

SABBATICAL REPORT
1997-1998

SUBMITTED TO THE
MT. SAN ANTONIO COLLEGE
SALARY AND LEAVES COMMITTEE

BY
THOMAS W. SMITH
PHYSICS AND ENGINEERING DEPARTMENT

SEPTEMBER 14, 1998

MT. SAN ANTONIO COLLEGE
Salary and Leaves Committee

APPLICATION FOR SABBATICAL LEAVE

Name of Applicant THOMAS W. SMITH

Address 709 E. LAUREL AVE GLENDORA CA 91741

Employed at Mt. San Antonio College beginning FEB 1965

Dates of last sabbatical leave:

From SEPTEMBER 1974 To JUNE 1975

Department PHYSICS and ENGINEERING Division NATURAL SCIENCES

Length of sabbatical leave requested:

One semester _____
Fall _____ Spring _____

Two Semesters X

Purpose of sabbatical leave:

Study _____ Project X

Travel _____ Combination
(specify) _____

NOTE: Sabbatical periods are limited to contractual dates of the academic year.

Effective dates for proposed sabbatical leave:

From AUGUST 1997 To MAY 1998

and (if taken over a two school year period)

From _____ To _____

Attach a comprehensive, written statement of the proposed sabbatical activity(ies) including a description of the nature of the activity(ies), a timeline of the activity(ies), an itinerary, if applicable, the proposed research design and method(s) of investigation, if applicable.

Attach a statement of the anticipated value and benefit of the proposed sabbatical activity(ies) to the applicant, his/her department or service area, and the College.

Any change or modification of the proposed sabbatical activity(ies) as evaluated and approved by the Salary and Leaves Committee must be submitted to the Committee for reconsideration.

Thomas W Smith
Signature of Applicant

NOVEMBER 25, 1996
Date

APPLICATION FOR SABBATICAL LEAVE

Page 2

Applicant's Name THOMAS W SMITH

THE ACKNOWLEDGMENT SIGNATURES REFLECT AWARENESS OF THE SABBATICAL PLAN FOR THE PURPOSE OF PERSONNEL REPLACEMENT. COMMENTS REQUESTED ALLOW FOR RECOMMENDATIONS PERTAINING TO THE VALUE OF THE SABBATICAL LEAVE PLAN TO THE COLLEGE.

APPLICANTS MUST OBTAIN THE SIGNATURES OF ACKNOWLEDGMENT PRIOR TO SUBMITTING APPLICATION TO THE SALARY AND LEAVES COMMITTEE.

ACKNOWLEDGMENT BY THE DEPARTMENT/DIVISION

Signature of Department Chairperson Thomas W Smith Date 11/25/96
Comments:

Signature of Division Dean Clarry J Reding Date 11/26/96
Comments:
See attached letter of support

ACKNOWLEDGMENT BY THE OFFICE OF INSTRUCTION

Signature of Executive Vice President, Instruction J. J. Zagorski Date 11-28-96
Comments:

This is a must do for a very deserving professor.

NOTE: DIVISION DEANS ARE REQUESTED TO SUBMIT A STATEMENT OF RECOMMENDATION REGARDING THE VALUE OF THE SABBATICAL PLAN TO THE COLLEGE, DIVISION/DEPARTMENT, AND INDIVIDUAL, IN CONSULTATION WITH THE APPROPRIATE DEPARTMENT CHAIRPERSON.

FINAL ACTION BY THE SALARY AND LEAVES COMMITTEE:

Recommend approval to the Board of Trustees

Not recommend approval to the Board of Trustees

Letitia Curran 3/7/97
Signature - Chairperson, Salary and Leaves Comm. Date

W. Kull 3-7-97
Signature - Authorized Agent of the Board Date

PROPOSED SABBATICAL ACTIVITIES

Background

For the past several years significant research in cognitive physics education has been performed across the country. Research findings have led to the development of several models that have been tested and found to be successful in significantly increasing student retention and in improving student comprehension in introductory physics courses. These models emphasize active-learning in cooperative groups, while making significant use of microcomputers and multimedia. These research efforts and the related curriculum development to date have been directed to either trig-based or calculus-based courses.

In the Spring of 1995 I submitted to the College Curriculum Committee, with the approval of the Physics and Engineering Department, a proposal to restructure the curriculum for the entry-level physics course, based on this research in the field of physics education. PHYS 1 is a one-semester algebra-level physics course that serves both as a general education course and as an entry-level course for those going on to the engineering physics sequence. It is the largest course in our department in terms of student enrollment. In order to move away from a lecture mode of delivery to the interactive, activity-based mode it would be necessary to change PHYS 1 from a traditional lecture/lab format to a format in which students meet in interactive guided discovery/activity sessions carried out in a facility equipped with computers, video-disc players and the necessary experimental set-ups and video resources. The Curriculum

Committee approved the concept and encouraged me to pursue the curriculum development.

Later that Spring I submitted, through the hoshin budget planning process, a budget request for purchase of the necessary computers and laboratory equipment and for released time to develop and implement the revised curriculum. Funds were approved for the purchase of the hardware. The hardware acquisition should be complete by the end of the 1996-97 school year. However, funds were not approved for the released time.

I am requesting a sabbatical leave for the purpose of developing the curriculum for the PHYS 1 course. I would be able to build upon work that has already been done by research and development groups; however since their work has been directed to trig or calculus-based physics courses, I need to make significant modifications in order to adapt the material to an algebra-based course. The necessary modifications to both the curriculum produced by the new models and to the current PHYS 1 curriculum are so major that the entire revision would need to be available for implementation at one time. A gradual introduction of the revised curriculum in stages over a multi-semester time period would be too chaotic.

Formal approval for the change-over to the new presentation format would be sought from the Curriculum Committee in the Spring of 1998, with anticipated implementation in the Fall of 1998.

Project Activities

- Review the following curriculum materials:
 - a) Multimedia College Physics Laboratory
 - b) Tools for Scientific Thinking
 - c) Workshop Physics Project
 - d) Real-Time Physics (have attended a workshop on this topic)
 - e) Physics by Inquiry (will be attending a workshop on this topic in January '97)

Time: four weeks

- Locate and network (via e-mail) with other physics faculty throughout the country that are engaged in similar curriculum development projects. I plan to begin this process in January 1997 when I attend the annual Winter meetings of the American Association of Physics Teachers, in Phoenix, Arizona. Through that networking I hope to gain access to materials that others may have developed that could have application to this proposal.

Time: ongoing throughout project

- Review the videodisc and CD-ROM resources available that could be used in the revised course.

Time: one week

- Become familiar with all the data acquisition sensors we have acquired for use in the revised course.

Time: one week

- Write the curriculum materials. The course would probably be offered in a four-day-a-week format, meeting one and one-half hours a day. Therefore, approximately sixty-six individual lessons would need to be

written, each one including detailed instructions for activities along with backup conceptual material. Each lesson would probably be about eight to ten pages in length.

Time: thirty weeks

Anticipated Value and Benefit of the Proposed Sabbatical Activities

Based on previous experience by researchers with the course delivery mode being developed in this proposal there should be significant improvement in student retention and comprehension. That should also improve student success for those who go on to take the Engineering Physics sequence.

It is possible that the experience gained in developing and implementing this curricular change will be transferable to similar changes in other physics courses we offer.

In conversations with one of the primary developers of the Real-Time Physics curriculum material I was told that the chance of successfully competing for National Science Foundation grants for curriculum development is improved by showing previous development experience. Experience gained through this project should then improve our chances as a college to receive such NSF grants in the future.

Natural Sciences Division

AGRICULTURE • BIOLOGY • CHEMISTRY • EARTH SCIENCES/PHOTOGRAPHICS/ASTRONOMY
MATHEMATICS/COMPUTER SCIENCE • NURSING • PHYSICS/ENGINEERING

MT. SAN ANTONIO COLLEGE

Salary and Leaves Committee
Mt. San Antonio College

NOV 27 1996

26 November 1996

OFFICE OF HUMAN RESOURCES

Re: Support for the Application for Sabbatical Leave for Thomas Smith (Physics & Engineering)

Dear Committee Members,

It is with my highest recommendation that I provide unconditional support on behalf of Professor Thomas Smith for his request for Sabbatical Leave in 1997-98. His attached proposal for the development of significantly improved and restructured Introductory Physics Program (Physics 1) is a well conceived plan which will provide a multitude of benefits for the students within Physics and other instructional areas.

The significance of this approach to curriculum presentation will be far-reaching for our students in all levels of instruction within the Physics, Engineering and general physical science areas. The project will also provide support for other sciences areas that call upon physics modeling for part of their instruction.

In the recent past Professor Smith was extremely effective in the reform and presentation restructuring of the content, curriculum, laboratory processes within the Physics 2A, 2B and 4A,B,C Curriculum. The significant enhancement and restructuring as proposed by Tom will add much needed options to the entire physics sequence. When in place, it will be a significant contribution to the comprehensive opportunities of our students.

This project is fully supported by the departments instructional faculty and by my office. Last Spring Professor Smith attempted to accomplish these Physics reforms and changes through the Hoshin Budget Process and through other means. Although release time was not supported in his request the change in design and the monetary investment for most of the necessary equipment was provided. This concept has been well designed and parallels similar versions which have been placed on line at other colleges. Professor Smith needs the time to prepare the material for implementation at Mt. San Antonio College.

I believe that given the successes of previous endeavors by Tom and the timeliness of this particular endeavor this Sabbatical request should be given the highest ranking.

If I can be of further assistance regarding clarification of support for Professor Tom Smith's Sabbatical Leave request please contact me at extension 4425 or at LREDINGER@IBM.MtSAC.Edu.

Sincerely,



Larry L. Redinger
Dean, Natural Sciences Division

STATEMENT OF PURPOSE

The ultimate purpose of my sabbatical leave was to develop curriculum for use in teaching PHYSICS 1 using an alternative method of delivery. In the past PHYSICS 1 has been offered in a traditional lecture/lab format, a method of delivery that is not the most effective in achieving the desired level of learning, comprehension, and long-term retention in students.

My goal was to develop curriculum materials for PHYSICS 1 that would enable the course to be taught as a workshop-style course. Taught in this fashion, small groups of students would work cooperatively and actively to discover for themselves physics concepts using a variety of equipment, in conjunction with desktop computers and special sensors.

TABLE OF CONTENTS

REPORT	page 1
CONCLUSIONS	page 6
APPENDIX	page 7

My sabbatical project consisted of several components: reviewing available curriculum material, networking with other physics faculty, reviewing physics CD-Rooms and a variety of videodiscs for possible use in class, familiarizing myself with the sensors and software purchased for use in the course, and writing the curriculum materials.

I began with the review of the following curriculum materials: Multimedia College Physics Laboratory, Tools for Scientific Thinking, Workshop Physics Project, Real-Time Physics, Physics by Inquiry, and the CASTLE material on electricity.

Multimedia College Physics Laboratory, Tools for Scientific Thinking, and Real-Time Physics were found not to be appropriate because they were primarily lab instructions for use in the laboratory component of a traditional course. The Workshop Physics Project, Physics by Inquiry, and the CASTLE material on electricity were found to be suitable; they were designed to be used in a hands-on, activity-based approach, not just as alternative laboratory exercises. Subsequently they were modified, as described later in this report, and prepared for use in the course.

Over the course of my sabbatical I received valuable advice and information (via e-mail) from the following individuals:

Gail Oliver, Workshop Physics Project Manager, Dickinson College, Carlisle, PA

Priscilla W. Laws, Department of Physics and Astronomy, Coordinator Workshop

Physics Project, Dickinson College, Carlisle, PA

Gerald (Jerry) Hart, Physics Department, Moorhead State University, Moorhead, MN

Peter Shaffer, Department of Physics, University of Washington, Seattle, WA

Howard Lukefahr, Physics Department, Whittier College, Whittier, CA

Maxine C. Willis, Gettysburg Area Senior High School, Gettysburg, PA.

Scott Sukrapanna, Technical Support, PASCO Scientific, Roseville, CA

Part of the modifications to the existing material involved inclusion of video assignments, in which students are instructed to watch applicable sections of a variety of video resources that were extensively reviewed as part of this sabbatical project. This involved evaluating and cataloging the contents of the following videodiscs: Physics and Automobile Collisions, Physics of Sports, Physics: Cinema Classics (a three disc set), The Puzzle of the Tacoma Narrows Bridge Collapse, Principles of Physics, The Mechanical Universe, and Saunders Physics Videodiscs (a two disc set). I was particularly looking either for effective demonstrations that are difficult to do in class or for animation sequences that

clearly show features of phenomena that are difficult to visualize. As an example, a list of the segments added to the CASTLE module on electricity is provided in the Appendix.

Several CD-ROM resources were also reviewed (Physics-The Core, by Saunders; Interactive Journey Through Physics, by Prentice Hall; CD Physics, by Wiley; Physics For The Computer Age, by McGraw Hill). Because of class-time constraints I decided not to include any CD-ROM assignments in the class activities, but did purchase ten copies of Interactive Journey Through Physics and made them available to students in the Natural Sciences Division Computer Lab. This particular CD-ROM was best suited for an algebra-level course. For each topic covered it includes the following segments: Topic Review, Animation, Video, Simulation, Problems, and MCAT Question. The quality of the product is very good. Physics For The Computer Age was also designed for a PHYSICS 1 level course but was not as good in quality as Interactive Journey Through Physics. Its video segments were in small 2"x2" windows and some of its graphing features were difficult to use. Physics-The Core and CD-Physics were targeted at a calculus-level course, and were therefore unacceptable.

One trade-off required in using the workshop approach to teaching physics is that less material can be covered than is covered in a traditional course. After a review of the currently available curriculum materials, I decided to cover topics in mechanics, electricity and electric circuits, and light and geometrical optics. As a result it was decided to focus on the adaptation of material from the following three sources: CASTLE - Electricity Visualized, Workshop Physics, and Physics by Inquiry.

The CASTLE material makes extensive use of capacitors and simple circuits to teach basic concepts of electricity. For this material, modifications included (a) correcting typo's and other errors, (b) adding video assignments and instructions for their use, (c) rewording some instructions for clarification, and (d) adding some commentary explaining selected concepts.

Workshop Physics was originally developed as a curriculum for a multi-semester, calculus-level course. I chose to use part of the mechanics segment of this material in our PHYSICS 1 course. It was necessary to rewrite the lessons to make them suitable for an algebra-level course. Also, instructions regarding equipment and software were rewritten in order to accurately reflect the

equipment and software our students would be using. Several new lessons (Introduction to the Macintosh Computer, Uniform Circular Motion, Resonance and Standing Waves, Polarization, Diffraction and Interference, and Resonance States in Atoms) were written to supplement the Workshop Physics material. In addition, typo's and other errors in the original material were corrected, and video assignments were added, as was done with the CASTLE material.

Physics by Inquiry is curriculum material that also covers a range of physics topics. I chose to use just portions of the material covering the topics of light and optics. Since this material is copyrighted, I negotiated with Wiley Publishers to gain permission to modify and publish the material I wished to use. In this case modifications involved combining material published in two separate volumes, omitting redundant or otherwise unwanted sections, rearranging some sections to form combined lessons, correcting typo's in the original material, and adding video assignments.

CONCLUSIONS

Altogether, forty-two lessons have been prepared, each designed for a two-hour class period. Of those, five (as mentioned earlier) were not adapted from the available curriculum materials listed above but were developed for our course. All lessons were formatted to have generally the same appearance and structure. The lessons were grouped into three modules, Electricity Visualized, Mechanics, and Light and Optics. These modules are being printed on campus and sold to students through the Sac Book Rac. Homework assignments for each lesson were also prepared.

Four sections of the modified course will be offered in the Fall semester. Over the next two years each of the full-time physics teachers in the Physics and Engineering Department will be given opportunity to teach the new course. After each department member has had a chance to use this method and we, as a department, have had the opportunity to evaluate its effectiveness, it is possible that this approach may be extended to other courses in the department.

The overall goal of the sabbatical project has been to develop an introductory, general education, physics course in which students will more successfully learn, retain, and apply physics concepts.

APPENDIX

Video Segments Included in the CASTLE module:

The Mechanical Universe

Program 28 "Static Electricity", frame numbers 20526-28600 (Electrostatics)

Program 29 "The Electric Field", frame numbers 19242-231890, 24430-27540
(Electric Force Fields)

Program 31 "Voltage, Energy, Force", frame numbers 22006-22500 (Electric
Potential)

Program 32 "The Electric Battery", frame numbers 26381-29000, 30671-35907
(Work Functions)

Program 33 "Electric Circuits", frame numbers 22804-25800 (Physical Properties
of a Resistor)

Program 33 "Electric Circuits", frame numbers 11783-13200 (Ohm's Law)

Program 33 "Electric Circuits", frame numbers 34158-39800 (Power, Kirchoff's
Laws)

Physics: Cinema Classics

Disc 2, Side D, Chapter 51 (Simple Electric Cells)

Disc 2, Side D, Chapter 41 (Electrostatics)

Saunders Physics Videodisc

Disc 2, Side 1, frame numbers 31228-32738 (Capacitors)

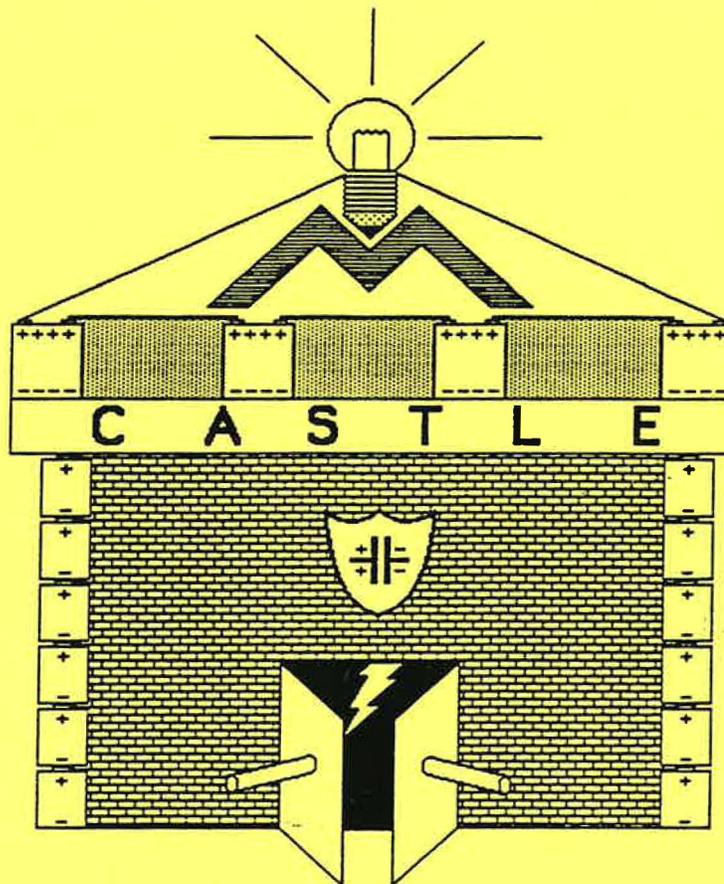
Disc 2, Side 1, frame numbers 23580-24050 (Coulomb's Law)

Principles of Physics

Side 2, Chapter 57 (Mapping Electric Fields)

ELECTRICITY VISUALIZED

The CASTLE Project



CAPACITOR-AIDED SYSTEM
for
TEACHING and LEARNING
ELECTRICITY

STUDENT MANUAL

The CASTLE Project

Project Director:

Melvin S. Steinberg, Department of Physics, Smith College

Authors:

Delphia N. Bryant, Frederick Douglass High School, Atlanta, Georgia
Sheila M. Cronin, Avon High School, Avon, Connecticut
Michael L. Cunha, Weaver High School, Hartford, Connecticut
Joseph Drenchko, Cicero-North Syracuse High School, Cicero, New York
Gene L. Ewald, Cuyahoga Falls High School, Cuyahoga Falls, Ohio
Richard B. Feren, Milford High School, Milford, New Hampshire
John D. FitzGibbons, Cazenovia High School, Cazenovia, New York
Mickey Maholtz, Curwensville Area Schools, Curwensville, Pennsylvania
Robert A. Morse, St. Albans School, Washington, D.C.
Marvin L. Nelson, Green River Community College, Auburn, Washington
Fred B. Otto, Maine Maritime Academy, Castine, Maine
Melvin S. Steinberg, Smith College, Northampton, Massachusetts
Louis C. Turner, Western Reserve Academy, Hudson, Ohio
Camille L. Wainwright, Pacific University, Forest Grove, Oregon

Editor:

Camille L. Wainwright, Director of the School of Education, Pacific University

This publication is a product of the CASTLE Project, which has been supported by the National Science Foundation under grant number MDR-9050189 and the US Department of Education National Diffusion Network (grant number RO73A 40037). Any opinions, findings, conclusions, or recommendations expressed in it are those of the authors and do not necessarily reflect the views of the grantees or the Publisher.

NOTICE:

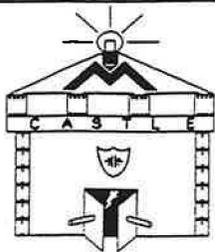
Teachers are expressly granted permission to copy the Student Manual for instructional purposes.

Copyright 1990, 1992, 1993, 1994, 1995 by Melvin S. Steinberg

TABLE OF CONTENTS

page

1	Section 1.	What Is Happening In The Wires?
12	Section 2.	Where Does The Moving Charge Originate?
26	Section 3.	What Do The Light Bulbs Do?
41	Section 4.	What Makes The Charge Move?
55	Section 5.	How Is The Pressure In A Wire Determined?
73	Section 6.	How Are The Values Of Circuit Variables Measured?
87	Section 7.	Which Variables Determine Energy Transfer?
101	Section 8.	What Causes Pressure In Distant Conductors?
119	Section 9.	How Is Charge Related to Electrons And Atoms?



Section 1

WHAT IS HAPPENING IN THE WIRES?

INTRODUCTION

Electricity is usually invisible. Except for lightning and sparks, you never see it in daily life. However, light bulbs and a magnetic compass can show you when something electrical is happening. By observing their behavior and making a few assumptions, you can begin forming ideas about what is happening. This type of thinking is called “building a model”.

INVESTIGATION ONE: WHAT IS NEEDED TO LIGHT A BULB?

1.1 Activity: Lighting bulbs in a loop

Insert three D-cells into the battery holder (Figure 1.1), and screw two **ROUND** bulbs (not long bulbs) into a pair of sockets. Use three wires to connect the sockets to each other and to the “terminals” of the battery holder — the spring and the metal screw post. The bulbs should light and be of equal brightness. The battery, bulbs and wires now form a “closed loop”.

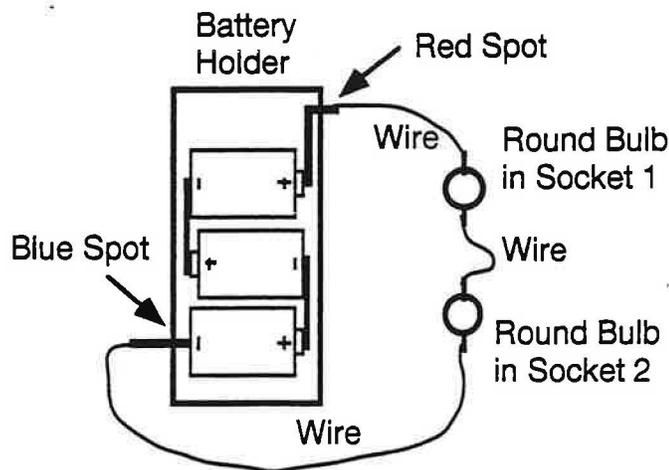


Figure 1.1
BASIC CLOSED LOOP

1. When do the bulbs light? Do you see both bulbs light at exactly the same time? Do you believe that both bulbs actually light at the same time?

“Break” the loop by disconnecting a wire from one end of the battery holder.

INVESTIGATION TWO: TESTING CONDUCTORS AND INSULATORS**1.3 Activity: Identifying conductors and insulators**

Use the same loop as before (Figure 1.1), but with an additional wire (Figure 1.3).

