pull the spring loose from the circuit board.*
4. Attach a Voltage Sensor to Analog Input B on the interface. Its black end should attach to the black patch cord from Output 1. Attach an alligator clip to the red end, clip it to a white wire and attach the white wire to a spring clip at the left end of the resistor. Note: this will be used to measure the current in the circuit since the voltage drop across the resistor divided by 1000 Ohms equals the current.
5. In PASCO Capstone, click open the Signal Generator at the left of the screen. Set Output 1 for a Triangle Waveform with a Frequency of 0.1 Hz and an amplitude of 10 V. Click Auto. Click the Signal Generator again to close the panel.
6. Set the common sample rate to 200 Hz.
7. In the calculator, create the following calculation:

$$i = [\text{Voltage, Ch B}] \quad \text{Units of mA}$$

The current is calculated using Ohm's Law: $i = V/R = [\text{Voltage, Ch B}]/(1000 \, \Omega)$ in units of Amps. In the above calculation, the units are mA because the voltage is not divided by 1000. Note that if the actual resistance of the resistor is not 1000 Ω , this calculation will not be accurate.
8. Create a graph of the calculation "i" vs. Voltage, Ch A.
9. Create a table with three columns (as shown below) and create user-entered data sets called "System", "Voltage at +2 mA" with units of V, and "Voltage at -2 mA" with units of V.

Table I: Diode Data

System	Voltage at + 2mA (V)	Voltage at - 2mA (V)
Diode		
Red LED		
Yellow LED		
Green LED		
Bicolor LED Green 2nd		
Bicolor LED Yellow 2nd		

Procedure

1. Click RECORD. Data collection will stop automatically after the entire curve has been traced (5 s).
2. Click on the Scale-to-Fit icon on the graph toolbar.
3. Click open Data Summary and re-label this run as “Diode”.
4. Find the red, yellow, green, and bicolor LEDs. The bicolor is actually clear when unpowered. It is the one shown in Figure 5. If the wires have not already been bent so they will bridge between the two springs as in Figure 5, do so now. Be careful not to break the wires. *When you are done, leave them bent, since repeatedly bending them will break them.*

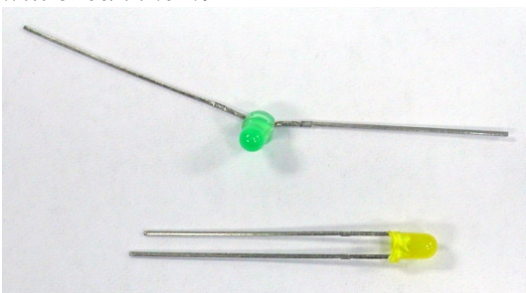


Figure 6: The LED Cathode wire is shorter.

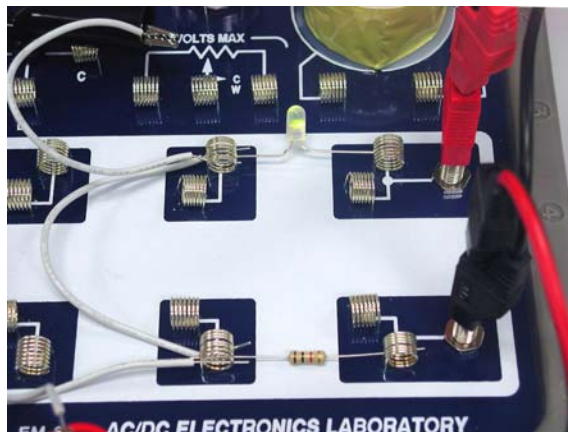


Figure 5: LED Setup

5. Identify the cathode (negative) side of the red, yellow, and green LEDs (doesn't matter for the bicolor). There are four ways to identify the cathode (refer to Figure 6): 1) the wire on the cathode side is shorter, 2) there is a flat spot on the plastic by the cathode (shows clearly on the right of the green LED in Figure 6), 3) if you hold the diode up in front of a light, you will see a triangle...the wide side is attached to the cathode, and 4) if you make a mistake you will find that the diode conducts when the voltage is negative rather than positive.
6. Replace the diode with the red LED so its cathode is to the left. Repeat steps 1-3. Label the run “Red LED”.
7. Repeat for the other yellow and green LEDs, labeling them appropriately.
8. Repeat with the bicolor LED. Watch to see which color is second and label the run “Bicolor Green 2nd” or “Bicolor Yellow 2nd”.
9. Reverse the bicolor LED and repeat.

Analysis

1. Click on the black triangle by the multicolored Run Select icon in the graph toolbar and select the “Diode” run. If necessary, click the Scale-to-Fit icon.
2. Click on the Coordinate icon.
3. Move the Coordinate tool to the point where $i = 2.00 \text{ mA}$ or as close as possible. Read the Voltage to two decimal places and record it in Table I in the “Voltage at +2 mA) column.
4. Repeat for the other runs. For the bicolor LED runs, also record the Voltage at -2 mA.

Conclusions

1. Do the diodes obey Ohm’s Law? How do you know?
2. Click the Run Select icon to allow display of multiple runs. Select the “Diode”, “Red LED”, “Yellow LED”, and “Green LED” runs. Click on the Selection icon and adjust the handles on the Selection box to select the positive voltages data. Click the Scale-to-Fit icon.
3. Why is the maximum voltage across the diode above 9.5 V while the maximum voltage across the LEDs is only about 8.0 V?
4. Now add both the bicolor runs and adjust the selection box to select only the data between 1.5 V and 2.2 V. Click Scale-to-Fit. Click Remove Active Element in the graph toolbar to remove the selection box.
5. Do the yellow and green LEDs have the same characteristic curves and the bicolor LED? Are all green (or yellow) LEDs the same?
6. Turn off all except the two bicolor runs. Click Scale-to-Fit.
7. In the circuit, replace the bicolor LED with the yellow LED (cathode to the left) and add the green LED so it is in parallel with the yellow LED but has its cathode to the right.
8. Click Record. Watch which diode is the second to glow. Does its curve match what you would expect?

Rectifier Circuit Build a DC Power Supply

Equipment

1	AC/DC Electronics Laboratory	EM-8656
1	Voltage Sensors	UI-5100
1	Short Patch Cords (set of 8)	SE-7123
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

Introduction

The purpose of this experiment is to build a half wave rectifier and to examine its properties. A RC filter circuit is then added to produce a DC power supply and the dependence on the RC values is examined.

Theory

A diode is an electronic device which allows current to flow in only one direction. In the Rectifier Circuit shown in Figure 1, V_o is a 60 Hz AC voltage with an amplitude of 10 Volts. When the red input is positive with respect to the black input, current flows to the left through the diode and the current passing through the diode then produces a voltage drop across the resistor (V_A) as it passes through the resistor. When the red input becomes negative, the diode prevents the flow of current and the voltage across the resistor drops to zero. This changes the sinusoidal input voltage into a voltage that is always positive, but is not constant.

To produce DC, a RC filter is added to the circuit as in Figure 2. If the RC time constant (time constant = τ = RC) is long enough, the charge on the capacitor does not vary much and the output voltage V_A is relatively constant. If a charged capacitor is allowed to discharge through a resistor, the charge will have fallen to 37% of its original charge when the time that has passed equal the time constant. Note that the discharge path is through both R and the 1000 Ω resistor and so:

$$\tau = (R + 1000 \, \Omega)C \quad (1)$$

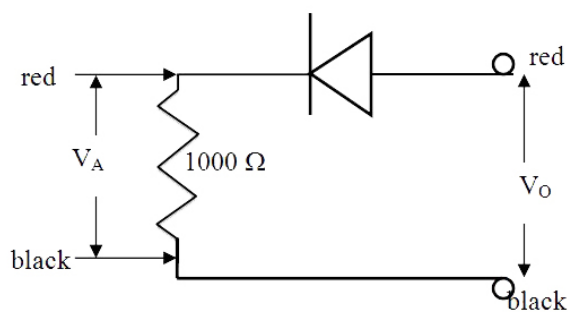


Figure 1: Half Wave Rectifier Circuit

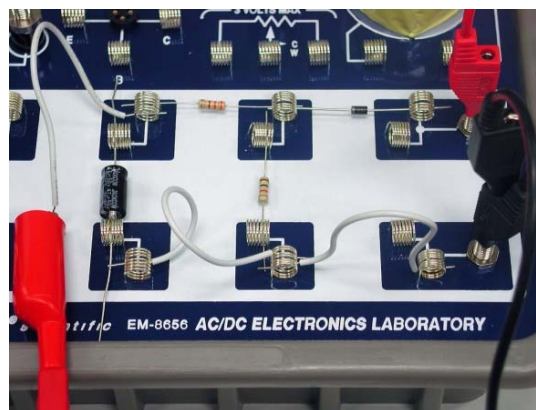


Figure 3: Rectifier Setup

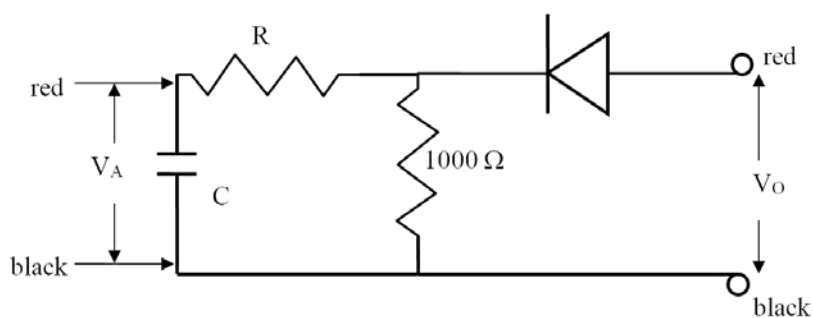


Figure 2: Filtered Rectifier Circuit



Figure 4: Filtered Rectifier Setup

Rectifier Setup

1. Setup the circuit shown in Figures 1 & 3 using the $1000\ \Omega$ (brown-black-red-gold) resistor between the spring clips. The gray band (cathode end) on the diode should be to the left away from the positive (red) terminal.
2. Attach patch cords from Output 1 on the 850 Universal Interface the banana jacks on the Electronics Laboratory. Observe the polarity shown so the red patch cord attaches to the jack by the right end of the diode.
3. Attach a Voltage Sensor to Analog Input A on the 850 Universal Interface. Its black end should attach to the black patch cord from Output 1. The Voltage Sensor will measure the voltage drop across the resistor. Attach an alligator clip to the red end, clip it to a white wire and attach the white wire to a spring clip at the left end of the diode. *Caution: if you attach the alligator clip directly to the spring clip, you will tend to pull the spring loose from the circuit board.*
4. In PASCO Capstone, open the Hardware Setup and click on Signal Generator #1 on the 850 Universal Interface and select Output Voltage Current Sensor.
5. Create an oscilloscope display and select Voltage A on the vertical axis. Then click on the measurement selector on the vertical axis and click Add Similar Measurement and select the Output Voltage.
6. On the Control Bar at the bottom of the Capstone window, select the Sampling Mode to be Fast Monitor Mode.

Procedure

1. Click open the Signal Generator at the left of the screen. Set Output 1 for a Sine Waveform with a Frequency of 60 Hz and an amplitude of 2 V. Click Auto. *Note that this the same frequency as the signal from an AC outlet in the wall, but at a safer voltage.*
2. Click Monitor. If the trace is not stable, click Trigger on the scope toolbar. Click Stop after the trace appears on the Scope.
3. Click on both runs in the Legend box so both data sets are highlighted (drag or shift-click). Click on the Create a Data Set icon on the graph toolbar. Click open Data Summary and re-label both of the Snapshots as “2V run”.
4. Change the Output 1 Amplitude to 10 V and repeat steps 2 & 3, labeling this as “10V run”.
5. Add a resistor, $R = 330\ \Omega$ (orange-orange-brown-gold), and a capacitor, $C = 47\ \mu\text{F}$, as in Figures 2 & 4 (polarity on the capacitor does not matter). Move the white wire attached to the red alligator clip (from Input A) to the top of the capacitor so the Voltage Sensor monitors the voltage drop across the capacitor. Add a white wire jumper between the springs attaching the bottom of the $1000\ \Omega$ resistor to the bottom of the capacitor (see Figure 4).
6. Repeat steps 2 & 3 above, labeling this run as “RC 330 47”.

7. Replace the 47 mF capacitor with a 470 mF. Repeat steps 2 & 3, labeling as “RC 330 470”. You will have to let the scope run for a bit as the capacitor charges and the V trace stops moving upward.
8. Replace the 330 Ω resistor with a 10,000 Ω (brown-black-orange-gold). Repeat steps 2 & 3, labeling as “RC 1000 470”. You will have to let the scope run for a bit as the capacitor charges and the V trace stops moving upward.

Analysis

1. Create a graph of Voltage Ch A vs. time and then click on the measurement selector on the vertical axis and click Add Similar Measurement and select the Output Voltage.
2. Click on the multicolored Run Select icon in the graph toolbar to allow display of more than one set of data. Then click the black triangle beside it and select both of the “2V run” sets. Click the Scale-to-Fit icon. Highlight both data sets. Click on the Properties icon in the toolbar and turn off Show Run Symbols and Show Data Points, but make sure Show Connecting Lines is on. Do this in both the Active Data Appearance box and the Future Data Appearance box.
3. Explain the differences between the two curves.
4. Turn off the “2V run” sets and select the two “10Vrun” sets. Click the Scale-to-Fit icon.
5. Explain any differences from the “2V run” data. It is useful to measure the height of the peaks using the Coordinate tool.
6. Leave the “10V run” sets active and add the “RC 330 47” data sets. Explain the appearance of the V curve.
7. Add the “RC 330 470” sets. Explain the difference. Hint: consider the RC time constant.
8. Turn off everything except the V data for the RC 330 470 run (looks like a straight line). Click Scale-to-Fit. Is the voltage really DC (i.e. constant)? What you see is called the ripple voltage. Measure its amplitude and record it below. It is present in any DC power supply that rectifies AC. To hear it, with no input to your amplifier at home (if you have one), turn the gain way up and you should hear a hum. It’s called the “60 cycle hum” and is the ripple voltage being amplified. How could you decrease the ripple?
9. Now turn on all the data sets except the “2V run” sets. Click Scale to Fit. How does V look for the 10,000 Ω data set? Pretty good DC? However, there is a problem with our power supply. The output DC voltage (across the capacitor) has dropped to less than 3V. What happened to the missing 2V? The problem is that there is too much resistance in the power supply and when current is drawn from the power supply the output voltage decreases. In this case, the current is being drawn by the Voltage Sensor and the 850 Universal Interface and is only a few microamps. If we wanted to draw a few milliamps, what would happen? So what would you need to do to make the power supply useful?

NPN Transistor as a Digital Switch & Amplifier

Equipment

1	AC/DC Circuit board	EM-8656
1	Voltage Sensor	UI-5100
1	BNC-to-Banana Cord for 850 Output	UI-5119
1	Short Patch Cords (set of 8)	SE-7123
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

Introduction

The purpose of this experiment is to investigate the operation of an NPN transistor.

Theory

A transistor is really two diodes arranged back to back as in Figure 1 where there is an np junction between the emitter and the base and a pn junction between the base and the collector. This is called an npn transistor. One can also have a pnp configuration. Note that in Figure 2, the schematic representation of the npn transistor shows the diode character of the np junction between the emitter and base explicitly as an arrow showing allowed current flow, but does not show the arrow for the base to collector. The base to collector arrow would also point away from the base. This is done as an easy way to identify the emitter on a schematic diagram without having to show the c, b, & e on the diagram. V_{supply} is always large enough so that the base/collector junction is forward biased, so current flows readily across this junction. Not shown in Figure 1, there is always a large resistance in series with the transistor base (as in Figure 2) to prevent much current through the base. However, any current through the emitter/base junction will flow freely through the base/collector junction. When V_{base} becomes positive by more than the bias voltage (the “turn-on” voltage from the Diode Properties lab), current flows through the emitter/base junction and thus through the base/collector junction and through the load resistor.

When current flows through the light emitting diode (LED), it will emit light, showing the use of the transistor as a digital switch. More commonly, the voltage across the load resistor will become the output voltage from the circuit used to drive the next stage of the overall circuit. A relatively small change in the base voltage can cause a large increase in the emitter current (as was shown in the Diode Properties lab). A large emitter current means a large collector current since the 22 k Ω resistor limits the base current. This means a large current flows through the load resistor and V_{Out} can be much larger the V_{In} (the voltage applied to the base). In this case, the circuit acts to amplify the signal.