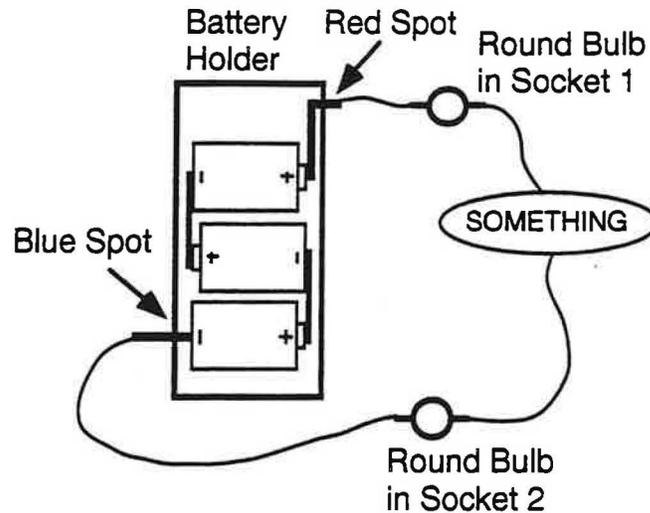


Figure 1.3
CIRCUIT FOR TESTING CONDUCTORS

This circuit in Figure 1.3 is referred to as the 'testing circuit'. The "something" may be anything you like — for example a key, a rubber band, or a comb.

IMPORTANT:

- Any material in the "something" test location that permits the bulbs to light is called a **CONDUCTOR**.
- Any material in the "something" test location that prevents the bulbs from lighting is called an **INSULATOR**.

Select several ordinary objects, and predict whether each will turn out to be a conductor or an insulator when you test it. Record your predictions in Table 1.3 on the next page.

Next assemble the loop in Figure 1.3 to check your predictions. Insert each object into the "something" spot and observe whether or not the bulbs light. Record your observations in Table 1.3, and classify each object as actually a conductor or insulator.



1. Refer to the diagram (Figure 1.4) on page 4. Test each pair of socket parts to determine if they act as a single continuous conductor. For example: if you connect one wire to each of the two clips, will the bulbs light? If they do, then the two clips act as though they were a single conductor. Record your observations in Table 1.4 and indicate whether or not each pair of conductor parts form a continuous conductor.

TABLE 1.4

Test Objects	Observations (Bulbs Light or Don't Light)	Continuous Conductor (Yes or No)
Clip-to-Other Clip		
Clip-to-Adjacent Plate		
Clip-to-Opposite Plate		
Plate-to-Opposite Plate		
Plate-to-Base		
Clip-to-Base		

1.5 Activity: Bulb testing — conducting path

Parts that behave like a single conductor are said to form a "continuous conducting path".

1. Look at the bulb in Figure 1.5a, and predict whether each of the accessible parts is a conductor or an insulator. Write your predictions in Table 1.5.

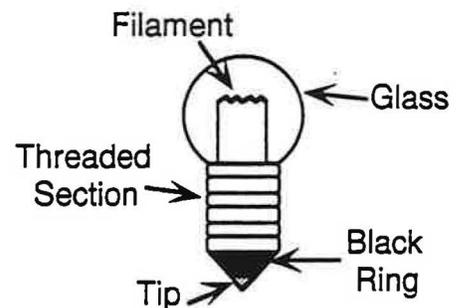


Figure 1.5a
Diagram of Light Bulb

2. Test your predictions and record your results in Table 1.5.

TABLE 1.5

Test Object	Prediction (Insulator/Conductor)	Observations (Lit or Not Lit)	Actual Classification (Insulator/Conductor)
Glass			
Threaded Section			
Black Ring			
Tip			

INVESTIGATION THREE: IS ANYTHING HAPPENING IN THE WIRES?**1.7 Activity: Using the compass to investigate**

Read and follow these instructions very carefully:

The magnetic compass in your kit can indicate electrical activity in the wires during bulb lighting.

- (1) Place the compass on the table top, as far away as possible from any metal parts. Stretch the circuit out as far as possible.
- (2) Tape the compass to the table — masking tape works best. Note that the compass is not part of the circuit, and is not connected to any wire. It is a detector for what is happening in the wires.
- (3) Disconnect the loop somewhere. Place one of the wires attached to the battery on top of the compass (Figure 1.7a), and align this wire parallel to the needle of the compass.

Keep the battery as far from the compass as you can, because D-cell casings may become magnetized and that will influence the compass.

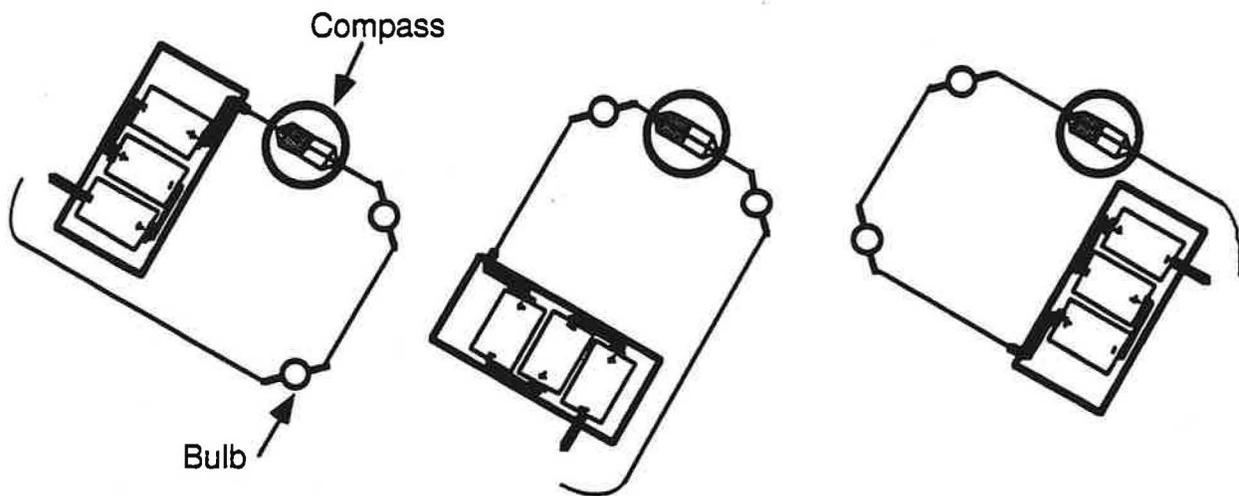


Figure 1.7a

Figure 1.7b

Figure 1.7c

COMPASS TAPED IN PLACE WHILE CIRCUIT IS ROTATED

Assemble the loop in Figure 1.7a. Connect and disconnect the loop several times while you watch the compass needle. It's a good idea for one person to hold the wire on top of the compass while another connects and disconnects the loop.

1. Does the compass needle deflect clockwise or counterclockwise? What happens to the compass needle when the battery is disconnected?

2. Is there any evidence that something happens in the wire on top of the compass when the loop is closed? Does the same thing happen when the loop is broken? What is the evidence, for or against?

1.9 Commentary: Which way is something moving?

The reversal of compass needle deflection when the battery orientation is reversed indicates a **change** in the direction of motion in the loop, but provides no information about which direction exists before the change. In the absence of any evidence, it's useful to **assume a direction** for the motion. Such an assumption is "conventional" — that is, simply an "agreement" which is neither right nor wrong but is **useful** because it is necessary for communication. The international convention is that the substance circulating around a circuit **leaves** the battery at the "positive" end (red spot) and **enters** at the "negative" end (blue spot).

1.10 Activity: Movement in the wires

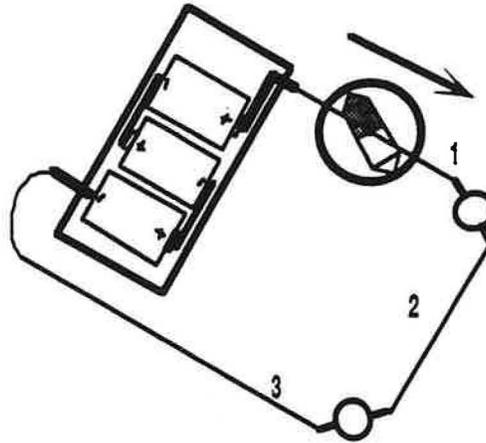


Figure 1.10
COMPASS DEFLECTION AND DIRECTION OF MOTION

1. Figure 1.10 shows the same circuit as in Activity 1.7, but an arrow has been added to show the assumed direction of motion through wire #1. Draw arrows next to wire #2 and wire #3 to show the direction of motion in these wires. Is the direction of motion in this circuit clockwise or counterclockwise?

2. If the battery leads were reversed, what would happen to the direction of motion in the wires? In what direction would the arrows be drawn?

1.11 Commentary: What's moving?

No one can see what moves through the wires, but something about the moving substance causes a compass needle to deflect. The property that enables the substance to do this is called **CHARGE**, from a Latin word that means "vehicle". Particles that carry charge from one place to another are called "charge carriers". The experiments you've done provide evidence that **CHARGE** is carried through wires, but they provide no evidence at all about the charge carriers.

7. What is your evidence that something happens in the wires when the bulbs are lit?
8. What assumption have you made about what is happening in the wires when the bulbs are lit?
9. What do you think happens in the wires when the battery connections are reversed? What is your evidence?
10. Speculate: What do you think the battery is doing when the bulbs are lit?
11. Assuming that something flows through wires when bulbs are lit in a circuit, is the direction of the flow the same in all the wires, or does it vary in different parts of the circuit? What is the evidence for your answer?

Besides the symbol for the battery, other symbols will be used for drawing schematic diagrams. (Figure 2.1d)

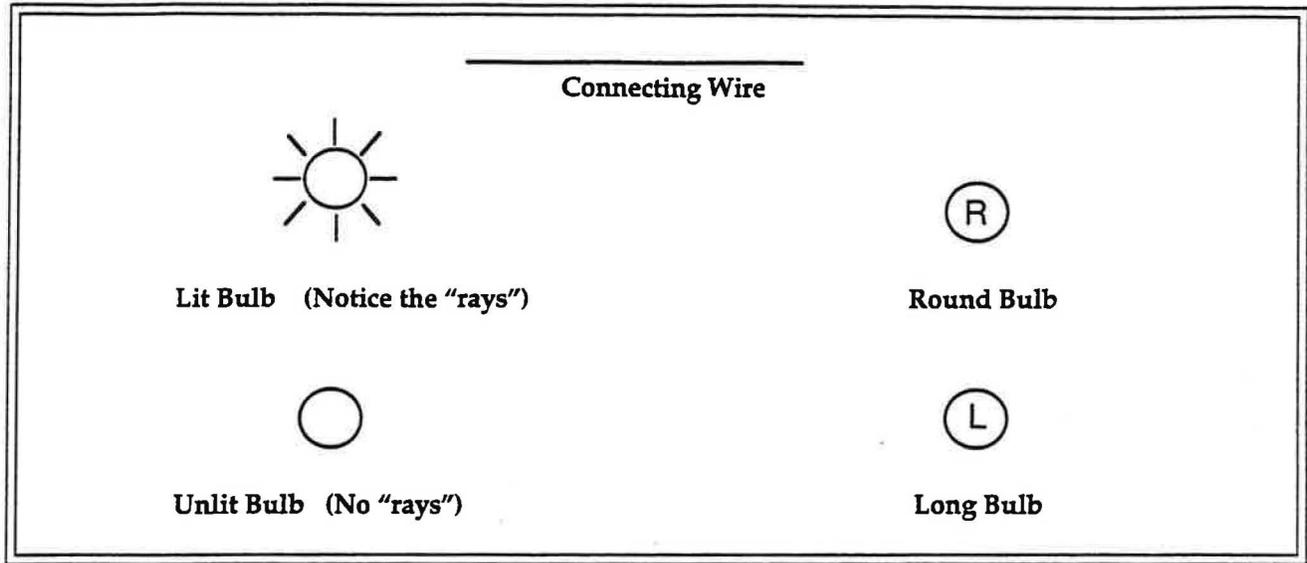


Figure 2.1d
SYMBOLS FOR WIRES AND BULBS

2.2 Commentary: Arrows representing charge flow

Charge could be moving either clockwise or counterclockwise in a simple circuit with lit bulbs, and the compass does not tell you which is actually occurring. The direction of needle deflection will reverse if the direction of flow reverses; while the compass needle can indicate the reversal, it cannot indicate the actual or absolute direction.

In Section 1, we discussed the best way to avoid confusion about the flow direction – to assume that charge travels in one of the two possible directions. The scientific and engineering professions have agreed on a choice, which they call the direction of “conventional flow”. The word “conventional” means by agreement. The agreement is that the direction of conventional flow in a circuit with a single battery is out of the “+” terminal of the battery and into the “-” terminal. This direction is illustrated by arrows in Figures 2.2a and 2.2b. The arrows in the schematic diagrams below are drawn as a continuous (unbroken) line to represent continuous flow through the bulbs and wires.

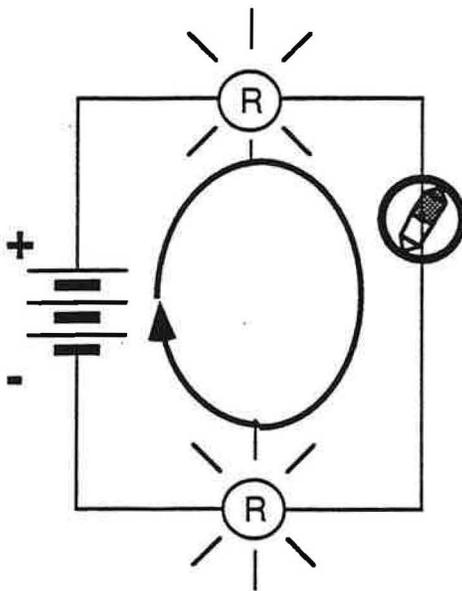


Figure 2.2a - Standard Battery Orientation

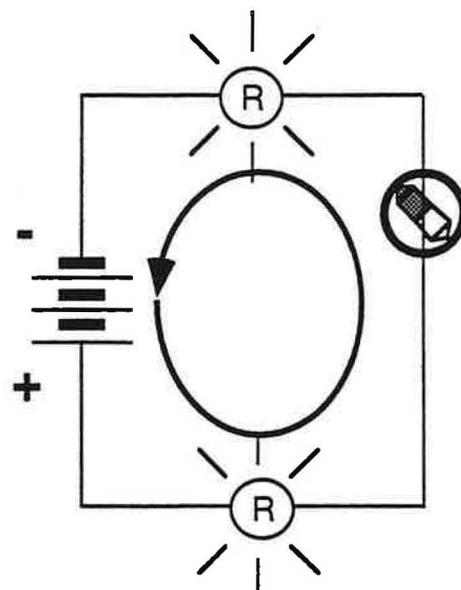


Figure 2.2b - Reversed Battery Orientation

ILLUSTRATIONS OF CONVENTIONAL FLOW DIRECTION

2.4 Commentary: What is a capacitor?

Two layers of conducting material separated by a layer of insulator form what is called a **CAPACITOR**. The name comes from the "capacity" of this three-layer device to store charge. The conducting layers are called capacitor **PLATES**. The insulating layer prevents movement of charge from one plate to the other inside the capacitor. You can make a capacitor by placing a sheet of waxed paper between two sheets of aluminum foil.

In most capacitors the plates have very large surface area, so that they can store a large amount of charge. The plates are also made very thin, so that the three layers can be rolled into a cylinder and placed inside a small can. Each plate has a screw or a wire attached to it, called a **TERMINAL**, which extends outside the can and allows the plate to be connected to a circuit.

The "charge-holding" ability of a capacitor is called its **CAPACITANCE**. Capacitance is measured in a unit called the **FARAD**, named after the British scientist Michael Faraday. The blue capacitor in your CASTLE kit has a capacitance of 0.025 farad (25,000 μf).

For a small number of activities you will also be provided with additional capacitors, one with a capacitance of 1.0 farad and one with a capacitance of 0.1 farad (100,000 μf).

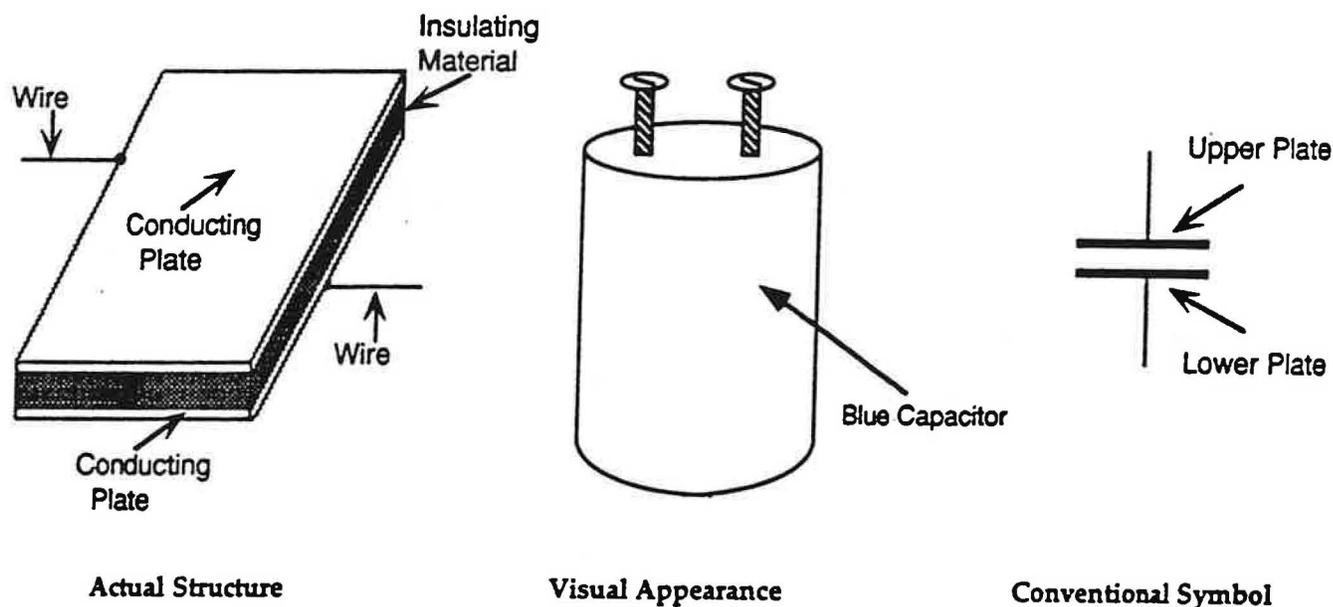


Figure 2.4
CAPACITOR DIAGRAMS

Repeat the capacitor charging and discharging processes a few times, to be sure of your observations.

Remove the blue capacitor from the circuit, and replace it with the large silver capacitor (0.1 f). Charge and discharge the large silver capacitor several times, observing the bulbs and compass needle.

5. Are the bulbs lit longer using the blue capacitor or the large silver capacitor?

Speculate: Why do you think this happens?

6. During the charging and discharging of the large silver capacitor, does the compass deflection stop when the bulbs go out?

Speculate: Why do you think this happens?



7. Which capacitor permitted more charge to flow? What is the evidence?

8. Does the charge that flows into the capacitor during charging go all the way through the capacitor and back to the battery, or does it get stored somewhere in the capacitor? How do you know?

9. How does the process of discharging provide evidence that charge was stored in the "upper plate" of the capacitor during the charging process? (Note: "Upper plate" refers only to the orientation in the circuit diagram. It actually means the plate which is attached to the (+) terminal of the battery in this circuit.)

10. Discuss your conclusions with your teacher.

5. Is the same thing happening in every wire in the discharging circuit? What is the evidence?
6. Where do you think the charge comes from that lights the top bulb during capacitor charging?
7. Where do you think the charge comes from that lights the bottom bulb during capacitor charging?
8. Where do you think the charge comes from that lights the bulbs during discharging?
9. To help you check your answers to the last three questions, look at Figures 2.6a and 2.6b—and decide where you think the very first charge that moves past each labeled point came from. Write your answers in Table 2.6b.

TABLE 2.6b

	<u>Source of Charge During CHARGING</u>	<u>Source of Charge During DISCHARGING</u>
Point A		
Point B		
Point C		
Point D		
Point E		

10. Consider this statement regarding these circuits: If charge is moving in one part of the circuit, then charge is moving everywhere in the circuit.

True or False? _____

Are the wires ever empty of charge? _____

11. Discuss your conclusions with your teacher.

6. How does the speed of cranking required to produce 2-cell brightness compare to that needed for 1-cell brightness?

7. Estimate the number of crank turns needed in ten seconds to match the bulb brightness that would be produced by three D-cells. Try it—was your prediction correct?

2.8 Exercise: The Genecon

1. When using a Genecon, where does the charge originate that moves through the bulbs?

Where does the "energy" come from that's needed to turn the Genecon crank and make charge move?

2. How are a Genecon and a battery similar when they are connected to a circuit? How are they different? (Use the terms "charge" and "energy" in your comparison.)

3. A hair dryer is a pump for air. Do a battery and a Genecon act like pumps for charge? Explain.

4. How is increasing the number of D-cells in a battery holder similar to cranking a Genecon faster?

5. Discuss your conclusions with your teacher.

2.9 Activity: Charging an air capacitor

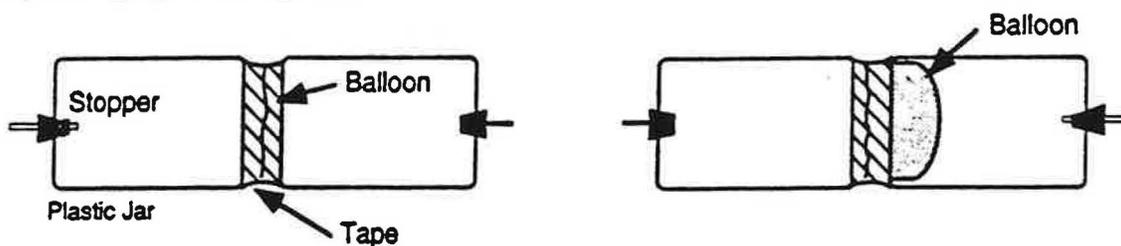


Figure 2.9a
NORMAL AIR CAPACITOR

Figure 2.9b
"CHARGED" AIR CAPACITOR

1. Blow through the tube at one end. What happens to the balloon in the middle?

2. Repeat, except this time hold your hand near the open tube as you blow in the other end. Does any air go in or come out? If air comes out, where did the air coming out originate?

3. A friend argues that the air capacitor is not really like the electric capacitor because movement of the balloon is what drives air out during charging. The friend points that there is nothing moving in the electric capacitor which could drive charge out during charging. How could you counter this argument?

4. Discuss your arguments with your teacher.

2.11 Commentary: Benjamin Franklin's "+" and "-" notation

Movable charge is normally present in all conducting matter. Adding some charge to a normal capacitor plate will result in there being more than the normal amount of charge in the plate, while removing some charge will result in there being less than the normal amount of charge in the plate. Benjamin Franklin came to the same conclusions when he did his pioneering work in electricity a few years before the American Revolution. Franklin is the person who first used (+) and (-) symbols in electricity. He used them to represent these two conditions:

(+) represents a **MORE-THAN-NORMAL** amount of charge ("extra" charge)

(-) represents a **LESS-THAN-NORMAL** amount of charge ("missing" charge)

In the next section we shall begin using these symbols with the same meanings Franklin gave them.

7. How would Benjamin Franklin have described the condition of the plates in a charged capacitor compared with the plates in an uncharged capacitor?

8. From the experiments you have done and the assumptions we have made, you now have an idea or model of the behavior of electricity. List the findings and assumptions that make up this model.

3.2 Activity: Switching bulbs

1. Charge a blue capacitor through two long bulbs (Figure 3.2a). Disconnect the battery, leaving a gap in the circuit (Figure 3.2b). Be very careful that the ends of the wires don't touch each other or anything else that might discharge the capacitor prematurely!

Remove the pair of long bulbs — leaving them in their sockets — and replace them with a pair of round bulbs in different sockets. Then reconnect the circuit (Figure 3.2c).

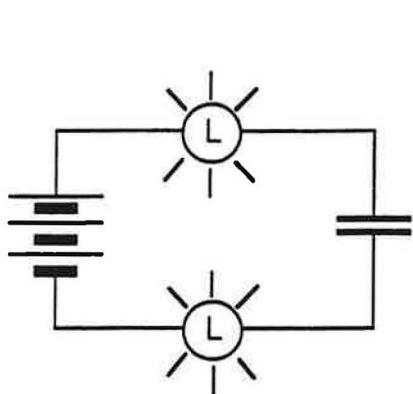


Figure 3.2a
CHARGE THROUGH LONGS

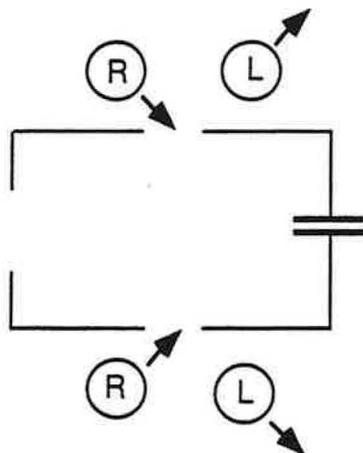


Figure 3.2b
REMOVE BATTERY
AND SWITCH BULBS

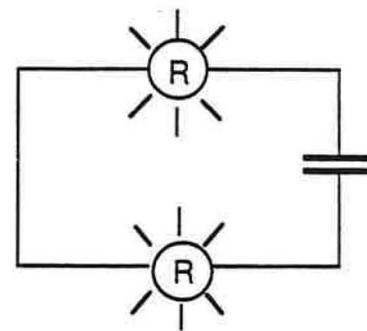


Figure 3.2c
DISCHARGE THROUGH ROUNDS

2. What do you observe during discharging? Do the round bulbs look like they did in the previous activity, or are they brighter, or are they dimmer?