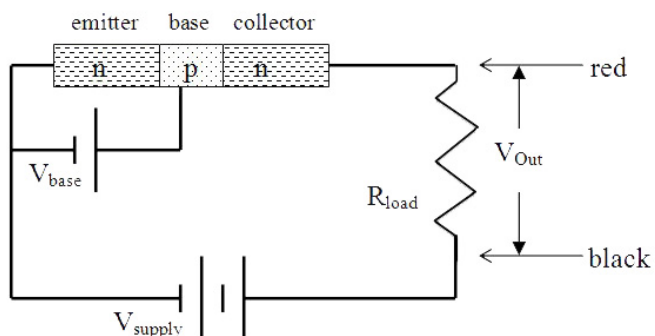


Figure 1: Transistor Theory

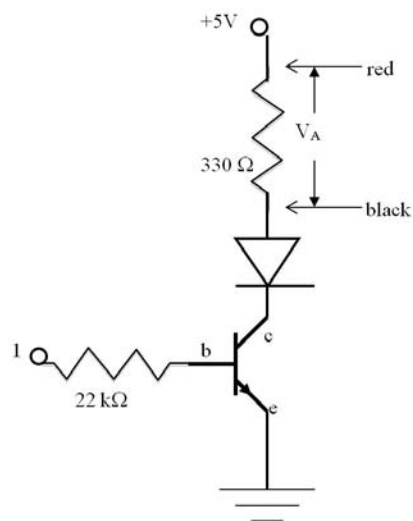


Figure 2: Transistor Switch Circuit

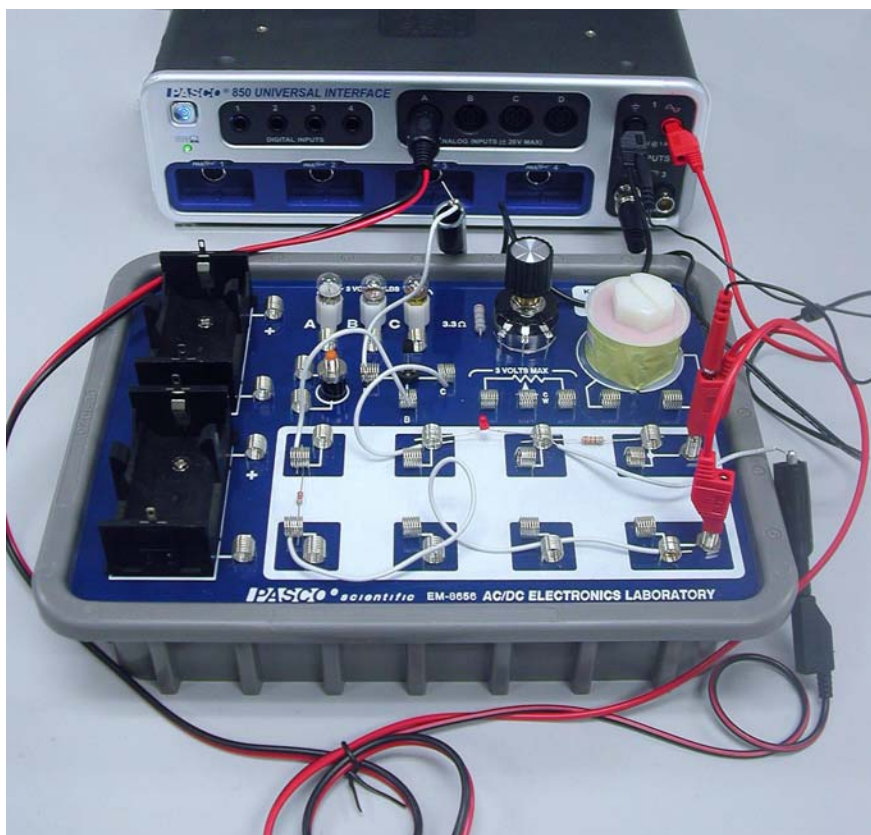


Figure 3: Setup



Figure 4: Close-up Setup

Setup

1. Locate the 2N-3904 transistor. Use Figure 5 to identify the base, emitter and collector. Bend the wires slightly to mount the transistor in the transistor mount as shown in Figure 6. Note that the flat side of the transistor is facing the base spring so the emitter is on the left.

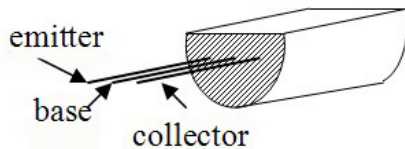


Figure 5: Emitter, Base, Collector

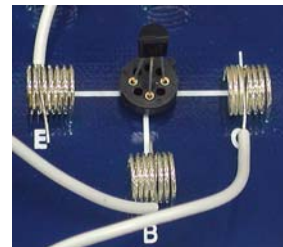


Figure 6: Mounting the Transistor

2. Find the red LED. If the wires have not already been bent so they will bridge between the two springs as in Figure 4, do so now. Be careful not to break the wires. When you are done, leave them bent, since repeatedly bending them will break them.

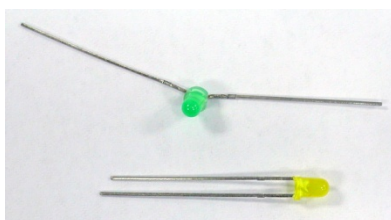


Figure 7: LED Cathode Is Shorter

4. Identify the cathode (negative) side of the red LED. There are four ways to identify the cathode (refer to Figure 7): 1) the wire on the cathode side is shorter, 2) there is a flat spot on the plastic by the cathode (shows clearly on the right of the green LED in Figure 7), 3) if you hold the diode up in front of a light, you will see a triangle...the wide side is attached to the cathode, and 4) if the diode doesn't flash when you do the experiment, it is probably backwards. Attach the diode to the spring clips so its cathode is to the left, toward the transistor.
5. Setup the circuit shown in Figures 2, 3 & 4 using the 330 Ω (orange-orange-brown- gold) resistor between the spring clips at top right, and a 22 k Ω (red-red-orange-gold) resistor at the left.
6. Attach the white jumper wires as shown in Figure 4.
7. Attach a Voltage Sensor to Analog Input A on the 850 Universal Interface. Its red end should attach to the upper jack on the circuit board by the 330 Ω resistor (see Figure 3). Attach an alligator clip to the black end, clip it to a white wire and attach the white wire to a spring clip at the right end of the diode. *Caution: if you attach the alligator clip directly to the spring clip, you will tend to pull the spring loose from the circuit board.*
8. Attach a red patch cord from red jack on Output 1 on the 850 Universal Interface, to the lower banana jack on the circuit board. Attach a black patch cord to the Output 1 black jack. Attach an alligator clip to the black end, clip it to a white wire and attach the white wire to a spring clip by the transistor emitter (E).
9. Attach the BNC connector to Output 2 on the 850 Universal Interface. Its red end should attach to the red patch cord in the upper jack on the circuit board (see Figures 3 & 4). The black plugs into the black patch cord already in the black jack from Output 1 so both output power supplies have a common ground.
10. In PASCO Capstone, open the Hardware Setup and click on Output 1 on the 850 interface and select the Output Voltage/Current sensor. Then click on Output 2 on the interface and select the Output Voltage sensor.
11. Create a graph of Voltage (Ch A) vs. time. Then click on the vertical axis measurement selector and choose "Add Similar Measurement" and select the Output Voltage (Ch 01).

Procedure: Digital Switch

1. Click open the Signal Generator at the left of the screen.
2. Set Output 1 for a Sine Waveform with a Frequency of 1 Hz and an amplitude of 2.0 V. Voltage Offset should be 0 V. Click Auto.
3. Set Output 2 for a DC Waveform. Set the DC Voltage to 5 V. Click Auto.
4. Click the Signal Generator again to close the panel.
5. Set the common sample rate to 200 Hz.
6. Open the Recording Conditions at the bottom of the screen. Set the Stop Condition to Time Based and set the time to 5 seconds.
7. Click RECORD. Observe the diode. Data collection will stop automatically after 5 s.
8. Click on the Selection icon in the graph toolbar. Adjust the handles on the selection box to select the data around the region where V_{out} first rises above 0 V.
9. Click on the Scale-to-Fit icon on the graph toolbar.
10. Determine the bias voltage (the value of V_{base}) required to allow the transistor to conduct. Enter the value in the box below to the nearest 0.1 V.

Analysis

1. How does the behavior of the LED correlate to the V_{out} graph?
2. Explain the relationship between the V_{out} and V_{base} curves.

Procedure: Amplifier

1. Replace the red LED with a white jumper wire.
2. Click open the Signal Generator at the left of the screen.
3. Set Output 1 for a Sine Waveform with a Frequency of 1 Hz and an amplitude of 2.0 V. Set the Voltage Offset to 0 V. Click Auto. Note: same as Digital Switch run.
4. Set Output 2 for a DC Waveform. Set the DC Voltage to 5 V. Click Auto.
5. Click the Signal Generator again to close the panel.
6. Change the Stop Condition to 2 seconds.
7. Click RECORD. Data collection will stop automatically after 2 s.
8. Click on the Data Summary icon. Re-label run #1 as “LED” and run #2 as “no LED”. Close the Data Summary box.
9. Click on the Run Select (multi-color) icon in the graph toolbar to allow display of multiple data sets. Click on the black triangle and select the “LED” and “no LED” runs. Answer Questions 1 & 2 under Amplifier Analysis.
10. Click on the Run Select icon so only one run shows.

11. Click open the Signal Generator. Decrease the Output 1 Amplitude to 0.7 V. Increase the Voltage Offset to 0.5 V.
12. Click Record.
13. Increase the Voltage Offset to 1.0 V. Click Record.
14. Increase the Voltage Offset to 1.5 V. Click Record.

Analysis

1. You may have thought that the LED was important in determining the behavior of the circuit. Was the LED important?
2. Why was the peak voltage for V_{out} different for the two cases?
3. Explain the difference in V_{out} between the last three runs.
4. For the last case, how does the output waveform compare to the input waveform?
5. For the last run, what is the gain = V_{out}/V_{base} ?

Current Gain of an NPN Transistor

Equipment

1	AC/DC Electronics Laboratory	EM-8656
2	Voltage Sensors	UI-5100
1	BNC-to-Banana Cord for 850 Output	UI-5119
1	Short Patch Cords (set of 8)	SE-7123
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

Introduction

The purpose of this experiment is to measure the current gain of an NPN transistor.

Theory

A transistor is really two diodes arranged back to back as in Figure 1 where there is an np junction between the emitter and the base and a pn junction between the base and the collector. This is called an npn transistor. One can also have a pnp configuration. Note that in Figure 2, the schematic representation of the npn transistor shows the diode character of the np junction between the emitter and base explicitly as an arrow showing allowed current flow, but does not show the arrow for the base to collector. The base to collector arrow would also point away from the base. This is done as an easy way to identify the emitter on a schematic diagram without having to show the c, b, & e on the diagram. V_{supply} is always large enough so that the base/collector junction is forward biased, so current flows readily across this junction. Not shown in Figure 1, there is always a large resistance in series with the transistor base (as in Figure 2) to prevent much current through the base. However, any current through the emitter/base junction will flow freely through the base/collector junction. When V_{base} becomes positive by more than the bias voltage (the “turn-on” voltage from the Diode Properties lab), current flows through the emitter/base junction and thus through the base/collector junction.

The current that flows through the 22 k Ω resistor and into the base is very small but the voltage it develops across the 22 k Ω resistor controls the much larger current through the emitter (which is nearly equal to the current through the collector). More importantly, the collector current is directly proportional to the base current, so the transistor acts as a linear current amplifier. The output signal is exactly the same as the input signal except larger. This remains true as long as the voltage on the base does not drop below the bias voltage and the current does not become so large that it begins to overdrive the system. The current gain is defined as

$$\text{Current gain} = \text{collector current/base current} \approx \text{emitter current/base current} \quad (1)$$

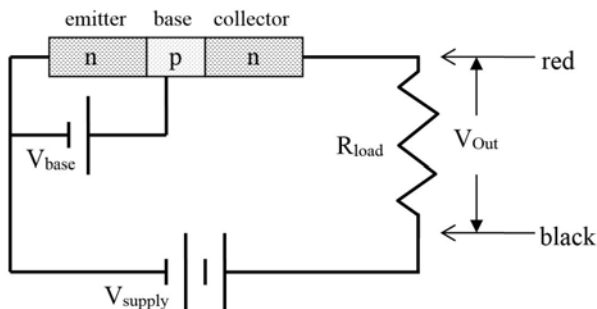


Figure 1: Transistor Theory

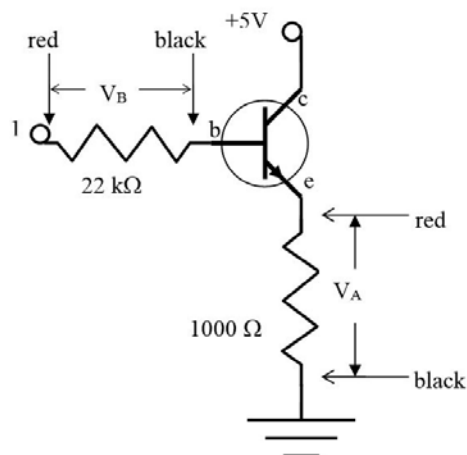


Figure 2: Gain Measurement Circuit

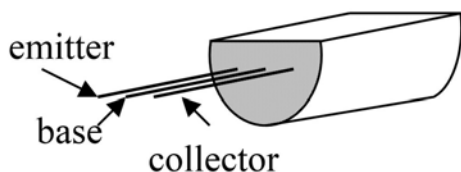


Figure 3: Physical Transistor

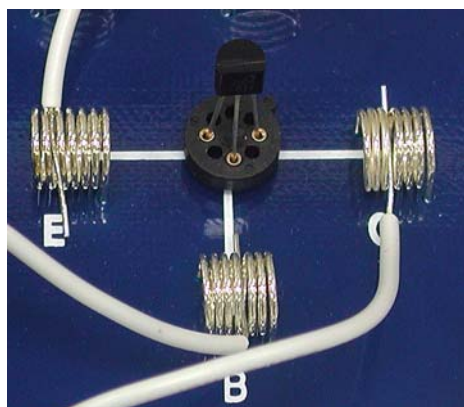


Figure 4: Transistor Mount

Setup

1. Locate the 2N-3904 transistor. Use Figure 3 to identify the base, emitter and collector. Bend the wires slightly to mount the transistor in the transistor mount as shown in Figure 4. Note that the flat side of the transistor is facing the base spring so the emitter is on the left.
2. Setup the circuit shown in Figures 2 & 5 using a 1000 Ω (brown-black-red- gold) resistor between the spring clips at far left in series with the transistor emitter (E). A 22 k Ω (red-red-orange-gold) resistor is in the middle left in series with the transistor base.
3. The red output of Output 1 on the 850 Universal Interface is connected to the lower jack on the Electronics Laboratory (point 1 in Figure 2) which is connected to the end of the 22 k Ω resistor away from the transistor base. The black output from Output 1 is connected to the end of the 1000 Ω resistor away from the transistor emitter.
4. The BNC connector is attached to Output 2 on the 850. The black banana from the BNC is

attached to the black output of Output 1 making the ground common for both power supplies. The red banana from the BNC is attached to the upper jack on the Electronics Laboratory which is attached to the transistor collector with a white wire.

5. Attach a Voltage Sensor to Analog Input B on the 850 Universal Interface as shown in Figure 6. Its red end should attach to the lower jack on the Electronics. Attach an alligator clip to the black end, clip it to a white wire and attach the white wire to a spring clip between the transistor base and the $22\text{ k}\Omega$ resistor. *Caution: if you attach the alligator clip directly to the spring clip, you will tend to pull the spring loose from the circuit board.* This Voltage Sensor will measure the voltage across the $22\text{ k}\Omega$ resistor. The current through the resistor will be calculated by dividing the voltage (V_B) by $22\text{ k}\Omega$.
6. Attach a Voltage Sensor to Analog Input A on the 850 as shown in Figure 7. Its black end should attach to the common ground coming from the 850 Output 1 black jack. Attach an alligator clip to the red end, clip it to a white wire and attach the white wire to a spring clip between the transistor emitter and the $1000\text{ }\Omega$ resistor. This Voltage Sensor will measure the voltage across the $1000\text{ }\Omega$ resistor. The current through the resistor will be calculated by dividing the voltage (V_A) by $1000\text{ }\Omega$.
7. In PASCO Capstone, open the calculator and make the following calculations:
$$i_{\text{base}} = [\text{Voltage, Ch B}]/22 \quad \text{Units of mA}$$
$$i_{\text{emitter}} = [\text{V out, Ch A}]/1 \quad \text{Units of mA}$$
8. Make a graph of “i emitter” vs. “i base”.
9. Set the Common Sample Rate to 200 Hz.

Procedure

1. Click open the Signal Generator at the left of the screen.
2. Set Output 1 for a Sine Waveform with a Frequency of 1 Hz and an amplitude of 2.0 V. Click Auto.
3. Set Output 2 for a DC Waveform. Set the DC Voltage to 5 V. Click Auto.
4. Click the Signal Generator again to close the panel.
5. Click RECORD. Data collection will stop automatically after 2 s.
6. Click on the Selection icon in the graph toolbar. Adjust the handles on the selection box to select the data where the current is not zero and the relationship appears linear.
7. Click on the black triangle by the curve Fit icon and select Linear.
8. Record the slope. Note that it is unitless.

Analysis

1. Why is there a bend in the curve?
2. Why is Equation 1 from Theory defining current gain not very satisfactory?
3. A better definition is to define the current gain as
Current gain = $\Delta I_c / \Delta I_b \approx \Delta I_c / \Delta I_b$ (for the linear region where $I_c > 0$)
Why is this a more useful definition?
4. Using this definition, what is the current gain for this circuit?
5. How linear is the linear portion? Why is this important?

Earth's Magnetic Field

Equipment

1	2-Axis Magnetic Field Sensor	PS-2162
1	Zero Gauss Chamber	EM-8652
1	Rotary Motion Sensor	PS-2120
1	Dip Needle	SF-8619
1	Large Rod Base	ME-8735
1	90 cm Stainless Steel Rod	ME-8738
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone	

Introduction

The magnitude and direction of the Earth's magnetic field are measured using a Magnetic Field Sensor mounted on a Rotary Motion Sensor. The Magnetic Field Sensor is rotated through 720 degrees in a horizontal plane and then 720 degrees in a vertical plane by rotating the Rotary Motion Sensor pulley by hand. This allows a determination of the horizontal component of the Earth's magnetic field, the total field and the dip angle. The Magnetic Field Sensor is zeroed using the Zero Gauss Chamber, the walls of which are made of a highly permeable material which redirects the magnetic field around the chamber.

Theory

The magnitude of the Earth's field varies over the surface of the Earth. The horizontal component of the Earth's magnetic field points toward the Magnetic North Pole (which must therefore have a South polarity). The north end of a compass needle is attracted to the south end of the Earth's magnetic field. So the pole which is referred to as "North Magnetic Pole" is actually a south magnetic pole. Don't get confused. The physics is straight forward; it's the language that gets confused.

The total field points at an angle from the horizontal. This angle (θ) is called the dip angle. An example for the Northern hemisphere is shown in Figure 1.

$$\cos \theta = B_{\text{Horizontal}}/B_{\text{Total}} \quad (1)$$

The Magnetic Field Sensor detects the component of the magnetic field in a direction that is parallel to the clear probe on the sensor. If we rotate the sensor in a horizontal plane, the sensor will detect the component of $B_{\text{Horizontal}}$ that lies along the clear probe and is given by

$$B_{90} = B_{\text{Horizontal}} \cos \alpha \quad (2)$$

where α is the angle from magnetic north (see Figure 2) and B_{90} is the component of $B_{\text{Horizontal}}$ (and of B_{Total}) in the horizontal plane (the 90 refers to the angle read by the angle indicator when horizontal).