3. Since long bulbs stay lit longer, suppose they let more charge through. How would the round bulbs look during discharging if the long bulbs had allowed more charge to reach the upper capacitor plate than round bulbs allow during charging?

How would the round bulbs look during discharging if long bulbs allow less charge to reach the upper capacitor plate than round bulbs do (because long bulbs are generally dimmer) ?

4. Do you think that long bulbs allow the same amount of charge to reach the upper capacitor plate as round bulbs do? Explain your reasoning.

5. Do you think that round bulbs and long bulbs allow charge to flow through them at the same rate? Explain your reasoning.

3. Now use the battery to charge the capacitor through two **long** bulbs. Then remove the capacitor from the circuit and carefully discharge it through the Genecon, counting the number of turns the crank makes. How many times does the crank go around during capacitor discharging—after the capacitor was charged through long bulbs?

Do your observations support the idea that both types of bulbs allow the same amount of charge to pass through? OR do they support the idea that both types allow charge to pass through at the same rate?

4. Discuss your answers with your teacher.

3.4 Commentary: Resistance and flow rate

The ability of a bulb filament to hinder the flow of charge through itself is called **RESISTANCE**. Any circuit component that hinders the flow of charge is called a **RESISTOR**. All light bulbs are resistors, but there are other kinds of resistors—usually made of carbon—that don't give off light. A resistor that allows charge to move through easily has low resistance, and one that hinders the flow of charge more strongly has high resistance. Resistance is measured in terms of a unit called the **OHM**—named after the German physicist Georg Ohm.

A resistor hindering the flow of charge can be compared to a coffee filter hindering the flow of coffee water. Coffee filters that make it very difficult for water to move through result in a low flow rate, while filters that allow water to move through more easily result in a high flow rate. In the same way, light bulbs with a great deal of resistance only allow charge to pass through at a low flow rate, while bulbs with less resistance permit charge to pass through at a high flow rate.

Long bulbs have more resistance than round bulbs. How do we know? Because the longer lighting time tells us that there is a lower flow rate of charge moving through the long bulbs.

Flow rate is measured in terms of a unit called the **AMPERE**—named after the French physicist Andre Ampere. Flow rate is not the same thing as speed or velocity. Knowledge of the flow rate tells you how much charge passes a point on a wire during each second, but provides no information at all about the speed of each bit of moving charge.

3.5 Commentary: The word "current"

Flow rate is called **CURRENT** in the professional literature. However, the English language creates some problems with this word. If you are in a boat or swimming in a river, it is natural to use the word "current" to mean the speed of the water. "Current" comes from a Latin word that means "run", so it's not a bad everyday word for the speed of moving water. But you need to remember that "current" does not mean "speed of movement" when used in electricity. When people use the term "current" in electricity, they mean "rate of flow".

There is also a problem with the word "rate". When a math book states "rate X time = distance", it intends "rate" to mean speed of movement. But speed is only one type of rate. There are many other things that are rates too. For example: When a supermarket sign says "Bananas 55 cents per pound", it means "price"—and price is a rate that has nothing to do with speed. Price is the rate of money charged based on weight, while speed is the rate of distance traveled based on time. The rate used in electricity—called "current"—is the rate of charge passing through based on time, or amount of charge/second.

Since "current" is so often confused with speed, this manual will continue to use the more natural term "flow rate" instead of "current".

Disconnect the battery from the circuit, and discharge the capacitor (Figure 3.7b)—again making very careful observations of brightness and lighting time.

1. Are the bulbs brighter during charging or discharging? _____ (If you don't observe any difference in brightness, ask your teacher for a substitute battery for this experiment.)

Based on bulb brightness, when does the circuit have more resistance?

2. Is the lighting time shorter during charging or discharging?

Speculate: How do you think lighting time is related to flow rate, and why?

3. Does the battery act as if it has resistance inside? How do you know?

4. Speculate: Does charge just flow out at one end of the battery and in at the other end—or does it also flow all the way through the battery?

5. If you notice that the bulb in a flashlight has become dimmer than when it was new, what has happened to the flow rate of charge through its filament? What has happened to the resistance of the circuit in the flashlight? Does this necessarily mean that the resistance of the bulb filament has changed?

6. Discuss your conclusions with your teacher.

3.8 Activity: Flow rate in branches

Set up the circuit in Figure 3.8a. Observe the brightness of the bulbs and the compass deflection under each of the four wires.

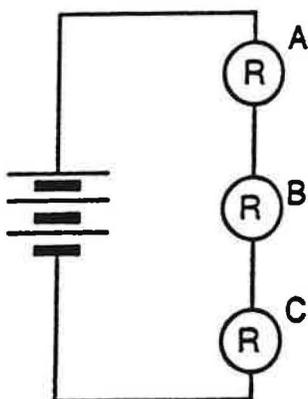


Figure 3.8a
NO BRANCHES

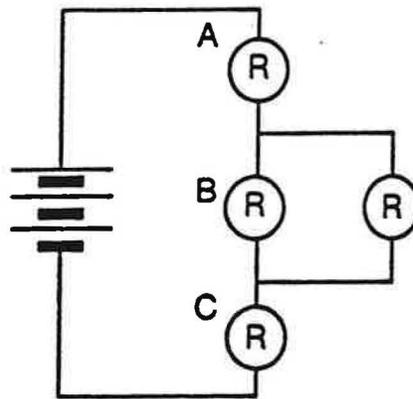


Figure 3.8b
BRANCH ADDED

1. Are all three bulbs equally bright? What does this tell you about the flow rate through each bulb?

INVESTIGATION THREE: HOW DO BULB COMBINATIONS AFFECT RESISTANCE?**3.9 Activity: Series and parallel circuits**

From now until the end of this investigation, connect each circuit as briefly as possible to avoid burning out the bulbs. We suggest wiring the entire circuit except for one connection — and then “tapping” the circuit closed as briefly as you can. “Tapping” means just barely touching an alligator clip against one of the socket clips — rather than attaching the alligator clip to the socket. If none of the bulbs light very brightly, then you may safely make the last connection and allow the circuit to stay lit.

Set up the circuits in Figures 3.9a and 3.9b. For each circuit observe the bulb brightness.

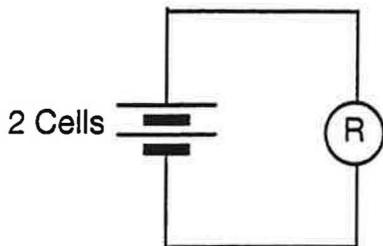


Figure 3.9a
SINGLE BULB

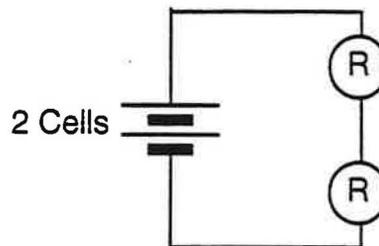


Figure 3.9b
BULB ADDED IN SERIES

1. Which circuit contains the brightest bulb(s)? What does this tell you about the flow rate?

Based on flow rate, which circuit has the greater resistance?

Set up the circuits in Figures 3.9c and 3.9d. Observe compass deflections under all the “upper” wires.

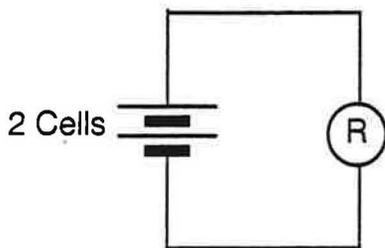


Figure 3.9c
SINGLE BULB

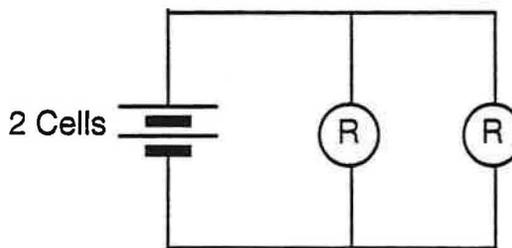


Figure 3.9d
BULB ADDED IN PARALLEL

2. Which circuit shows greater compass deflection for the wire connected to the battery? What does this tell you about flow rate?

3. Which circuit has the smaller overall resistance?

Now, tape a soda straw and a coffee-stirrer straw together side-by-side (Figure 3.10b). Blow through them, and notice how hard you have to blow and how readily air moves through.

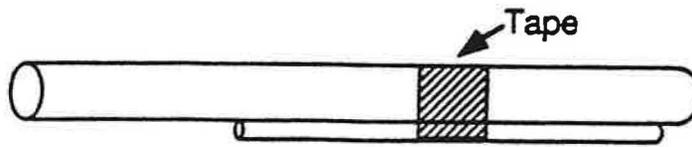


Figure 3.10b
SODA AND COFFEE STRAWS SIDE-BY-SIDE

6. Is the resistance to air flow more like it would be with a soda straw alone—or more like with a coffee stirrer alone? Is the flow rate of air more like it would be with a soda straw alone—or with a coffee stirrer alone?

Does air flow more easily through the soda straw or through the coffee stirrer?

7. At right, draw a circuit diagram containing a long bulb and a round bulb that is like the side-by-side straw. Is this a series circuit or a parallel circuit? Will charge flow at the same rate through all parts of the circuit?

3.11a Commentary: Resistors in series and in parallel

When resistors are placed one after another along a single path, they are said to be arranged "in series". A series is a group of events that follow one after another—like detective novels, movies, or baseball games. In a series circuit, moving charge flows sequentially through each and every component—and it flows at the same rate in every part of the circuit it passes through.

When a circuit contains "forks" leading to more than one "branch", the components located on the branches are said to be arranged "in parallel". The word "parallel" refers to the side-by-side appearance that these branches usually have on a circuit diagram. Only a part of the charge travels through each branch, and there may be different flow rates for the charge moving through different branches.

3:11b Video: Resistors in series and in parallel

Go to the video-disc set-up and watch the following segment:

The Mechanical Universe, Program 33 "Electric Circuits", frame numbers 22804-25800.

According to this segment, what physical properties of a resistor determine its resistance?

In terms of these physical properties, why does the resistance increase when resistors are combined in series?

In terms of these physical properties, why does the resistance decrease when resistors are combined in parallel?

Does the water pipe analogy seem reasonable to you? Why or why not?

5. **Predict:** If you start removing long bulbs one at a time from the circuit in Figure 3.12b, will the parallel combination of long bulbs become a more difficult, or a less difficult, place for charge to move through? Will the overall resistance of the circuit increase or decrease? Will the flow rate through and from the battery increase or decrease? Will the upper round bulb get brighter or dimmer?

PREDICTIONS:

Try it. What do you observe?



3.13 Activity: Air resistance in straws — Analogy II

In the previous activity you saw that five long bulbs in parallel behave like one round bulb. Sometimes it isn't easy to imagine how charge flows through wires, but it's always easy to blow air through straws.

Take a standard soda straw and cut it to the same length as a coffee-stirrer straw. Blow through each straw. Notice how much effort is required to move the air through the straw, and how readily the air flows through.

1. Which straw is easier to blow through?

Which straw has the greater flow rate of air passing through it?

Which straw has the greater resistance to the flow of air?

2. Which straw is comparable to a round bulb? Which straw is comparable to a long bulb?

Round Bulb:

Long Bulb:

Take five coffee-stirrers and tape them together to form one "bunched" straw (Figure 3.13a). Blow through the "bunched" coffee stirrers and then blow through the single soda straw.

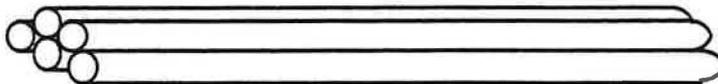


Figure 3.13a
"BUNCHED" STRAW OF COFFEE STIRRERS

3. How does the difficulty of moving air through the single straw and the bunched stirrers compare?

Which of these straws can be compared to the parallel combination of long bulbs in the last activity?

4. Remove one or two coffee stirrers from the "bunched" straw and blow through the remaining ones. Has it become more difficult or less difficult to blow air through the "bunched" straw?

Compare this to how the resistance of the parallel combination of bulbs changed in the last activity when some of the branches were removed.

SUMMARY EXERCISE

1. Does a light bulb filament control the amount of charge that passes through it or the rate at which charge flows? What is your evidence?

2. Does the amount of charge stored in a charged capacitor depend on the type of bulbs through which it was charged? What is your evidence?

3. What are the minimum components a circuit must contain in order to charge a capacitor?

4. Give an example to illustrate the difference between flow rate and speed.

5. What happens to the flow rate of charge in a circuit as more bulbs are added in series? What is your evidence?

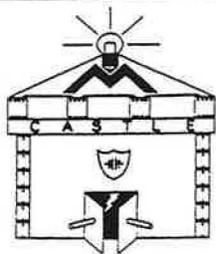
6. Does a battery have resistance? What is your evidence?

7. Suppose that a charged capacitor were discharged through each of the following combinations of bulbs:
 - (a) a single long bulb,
 - (b) two long bulbs in series,
 - (c) two long bulbs in parallel.

Without doing the experiment, predict in which case the bulbs would be lit for —
the longest time:

the shortest time:

Explain your reasoning.



Section 4

WHAT MAKES THE CHARGE MOVE?

INTRODUCTION

Why does the process of capacitor charging stop? How can discharging occur at all, since there is no battery in the circuit to make it happen?

INVESTIGATION ONE: WHY DOES CAPACITOR CHARGING STOP?

4.1 Activity: Can you fill or empty a capacitor plate?

Charge a blue capacitor through two long bulbs, using a 3-cell battery as shown in Figure 4.1a. Notice the brightness of the bulbs and the length of time they stay lit.

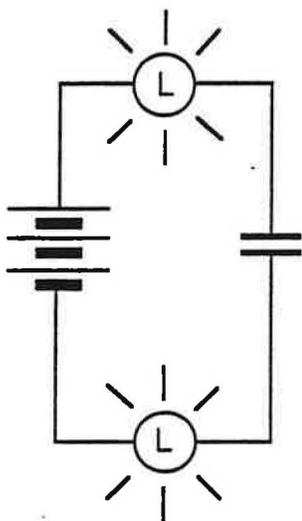


Figure 4.1a
CHARGING

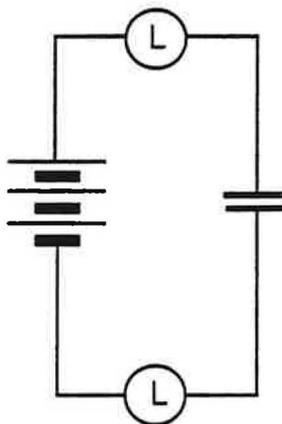


Figure 4.1b
CHARGING COMPLETED

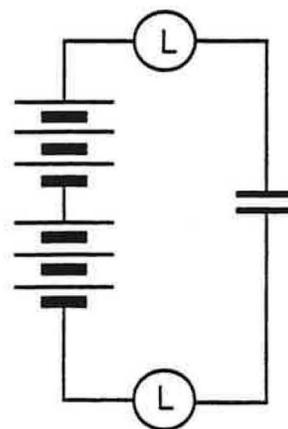


Figure 4.1c
ADDED BATTERY

Draw arrows by the wires on Figure 4.1a to show where charge moved while the bulbs were lit.

Figure 4.1b shows the capacitor already charged. Draw (+) signs by the plate that now contains extra charge and draw (-) signs by the plate that has lost some charge.

Next, imagine that you have opened the circuit in Figure 4.1b near the battery, and added three more cells by inserted a second battery pack. Don't actually do this right now. Just think about the charged capacitor suddenly finding itself in a circuit with a stronger battery.

10. What do you think the second battery was doing during the second lighting?

11. Do you think the (+) capacitor plate is completely full after the second lighting? Do you think the (-) capacitor plate is empty?

12. If you repeat the first two lightings and then add a third battery, do you think the bulbs will light a third time? Why or why not?

13. Now your teacher will add a third battery pack to the circuit. What do you observe?

14. Speculate: Why do you think charging stopped after the first lighting? Why do you think it stopped after the second lighting?



4.2 Commentary: Is charge compressible?

You've seen that capacitor charging stops after a short time. How can that happen while there's a battery in the circuit which is "trying" to keep the process going? Here are two possibilities:

(1) Perhaps the (+) plate has become completely full, and is therefore unable to receive any more charge. In this case charge would be behaving like water: When a container is filled with water, no more can be poured into it because the water can't be compressed to make room for more. Perhaps charge, like water, is essentially not compressible.

There is also the possibility that all the charge in the (-) plate is removed during charging, so there isn't any more available for the battery to pump out and then into the (+) plate. That would also be behaving like water.

(2) Perhaps the extra charge that has been added to the (+) plate has increased the concentration of the charge in the plate, and the compressed charge "pushes back" toward the (+) battery terminal — making it more difficult for the battery to push more out toward the capacitor. Likewise, some charge has been removed from the (-) plate, decreasing its concentration in that plate and making it no longer able to push itself out toward the (-) battery terminal. In this case charge would be acting like air: More and more can be compressed into a container, and when some is removed the remaining charge expands to fill the container. Perhaps charge, like air, is compressible.

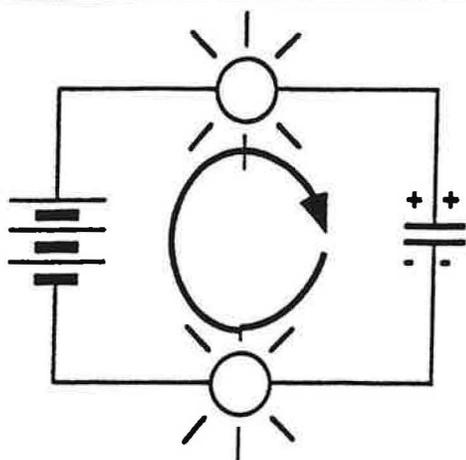


Figure 4.4a
CHARGING

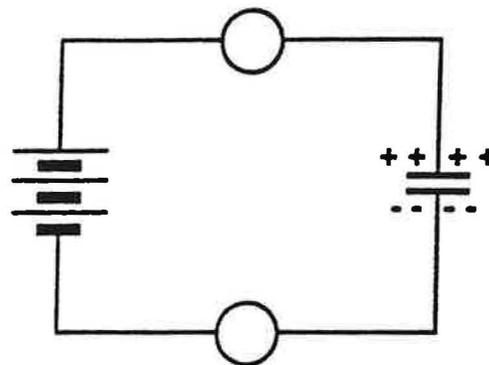


Figure 4.4b
CHARGING COMPLETED

Bulbs can hinder the movement of charge but can never stop it, so it's not the bulbs that stop capacitor charging. It's the pressures in the capacitor plates that eventually stop the charging process! To help understand why these pressures are important, let's take a look at what happens during the discharging process:

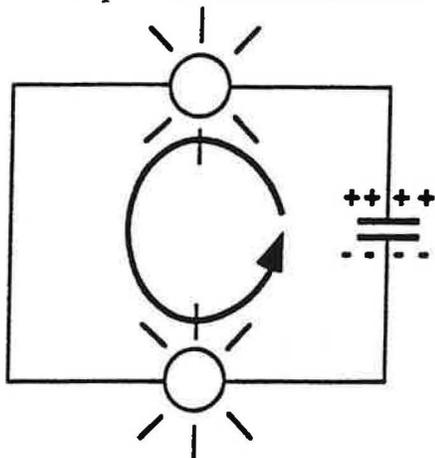


Figure 4.4c
DISCHARGING

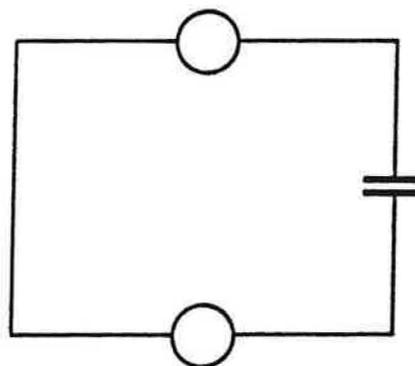


Figure 4.4d
DISCHARGING COMPLETED

The (+) and (-) capacitor plates remain at high and low pressure, respectively, after the battery is removed. When the free ends of the wires are connected, the pressure difference between the (+) plate (compressed charge) and the (-) plate (depleted charge) pushes charge out of the (+) plate and back into the (-) plate. Look at Figure 4.4c, and notice that charge is moving from a region of HIGH pressure to a region of LOW pressure. The discharging process is complete (Figure 4.4d) when the high pressure on the (+) plate has decreased to normal pressure and the low pressure on the (-) plate has increased to normal pressure—in other words, when the two pressures become equal.

Capacitor discharging stops when the charge stops moving, and charge stops moving when both ends of its path have the same electric pressure. In this example, both ends have normal pressure when the process is over, but the important thing is that both places have the same pressure—whether it's normal or not.

The pressures in the capacitor plates are not normal when the capacitor charging stops. The charging stops when the pressure in the (+) capacitor plate is as high as the pressure in the (+) battery terminal, and when the pressure in the (-) capacitor plate is as low as the pressure in the (-) battery terminal.

PRESSURE DIFFERENCE is what makes charge move, and when charge moves it always moves from a place of higher pressure to a place of lower pressure.

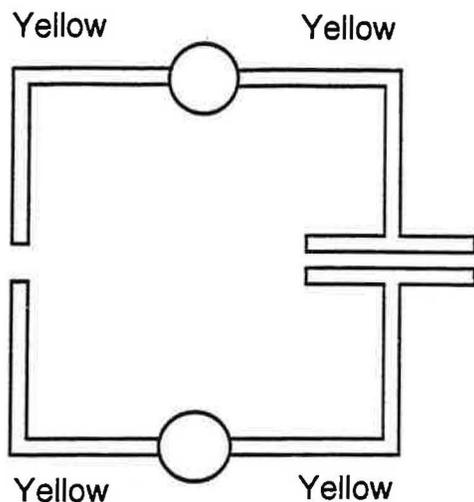


Figure 4.7a
NO BATTERY

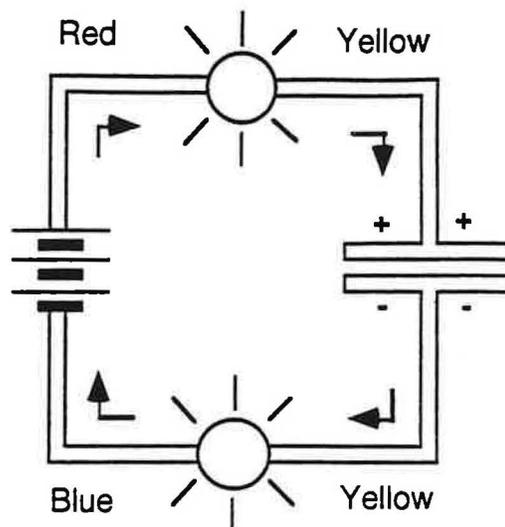


Figure 4.7b
CHARGING BEGINS

Figure 4.7a shows a circuit containing a capacitor and two light bulbs. The circuit is not closed, and it has no battery. The color yellow represents the electric pressure that normally exists everywhere in the circuit before the battery is connected. Bulbs are never colored because the filament of a bulb does not have the same pressure at all points.

In Figure 4.7b a battery has just been inserted into the circuit. The (+) terminal of the battery is a place that the pumping action of the battery keeps at HIGH electric pressure, and so it is colored red. The red-to-yellow pressure difference will instantly push enough extra charge into a resistanceless wire attached to the battery's (+) terminal to raise the pressure in that wire to the same high (red) value. Because the resistance of the bulb connected to the other end of this wire hinders the movement of charge, only a minute amount of charge will have moved through the upper bulb and into the top capacitor plate during this first brief time interval. Since an enormous amount of charge is needed to change the pressure of the upper capacitor plate, it and the wire attached to it are still at essentially normal pressure (yellow).

The (-) terminal of the battery is a place of LOW electric pressure and so it is colored blue. The yellow-to-blue pressure difference will instantly push enough charge out of the low resistance wire attached to the battery's (-) terminal to lower the pressure in that wire to the same low (blue) value. Because the resistance of the lower bulb hinders the movement of charge, only a minute amount of charge will have moved out of the bottom capacitor plate and through the lower bulb during this very short time interval. Since an enormous deficiency of charge is needed to change the pressure of the lower capacitor plate, it and the wire attached to it are still at essentially normal pressure (yellow).