If we rotate the sensor in a vertical plane that includes B_{Total} , then the sensor will detect B_{00} , the component of B_{Total} in that plane and is given by

$$B_{00} = B_{\text{Total}} \cos \beta \quad (3)$$

where β is defined in Figure 3. The angle from horizontal, θ , where B_{00} is maximum ($\beta = 0$) will be the dip angle.

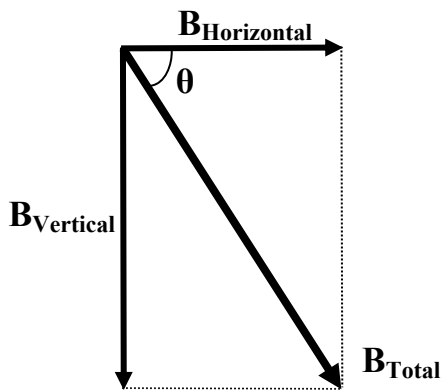


Figure 1: Components of the Magnetic Field (Northern Hemisphere)

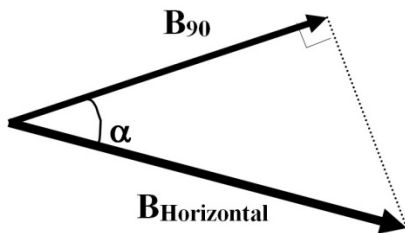


Figure 2: Horizontal Plane

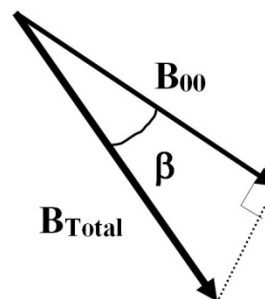


Figure3: B_{Total}

Setup

NOTE: During this experiment, keep the apparatus away from all sources of magnetic fields (electrical, computers, computer interface, bar magnets). Also keep away from all ferromagnetic materials (iron, steel chairs and tables). This is essential for good results since the Earth's Field is orders of magnitude smaller than the field near a refrigerator magnet.

1. Assemble the system as shown in Figure 4. Note that the raised key inside the Magnetic Field Sensor handle slides into the notch on the shaft of the Rotary Motion Sensor. Use a nonmagnetic stainless steel rod in the rod holder. Attach the Rotary Motion Sensor as high as possible on the stainless steel rod to keep the Magnetic Field Sensor as far away from the rod as possible. Set up on the floor away from the lab table (see Figure 4) to help minimize the presence of stray fields.
2. Plug the Rotary Motion Sensor and the Magnetic Field Sensor into any two *PASPORT* inputs on the 850 Universal Interface.
3. In PASCO Capstone, set the Common Sample Rate to 20 Hz.
4. Create a graph of Magnetic Field Strength (Axial) vs. Angle. Select units of mT for the Magnetic Field Strength and degrees for the Angle.

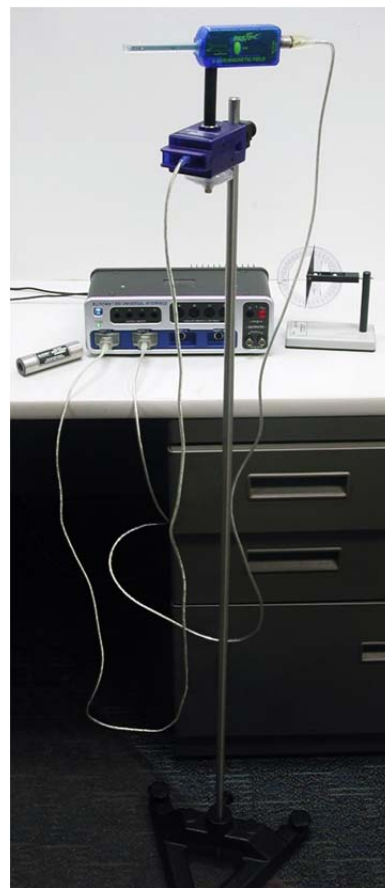


Figure 4: Setup

Procedure A: Horizontal Component of the Magnetic Field of the Earth

1. Put the Dip Needle in its horizontal orientation and position the base of the Dip Needle directly against the case of the Rotary Motion Sensor as shown in Figure 5. Rotate the Rotary Motion Sensor until the compass needle is aligned with its holding fork (as shown in Figure 5) and the north end of the needle is at the 270 degree mark. Remove the Dip Needle so its magnetic field won't interfere with the experiment.



Figure 5: Aligning with North

2. If a level is available, level the top of the case of the Rotary Motion Sensor along its long axis. If it is off by less than 10 degrees, it won't noticeably affect the magnitudes of the magnet fields, but will affect the value of the dip angle.
3. Rotate the Magnetic Field Sensor so the length of the probe is perpendicular to the direction of the Earth's field as indicated by the long axis Rotary Motion Sensor case. Slip the Zero Gauss Chamber over the Magnetic Field Sensor probe and press the Tare button on the Magnetic Field Sensor. Release the Tare button and then remove the Zero Gauss Chamber. The horizontal component of the magnetic field is zero at an angle of 90 degrees from north. Pushing the Tare button here should set the sensor zero to zero at this point. However, the magnetic field strength is only a few hundredths of a mT and the noise is of the same order of magnitude. This means that instead of seeing zero when perpendicular to the field and a field that goes symmetrically above and below zero, the measured field will be shifted vertically a bit by this zero error depending on which reading it uses for zero. This will not affect the experiment at all.
4. Align the Magnetic Field Sensor with the long axis of the Rotary Motion Sensor (as in Figure 5) so it points due north. Click RECORD. Slowly and steadily rotate the Rotary Motion Sensor pulley through two and one quarter revolutions clockwise. Click STOP. It

will help if someone holds the cable clear. If the angles on the graph are negative it will not affect anything, but you can get positive angles by deleting this run and repeating the run while rotating in the opposite direction.

5. The field should have its most negative (most positive if you aligned south instead of north) value at 0° , 360° , and 720° . If not, you probably have not aligned the system correctly and need to correct it and repeat the run.
6. Click on Data Summary at the left of the screen. Double click on this run (probably Run #1) and re-label it "Horizontal 1".
7. Repeat steps 5-7 twice more, labeling the runs "Horizontal 2" and "Horizontal 3".

Procedure B: Total Magnetic Field of the Earth

1. To allow the Magnetic Field Sensor to rotate in a vertical circle, remove the Rotary Motion Sensor from the rod, rotate it 90° and reattach it to the rod. As before (see Figure 5), align the Rotary Motion Sensor with the Earth's field using the Dip Needle.
2. Point the Magnetic Field Sensor probe horizontally.
3. With the Magnetic Field Sensor still horizontal, click RECORD. Slowly and steadily rotate the Rotary Motion Sensor pulley through two-and-one-quarter revolutions in a direction so probe turns downward first. Click STOP.
4. Click on Data Summary at the left of the screen. Double click on this run and re-label it "Vertical 1".
5. Repeat steps 2-4 twice more. Label the runs "Vertical 2" and Vertical 3".
6. Hold the Dip Needle (still in its horizontal position) on top of the Rotary Motion Sensor case so it is level and align it so the needle points to the 270° mark. Rotate the fork 90° so the needle pivots in a vertical plane. Allow the needle to come to rest and read the number of degrees it is below horizontal (270°). Record the value in the table on the Dip Angle page in line 5 of the Dip Angle table.

Analysis

1. Create a table as shown below:
The columns labeled “Field”, “Run 1”, “Run 2”, and “Run 3” are User-Entered Data sets.
The last two columns are calculations:

$$\text{Average} = ([\text{Run 1}] + [\text{Run 2}] + [\text{Run 3}])/3$$

$$\text{Uncertainty} = ((([\text{Run 1}] - [\text{Average}])^2 + ([\text{Run 2}] - [\text{Average}])^2 + ([\text{Run 3}] - [\text{Average}])^2)/2)^{1/2}$$

Field	Run 1 (mT)	Run 2 (mT)	Run 3 (mT)	Average (mT)	Uncertainty (mT)
Horizontal					
Total					

2. Select the “Horizontal 1” run on the graph. Click the Scale-to-Fit icon on the graph toolbar.
3. Click the Selection icon on the graph toolbar and drag the handles on the Selection box to highlight the data from just after you began taking data to just before you ended. Stay away from the endpoints.
4. Select a Sine fit (see the Theory section to see why the data should fit a sine curve). The sine curve on the screen may match your data well, but the computer has some problems matching such noisy data. If the curve is clearly wrong, click on the annotation box for the curve fit and open the Curve Fit Editor at the left side of the page. Put in an initial guess for the amplitude (A) that is approximately half of the peak-to-peak value. Then click Update Fit.
5. Record the value of the amplitude of the sine curve (A in the Sine box) in the Horizontal row, Run 1 column of the table above. Ignore any minus sign. This is the value for $B_{\text{Horizontal}}$ (B_{Total} for the vertical runs) since it is the maximum value if the curve were symmetric about zero.
6. Repeat steps 1-4 for the other two horizontal runs.
7. Repeat steps 1-4 for the three vertical runs recording the amplitudes in the Total row of the table.
8. Note that for both the Horizontal field and the Total Field, the computer calculates the average value and the uncertainty for the fields from your three values.