The interior of the battery is never colored because, like a light bulb, it doesn't have the same pressure at all points.

RULES FOR COLOR-CODING:

1. The pumping of the battery forces a RED pressure above it (on the positive side) and a BLUE pressure below it as soon as it is connected.
2. A continuous wire, or connected wires, must be the same color throughout, since the near-zero resistance could not maintain any pressure difference.
3. A difference in pressure (color) on two sides of a conductor will cause charge to flow until the pressure are equalized.

4.8 Activity: Color coding for discharging a capacitor

Figures 4.8a,b,c, and d are circuit diagrams that show a sequence of events in the discharging of a capacitor. Arrows show the movement of charge, and the number of "+" and "-" symbols show the degree of compression or depletion of charge in the capacitor plates.

1. Think about which electric pressures are present in the capacitor plates and connecting wires. Use colored pencils or markers to color-code each plate and wire.

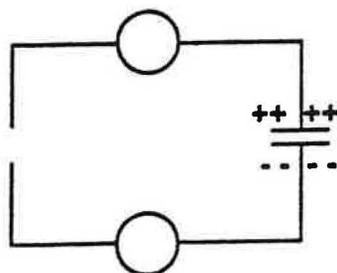


Figure 4.8a
BATTERY REMOVED

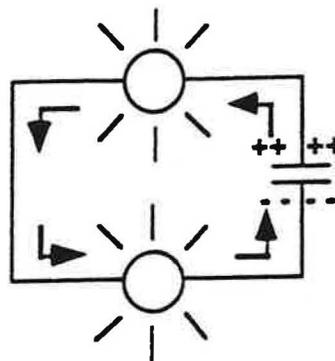


Figure 4.8b
DISCHARGING BEGINS

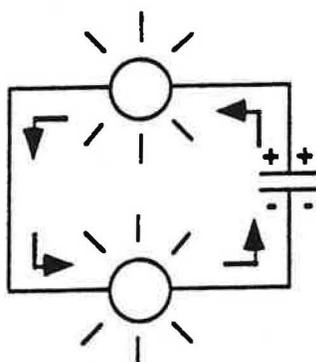


Figure 4.8c
DISCHARGING CONTINUES

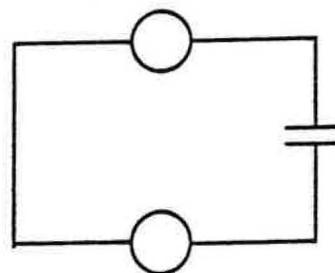


Figure 4.8d
DISCHARGING COMPLETED

2. Which figure has the greatest pressure difference across the bulbs?
3. In which figure is charge being driven through the bulbs at the greatest flow rate ?
4. In which figure do the bulbs become dim?
5. Discuss your observations with your teacher.

5. Consider the color coding you have learned. What color would you use to indicate the pressure on each side of the upper bulb in this circuit? What color would you use to indicate the pressure on each side of the lower bulb? How does this explain what you observed about bulb lighting?

6. Predict: What will you see if you disconnect the blue capacitor, reverse it, and reconnect it as shown in Figure 4.9d?

7. Do the reversal. What do you observe?

8. On the diagram below show the location of excess and deficiency of charge after the bulbs have gone out. How do the amounts of excess charge below compare with the amounts of excess charge in Figure 4.9c? How does the deficiency of charge compare?

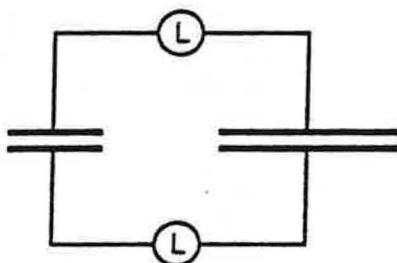


Figure 4.9d
LABEL EXCESS AND DEFICIENCY OF CHARGE

9. Reverse the blue capacitor again and reconnect it. How many times can you reverse the blue capacitor and still have the bulbs light?

10. Why do the bulbs light less brightly after each reversal?

11. In a circuit where the same battery is always used, what determines the pressure difference across any capacitor charged by this battery?

12. In a circuit where the same battery is always used, what determines the amount of charge that ends up on the plate of any capacitor charged by this battery?

13. In a circuit where the same battery is always used, what determines the time it takes to charge any capacitor charged by this battery?

14. Discuss your conclusions with your teacher.

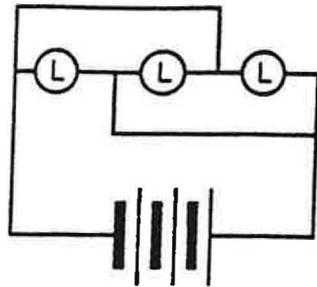


Figure 4.11c

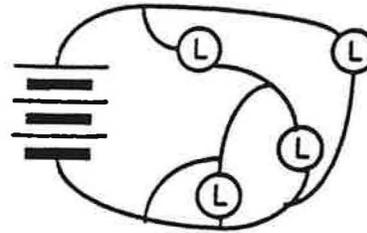


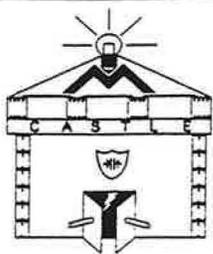
Figure 4.11d

Check with your teacher if you have any questions.

4.12 Commentary: Is the Compressed-Air Model really correct?

Yes and no. Yes, because charge really does compress and deplete in conductors, and this is ultimately responsible for the flow of charge. No, because compression and depletion actually take place on the surface of conductors, while the compression and depletion of air takes place throughout the volume of a container.

Why has so much time been spent on developing a model that isn't exactly "true"? First, because there is no common situation that can be compared to charge being compressed only on the surface of conductors—but compressed air inside a balloon is familiar to everyone. Second, because no model is ever perfect. Our air model is an analogy—it helps people create mental pictures that help them understand complex concepts. The analogy to compressed air provides a strong foundation on which to build. We will continue to improve the model as we acquire more information from additional experimental investigations.



Section 5

HOW IS THE "PRESSURE" IN A WIRE DETERMINED?

INVESTIGATION ONE: WHAT DOES A BATTERY DO?

A battery pushes charge through wires in much the same way that a pump pushes air through pipes. In this first investigation we shall inquire into some important details of that pushing process. Consider these questions before beginning the following activities. Does a battery maintain the same pressure difference across itself in all circumstances, regardless what is connected to it? Or does a battery pump the same flow rate through itself in all circumstances? Or do circuit components connected to a battery influence both the pressure difference across it and the flow rate through it?

5.1 Activity: Does a battery always maintain the same pressure difference?

In Section 4 we learned that the brightness of a light bulb provides information about the magnitude of the pressure difference that is driving flow through the bulb. High brightness indicates a large pressure difference across the bulb, and dimming indicates a reduced pressure difference, while unchanging brightness indicates unchanging pressure difference across a bulb. In this Activity you will use bulb brightness to detect either changing or constant pressure difference across a battery.

Connect the circuit shown in Figure 5.1a, and note the brightness of bulb A. You are going to add more bulbs to this circuit, and observe how that affects the brightness of bulb A. The added bulbs will be placed in an alternative flow path — thus connecting them in parallel with bulb A. Placing them to the right of the battery makes it easier for you to focus carefully on observing any changes of brightness of bulb A at the left.

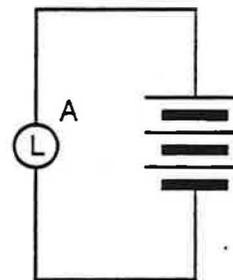


Figure 5.1a

1. Your first experiment will be to add a single parallel bulb, labeled B, as in Figure 5.1b — and then observe what happens to the brightness of bulb A when you close the switch as in Figure 5.1c. Answer the questions below before you do the experiment.

Suppose bulb A were to become brighter when you close the switch to light bulb B. What would that tell you about the pressure difference across the battery when it is pumping flow through bulbs A and B, compared to pumping through bulb A alone?

Suppose bulb A were to become dimmer when bulb B is lit. What would that tell you about the pressure difference across the battery when it is pumping flow through bulb A and bulb B, compared to pumping through bulb A alone?

What would it tell you about pressure difference across the battery if bulb A were to show no change in brightness?

6. Is a battery a device which maintains a constant pressure difference in its terminals under all circumstances? Explain your reasoning.

7. Color code the circuit in Figure 5.1a, containing only bulb A. What is the pressure difference across the battery, expressed in terms of colors?

8. In each of Figures 5.1a, 5.1b, 5.1c, and 5.1d use red (highest pressure) to color wires connected to the (+) battery terminal, and use blue (lowest pressure) to color wires connected to the (-) battery terminal. Do not color any wires that are not connected directly to the battery. These wires will be investigated later on.

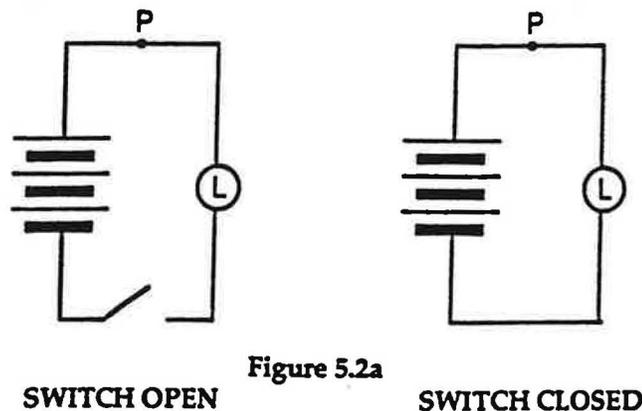
Does red-to-blue represent the same highest-to-lowest pressure difference in all four cases? Or does red-to-blue represent a different pressure difference in the battery terminals in different cases? What is the evidence from your observations?

9. Will there be a red-to-blue pressure difference across any of the added bulbs in Figures 5.1b, c, or d? Explain your reasoning? Discuss your conclusions with your teacher.

5.2 Activity: Does a battery always provide the same flow rate?

In Section 2 we learned that the deflection of a compass needle provides information about direction and rate of flow in a nearby circuit wire. In this Activity you will use your compass to find out whether a battery always pumps the same flow rate through itself, no matter what circuit components are connected to it—or whether it pumps different flow rates in different circumstances.

Set up the circuit in Figure 5.2a, with your compass under the wire at point P. One partner should hold the wire down parallel to the compass needle. Leave one wire unconnected to the battery as shown—forming an open switch. Then observe the deflection of the compass needle as you close the switch to light the bulb. Record the amount of deflection in Table 5.2.



5.3 Activity: Two identical bulbs in series

Set up the circuit as shown in Figure 5.3a below, but leave the upper end of the wire between the bulbs unconnected — as shown in the circuit diagram.

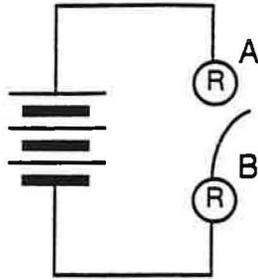


Figure 5.3a
MIDDLE WIRE
UNCONNECTED

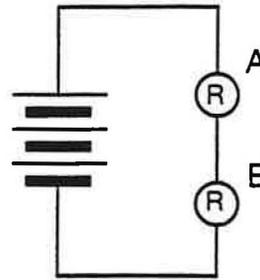


Figure 5.3b
MIDDLE WIRE
CONNECTED

1. With the middle wire not connected to bulb A, color code the circuit of Figure 5.3a consistent with the four statements above.

How much pressure difference is there across each bulb in Figure 5.3a?

2. What color would be appropriate for the filament of bulb A? Bulb B?
3. Now complete the circuit (as in Figure 5.3b) and observe the relative brightness of the two bulbs. Color code the completed circuit and explain the reasoning you used in assigning a color to the middle wire.
4. Explain how your color coding correctly explains the observed bulb brightness.

5.4 Activity: How does completing a loop change the pressure in a wire?

The pressure in the wire between the two bulbs in Figure 5.3a has to change when the switch is closed. How does this change occur? What makes it happen?

We have been using the conception that charge is always present in a capacitor plate, that the charge can be compressed by pushing more charge into the plate, and that compression will increase the electric pressure in the plate. This is like reasoning that air pushed into a tank will compress air which is already there, and that compression will increase the air pressure in the tank. We should expect that the pressure value in a wire can change, for the same reasons it can change in a capacitor plate:

- A wire is made of conducting matter. So it is always full of charge.
- Charge inflow results in compression, which increases the pressure.
- Charge outflow results in depletion, which decreases the pressure.

5. Describe what you see upon completing the circuit.

6. Measure the time it takes for both bulbs to become equally bright. (Use a stopwatch if available.) Repeat your measurement of the time until you are confident of your result. You can discharge the capacitor before each repetition by disconnecting one of the wires connected to the battery. This allows the capacitor to discharge through the lower bulb B. Record your measurements below.

7. Now replace the silver capacitor with a blue capacitor. Again measure and record the time it takes for both bulbs to reach equal brightness. Remember to discharge the capacitor between trials.

8. If available, your teacher will now provide you with an even smaller capacitor. Again measure the time it takes for both bulbs to be of equal brightness.

9. You may make a very small capacitor with a pair of roofing nails. Just connect the clip leads for the capacitor to the shanks of the nail, and then press the flat nail heads together with a small piece of paper between them. This makes a capacitor in which the nail heads are the plates. The charging process for this capacitor will take a very short time.

Can you tell the difference between a two-nail capacitor and no capacitor at all?

5.5 Commentary: Comparing currents in unlike bulbs

The flow rate through a bulb is determined by the pressure difference, which drives the flow. You can see this relationship in the circuit of Figure 5.4b: As the pressure in the top capacitor plate increases, the pressure difference across the top bulb A decreases and the reduced flow rate results in a dimmer bulb. But the flow rate through a bulb is also determined by the bulb's resistance, which hinders movement through the bulb. The driving and hindering factors must be coordinated whenever you want to compare flow rates through unlike bulbs.

These two factors are coordinated visually by the arrows of different widths in Table 5.5. The columns indicate that the current through either kind of bulb decreases as the pressure difference across the bulb decreases. The rows indicate that, for the same pressure difference, a low resistance round bulb always allows a greater flow rate to pass through it than a high resistance long bulb does.

The table is especially useful for cases where a long bulb and round bulb have equal currents passing through them. Study Table 5.5 before continuing to determine what circumstances must exist in order for a round bulb and a long bulb to have exactly the same flow rate.

Set up the circuit in Figure 5.6a. This time connect one end of the middle wire to the upper long bulb A and leave the lower end unconnected.

1. Color code the circuit consistent with the fact that there is not yet any current in the loop.
2. Now complete the loop. Compare the brightness of the two bulbs. What do you observe?

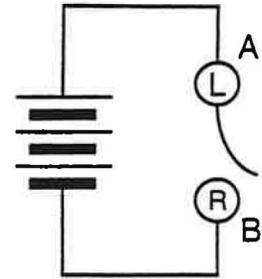


Figure 5.6a

3. Predict whether there is an equal flow rate through all wires in the circuit.

Prediction:

Then tape a compass to the table, and use it to check the flow rate in each of the wires. Record the observations below. Is the flow rate the same all the way around the loop?

4. In this circuit — containing more than one type of bulb — does bulb brightness indicate flow rate? Why or why not?
5. Can the pressure difference across the long bulb be equal to the pressure difference across the round bulb? Use the information from Question 3 and Table 5.5 to justify your response.
6. At the instant of connection, what is the pressure in the middle wire?
7. Color code Figure 5.6b to show the final, steady-state pressure in the middle wire.

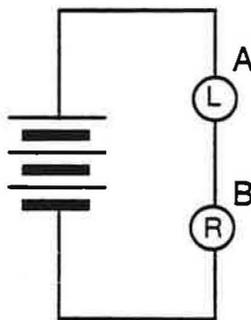


Figure 5.6b
COLOR-CODE STEADY STATE

8. Using the ideas discussed in Activity 5.4, explain how the pressure in the middle wire changed from its initial value at the instant of connection to its final steady-state pressure.

2. Add a third bulb as a parallel branch across the bottom bulb to make the circuit in Figure 5.8b. Describe how the brightness of the two original bulbs changes when the third bulb is added.

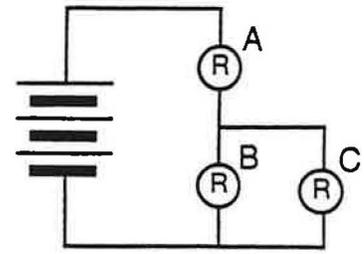


Figure 5.8b
COLOR-CODE BASED ON BRIGHTNESS

- Has the pressure difference across the top bulb A increased, decreased, or stayed the same? Explain your reasoning.
- Has the pressure difference across the original bottom bulb B increased, decreased, or stayed the same? Explain your reasoning.
- Compare the pressure differences across each of the two parallel bulbs, B and C. Justify your answer.
- Now color code the circuit in Figure 5.8b consistent with your answers to questions 1 through 5.

“Parallel” connections have until now been defined as alternative paths for flow from one branching point to another. Your ability to assign pressure values to wires makes a second definition available to you: “Parallel” connections mean any alternative paths for flow from one specific pressure value (or color value) to another. The pressure-value definition is more powerful because it works better for complicated circuits.

7. Explain how Figure 5.8b illustrates the validity of the branching-point definition and the pressure-value definition.

5.9 Commentary: The “equivalent resistance” idea

Suppose you have two boxes, each of which contains a combination of bulbs. The bulbs inside will make the box itself behave like a resistor, and the resistance of the box is called the “equivalent resistance” of the arrangement of bulbs contained in it.

In Figures 5.9a and 5.9b below, the shaded areas A and B represent two boxes which contain two arrangements of bulbs. The equivalent resistances of the boxes will be compared by connecting them to identical batteries and measuring the flow rates through them. P and Q represent points where the currents are to be measured — using either compasses or identical bulbs.

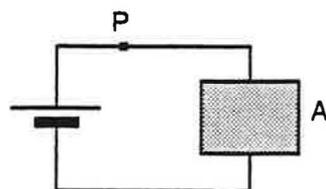


Figure 5.9a
CIRCUITS WITH EQUIVALENT RESISTANCES

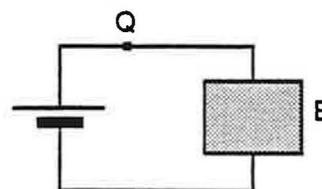


Figure 5.9b

5.11 Commentary: How does adding branches lower resistance?

It seems to defy common sense that adding more resistors to part of a circuit can make less equivalent resistance of that part. But that's exactly what happens when resistors are added in parallel. Thinking about steady-state flow in the circuit of three identical bulbs shown in Figure 5.11 can help make sense of this idea.

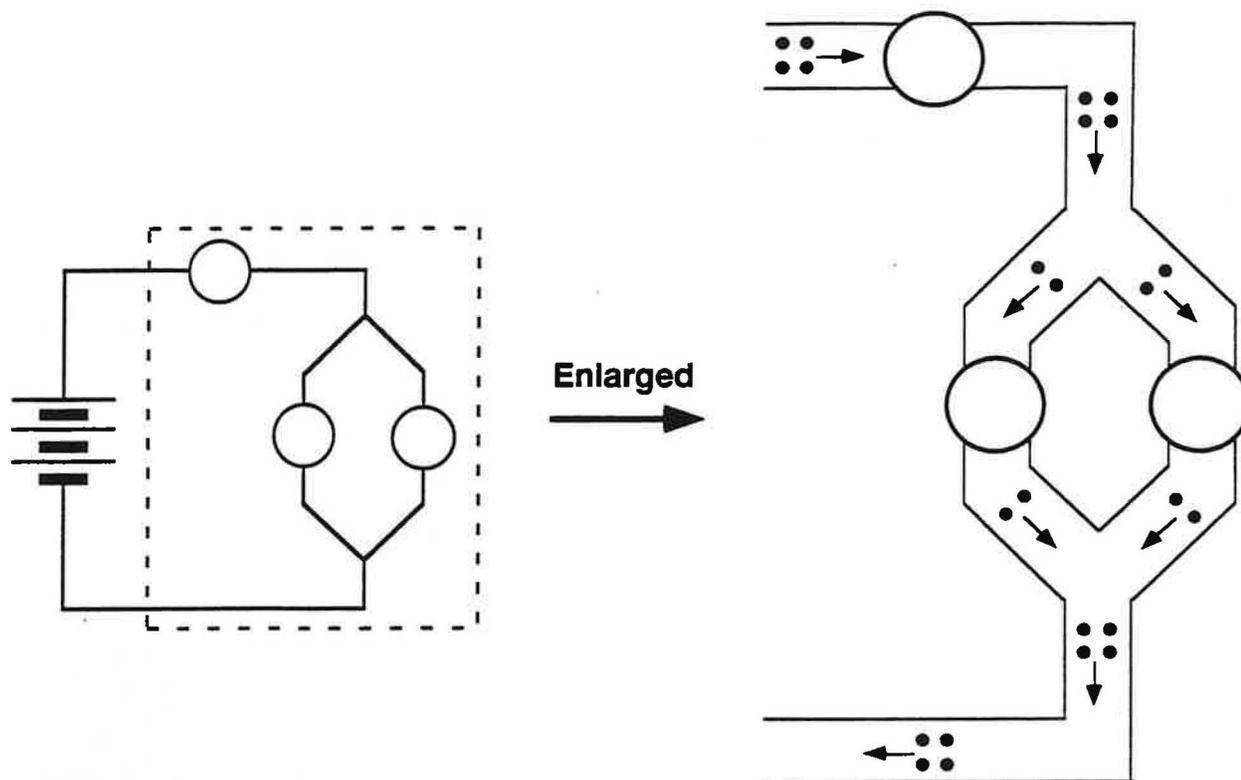


Figure 5.11
STEADY-STATE FLOW WITH ENLARGED VIEW

You'll need to keep a couple of things in mind about steady-state flow:

- (1) Each wire in the circuit is filled with mobile charge, and all of this charge is being driven forward by differences of pressure in the wires.
- (2) Different pressures were established by compression and depletion in the wires, during a brief transient stage that was completed long ago.

You can visualize the flow pattern by thinking of a moving collection of "little bits." Figure 5.11 shows four bits (small black circles) entering the single series bulb at the top, at the same time that four other bits are entering the parallel pair at the bottom.

Note that the pressure differences are pushing only two bits through each bulb in the parallel pair, while pushing all four bits through the single series bulb. So charge is moving at only half the rate through each parallel bulb as through the single series bulb.

How much pressure difference is required to drive a stream of charge at half the rate through one bulb as through another identical bulb? The answer is:

Only half as much pressure difference is needed!

- Describe how the brightness of the two original bulbs A and B change when the third bulb C is added.
- Describe how the current through the battery and through the original long bulb have changed.
- How does the resistance of two long bulbs in parallel compare with the resistance of a single long bulb? Explain how you know.
- Remove the added long bulb C and replace it with a round bulb D to make the circuit in Figure 5.13c. Describe how the brightness of the original bulbs changes from circuit 5.13b to circuit 5.13c.

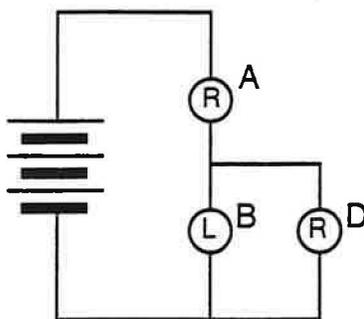


Figure 5.13c

- Remove the added round bulb and replace it with a simple wire as in Figure 5.13d. **Note: Connecting this wire will quickly burn out the top bulb.** Therefore you should make the connection by briefly tapping the wire in place.

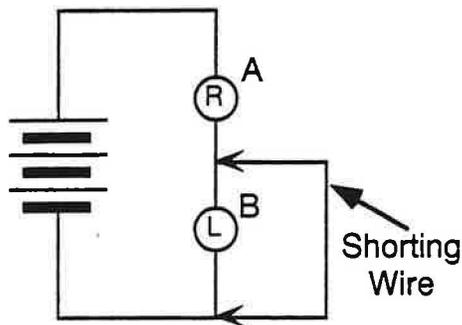


Figure 5.13d
ADDING A SHORTING WIRE



Describe the changes of bulb brightness from circuit 5.13c to circuit 5.13d.

- While the round bulb is still lit in Figure 5.13d, remove the long bulb or simply lift it within its socket to break the connection. (Work quickly.) Can you detect any change in brightness of the round bulb?

In the circuit for Figure 5.13d, how much current goes through the long bulb when it is inserted back into its socket?

SUMMARY EXERCISE

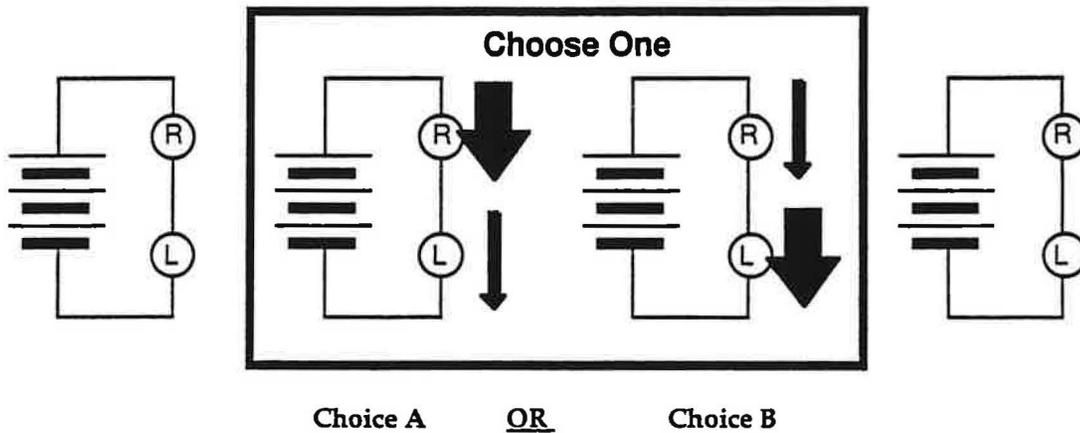
1. A single bulb is connected to a fresh battery. When a second bulb is added in parallel to the first bulb, there is an (Increase, Decrease, or No Change) in

- a) the electric pressure difference across the battery _____
- b) the electric pressure difference across the first bulb _____
- c) the flow rate of charge through the battery _____
- d) the flow rate of charge through the first bulb _____

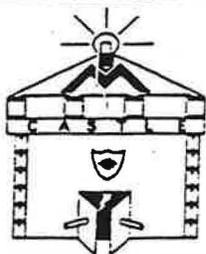
2. A circuit contains one battery and two bulbs in parallel. When a second battery of the same voltage is connected in parallel to the first battery, there is an (Increase, Decrease, or No Change) in

- a) the electric pressure difference across the first battery _____
- b) the electric pressure difference across the first bulb _____
- c) the electric pressure difference across the second bulb _____
- d) the flow rate of charge through the original battery _____
- e) the flow rate of charge through the first and second bulb _____

3. Look at the figures below, beginning the instant the circuit is completed, through the transient stage, and leading to the steady-state condition.



Determine whether Choice A or Choice B is the best representation of the transient process. Explain your reasoning.



Section 6

HOW ARE VALUES OF CIRCUIT VARIABLES MEASURED?

INTRODUCTION

People who use electric circuits for practical purposes often need to measure quantitative values of electric pressure difference and flow rate of charge. To do this they use instruments called **voltmeters** and **ammeters**. In this section you will investigate the behavior of these instruments. You will then combine these instruments in a circuit to measure the resistance of circuit components.

6.1 Commentary

Your teacher will provide you with an instrument labeled voltmeter and with a digital multimeter which will be used as an ammeter. The circuit diagram symbol for a voltmeter is a box labeled "V", and the symbol for an ammeter is a box labeled "A".



There are two main types of voltmeters and ammeters: The "analog" type has a number line scale and a movable pointer, while the "digital" type provides a numerical readout. The proper use of the instruments available in your classroom will be demonstrated by your teacher. Please note that ammeters can often be damaged by connecting them directly to a battery; follow instructions carefully.

Do not connect an ammeter in any circuit until your teacher has shown you how to do this properly.

INVESTIGATION ONE: WHAT DOES A "VOLTMETER" DO?

The readout of an instrument labeled "voltmeter" is intended by the manufacturer to tell you the electric pressure difference between any two points on a circuit to which it is connected. In this investigation you will investigate the actual behavior of your voltmeter.

4. **Predict** how these pressure differences will compare:

a) across bulb A (as in Figure 6.2c) compared to the battery (Figure 6.2b)?

b) across bulb B (as in Figure 6.2d) compared to the battery (Figure 6.2b)?

c) across bulb A (Figure 6.2c) and then across bulb B (Figure 6.2d)?

6.3 Commentary

The symbol for the quantitative value of electric pressure is "V". The symbol " ΔV " will be used for the difference of two electric pressure values.

The unit for expressing quantitative values of electric pressure and of electric pressure difference is the VOLT. Values of electric pressure difference are measured by a voltmeter in volts.

D-cells are designed to maintain their (+) terminals at 1.5 volts electric pressure higher than their (-) terminals.

6.4 Activity: Testing the voltmeter quantitatively

1. Color code the wires for the circuit diagram in Figure 6.4a, using red-to-blue for the pressure difference maintained by the battery between its terminals. Do not connect the voltmeter yet.

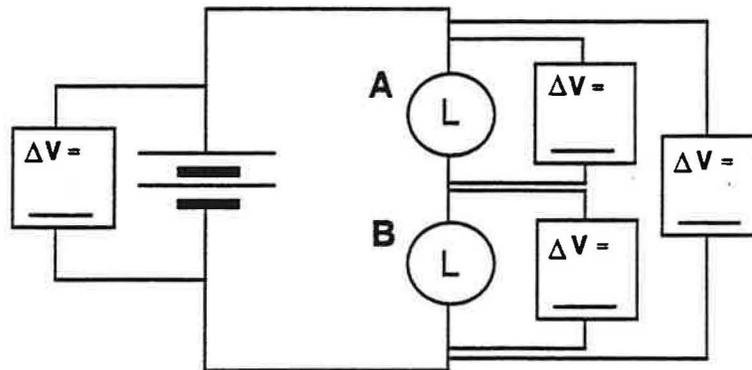


Figure 6.4a
VOLTMETER READINGS

2. **Predict** how many volts of electric pressure difference your red-to-blue color difference correspond to in this situation where the battery consists of two D-cells connected in series. Explain.

3. Your teacher will provide a voltmeter. Connect the voltmeter to each of the locations indicated in Figure 6.4a, and record the readings provided by this instrument in the corresponding spaces on the figure above.

10. How do the three pressure differences compare?

Speculate: How would they compare if the battery and the bulbs were connected in a series circuit?

6.5 Activity: Investigating voltmeter resistance

1. Connect the circuit shown in Figure 6.5a. Describe the observed behavior of both the bulb and the voltmeter.

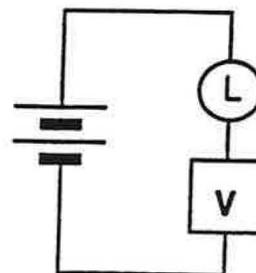


Figure 6.5a
VOLTMETER CONNECTED IN SERIES

2. What do your observations tell you about the resistance of a voltmeter?

3. Speculate why a voltmeter is designed with that resistance?

4. Why isn't a voltmeter normally connected to a circuit as in Figure 6.5a?

INVESTIGATION TWO: USING A VOLTMETER WITH A CAPACITOR

6.6 Activity: Pressure difference during charging and discharging

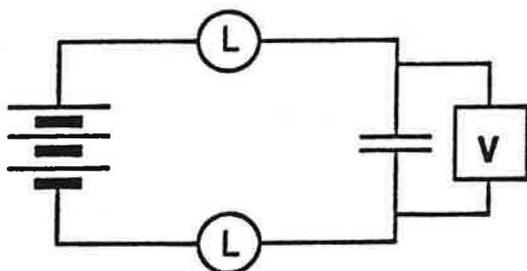
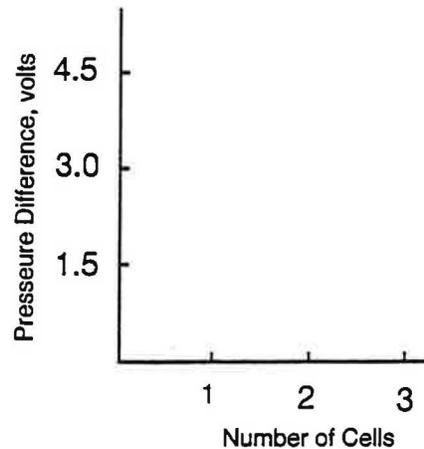


Figure 6.6a
VOLTMETER CONNECTED ACROSS A CAPACITOR

1. Color code the diagram above when the capacitor is fully charged.

2. Draw a bar graph of the maximum pressure difference as a function of the number of cells.

Maximum Pressure Difference vs. Number of Cells



3. According to your observations, what do you think determines the amount of the maximum pressure difference in a circuit?

INVESTIGATION THREE: WHAT DOES AN AMMETER DO?

DO NOT BEGIN THIS INVESTIGATION UNTIL YOUR TEACHER HAS DESCRIBED HOW TO USE AMMETERS WITHOUT DAMAGING THEM.

6.7 Activity: Testing the ammeter in series circuits

Using two D-cells in the battery and two long bulbs, connect each of the circuits shown below.



Read Directions Carefully!

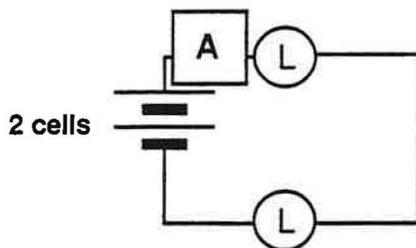


Figure 6.7a

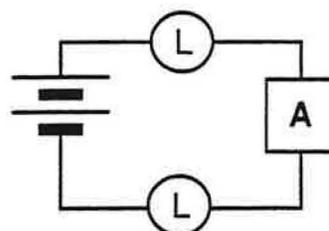


Figure 6.7b

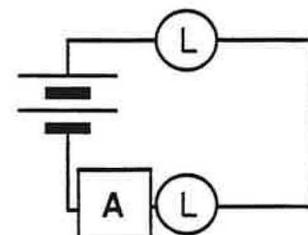


Figure 6.7c

SERIES CIRCUITS WITH AMMETER

1. Observe the reading of the ammeter in each case. How do the meter readings compare?

6.10 Activity: Investigating ammeter resistance

1. Predict: Suppose you were to "short circuit" the long bulb in Figure 6.10a using a wire as shown in the diagram. That would, in effect, remove the long bulb's resistance from the circuit. How would you expect the ammeter's reading to change?

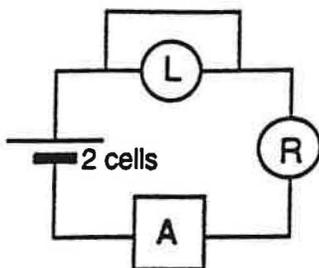


Figure 6.10a
SHORTING OUT ONE BULB

2. Set up the circuit and do the experiment. Was your prediction correct? What did you observe?

3. Now connect the circuit shown in Figure 6.10b. Compare the meter reading change to what you observed in the previous investigation.

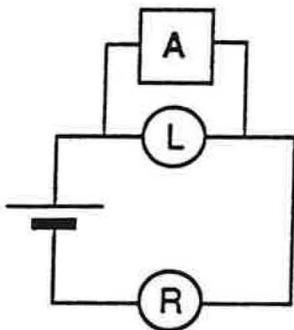


Figure 6.10b
AMMETER CONNECTED AROUND BULB

4. Considering the change in bulb brightness for the long bulb and for the round bulb, does the ammeter act like a short circuit?
5. What can you conclude about the resistance of the ammeter? Explain.
6. Speculate why it is easy to damage an ammeter.
7. Why would an instrument designer plan to manufacture an ammeter with this resistance?
8. Discuss your conclusions with your teacher.

TABLE 6.12

	R_x			R_y		
Cells	Pressure Difference (volts)	Flow Rate (amps)	$\frac{\text{Volts}}{\text{Amps}}$ (ohms)	Pressure Difference (volts)	Flow Rate (amps)	$\frac{\text{Volts}}{\text{Amps}}$ (ohms)
1						
2						
3						

2. Compare the values you found for R_x when using three different driving voltages. Are the values approximately the same?

What about the values for R_y ?

Important:

If a resistor has the same value of resistance when measured at different voltages, then we say that the resistor obeys Ohm's law.

3. Does the resistor labelled R_x obey Ohm's law? Does the one labelled R_y ?

6.13 Activity: Resistance of a long bulb

1. Design a circuit to determine the resistance of a long bulb. Sketch your circuit below and have your teacher check it.

SUMMARY EXERCISE

1. Explain what electrical quantity each of the two meters measures, and what units are used for the measurement.

Voltmeter:

Ammeter:

2. In terms of experimental measurements, how is resistance defined? What units are used for measuring resistance?
3. A good measuring instrument should have as little interference as possible on the system being measured.

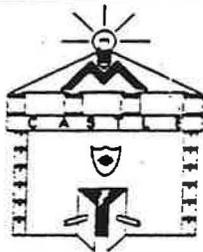
Describe:

- a) whether the resistance of each meter (Voltmeter and Ammeter) should be high or low
- b) how the meter should be connected in a circuit in relation to the other circuit elements
- c) why each meter needs to have its particular resistance to be a good measuring device

Voltmeter:

Ammeter:

4. Describe how the resistance of the X and Y resistors was affected by the different voltages you used. Describe how the resistance of the long bulb was affected by the different voltages you used. Compare the behavior of the two kinds of devices. Does each type of device obey Ohm's law?



Section 7

WHICH VARIABLES DETERMINE ENERGY TRANSFER?

INTRODUCTION

This section will focus on an idea about electric circuits that has probably already occurred to you. It is the idea that something originating in the battery is going to the lighted bulbs and is not coming back to the battery. The fact that this "something" is being transferred irreversibly from the battery to the bulbs makes it very different from the moving charge that circulates through the bulbs without being used up.

INVESTIGATION ONE: ENERGY TRANSFER IN CIRCUITS

7.1a Exercise: Seeing the light

1. What evidence do you have that energy is being delivered to a glowing bulb?
2. What evidence is there which suggests that the battery is the source of the energy being transferred to a glowing bulb?

7.1b Video: The electric battery

Go to the video-disc set-up and watch the following segment:

Physics: Cinema Classics, Disc 2, Side D, Chapter 51 "Simple Electric Cells". Follow the directions within the segment to proceed through the segment. Set the AUDIO to "Analog 1/L". If you are not sure of the answers to the questions posed, set the AUDIO to "Analog 2/R" and watch the entire segment again.

7.2 Commentary

To help visualize the heating of a light bulb filament by a battery, think about heating a hot water radiator in a house. To heat the radiator you burn fuel in a furnace. Energy stored in the fuel is transferred from the furnace to the radiator and then to everything else in the house, including people. The transfer is made possible by a working fluid—in this case heated water—which circulates through the furnace and the radiator without any of it being used up by the energy transfer process.

When a light bulb glows, the filament emits light because it is hot. The light emission is obvious, but the bulbs we are using are so small that the heating may not be noticed. With household light bulbs the heating is easier to notice—a 100 watt bulb quickly becomes hot enough to burn your fingers.

To heat a bulb filament you use a battery, which contains compounds that store energy in much the same way fuel does. Chemical reactions in the battery release this energy from storage in much the same way that burning fuel in a furnace does. Energy transfer to the bulb filament is made possible by a working fluid—now a fluid of charge rather than heated water—which circulates through the battery and the bulb without any of it being used up by the energy transfer process. In this investigation you will determine a way to measure the amount of energy that is transferred irreversibly from a battery to a light bulb.

1. Write down your impression of the effort required to turn the crank when the circuit is broken, compared to the effort required to light the bulb.
2. Next turn the crank faster (just a little faster) and observe the bulb brightness.
Is there evidence of more energy transferred to the bulb, or less? Explain.
3. Is there evidence of more energy transferred from your muscles, or less?

7.5 Activity: Muscle Energy Output Variables

1. Study the circuits below. In each circuit — one series and one parallel — you will use the hand generator to light two bulbs to equal brightness.

First write a prediction: Describe the cranking motion that you think will be required as you turn the crank for the series circuit, compared to the motion that will be required for the parallel circuit.

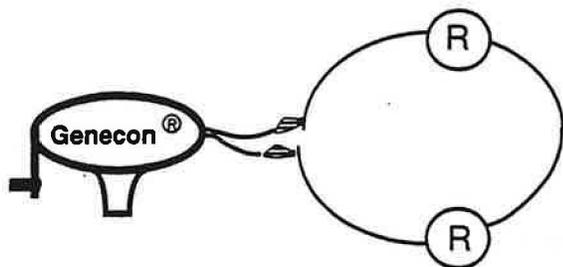


Figure 7.5a

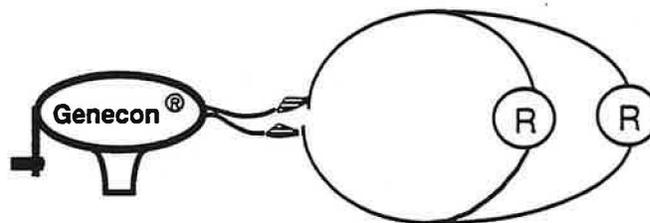


Figure 7.5 b

GENECON WITH TWO ROUND BULBS (SERIES & PARALLEL)

SERIES: Connect a shorting wire across one bulb — so only the other bulb lights when you crank the Genecon. One partner should tap the shorting wire on and off to control the bulb lighting, while the other partner turns the crank and feels what the muscles are having to do in order to continue producing the original bulb brightness.

PARALLEL: Loosen one bulb — so only the other bulb lights when you crank the Genecon. One partner should turn on the second bulb by tightening it while the other partner turns the crank and feels what the muscles are having to do in order to continue producing the original bulb brightness.

Before you turn the second bulb on in either case, you are producing a steady brightness for one bulb. When you turn on the second bulb with equal brightness, you are delivering twice as much energy per second to the pair as you were giving to the single bulb.

SERIES CASE:

1. How do you know the current through the pair is the same as through the original single bulb?

7.7 Commentary: Energy Transfer

The diagram below depicts a source supplying energy to a receiver. The source can be fuel in a furnace in a heating system or chemicals in a battery or a Genecon in an electric circuit. The receiver can be a group of radiators in the heating system or a group of bulbs in the circuit. The diagram also indicates that transfer occurs only with the help of a working fluid moving around a loop. Note that energy is transferred only in one direction — from the source to the receiver — while the working fluid circulates continuously around the loop.

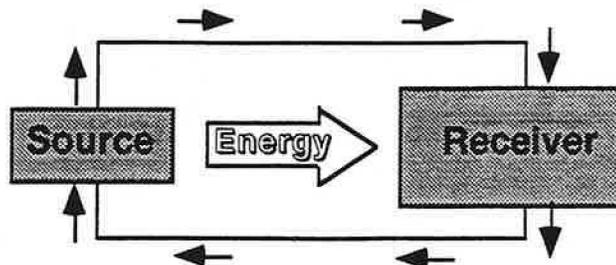


Figure 7.7a

SMALL ARROWS INDICATE MOVEMENT OF THE WORKING FLUID.

In our electric circuits a battery is the source of stored energy, a group of light bulbs is the receiver, and the mobile working fluid is made up of charge carriers. In Figure 7.7b, the receiver is a single bulb. **This circuit establishes special conditions for further discussion.**

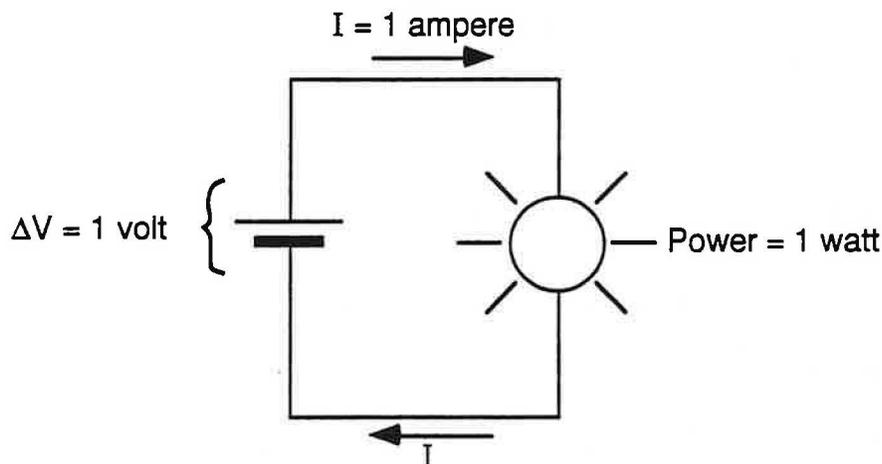


Figure 7.7b

SPECIAL CONDITIONS

In the diagram in Figure 7.7b, we are defining a set of special conditions:

- 1) The electric pressure difference will be exactly 1 volt
- 2) The bulb's resistance will be such that the battery drives a current of exactly 1 ampere through it.

This special battery-and-bulb combination will be used throughout the following discussion in order to define the WATT, which is the unit in which power is measured.

When a pressure difference of 1 volt drives a flow rate of 1 ampere through a light bulb, the rate of energy input to that bulb is defined to be 1 watt of power.

With this definition, we can now determine the power input to any group of such bulbs operating at a pressure difference of 1 volt simply by counting the number of bulbs in the group.

2. Use your knowledge about electric pressure caused by batteries in the wires of series and parallel circuits to determine the electric pressure difference measured in volts across each battery and each resistor. The bulbs are identical to those in Figure 7.7c; all cells are 1 volt.

Complete Table 7.8 for the following circuits: (ΔV is the pressure difference across the battery, and I is the total current in the circuit.)

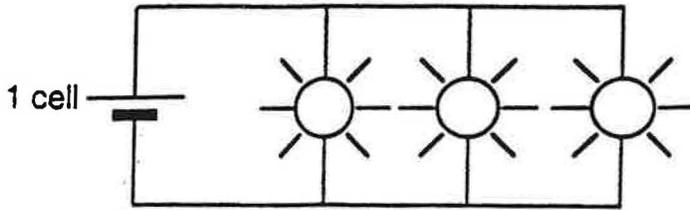


Figure 7.8a

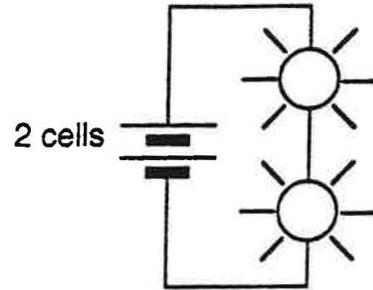


Figure 7.8b

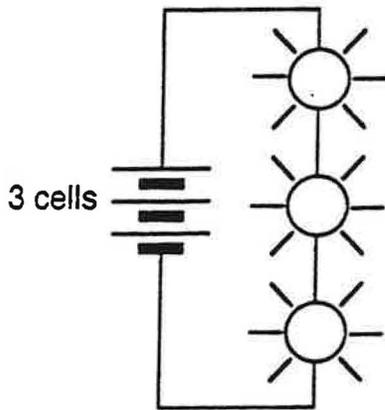


Figure 7.8c

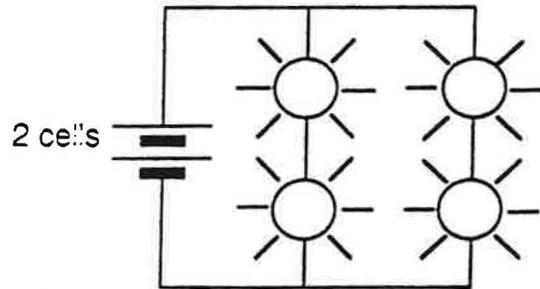


Figure 7.8d

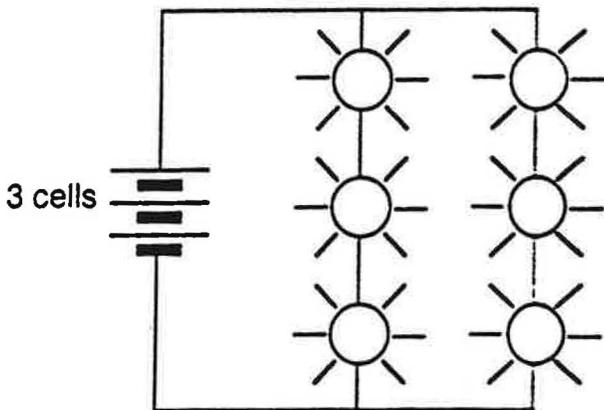


Figure 7.8e

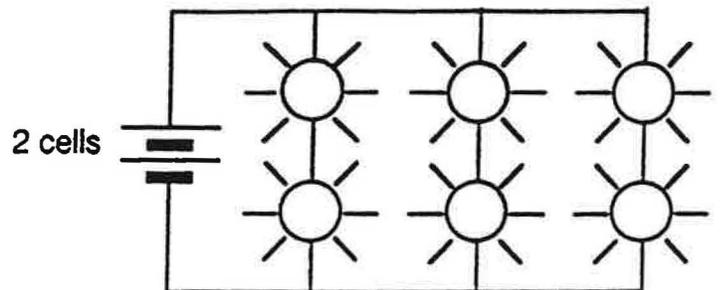


Figure 7.8f

1. Study Figure 7.9 representing a circuit containing two cells with two unlike bulbs. set up the circuit and, using meters, make the appropriate measurements and calculations in order to complete Table 7.9 below.