The Dip Angle

1. Create a table as shown below:

	Angle From	Dip Angle (degrees)
1	Graph Vertical 1	
2	Graph Vertical 1	
3	Graph Vertical 1	
4	Graph Average	
5	Dip Needle	
6	Equation 1	

2. Select the “Vertical 1” run on the graph.
3. Click on the Selection icon and drag the handles on the Selection box to highlight data from just after you started the run to around 400° (one full cycle plus a little). Click the Scale-to-Fit icon.
4. Select a Sine fit. As before, you may have to supply an initial guess for the amplitude (A).
5. Estimate the angle at which the first minimum (first maximum if in magnetic southern hemisphere) occurred. The best way to do this is to pick a horizontal line (constant magnetic field strength) and average the values for the angle where the sine curve crosses the line before the minimum with the angle where it crosses the line after the minimum. This is more accurate than trying to judge the minimum since it is rather flat on the bottom. Enter your value in line 1 of the table. Repeat for the other two vertical runs, entering the values in lines 2 and 3 of the table. Calculate the average of the three values and enter it in line 4.
6. Use the average values of $B_{\text{Horizontal}}$ and the total magnetic field, B_{Total} , to calculate the dip angle. Enter the value in line 6 of the Dip Angle table.
7. Do the different methods of finding the Dip Angle agree?

Magnetic Field Mapping

Equipment

1	Plotting Compasses (Set of 20)	EM-8680
1	Bar Magnet Alnico (Set of 2)	EM-8620
Required but not included:		
	Paper & Pencil	
1	PASCO Capstone	

Introduction

The purpose of this experiment is to help visualize the magnetic field by using small compasses to trace magnetic field lines for a dipole, a repulsive dipole, and a quadrupole field.

Theory

Magnetic field lines are used to help visualize the magnetic field. There are some rules for drawing these lines.

1. The lines begin on a north pole and terminate on a south pole. This is actually only true for the field external to the magnet. Inside the magnet, the lines complete full loops and point from south to north. See Figure 1.
2. The magnetic field strength is directly proportional to the density of the field lines. This is really only true in three dimensions, but in 2-D drawings it is still true that the field is stronger where the lines are closer together.
3. The magnetic field strength (B) is tangent to the field line at any point. Note that B is a vector.
4. The field should have the same symmetry as the magnet configuration that produced it.
5. The lines (of the total field) cannot cross (although since the compasses used to trace the lines are not infinitely small, places where the field is sharply curved can be hard to follow and lines may seem to cross.)
6. The lines cannot stop or start in space. There is one exception here. On a symmetry axis there may be a place where the field is zero. Most lines must avoid such a place, but a line on the symmetry axis must stay on the symmetry axis. On either side of the zero, the field must either point toward the zero or away from it. Thus it appears as if two lines have either started or stopped at the zero. However, there are at most only a few symmetry axes, but an infinite number of field lines (we don't draw them all). This means the fraction of badly behaved lines is (small #)/infinity = 0, so we may ignore the poorly behaved lines. Trouble is that people tend to pick the symmetry axes and see the poorly behaved lines.

A compass needle (small magnet) will align with the (average) B field at the region where the needle is as shown in Figure 1. Thus, we can use a small compass to trace the lines. Why wouldn't a larger compass work as well?

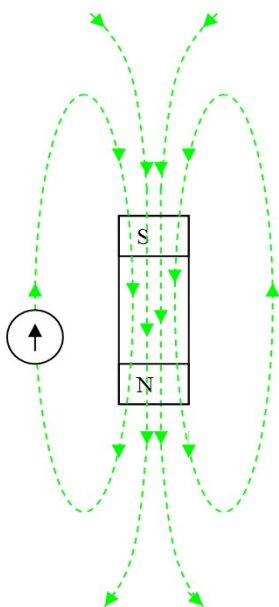


Figure 1: Dipole Field with Compass

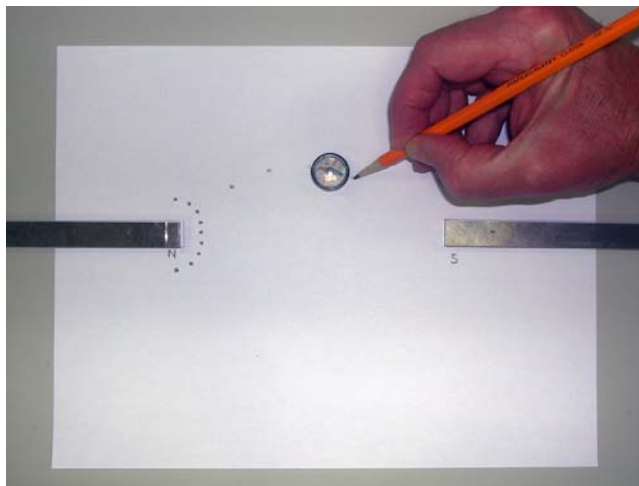


Figure 2: Attractive Dipole Setup

Setup and Procedure

Note 1: the PASCO EM-8620 Alnico magnet has a groove near the North end.

Note 2: if the laboratory tables have metal parts, they can become magnetized and add to the total magnetic fields you are mapping. You can check you table top with a compass to see if it is affected in the region where you intend to do your field plotting. If it is, find a spot that isn't.

Attractive Dipole

1. Position the magnets so they are about halfway onto a piece of $8\frac{1}{2} \times 11$ inch paper as shown in Figure 2. The north pole of one magnet should face the south pole of the other. Draw a line around each magnet and label the poles. Near the north end, make a semi-circle of nine dots with one dot on the symmetry axis and four above the axis and four below as shown.
2. Position the compass so the south end of the compass points to one of the dots in the semi-circle (in Figure 2, I started at the third dot from the top). Using a wooden pencil (why?) make a dot on the paper where the north end of the compass needle points. Then move the compass so the south end points to the dot you just made and mark a new mark where the north end points. Continue until you go off the paper or reach the south pole of the other magnet. Fit a smooth curve to the dots. Don't forget that the field is a vector!

3. Now do the other eight points. Note: This should not require a lot of time. This is a quick and qualitative exercise. We are not working to three significant figures.

Repulsive Dipole

1. Set up as before with the two north ends facing. Draw a semi-circle of nine dots around each North pole. See Figure 3.
2. Trace all 18 lines.

Quadrapole

1. Tape two pieces of paper together. Draw an arrow on the paper with the north direction indicated as shown in Figure 4. With the magnets far away, use your compass to align the paper so the arrow points at magnetic north. Tape the paper down so it can't shift position.
2. Put the magnet on the paper at about a 45 degree angle as shown. Mark the position of the magnet and indicate which pole is north.
3. Put a semi-circle of nine dots around each pole. In addition, put two dots along the body of the magnet and above the magnet near the north end (see Figure 4) and a matching two dots below it (the compass South pole is pointing to one of them).
4. Trace all 22 lines.



Figure 3: Repulsive Dipole

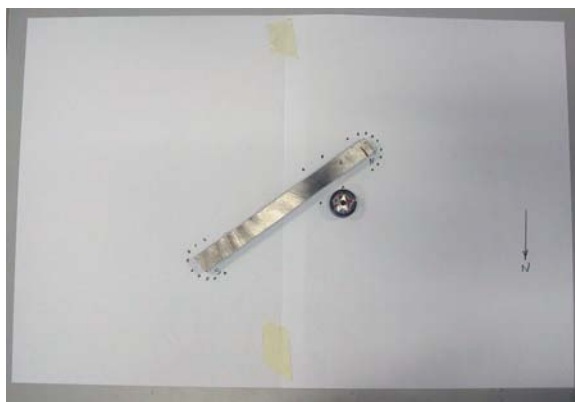


Figure 4: Quadrapole

Analysis

Discuss each of the three patterns briefly. Consider the six points discussed in the Theory section. Where is the field relatively strong? Are there any symmetries? Are there any zeroes? Do the lines cross? Do any lines start or stop in space?

Induction: Magnet through a Coil

Equipment

1	AC/DC Electronics Laboratory	EM-8656
1	Voltage Sensor	CI-6503
1	Bar Magnet Alnico (set of 2)	EM-8620
1	No-Bounce Pad	SE-7347
Required but not included:		
1	850 Universal Interface	UI-5000
1	PASCO Capstone Software	

Introduction

The purpose of this experiment is to examine Faraday's Law of Induction. A magnet will be dropped through a coil and the voltage across the coil graphed as a function of time. The total integrated flux as the magnet moves into the coil will be compared to the flux as it moves out of the coil.