2. Does the Power Output equal the total Power Input in this circuit?
Comment.

3. Discuss your results with your teacher.

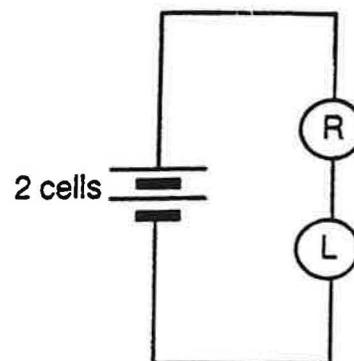


Figure 7.9

TABLE 7.9

Circuit Components	ΔV	I	Power Output from Battery	Power Input to Each Bulb
Battery				
Round Bulb			 	
Long Bulb			 	
TOTALS				

7.10 Activity: Circuit with more than one battery

1. Study Figure 7.10 below. Note that this circuit contains a 2-cell battery and an additional single cell, along with one long bulb.

a. Predict how the bulb brightness in the first circuit (Figure 7.10a) would compare to a bulb in a circuit with only the two-cell battery.

b. Predict how the bulb brightness in the second circuit (Figure 7.10b) would compare to a bulb in a circuit with only the two-cell battery.

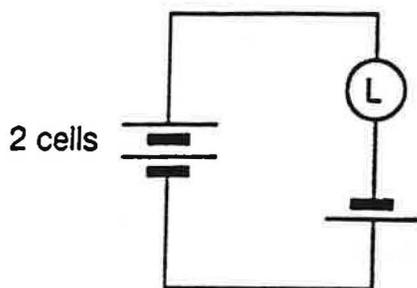


Figure 7.10a

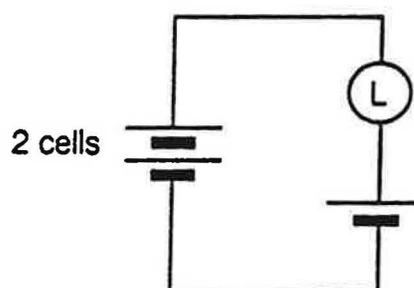


Figure 7.10b

then the corresponding equation for amounts is:

$$\Delta E = \Delta V \cdot q.$$

This equation says that the amount of energy ΔE that is transferred to a circuit from a battery with pressure difference ΔV is proportional to the amount of charge q that passes through the battery.

The equation also says that batteries with greater pressure difference give up more energy for the same amount of charge passing through — specifically, that the amount of energy ΔE transferred to the circuit is proportional to the pressure difference ΔV of the battery.

7.12 Commentary: An energy-related interpretation of ΔV

Rearrange the energy transfer equation to obtain

$$\Delta V = \frac{\Delta E}{q}$$

This equation makes it possible to think of the quantity ΔV as the amount of energy transferred per unit charge that passes between two points on a circuit. This is an alternative energy-related interpretation of the quantity ΔV .

For most purposes, the electric pressure approach or causal-agent interpretation that we have been using until now is more useful. To understand what happens in resistors, for example, it makes more sense to think of the quantity ΔV as a measure of the pressure difference that drives charge through a flow-hindering circuit component. The energy-related interpretation is useful, however, for understanding the behavior of batteries.

7.13 Activity: Series vs. parallel batteries

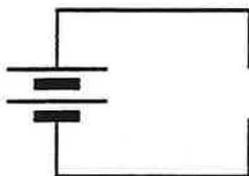


Figure 7.12a
CELLS IN SERIES

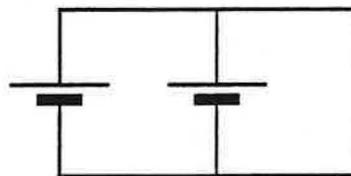


Figure 7.12b
CELLS IN PARALLEL

- Use the equation $\Delta V = \Delta E/q$ to predict the potential difference (ΔV) across
 - a battery consisting of two identical cells connected in series _____
 - a battery consisting of two identical cells connected in parallel _____
- Use a voltmeter to test your predictions.
 - Measure the potential difference across two 1.5 volt cells in series: _____
 - Measure the potential difference across two 1.5 volt cells in parallel: _____
- Using the energy-related interpretation of ΔV , explain the results you obtained from testing the series and the parallel cases.

7.16 Exercise: Energy Sources, Receivers and Storage

1. After charging your blue capacitor with no bulbs in the circuit, discharge the capacitor through two bulbs (see circuits in Figures 3.7 a,b, but use long bulbs). During discharging, energy is being transferred from a source to a receiver. Which component is the receiver? Which circuit component is the source?

Receiver:

Source:

2. What is the evidence that the charged capacitor had energy stored in it?

3. Charge the capacitor through two bulbs and discharge it through the same two bulbs. Compare the brightness of the bulbs with your observation from question #1 above. Is the same amount of energy released?

4. Does a battery give out some of its supply of energy while charging a capacitor? Think of an experiment that would prove this; describe it.

5. Speculate: In what form do you think the energy is stored in a charged capacitor?

6. Your capacitor stores a certain amount of energy when charged by a 4.5 volt battery. List two things you could do to obtain a larger amount of capacitor-stored energy.

7.16b Video: Energy stored in a capacitor

Go to the video-disc set-up and watch the following segment: Saunders Video Discs, Disc 2, Side 1, Electricity, frame numbers .

7.17 Activity: Energy and the Hand-held Generator

This activity requires using a small green capacitor (1.0 f) which your teacher will provide. Use the hand-operated generator (Genecon) to charge the capacitor through two round bulbs.

1. What evidence is there that you are transferring energy to the bulbs and the capacitor?

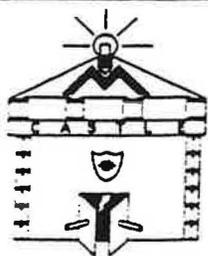
When the bulbs go out (indicating that the capacitor is fully charged), stop cranking but still keep a firm grip on the handle. After a few seconds let go of the handle. Grab and release the handle every few seconds until the capacitor is discharged.

2. Describe what you see.

3. Explain the behavior of the bulbs and the generator in terms of energy.

4. How does the current in the circuit vary?

5. Discuss your conclusions with your teacher.



Section 8

WHAT CAUSES PRESSURE IN DISTANT CONDUCTORS?

INTRODUCTION

In this section you will observe bulb lighting that cannot be completely explained by a model in which compression of mobile charge creates pressure differences that drive the flow. But we should not hastily discard this very useful model at the first sign of difficulty. We shall instead try to imagine new features that can be added to the model, which will enable it to explain the new phenomena as well as the old. Model improvement is an important ingredient of scientific work because no model is completely correct and the need for a better one always appears sooner or later.

INVESTIGATION ONE: THE BEHAVIOR OF A NEON BULB

8.1 Activity: A new look at insulating materials

In this Activity we will find out how insulators behave when we place large pressure differences across them. Our investigation will begin with an experiment on neon gas. A small quantity of this gas is contained in a neon bulb which your teacher will hand out in class.

Look carefully at the neon bulb. It has two wires, to which you may attach clip leads. These wires pass through the glass, and in this respect the neon bulb is like the long and round flashlight bulbs. But the wires terminate inside the bulb at two metal rods, called electrodes. There is no metal filament to provide a conducting path between the electrodes. There is only neon gas in the space between the electrodes.

Identify one of the electrodes by putting a small piece of masking tape on the wire connected to it. Connect a yellow clip lead to the wire with the tape, and a green clip lead to the other wire. Take four 9-Volt cells and clip them together in series. Then connect the free terminals to the clip leads as illustrated in Figure 8.1.

NOTE: You will find a resistor (33 k Ω) connected in series with the neon bulb. Its purpose is to limit the flow rate and prevent arcing, which can destroy the bulb.

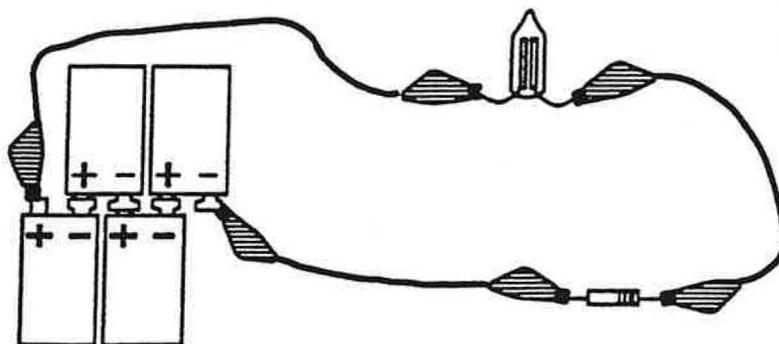


Figure 8.1
NEON BULB WITH FOUR 9-VOLT CELLS

8.3 Activity: Using the neon bulb to determine the direction of flow

In this section we will be using neon bulbs. This type of bulb responds to the direction of movement of charge passing through it. You can verify this by setting up the circuit in Figure 8.1 so that the neon bulb lights.

1. Look carefully at the neon bulb, and describe what you see.
2. Reverse the clip leads connected to the battery. How is the glow pattern different than before?
3. How does the glow pattern identify the electrode that is connected to a higher electric pressure?
4. Describe how you can use the neon bulb to tell the direction of charge flow?
5. Discuss your conclusions with your teacher.

INVESTIGATION TWO: WHAT'S CAUSING THE PRESSURE DIFFERENCES?

8.4 Commentary: Reviewing the compressible fluid model of charge flow

Our earlier investigations have led us to build a conceptual model in which pressure difference in a compressible fluid of mobile charge is the cause of charge flow through a resistor. Using this model, we can correctly predict the observed behavior of mobile charge in every electric circuit we have investigated so far. That's a highly successful model! Let's review its main features:

- a) Mobile charge can be pushed around a conducting loop by a battery, in much the same way that air can be pushed around a loop of tubing by a pump.
- b) Charge compressed in a capacitor plate creates high electric pressure, in much the same way that air compressed in a rigid storage tank creates high air pressure.
- c) High electric pressure in a capacitor plate can be returned to normal pressure by connecting it (using a wire) to the low pressure plate, in much the same way that high air pressure in a rigid storage tank can be returned to normal pressure by connecting it (using a tube) to another air tank at below-normal pressure.



Beginning in the following Activity, we shall see that this model can make false predictions when there are breaks in the continuity of the conducting loop.

3. If the bulbs light, use a compass (or an ammeter) to determine how the direction and magnitude of the current in the “island” compares with the direction and magnitude of the current in the wires between each capacitor and a battery terminal?

4. What have you observed that cannot be explained by a compressible fluid model of charge flow, as we have developed it up to this point?

8.6 Commentary: Improving the compressible fluid model

The compressible fluid model of charge flow falsely predicts that the bulbs in the conducting island will not light. Clearly, something is wrong with this model. But should we abandon a model that works perfectly everywhere except in “conducting islands”? Let’s try instead to improve the model — in a way that makes it valid also for “conducting islands.” Let’s start by applying the compressible fluid model to the bulb lighting which actually does occur in the “island” part of the circuit, and see if that suggests ideas about improvement:

- 1) The glowing bulbs show that mobile charge is being driven through the “island.”
- 2) In order for that to happen, there must be pressure changes inside the “island.”
- 3) These pressure changes are not caused by charge entering or leaving the “island.”
- 4) So the cause must be charge that enters or leaves the plates outside the “island.”

How can charge located outside the “island” cause pressure changes inside the island without entering the “island” and being compressed there? Let’s look for analogies in some familiar situations where external zones of influence produce effects without actual physical entry.

Situation #1:

- A street lamp supports an exterior zone of above-normal illumination.
- Matter placed in this zone is illuminated without touching the lamp.
- The illumination decreases toward normal at greater distances from the lamp.

Situation #2:

- A candle flame supports an exterior zone of above-normal temperature.
- Matter placed in this zone is made hotter without touching the flame.
- The temperature decreases toward normal at greater distances from the flame.

Zones of above-normal illumination in the space around luminous objects are often called “halos.” We shall use this term to connote external zones of influence of any kind. Thus, we shall say that there is an “illumination halo” (bright zone) in the space around a street lamp and a “temperature halo” (hot zone) in the space around a candle flame. These halos are illustrated in Figures 8.6a and 8.6b.

In principle, the test could be carried out using the (+) plate of a charged capacitor. But that would require tearing up an expensive capacitor. Also, handling a capacitor tends to discharge it—because charge moves so easily in conductors. We can avoid both of these problems by using a piece of insulator with excess charge on it. Our experiment with neon bulbs in Investigation One showed that neon contains charge—suggesting that charge is present in all insulators. We shall use our muscles (instead of a battery) to transfer some charge from one type of insulating material to a dissimilar type by rubbing the two against each other.

Because the excess charge we obtain in this manner will not be mobile, there should be a good chance of its remaining in place during normal handling. But the amounts of charge transferred by rubbing will be small compared with the amounts a battery can pump into a large capacitor plate. We shall therefore use neon bulbs, which will glow when even very small amounts of charge pass through them—amounts much smaller than are needed to make flashlight bulbs glow. The electrode at which a neon bulb glows also reveals the direction of movement through the bulb.

8.8 Commentary: Visualizing “pressure halos” around charged objects

Figure 8.8 shows how we should visualize the distribution of pressure in the halo around an object carrying excess charge. Each dashed line connects points in the plane of the paper that are at the same electric pressure. The numbers by the dashed lines represent degrees of pressure above normal. Figure 8.8 shows highest pressure value near the excess charge, with values approaching zero (normal pressure) at points farther and farther away. The numbered dashed lines are like contours showing points of equal elevation on a map, or like lines connecting points of equal temperature around a hot candle flame.

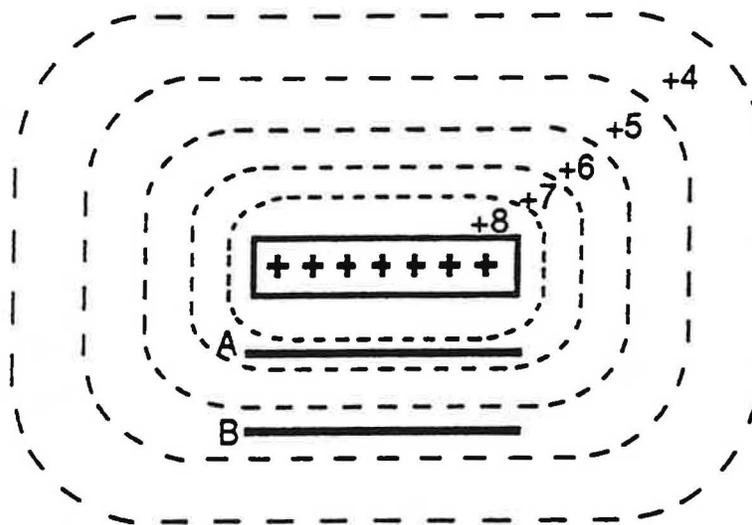


Figure 8.8
PRESSURE HALO AROUND AN OBJECT WITH EXCESS CHARGE

Figure 8.8 also shows two uncharged metal plates labeled A and B, which are placed at different distances from the charged object.

1. According to this description of electric pressure in the halo around an object containing excess charge, which metal plate (A or B) is at higher pressure?
2. We are interested in what this description of pressure variation in the halo predicts if plates A and B are connected through a neon bulb. Will charge move through the bulb in the A-to-B direction, or will it move in the B-to-A direction? Which electrode in the bulb will glow? Which metal plate will lose charge, and which will gain charge?

Attach one end of a clip lead to the bottom metal plate, and connect the other end to one electrode of a neon bulb as shown in Figure 8.9b. Attach one end of a second clip lead to the second electrode of the bulb, and leave the other end unconnected for the time being. At the appropriate time, you will test for charge flow by touching the top metal plate with the unattached end of this second clip lead. Light from the neon bulb will be easy to observe if you follow these two rules:

- (1) The current limiting resistor attached to the neon bulb should not be in the conducting path between the top and bottom metal plates.
- (2) The final connection to the top metal plate should be made only after the charged insulator has been brought close to the top plate.

We shouldn't expect very high flow rates in this experiment, since there is no battery to drive the flow. However, a neon bulb is much better than one of our round or long bulbs for detecting low flow rates, because it does not have a filament that must warm up before it can emit light. That enables it to emit light with flow rates so low that a flashlight bulb will not give out any light at all.

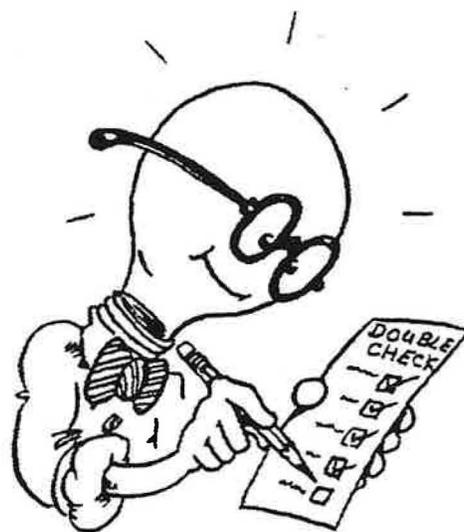
To get started on the experiment, you should rub the bottom of a Styrofoam picnic plate against a sheet of acrylic. If this rubbing transfers some charge from one of the plastic materials to the other, then one material will have an excess of charge while the other will have a deficiency.

Handle these materials near their edges. Since both are nonconductors, they will then retain any charge you give them for a relatively long time — provided you do not give the charge an opportunity to run off by letting other objects touch them. We will first test the acrylic sheet — to see if it is the object with an excess of charge.

The complete sequence of steps for this experiment is as follows.

- 1) Bring the acrylic in close to the top metal plate.
- 2) Touch the loose clip lead to the top plate, and observe which bulb electrode glows.
- 3) Remove the clip lead from the top metal plate.
- 4) Remove the acrylic.
- 5) Touch the loose clip lead to the top plate, and observe which bulb electrode glows.
- 6) Start over again.

If you get lost at any step, discharge the metal plates by connecting them with a wire and start over. Try to focus on observing just one electrode, to see if it is the one that glows. A white paper background placed under the neon bulb will improve visibility.



Repeat the above sequence as often as you need in order to confidently answer the following questions.

1. In step 2, which electrode glows?
2. In terms of the upper and lower pie plate, in which direction did positive charge move through the bulb?
3. Which aluminum plate was at the higher pressure?
4. Describe the location and type of excess charge on the two pie plates after charge has moved through the bulb.

2. If the neon bulb does glow, then you should repeat the experiment with both the acrylic and with the Styrofoam — one right after the other — to see if there is a difference in the way these rubbed materials influence the surrounding space. Do this now, and summarize your observations and your conclusions in the space below.

8.11 Commentary: A second kind of charge?

The experiment you have just performed suggests that charge depletion (-) in rubbed Styrofoam actually does influence other matter in the surrounding space. The fact that directions of flow through the neon bulb are opposite when we use rubbed acrylic and rubbed Styrofoam tell us that the two materials have opposite influences:

- Rubbed acrylic causes higher pressure in plate A than in plate B
- Rubbed Styrofoam causes lower pressure in plate A than in plate B

A straightforward way to explain this oppositeness of influence is to assume that there is a second kind of charge in normal matter, which supports a halo of below-normal electric pressure in the space around it. “Negative charge” is a good name for capturing the “oppositeness” of this pressure-lowering kind of charge. “Positive charge” then becomes a good name for the pressure-raising kind of charge that we have been talking about until now. This explanation adds more new features to our model:

- Negative charge supports an exterior zone of below-normal pressure.
- Matter placed in this zone has its pressure lowered without touching the charge.
- The pressure becomes less below normal at greater distances from the charge.

A useful analogy to negative charge and its pressure-lowering halo is provided by an ice cube, with its halo of below-normal temperature — in which the temperature becomes less and less below normal at farther and farther distances from the ice. This analogy can help you visualize a halo of below-normal pressure in the space around negative charge, which is illustrated in Figure 8.11. This diagram shows electric pressure having its greatest value below normal near the negative charge, with the value rising to zero (normal pressure) at points farther and farther away. The short heavy lines labeled A and B represent two metal pie plates placed in the halo, just as in Figure 8.8 for the halo around positive charge.

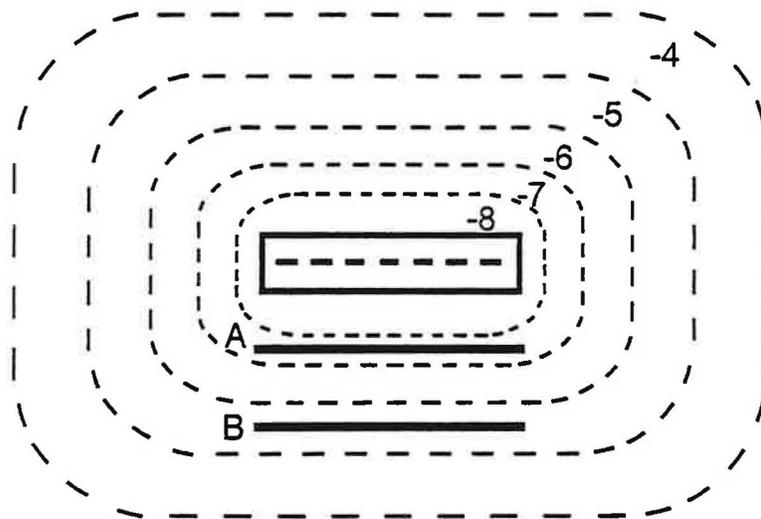


Figure 8.11
PRESSURE HALO AROUND AN OBJECT WITH NEGATIVE CHARGE

7. Explain why each of the following should be color-coded red:
- The left plate of capacitor A
 - The right plate of capacitor A
 - The left bulb and the wire connecting it to capacitor A
8. Explain why each of the following should be color-coded blue:
- The right plate of capacitor B
 - The left plate of capacitor B
 - The right bulb and the wire connecting it to capacitor B
9. How does the island circuit in Figure 8.12 support the existence of a second type of charge? Explain.
10. Does the island circuit support the idea that both types of charge exhibit distant action? Explain.
11. Discuss your conclusions with your teacher.

8.13 Commentary: How (+) and (-) charges work together

We rarely notice any external effects due to either kind of charge when we are dealing with normal matter. In normal experience, material objects don't appear to be electrical at all. Effects which are obviously electrical in nature are observed only when we have reason to believe that some charge has been transferred from one object to another. How this occurs depends on whether we are dealing with insulators or conductors.

Insulators: if we scrape charge off one object by rubbing it against a dissimilar object

Conductors: if a battery pumps charge out of one capacitor plate, into the other plate

These facts can only be explained by adding still more new features to our model. Let's assume the following:

- There are equal amounts of (+) and (-) charge in normal matter.
- Halos of (+) and (-) charges are identical except for "oppositeness."

There is a great amount of evidence that these features are accurate representations of electrical reality, coming from their ability to correctly predict two major facts of life about how the two kinds of charge work together:

- The pressure-raising and pressure-lowering effects of the (+) and (-) kinds of charge will cancel out for normal matter, so that no effect is observed.
- An effect is observed only if there is an excess of one kind over the other, as occurs when charge is transferred from one normal object to another.

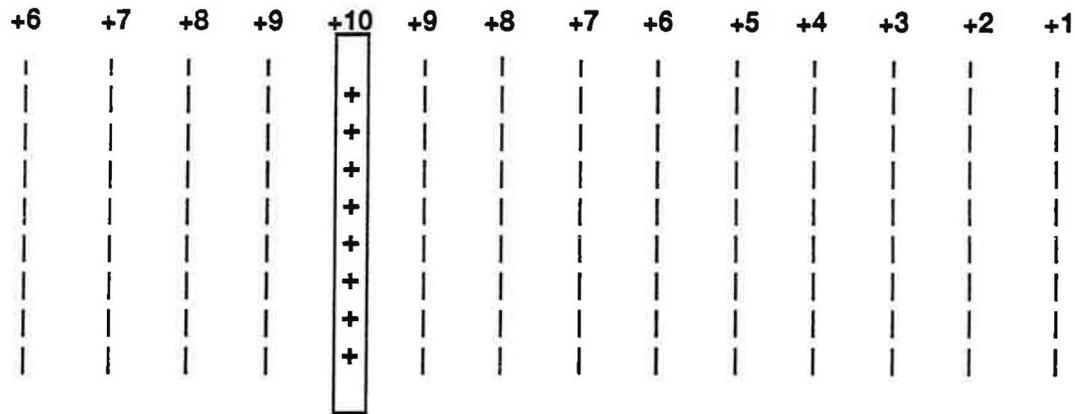


Figure 8.15a
VARIATION OF ELECTRIC POTENTIAL NEAR OF A SHEET OF (+) CHARGE

Figure 8.15b illustrates the halo pattern for a large uniform sheet of negative charge. The negative numbers in this case indicate electric potential below normal.

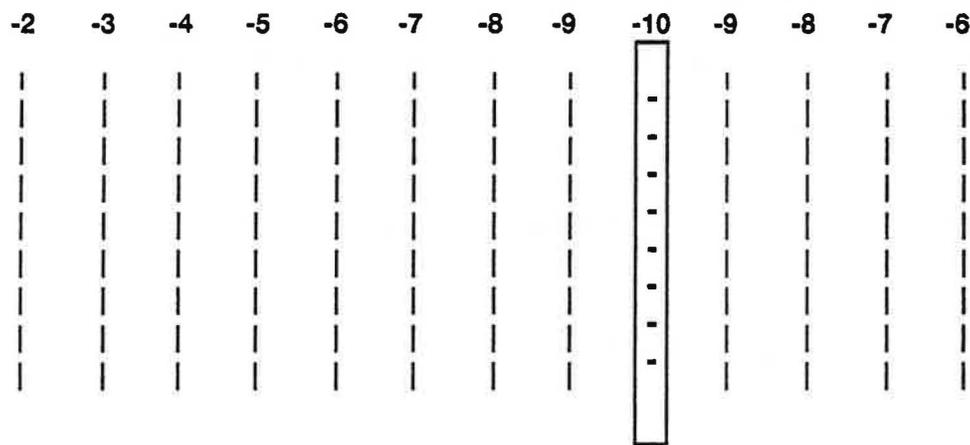


Figure 8.15b
VARIATION OF ELECTRIC POTENTIAL NEAR OF A SHEET OF (-) CHARGE

The first halo has high electric potential which becomes less high with distance from the charge, while the second has low electric potential which becomes less low with distance from the charge.

Important question: How does the electric potential vary in the halo of the (+) and (-) charge sheets together — that is, in the halo of a charged capacitor?

Plausible answer: The net electric potential at any given point is the numerical sum of the values at that point due to the halos of the (+) and (-) charge sheets.

This answer is based on the fact that normal objects show no distant action on each other. So the halos of the (+) and (-) charges in normal matter must cancel out — or the net above-normal electric potential must be zero at every space point. For this to be true, the net electric potential at each point must be the numerical sum of the values due to the individual halos. Figure 8.15c shows the combined halo for large uniform parallel sheets containing equal amounts of (+) and (-) charge. Determine the values by superimposing Figure 8.15a over Figure 8.15b and adding algebraically.

5. In question 3, would charge flow, or would there be no flow, in:

a) the wire connected to the left hand plate? Explain why.

b) the wire connected to the right hand plate? Explain why.

6. Discuss your conclusions with your teacher.

8.17 Exercise: Location of the excess charges

Since capacitor plates have thickness, you can think of the excess charge on a plate as having a location within the plate. Figure 8.17 shows equal excess (+) and (-) charges located at the inner surfaces of the plates—as near each other as they can possibly get.

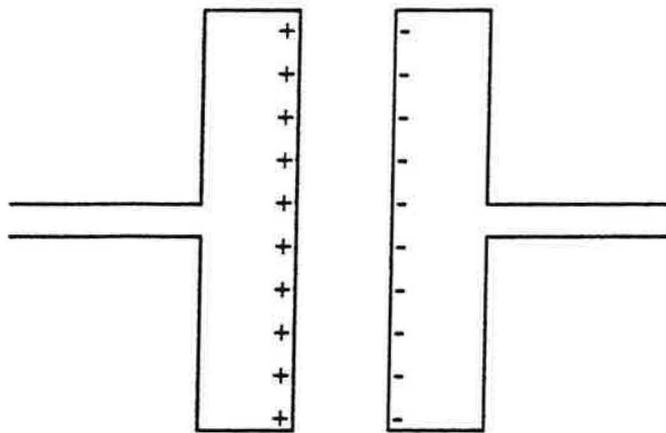


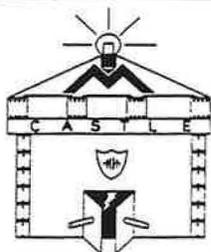
Figure 8.17
THICK CAPACITOR PLATES AND CONNECTING WIRES

1. Explain why these "sheets" of (+) and (-) charge have a combined electric potential halo which is uniform in the plates as well as in the wires.

Now suppose the same sheets of excess (+) and (-) charge were to be located elsewhere in the capacitor plates. To be specific, suppose they are located at the mid-planes of the plates.

2. Explain why the combined electric potential halo then would not be uniform in the plates.

3. Explain why the excess charges would then be quickly driven to the inner surfaces of the plates.



Section 9

HOW IS CHARGE RELATED TO ELECTRONS AND ATOMS?

INTRODUCTION

This section investigates the forces that concentrations of charge exert on each other. The experiments provide evidence that repulsions and attractions between very small amounts of charge — carried by parts of atoms that are too small to see— can explain much of the large scale behavior that we have observed throughout the course.

INVESTIGATION ONE: THE ORIGIN OF FORCES ACTING ON CHARGES

9.1 Activity: Forces on insulating plates charged by rubbing

In Section 8 we created a pair of charged insulators by rubbing a flat plate of acrylic and a Styrofoam picnic plate against each other. The behavior of the two plates suggests that the rubbing scrapes some charge off one material and transfers it to the other, leaving one with excess (+) charge and the other with excess (-) charge. (Many other pairs of materials behave the same way after being rubbed against each other.)

We verified the presence of excess (+) charge on the rubbed acrylic, and of excess (-) charge on the rubbed Styrofoam, by observing how these materials influence mobile charge in nearby conductors. This was done by bringing each rubbed insulator near a capacitor made of two aluminum pie plates, and observing that this caused mobile charge to move through a neon light bulb from one metal plate to the other.

The observed effects can be explained by the following model: (a) A halo of electric potential surrounds every concentration of excess charge. (b) The halos around (+) charges have above-normal potential, while those around (-) charges have below-normal potential. (c) The potential is more above normal or below normal at points nearer the charge, and less above or below normal at points farther away. (c) Values of electric potential in a halo become values of electric pressure in conducting objects placed in the halo.

The predictions of the model for the aluminum pie plates are: (1) Placing two metal plates near a rubbed insulator creates a pressure difference between the nearer and farther plates. (2) Connecting the plates through a neon bulb allows this pressure difference to drive mobile charge through the bulb in one direction. (3) Halos around the (+) acrylic and the (-) Styrofoam push mobile charge through the bulb in opposite directions.

Model checkup: Circle the correct word in each parenthesis in statements (a) and (b) below. Ask the teacher to check your choices and (if needed) discuss them with you.

Statement (a): When rubbed against a Styrofoam plate, an acrylic plate gains an excess of (positive/negative) charge, which (increases/decreases) the electric potential in the space surrounding it and causes positive charge to move through a neon bulb connected between the plates (towards/away from) the acrylic plate.

Statement (b): When rubbed against an acrylic plate, a Styrofoam plate gains an excess of (positive/negative) charge, which (increases/decreases) the electric potential in the space surrounding it and causes positive charge to move through a neon bulb connected between the plates (towards/away from) the foam plate.

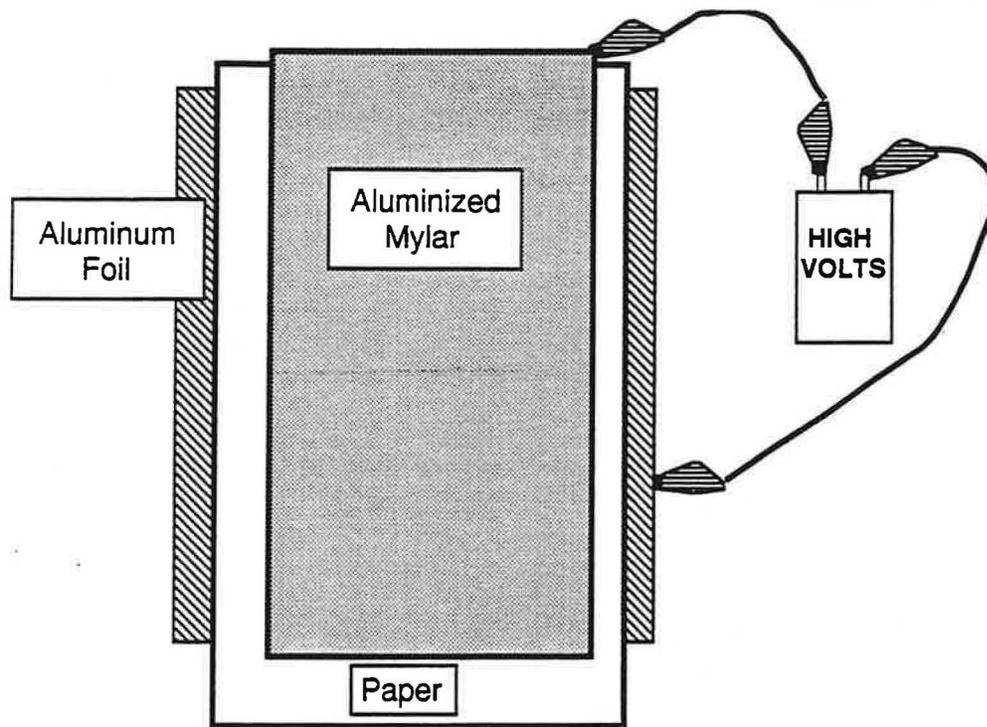


Figure 9.2
THE FLEXIBLE CAPACITOR

2. What did you observe during the demonstration?

3. What does your experience with the charged acrylic and foam plates suggest would happen if the connections to the Mylar and the other plate are reversed?

4. What do you observe?

5. What have you observed which supports the conclusion that the (+) and (-) charges placed in capacitor plates by batteries are the same as the (+) and (-) charges placed on insulators by rubbing them against each other?

9.3 Commentary: From charges pushing to halos pushing

We can explain the behavior of the rubbed and acrylic plates in Activity 9.1, and the similar behavior of the battery-charged capacitor with Mylar plate in Activity 9.2, as consequences of the following principles about charge in matter and the forces they exert on each other:

- (+) and (-) charge is present in all matter.
- Charge in insulators is identical to charge in conductors.
- Like charges repel each other, and unlike charges attract each other.

INVESTIGATION TWO: FORCES ACTING ON TINY CHARGES IN ATOMS

Our experiments up to this point have revealed principles that are valid for relatively large amounts of excess charge — in objects big enough to hold in your hands. The rest of this section will provide evidence that the same principles are valid for much smaller amounts of charge — all the way down to the tiny amounts found in atoms.

9.4 Activity: Forces exerted on smaller amounts of charge

We shall get started on the trail of that evidence by placing a metal pie plate on a table — supported on a Styrofoam cup to insulate it electrically from the table — and bringing a charged acrylic plate near the pie plate as shown in Figure 9.4a.

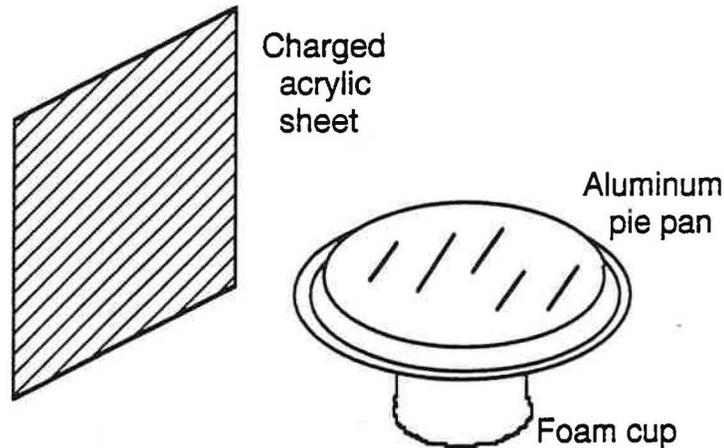


Figure 9.4a

1. Describe the movement of charge that will occur in the aluminum pie plate because of its presence in the electric potential halo of the acrylic plate.
2. Locate the concentrations of (+) and (-) charge that will result from this movement of charge.
3. What would you expect to see if some tinsel is attached to the plate as shown in Figure 9.4b? Write your prediction here before trying it.

Prediction:



Eventually, the combination of repelling forces exerted by excess (+) charges in the (+) plate and attracting forces exerted by excess (-) charges in the (-) plate becomes great enough to balance the propelling force exerted by the battery—and the charging stops. It is then easy to visualize why capacitors spontaneously discharge when the battery is removed and the clip leads are connected: The repelling force exerted by excess (+) charges in the (+) plate and the attracting force exerted by excess (-) charges in the (-) plate are still present, but they are no longer opposed by a propelling force exerted by the battery.

That's how capacitor charging and discharging looks from a microscopic point of view. From a macroscopic point of view, the process is analyzed in terms of electric pressures acting in continuous matter—rather than in terms of forces acting on tiny charged particles. The connection is that pressure values in circuits are the results of forces between charge carriers.

9.7 Activity: Behavior of a conductor in a halo of electric potential

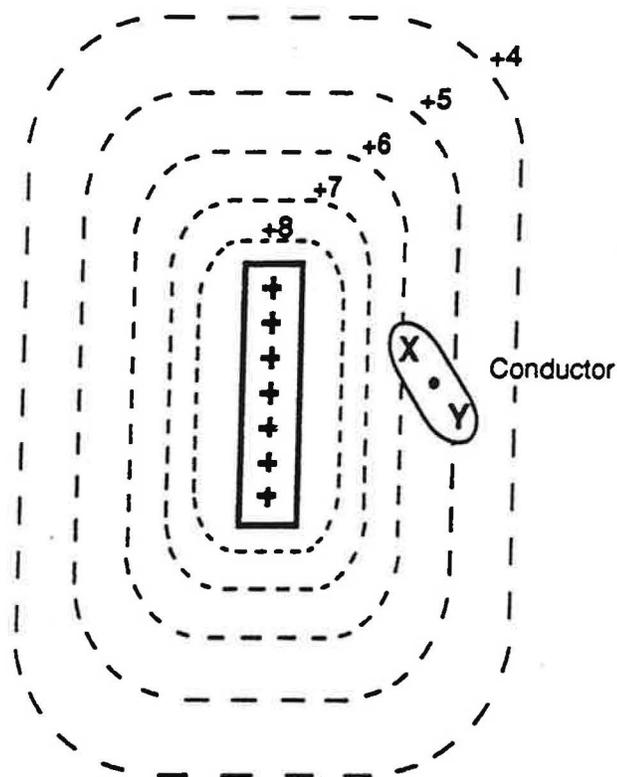


Figure 9.7
A CONDUCTOR IN A HALO OF ELECTRIC POTENTIAL

Imagine a piece of uncharged conductor placed in a halo of electric potential as illustrated in Figure 9.7. This will create differences of actual electric pressure in the conducting body.

1. Which end of the conductor will be at higher electric potential—X or Y?
2. What effect will the potential difference have on movement of positive mobile charge in the conductor?

3. Would the piece of aluminum again be polarized? Would there be any difference in the polarization? Explain.

4. When the foam plate is brought near the versorium, **predict** how you think the behavior of the aluminum foil would be different than when the acrylic plate is brought near the versorium.

5. Try it. Was your prediction correct? Explain your observations.

6. Discuss your observations with your teacher.

9.9 Activity: Behavior of charges in insulators

We have suggested that the difference between conductors and insulators is that it takes a large pressure difference to separate the two kinds of charge in insulators, because charge seems unable to move in those materials. On this basis, we would not expect a versorium made from insulating matter to exhibit the same behavior we have just observed.

To find out if this expectation is actually correct, cut a piece of paper 2 cm by 8 cm and crease and fold it as you did with the foil. Replace the foil paper strip on your pencil point with the paper strip and bring first the charged acrylic and then the charged foam plate near the paper strip.

1. Compare what you observe with the previous behavior of the aluminum foil.

2. Try using other insulating materials to construct a versorium. Summarize your results in the space below.

9.10 Commentary: Separation of charges in atoms

It is possible to explain the behavior you have just observed by making the following assumptions about charges in microscopically small atoms:

- Particles carrying tiny amounts of positive and negative charge are able to move in insulating materials—but only within the confines of the atoms.
- These charge carriers are affected by halos of electric potential the same way as charge carriers that are free to move much larger distances in conductors.

When a charged acrylic plate is brought near the paper strip, the assumptions predict that positive charge carriers in each atom of the paper are pushed away while negative carriers are pulled toward the plate. The distance moved by each charge carrier would be tiny, so the resulting separation between positive and negative charges would be extremely small (less than the diameter of an atom). Within each atom in the piece of paper, however, the negative charge would be a tiny bit closer than the positive charge to the acrylic plate—so all the atoms would be polarized. Although individual polarized atoms are extremely small, there are huge numbers of them in the piece of paper, and the cumulative effect of all of them acting together can cause the paper to behave in much the same way as the polarized piece of aluminum foil.

For a slightly different demonstration of the same phenomenon (the polarization of charge within an insulator) bring each of the charged acrylic and Styrofoam plates, in turn, close to a fine stream of water. In this case the water molecules are permanently polarized because of the unsymmetrical distribution of (+) and (-) charge within each molecule.

When light is continually knocking charged particles out of the half-cylinder, some of these particles will continually be found on the wire. Since the charged particles that have already reached the wire are repelling newcomers back toward the half-cylinder, the amount of charge that reaches the wire cannot increase forever. This amount will reach a steady value when the rate at which particles are repelled back toward the half-cylinder becomes equal to the rate at which they are being knocked out by the incoming light. The axial wire will then have a steady excess of whichever kind of charge the knocked-out particles possess, and the half-cylinder will have an excess of the other kind.

Figure 9.11c illustrates the situation that will exist if the knocked-out particles carry (+) charge, with the axial wire at HIGH electric potential and the half-cylinder at LOW potential. If these particles carry (-) charge, however, the axial wire will be at LOW electric pressure, while the half-cylinder will be charged (+) and be at HIGH electric pressure as illustrated in Figure 9.11d. To find out which of these two possibilities actually occurs, connect a voltmeter to the axial wire and the half-cylinder. (Note: The voltmeter must have very high resistance so that it will not easily discharge the “capacitor.” Analog meters do not have enough resistance for this measurement, but most digital meters do.)

Your voltmeter will probably register several tenths of a volt when ordinary room light is used to illuminate the phototube. You can show that this effect is caused by the light, simply by putting your hand over the phototube. The voltmeter readout will drop to essentially zero when your hand prevents light from getting to the half-cylinder, and will go back up to several tenths of a volt when you remove your hand. The existence of this potential difference, caused by light knocking charge carriers out of matter, is called the “photoelectric effect.”

The polarity of the voltmeter readout shows that the high and low electric potential values correspond to Figure 9.11d — and not to Figure 9.11c. Therefore, the particles knocked out by light striking the metal half-cylinder have to be carriers of (-) charge. Therefore, the “photoelectric effect” shows that (-) charge is more mobile than (+) charge in conducting matter. Since circuit wires are made of metal, just like the semi-cylinder in the phototube, this experiment suggests that the mobile particles moving through the wires of operating circuits are carriers of negative charge.

9.12 Commentary: A second look at neon bulbs

A neon bulb can glow steadily for hundreds of hours. This shows that the atoms of neon in the gas contained by the bulb are not used up in bulb lighting. The atoms are simply broken apart, and the parts carrying (+) and (-) charge are separated, when the bulb is connected to a battery that provides more than 70 volts potential difference.

In order to maintain a steady glow by continual separation of (+) and (-) parts, there must also be continual recombination of the parts (and recycling of the resulting new whole atoms). Where is this recombination occurring? The phototube demonstration suggests the following answer:

- Separation of (+) and (-) charges can result from absorption of light. We can be certain of this from the phototube demonstration.
- Perhaps recombination can lead to emission of light. Emission near one electrode of a neon bulb suggests recombination is occurring there.

You may be skeptical of this conjecture. Certainly, there are two objections that need clarification:

Objection #1: Why must there be absorption of light in the phototube, but not in neon bulbs, in order for separation of to occur? Answer: Separation can occur in more than one way. In neon bulbs, atoms are broken into (+) and (-) parts by the pressure difference due to a strong battery, rather than being hit by incoming light.

Objection #2: Why must there be emission of light in neon bulbs, but not in the phototube, in order for recombination to occur? Answer: Recombination can occur in more than one way. In the phototube demonstration, the knocked-out parts of atoms that reach the axial wire flow back to the half-cylinder through the voltmeter.

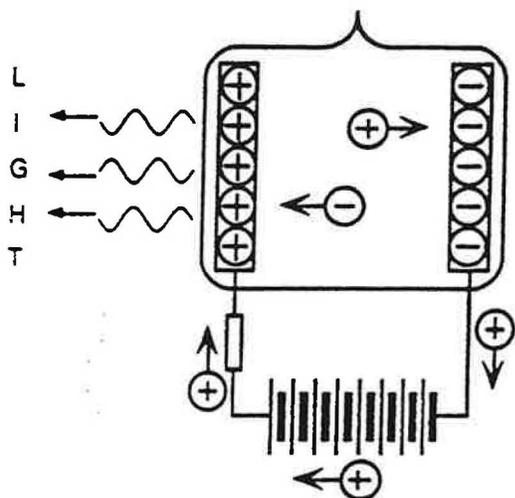


Figure 9.12b
Illustration of what must be happening if particles move through wires and battery carrying (+) charge.

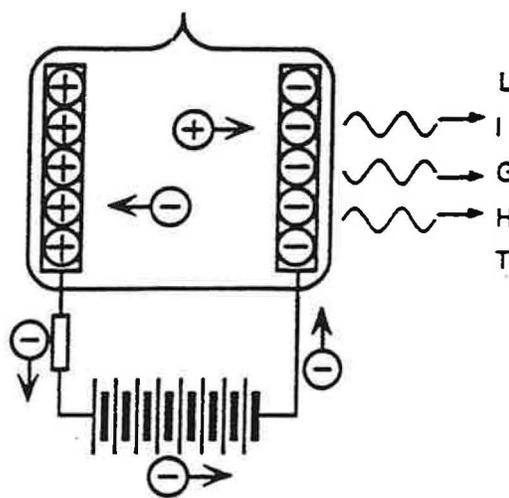
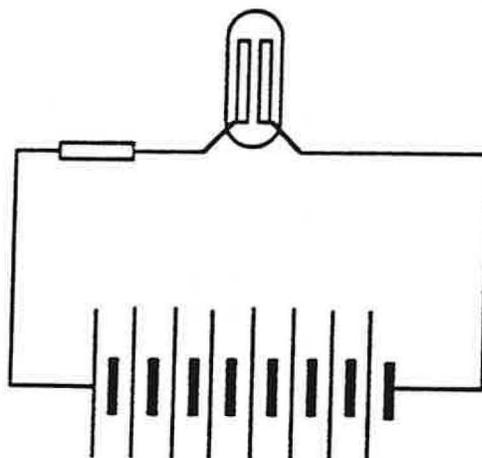


Figure 9.12c
Illustration of what must be happening if particles move through wires and battery carrying (-) charge.

To help you understand the process represented in Figure 9.12c, you should rephrase points (1) to (5) above on the assumption that (-) charge is what's moving through the circuit wires.

9.13 Activity: Which type of charge is moving through the wires?

Set up a circuit with a neon bulb (and its attached resistor) and eight 9-volt batteries, and note the electrode at which light emission occurs. (You may recall having seen this before in Section 8.) As before, the resistor in the circuit limits the flow rate through the bulb and avoids burnout.



CIRCUIT FOR OBSERVING THE SITE OF LIGHT EMISSION
Figure 9.13

The pioneers of electricity research had to face this same dilemma when the electron was discovered at the end of the nineteenth century. They decided to keep on reasoning with the fiction that positive charge moves out of the (+) terminals of batteries. That decision was reasonable, because it always leads to correct conclusions. For example, the charges that end up in the plates of a capacitor are the same whether you say (+) charge moves in one direction or (-) charge moves in the other direction.

So there is no need to change the way you have been reasoning about circuits. Just remind yourself that you are using a convenient fiction by using the phrase "conventional charge flow," as this book has done. You are welcome to reason with "negative charge flow" moving in the opposite direction. However, it is easier to reason with conventional flow—because thinking of positive charge as being pushed through a resistor toward lower "pressure" is intuitive. Since thinking of negative charge as being pushed toward higher "potential" is not intuitive and must be memorized, physicists generally communicate using conventional charge flow.