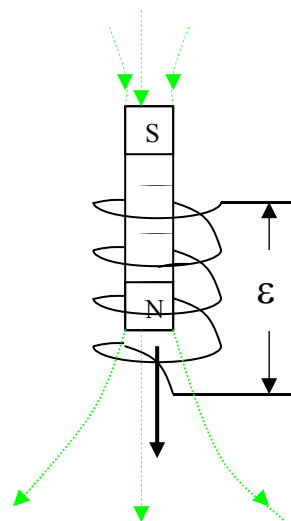


Figure 1: Falling Magnet

Theory

When the magnetic flux thru a coil of wire changes (as in a magnet falling thru a coil of wire in Figure 1), there is an EMF (\mathcal{E}) generated between the ends of the coil given by Faraday's Law:

$$\mathcal{E} = -N(d\Phi/dt) \quad (1)$$

where N is the number of turns in the coil and $d\Phi/dt$ is the time rate of change of the magnetic flux, Φ , or the derivative of the magnetic flux with respect to time. The magnetic flux may be thought of as the number of magnetic field lines (green arrows in Figure 1) passing thru the coil. Integration of Equation 1 yields:

$$\int \mathcal{E} dt = -N\Delta\Phi = [\text{the area under the curve on an } \mathcal{E} \text{ vs. } t \text{ graph}] \quad (2)$$

where $\Delta\Phi$ is the total change in flux (or total number of field lines).

Setup

1. Remove the large plastic bolt from the center of the coil. Note: replace the bolt at the end of the experiment. Otherwise the coil tends to be pulled loose from the circuit board.
2. Connect white wire jumpers from the coil connector springs to the banana inputs for the Electronics Laboratory as shown in Figure 2. Connect red and black ends of the Voltage

Sensor to the banana inputs on the Electronics Laboratory and plug the Voltage Sensor into Channel A on the 850 Universal Interface.

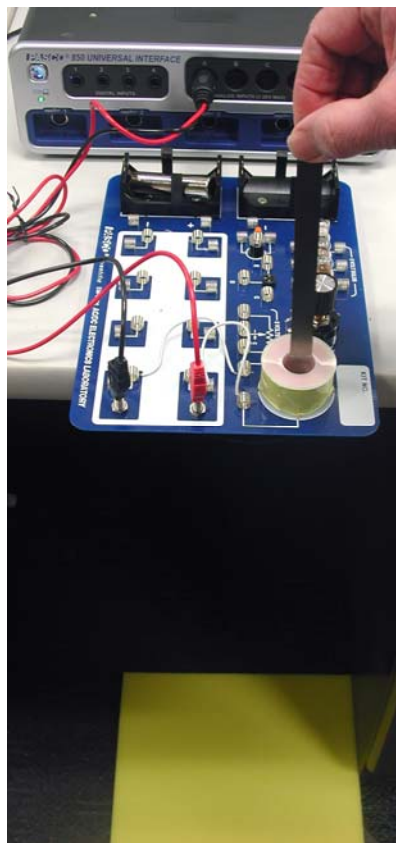


Figure 2: Setup

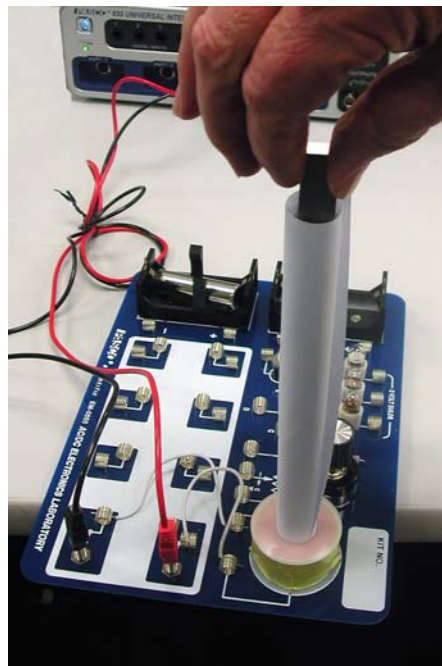


Figure 3: Paper Roll Guide

3. In PASCO Capstone, set the sample rate to 2.0 kHz and create a graph of Voltage vs. time.
4. Open the Recording Conditions and set a start condition for the measurement of Voltage rising above 0.01 V and set a stop condition based on a time of 0.25 seconds.
5. Position the Electronics Laboratory so it hangs over the desk enough so a magnet can be dropped through the coil. Placing the iron core for the coil (or any convenient mass) in one of the battery holders will prevent the Electronics Laboratory from tipping.
6. Place the No-Bounce pad on the floor where the magnet will hit. If the magnet hits the floor without the pad, it may break.
7. Tightly roll up a piece of paper to make a tube 8.5 inches long and insert it into the coil. This will guide the falling magnet so it hits the hole. Note where the magnet must be held so its lower end is about 5 cm above the coil.

Procedure

Note: The PASCO EM-8620 Alnico magnet has a groove near the North end. Hold one magnet so its north end is downward and is in the paper tube about 5 cm above the coil.

1. Click RECORD. Drop the magnet. Data collection will start and stop automatically. If you only see an “up pulse”, reverse the connections on the coil by reversing the red and black banana plugs from the voltage sensor.
2. Click open the Data Summary at the left of the page. Re-label this run as “N down”.
3. Click on Recording Conditions at the bottom of the page. Change the Start Condition to “Falls Below” and the Value to -0.0100. Click OK.
4. Repeat steps 1 & 2 with the south end down. Label it “S down”.
5. Click on Recording Conditions at the bottom of the page. Change the Start Condition to “Rises Above” and the Value to 0.0100. Click OK.
6. Repeat steps 1 & 2 with the north end down but held as high as possible in the paper tube. Label this run “N down hi”.
7. Remove the paper tube.
8. Stick the two magnets together (north to south). Hold them so one end is already in the top of the coil (they will just barely fit). Repeat step 2 and label “N to S”.
9. Tape the two magnets together so the north poles are together and the south poles are together. Hold them so the north end is already in the top of the coil (they will just barely fit). Repeat step 2 and label “N to N”.
10. Replace the plastic bolt holding the coil to the circuit board.

Analysis

1. Create a table as shown below: All the columns are User-Entered Data sets.

Table I: Change in Magnetic Flux = $N \Delta\Phi$

	System	First Pulse (Vs)	Second Pulse (Vs)
1	N down		
2	S down		
3	N down hi		
4	N to N		

2. Select the “N down” run on the graph. Click on the Scale-to-Fit icon. Click on the Properties icon in the graph toolbar. Show Run Symbols and Show Data Points should not be selected (so you can see the line better). If they are selected, de-select them in both the Active Data Appearance box and the Future Data Appearance box. Click OK.
3. Click on the Selection icon in the graph toolbar. Adjust the handles on the selection box to select the data time = 0 to the point where $V = 0$ as the curve crosses the horizontal axis. You should have selected all the positive data.
4. Click the Area icon. It will calculate the area under the curve. Recall from Theory that this is the change in the magnetic flux through the coil. If the Area box does not show three significant figures, click on Data Summary. Click on the Voltage Properties icon (not the Voltage Sensor Properties) and change to three significant figure under the Number Format. Enter the value in the First Pulse column of Table I on the N down line.
5. Move the selection box to select all the negative data. Enter the value in the Second Pulse column of Table I.
6. Repeat for the “S down”, “N down hi”, and “N to N” data sets.

Conclusions

1. On the graph, select the “N down” run. Why is the peak voltage higher on the 2nd pulse than on the 1st pulse?
2. Why is one pulse up and the other pulse down?
3. Explain why the value for the magnitudes of the change in magnetic flux for the “N down”, “S down”, and “N down hi” are all essentially equal.
4. Select both the “N down” and “S down” runs. In terms of the magnetic flux, explain why they are reversed.
5. Select the “N down” and “N down hi” runs. Explain why they are different. Why doesn't this change the area under the curve?
6. Select the “N down” and “N to S” data. Explain the difference.
7. Explain why the “N to N” data in Table 1 are different from the other cases. Note: the two magnets probably were not equally strong. A 10% difference would not be surprising. You could check if you want.

Magnetic Field of a Current Carrying Coil

Equipment

1	AC/DC Electronics Laboratory	EM-8656
1	Rotary Motion Sensor	PS-2120
1	2-Axis Magnetic Field Sensor	PS-2162
1	Short Patch Cords (set of 8)	SE-7123
1	Large Rod Base	ME-8735
1	90 cm Rod, Stainless Steel	ME-8738
1	Mass and Hanger Set	ME-8979
1	Black Thread	ME-9875

Introduction

The radial and axial magnetic fields of a current carrying coil are plotted versus position as the Magnetic Field Sensor is passed through the coil. The position is recorded by a string attached to the Magnetic Field Sensor that passes over the Rotary Motion Sensor pulley to a hanging mass.

Theory A

Single Coil

For a coil of wire of negligible length having radius R , N turns of wire, and current I , the magnetic field along the perpendicular axis through the center of the coil is given by

$$B = \frac{\mu_0 N I R^2}{2(x^2 + R^2)^{3/2}} \quad (1)$$

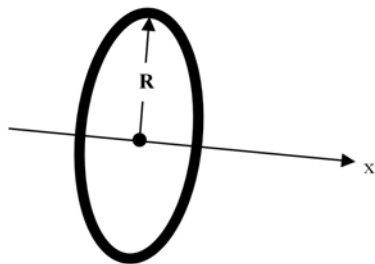


Figure 1: Single coil of Radius R

Long Solenoid (= coil)

For a long solenoid with n turns per unit length, the magnetic field is

$$B = \mu_0 n I \quad (2)$$

The direction of the field is straight down the axis of the solenoid. To be considered "long", the length of the coil must be much longer than the diameter of the coil as shown in figure 2. In addition, Equation 2 will begin to fail when the ends of the solenoid are approached and the magnetic field strength will begin to decrease.

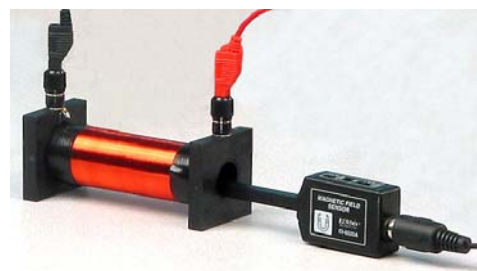


Figure 2: Long Solenoid

Short Solenoid

For the short solenoid on the AC/DC Electronics Laboratory, neither Equation 1 nor Equation 2 is correct since the coil is too long for Equation 1 to work and too short to use Equation 2. The coil has about 600 turns, an average radius of about $R = 1.5$ cm and a length of $L = 2.5$ cm. However, both equations tell us something about the behavior of the magnetic field. Both equations should yield upper bound values for the magnetic field at the exact center of the coil, since in the first case squeezing the 600 turns into zero length would make all of the coils closer and in the second case adding more coils would clearly increase the field. After completing the Procedure page, calculate the upper bound values at the center of the coil ($x=0$) using both equations and enter them in the box to the right. Click open the Calculator at the left of the screen and note that B_{theory} is calculated using Equation 1. Ignore the "d" term. It will be used to shift the origin later.

Setup

1. Remove the large plastic bolt from the center of the coil. Note: replace the bolt at the end of the experiment. Otherwise the coil tends to be pulled loose from the circuit board.
2. Connect white wire jumpers from the coil connector springs to the banana inputs for the Electronics Laboratory as shown in Figure 4. Connect red and black patch cords from the Electronics Laboratory inputs to red and black jacks for Output 1 on the 850 Universal Interface.

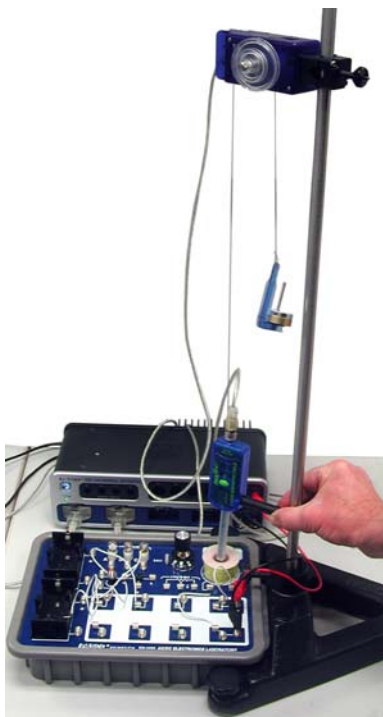


Figure 3: Setup

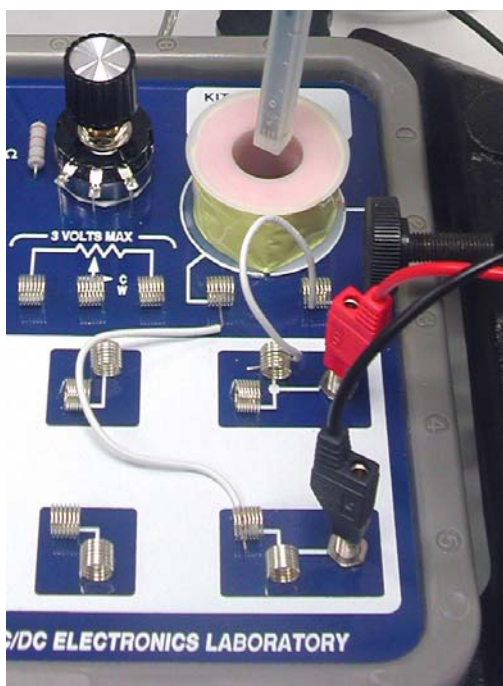


Figure 4: Circuit Board Connections

3. Attach the 90 cm rod to the base and position the base by the Electronics Laboratory as shown in Figure 3.
4. Attach the Rotary Motion Sensor (RMS) to the rod as in Figure 3. Cut a piece of thread about 1 m long. Tie one end of the thread around the strain relief in the cable attached to the Magnetic Field Sensor so it catches in one of the grooves as shown in Figure 4. Pass the other end of the thread over the large step of the RMS pulley and attach a mass holder carrying an additional 60 g of mass.
5. Adjust the positions so the thread between the RMS and the Magnetic Field Sensor is vertical when the sensor is centered on the coil. Attach the sensor handle to the Magnetic Field sensor. Adjust the positions so that while holding the end of the sensor handle against the 90 cm rod, you can move the sensor up and down along the magnetic field axis.
6. Plug the Magnetic Field Sensor and the Rotary Motion Sensor into any two of the PASPORT inputs on the 850 Universal Interface.
7. In PASCO Capstone, open the Hardware Setup and click on the Signal Generator #1 and select the Output Voltage Current sensor.
8. Set the Common Sample Rate to 20 Hz.
9. Create a graph of Magnetic Field Strength (Axial) vs. Position.

Solenoid Procedure

1. With the DC power off, put the Magnetic Field Sensor probe into the coil so the sensor is at the center of the coil. Note that the actual vertical position of the sensor is indicated by the white dot on the side of the probe away from the labels on the sensor body. Press the Tare button to zero the sensor. On the Experiment Control Bar, select the Rotary Motion Sensor and click on the Zero Now button.
2. Click open Signal Generator. Set Output 1 for a DC Voltage of 5 V. Click Auto. Click the Signal Generator closed.
3. Insert the magnetic sensor probe through the solenoid as far as possible keeping the sensor handle against the steel rod.
4. Start recording. Move the probe slowly out of the solenoid and about 10 cm beyond, holding the sensor handle against the steel rod. Try to keep the sensor probe centered on the coil. Click STOP.
5. Examine the curve. If it is not symmetric about Position = 0, repeat the "Zero Sensor Now" adjust from step 1 above. It does not have to be perfect.

6. Click open Data Summary and re-label this run as "Center".
7. Repeat step 4 except this time rotate the Magnetic Field Sensor (keeping the sensor handle against the steel rod) so the probe is against the left edge of the coil. Label this run as "Left".
8. Repeat with the probe against the right edge of the coil. Label as "Right".
9. Reverse the red and black patch cords so current flow through the coil in the opposite direction. Repeat step 8 and label it "Right Reversed".
10. Replace the plastic bolt holding the coil to the circuit board.
11. Use Equations 1 and 2 to calculate the upper and lower bound values for the magnetic field.

Axial Field

1. How do the first three runs compare with each other? What does this show about how uniform the magnetic field is across the coil (moving perpendicular to the axis of the coil)?
2. Note that the arrows on the Magnetic Field Sensor indicate the positive direction, so a positive field means that the field direction points upward. Does your data indicate that the field is upward or downward? Is the current in the coil clockwise or counterclockwise viewed from above?
3. Why is the "Right Reversed" run different from the other three?
4. How well did the estimates (since the values we used were only approximate) calculated using Equations 1 & 2 work out?

Radial Field

1. Create a graph of the Magnetic Field Strength (Perpendicular) vs. Position. Select the Right, Left, and Center runs on the graph.
2. On the axis, there should be no perpendicular field due to the symmetry of the system. There is probably a small radial field due to failure to get the sensor right on the axis. Does the field appear small for the "Center" run? Click the black triangle by the Run Select icon on the graph toolbar. Click "Center" to de-select it. The "Left" and "Right" runs should still show.
3. Note that the positive direction for the radial field is coming out of the side of the sensor with the labels on it. Explain why the "Left" radial field looks the way it does.

4. Explain why the "Right" radial field look the way it does.
5. Click on the black triangle by the Run Select icon and select "Right Reversed" and click on "left" to de-select it. Explain why they are different.

Magnetic Field Model

1. Open the Capstone calculator and make the following calculation:

$$B_{\text{theory}} = 0.5 * \mu_0 * N * [\text{Output Current}] * R^2 * (([\text{Position}] - [d])^2 + R^2)^{-1.5}$$

with units of T

μ_0 = [Permeability constant (H/m)]

N = 600 unitless

I = 0.8 with units of A

R = 0.015 with units of m

d = 0.0018 with units of m

2. On the graph of Magnetic Field Strength (Axial) vs. Position, use Add Similar Measurement on the vertical axis to add B_{theory} .
3. Recall from the theory that the B_{theory} model is based on Equation 1, which treats the coil as if it had zero length. Why is the B_{theory} curve narrower than the experimental curve?
4. For positions outside the coil ($-1.2 \text{ cm} < \text{position} < +1.2 \text{ cm}$), the theory curve looks very similar to the experimental data. To see this, click open the Calculator and adjust the "d" value to shift the theory curve. Try to make B_{theory} match the data for positions $> 1 \text{ cm}$. The best "d" value is probably around 0.0025 m, but the exact value depends on how well you set the zero and centered the curve on zero position. Can you make the model match the data for positions $< -1 \text{ cm}$? What does this tell us?