9.14b Video: Electrostatic Demos

Go to the video-disc set-up and watch the following segment:

Physics: Cinema Classics, Disc 2, Side D, Chapter 41 "Demonstrations". Follow the directions within the segment to proceed through the segment. Set the AUDIO to "Analog 1/L". Can you answer each of the questions? If you have difficulty, the next video assignment will help.

9.14c Video: Ions and electrons

Go to the video-disc set-up and watch the following segment:

The Mechanical Universe, Program 28 "Static Electricity", frame numbers 20526 - 28600.

How would this video segment explain the behavior of the versorium (in section 9.8)? How would it explain the ability of a "rubbed" balloon to attract and stick to a wall (as in the video segment in 9.14b)?

Explain the process called "grounding". Why do you think it has that name?

9.14d Video: Batteries

Now that we know it is electrons that are the mobile charge carriers in conductors we can see how a battery works. Go to the video-disc set-up and watch the following segments:

The Mechanical Universe, Program 32 "The Electric Battery", frame numbers 26381 - 29000 and 30671 - 35907.

The "work function" is a measure of the electric pressure (or potential) that keeps electrons from leaving the surface of a metal. The higher that pressure is, the more difficult it would be for electrons to leave the metal. An "electrolyte" is a substance containing mobile ions, both (+) ions and (-) ions. The (-) ions consist of neutral atoms or molecules that have become negative by gaining one or more electrons, while (+) ions are neutral atoms or molecules that have become positive by losing one or more electrons.

Why must batteries be constructed using different types of metal for the two electrodes?

What is the role of the electrolyte in a battery?

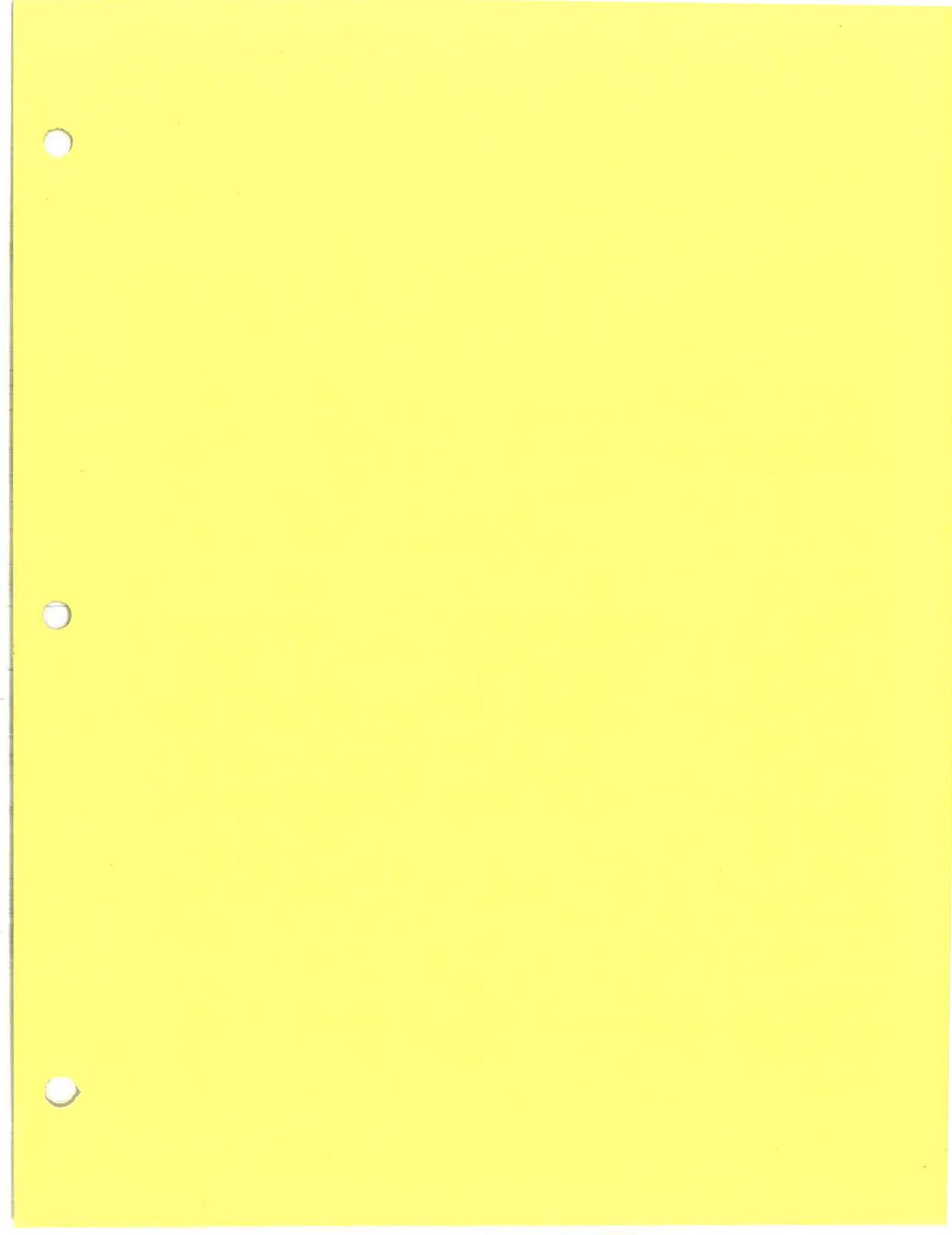
What do you think has happened when a battery becomes "dead"?

What is the relationship between the strength of the electric field and the spacing of the "lines of force" (the lines representing the electric field) ?

Why does the spacing between the lines increase as you get farther from the charge responsible for establishing the electric field?

Why don't the lines of an electric field cross one another? (Hint: Think about the direction of the force felt by a test charge located at a point where two electric field lines cross.)

Discuss your conclusions with your teacher.



Introduction to the Macintosh Computer

During this course you will use the Macintosh computer for many tasks. It will make life easier for you by assisting with data collection, data analysis, graphing, and the process of creating models to explain your observations and discoveries. Using it you will also have access to instructional CD-ROMs covering the material in the course. You will find that the computer skills you develop here will be helpful to you in other courses as well.

1.1 Exercise

To begin, turn on the switch on the power strip your computer and monitor are plugged into. It should be mounted on the front of the wall cabinet. If necessary, turn on the switch for the computer itself, which is the key located at the upper right-hand end of the keyboard; it contains the " \triangleleft " symbol. Also turn on the power switch on the monitor; it is located at the lower right on the front of the monitor.

Once the computer comes on you will see a picture of a question mark at the top right of the computer screen. Maneuver the "arrow" with the mouse until the arrow touches the  picture. Hold the mouse button down and drag down to the line that reads **Macintosh Tutorial**, which will cause it to change from black lettering on a white background to white lettering on a black background. When that occurs release the mouse button. The tutorial will then begin. Start with PART 1. You select it by positioning the arrow over the words "PART 1" and clicking the mouse button once to select it. This part will take about 15 minutes. Once completed you will know how to use the mouse to "point", "click", and "drag".

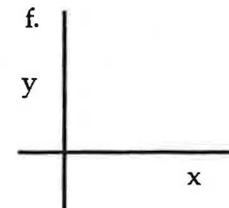
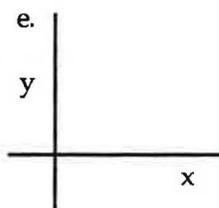
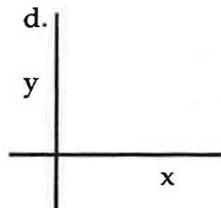
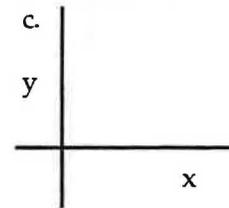
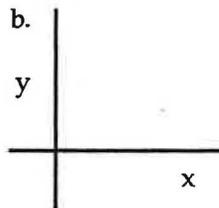
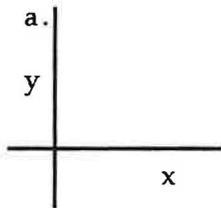
When you finish PART 1, continue on with PART 2 and work through all 9 sections. This should take you about 45 minutes.

1.2 Exercise

Built into the Macintosh is a graphing calculator. It is available under the " " menu, which is located at the upper left on the monitor screen. Position the arrow on the  and drag down to **Graphing Calculator**, releasing the mouse button when that line becomes highlighted. A window will open containing a text box across the top and a blank graph (containing axes labeled with numerical scales) below it.

In this exercise you will enter the following equations in the text box and then instruct the computer to draw the corresponding graph (by clicking on the Graph button at the lower right on the Graphing Calculator window). For each graph, draw a sketch of it on one of the graphs on this page. Be sure to also write the equation on the graph.

- a. $y = x$
- b. $y = 2x + 1$
- c. $y = x/2 - 2$
- d. $y = -x$
- e. $y = -x + 2$
- f. $y = -x - 2$



What do these six graphs have in common?

How do the first three differ among themselves? What property of the equations causes the differences?

How are the first three different from the last three? What property of the equation causes the difference?

Why do the graphs in Step b and Step f have the same appearance?

In what way(s) are the graphs in Step d and Step e similar? How are they different?

In what way(s) are the graphs in Step c and Step g similar? How are they different?

1.5 Commentary

Multiplying both sides of the equation in Step c by x gives the equivalent equation $xy = 1$. The graph obtained for Step c is characteristic of all situations where the product of two quantities remains constant. In this case the constant equals 1. Two quantities related in this way are said to be inversely proportional to each other.

Comparing the graphs drawn in Exercises 1.2 and 1.4 with those you will draw as the course progresses may help give you an idea of the mathematical relationship between the quantities you are investigating.

In the following exercise you will gain practice using a graphing software to plot two sets of data.

1.6 Exercise

Open the hard disc by double-clicking on the Mac HD icon located near the upper right portion of the screen. In a similar manner, open the Graphical Analysis folder, and the Graphical Analysis software program by double-clicking on each of these icons in succession. The screen that appears contains three parts: (1) a data set region, (2) a graph region, and (3) a text window. Notice that both the data quantities and the graph axes are labeled X and Y, and that the X data will be plotted along the horizontal axis, while the Y data will be plotted along the vertical axis.

The following data represents the position of an object as a function of time.

Time (s)	Position (cm)
0.000	0.00
0.033	2.50
0.067	6.10
0.100	10.75
0.133	16.45
0.167	23.25
0.200	31.15
0.233	40.10
0.267	50.10
0.300	61.25
0.333	73.40
0.367	86.70

MECHANICS

**PHYSICS 1
MT. SAN ANTONIO COLLEGE**

Table of Contents

page		
4	Unit 1	Measurement and Uncertainty
17	Unit 2	One-Dimensional Motion
18	Lesson 2	Describing Motion with Words and Graphs
32	Lesson 3	Changing Motion
43	Lesson 4	Slowing Down, Speeding Up, and Reversing Direction
53	Lesson 5	Describing Motion with Equations
64	Unit 3	One-Dimensional Forces, Mass, and Motion
66	Lesson 6	Combining Forces
83	Lesson 7	Force, Mass and Acceleration
94	Lesson 8	Gravitational Forces
112	Lesson 9	Newton's Third Law and Passive Forces
124	Unit 4	Two-Dimensional Motion
125	Lesson 10	Projectile Motion
134	Lesson 11	Uniform Circular Motion
145	Unit 5	One-Dimensional Collisions
147	Lesson 12	Momentum and Momentum Change
154	Lesson 13	Impulse, Momentum and Interactions
161	Lesson 14	Newton's Laws and Momentum Conservation
170	Unit 6	Work and Energy
172	Lesson 15	Physical Work and Power
179	Lesson 16	Work and Kinetic Energy
187	Lesson 17	Conservation of Energy
197	Unit 7	Harmonic Motion, Waves, and Wave Behavior
199	Lesson 18	Simple Harmonic Motion
206	Lesson 19	Wave Motion
211	Lesson 20	Resonance and Standing Waves
218	Lesson 21	Polarization, Diffraction, and Interference
222	Lesson 22	Resonance States in Atoms

Our ideas about how things work in the real world are generally formed through our personal experience and through our observations. Sometimes the concepts we form are accurate and true to nature. Sometimes they are not, often because our experience is limited. But sometimes our observations are not of real world experiences, but rather of contrived, artificial experiences, particularly in science fiction movies and in cartoons.

The following is a list called The Cartoon Laws of Physics.

Law I: Any body suspended in space will remain in space until made aware of its situation.

Daffy Duck steps off a cliff, expecting further pastureland. He loiters in midair, soliloquizing flippantly, until he chances to look down. At this point, the familiar principle of 32 feet per second per second takes over. However, he will not necessarily fall immediately. He may be given the chance to run (on air) back toward the precipice before he begins to accelerate downwards. He usually cannot run fast enough, and starts to fall JUST before his arms can reach the edge.

Nor does he necessarily always accelerate at 32 feet per second per second, but often reaches a high velocity instantaneously. Also, this high velocity causes tidal forces such that his arm stretches (while the rest of him falls) long enough to wave bye-bye.

Law II: Any body in motion will tend to remain in motion until solid matter intervenes suddenly.

Whether shot from a cannon or in hot pursuit on foot, cartoon characters are so absolute in their momentum that only a telephone pole or an outside boulder retards their forward motion absolutely. Sir Isaac Newton called this sudden termination of motion the stooge's surcease.

Law III: Any body passing through solid matter will leave a perforation conforming to its perimeter.

Also called the silhouette of passage, this phenomenon is the specialty of victims of directed-pressure explosions and of reckless cowards who are so eager to escape that they exit directly through a wall, leaving a cookie-cutout-perfect hole. The threat of skunks or matrimony often catalyzes this reaction.

Law IV: The time required for an object to fall twenty stories is greater than or equal to the time it takes for whoever knocked it off the ledge to spiral down 20 flights to attempt to capture it unbroken.

Such an object is inevitably priceless, thus the attempt to capture it will be inevitably unsuccessful.

Law V: All principles of gravity are negated by fear.

Psychic forces are sufficient in most bodies for a shock to propel them directly away from the earth's surface. A spooky noise or an adversary's signature sound will induce motion upward, usually to the cradle of a chandelier, a treetop, or the crest of a flagpole. A character's feet when running or the wheels of a speeding auto need never touch the ground, especially when in flight.

Law VI: As speed increases, objects can be in several places at once.

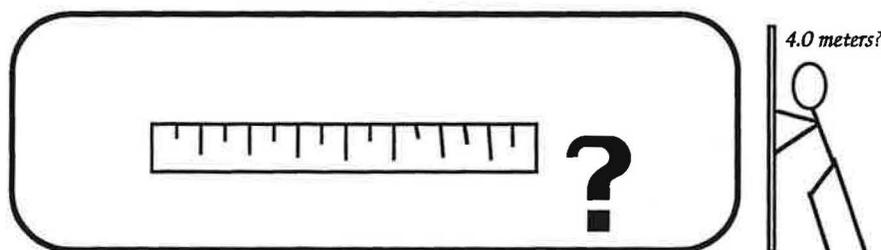
This is particularly true of tooth-and-claw fights, in which a character's head may be glimpsed emerging from the cloud of altercation at several places simultaneously. This effect is common as well among bodies that are spinning or being throttled. Only at manic high speeds, the wacky guy may ricochet off walls to achieve the velocity required.

Law VII: Certain bodies can pass through solid walls painted as tunnel entrances; others cannot.

This *trompe l'oeil* inconsistency has baffled generations, but at least it is known that whoever paints an entrance on a wall's surface to trick an opponent will be unable to pursue him into this theoretical space. The painter is flattened against the wall when he attempts to follow into the painting. This is ultimately a problem of art, not of science.

Corollary: Portable holes work.

Unit 1: MEASUREMENT AND UNCERTAINTY



OBJECTIVES

1. To define fundamental measurements for the description of motion and to develop some techniques for making indirect measurements using them.
2. To learn how to quantify and minimize sources of random uncertainty so that the precision of measurements can be enhanced.
3. To learn how to compensate for systematic error in measurements so that accuracy can be improved.

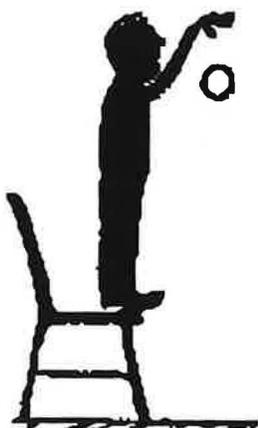
OVERVIEW

Initially in this section of the course you will focus on the task of developing a mathematical description of the motion of objects. The study of how objects move is known as kinematics, and it can be conducted using only two fundamental types of measurements – length and time. For instance, if you are interested in determining how fast a pitched baseball is moving in a horizontal direction, you need to do several things: define horizontal speed (i.e. the meaning of "how fast") in terms of distance moved in space and time-of-flight; measure the distance and time-of-flight of a moving baseball; and calculate the speed of the baseball from your measurements.

The measurement of the speed of a pitched ball is, in reality, an indirect measurement. Almost any quantity has to be measured indirectly under certain circumstances. In this lesson, you will make direct measurements of distance and time, and use them to get an indirect measurement of speed. This should provide first-hand experience with an age old question about the measurement process: Is it possible to make exact measurements?

You will make direct measurements of time by dropping a ball repeatedly. Many sources of variation of the time-interval data will be explored including mistakes, systematic error and random uncertainty.

The major goal of this lesson is to help you determine, for a number of measurements you will make in this course, whether or not the results of a given experiment are compatible with theory.



You and your partners can take repeated data on the time of fall of a ball and eventually share it with the rest of the class. In this way, the class can amass a lot of data and study how it varies from some average value for the time-of-fall.

- (a) Drop the ball so it falls through a height of exactly 2.0 m at least 20 times in rapid succession and measure the time of fall to two significant figures. Take turns so that each of you gets a chance to make some measurements. Be as exact as possible about the height from which you drop the ball; we will be compiling data from the entire class in a later exercise. Record the data in the table below and enter it in a computer spreadsheet. To get a spreadsheet, open **ClarisWorks** in the ClarisWorks 4.0 folder and select **Spreadsheet** from the **New Document** window. When the spreadsheet appears, click on cell A1 to select it and type the first measurement. Press the return key on the keyboard to enter the data. This will also move you down to the next cell. Continue until all 20 measurements are entered.

Reading Number	Time (s)	Reading Number	Time (s)
1		11	
2		12	
3		13	
4		14	
5		15	
6		16	
7		17	
8		18	
9		19	
10		20	

- (b) Use the spreadsheet to determine the average time-of-fall, $\langle t \rangle$, for your 20 measurements. Do this as follows:

Click in cell B1.

Type "=" (without the quotes, of course).

Drag down in the **Edit** menu until **Paste Function** is highlighted.

Scroll down the **Paste Function** window to the function **AVERAGE(number 1, number 2,...)** and release the mouse button when that function is highlighted. Click **OK**.

Select all your data by clicking on cell A1 and, holding the mouse button down, dragging down to the last cell containing data - which should be cell A20 - before releasing the mouse button. You will notice that the argument of **AVERAGE** has changed from "number 1, number 2,..." to "A1..A20". Press the return key to enter this equation. The average will be calculated and recorded in cell B1.

Report the average value in the space below using three significant figures. **Note:** Be sure to save your spreadsheet as you will be using it again.

$t(\text{ave}) =$

number of lines that can be drawn into a centimeter length of the stick. The same is true of a stopwatch, since there is a limit to the number of equal divisions one can divided a second of time into.

Another cause of inherent uncertainties is the large number of random variations affecting any phenomenon being studied. For instance, when you repeatedly dropped a ball from the top of a two-meter stick and measured the time of each fall, the measurements were not all the same. Even if the stop watch was gated electronically so as to be as precise as possible, there would be small fluctuations in the flow of currents through the circuits as a result of random thermal motion of atoms and molecules that make up the wires and circuit elements. This could change the stop watch reading from measurement to measurement. The sweaty palm of the experimenter could cause the ball to stick to the hand for an extra fraction of a second, slight air currents in the room could change the ball's time of fall, vibrations could cause the floor to oscillate up and down an imperceptible distance, and so on.

How certain are we that the average fall-time determined in Experiment 1.2 is accurate? The average of a number of measurements does not tell the whole story. If all the times you measured were the same, the average would seem to be very precise. If each of the measurements varied from the others by a large amount, we would be less certain of the meaning of the average time. We need criteria for determining the certainty of our data. Statisticians often use a quantity called the standard deviation as a measure of the level of uncertainty in data. In fact, almost all scientific and statistical calculators and spreadsheets have a standard deviation function. The standard deviation is usually represented by the Greek letter σ (sigma; since sigma sometimes has other meanings in physics, we will designate the standard deviation by using a subscript: σ_{sd}). σ_{sd} has a formal mathematical definition which we will not be concerned with in this course. The value of σ_{sd} is often used to measure the level of uncertainty in data.

In the next exercise you will use the spreadsheet to calculate the value of the standard deviation for the repeated fall-time data you obtained in experiment 1.2 and explore how the standard deviation is related to variation in your data. In particular, you will try to answer this question: What percentage of your data lies within one standard deviation of the average you calculated?

1.6 Exercise. Standard Deviation

Open the spreadsheet containing the time-of-fall data you collected in Experiment 1.2. Calculate the standard deviation of the set of 20 measurements as follows.

Click on cell B4 to select it.

Type "=" (without the quotes, of course).

Drag down in the Edit menu until **Paste Function** is highlighted.

Scroll down the **Paste Function** window to the function **STDEV(number 1, number 2,...)** and release the mouse button when that function is highlighted. Click **OK**.

1.7 Commentary. Systematic Error – How About the Accuracy of Your Timing Device and Timing Methods?

As the result of problems with your measuring instrument or the procedures you are using, each of your measurements may tend to be consistently too high or too low. If this is the case, you probably have a source of systematic error. There are several types of systematic error.

Most of us have set a watch or clock only to see it gain or lose a certain amount of time each day or week. In ordinary language we would say that such a time keeping device is inaccurate. In scientific terms, we would say that it is subject to systematic error. In the case of a stopwatch or digital timer that doesn't run continuously like a clock, we have to ask an additional set of questions. Does it start up immediately? Does it stop exactly when the event is over? Is there some delay in the start and stop time? A delay in starting or stopping a timer could also cause systematic error.

Finally, systematic error can be present as a result of the methods you and your partners are using for making the measurement. For example, are you starting the timer exactly at the beginning of the event being measured and stopping it exactly at the end? Are you dropping the ball from a little above the exact starting point each time? A little below?

It is possible to correct for systematic error if you can quantify it. Suppose that God, who is the supreme theoretical physicist, said that the distance in meters, y , that a ball falls after a time of t seconds near the earth's surface in most places is given by the equation

$$y = (1/2) a_g t^2$$

where a_g is called the gravitational constant (equal to 9.8 m/s/s). (In this idealized equation the effects of air resistance have been neglected.)

Does the theoretical value for the time-of-fall lie within the calculated uncertainty of your average measured value? In the activity that follows, you should compare your average time-of-fall with that expected by theory. If you determine that a systematic error probably exists, can you devise a way to determine its cause and magnitude?

1.8 Exercise. Is There Systematic Error in the Data?

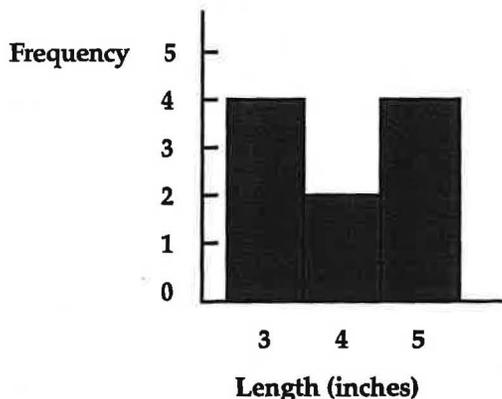
- (a) Measure the distance of fall and calculate the theoretical, God given, time-of-fall in the space below.

- (b) Does the theoretical value lie in the range of your own average value with its associated uncertainty? Use your calculated standard deviation (from Exercise 1.6) as the measure of your value's uncertainty. If not, you probably have a source of systematic error.

- (c) If you seem to have systematic error, explain whether the measured times tend to be too short or too long and list some of the possible causes of it in the space below.

- The horizontal axis of your graph indicates the quantities whose frequencies you are graphing; the vertical axis of your graph gives the frequencies. Above each quantity on the horizontal axis, draw a rectangle whose height corresponds to the frequency of that quantity. Repeat this step for each quantity measured.

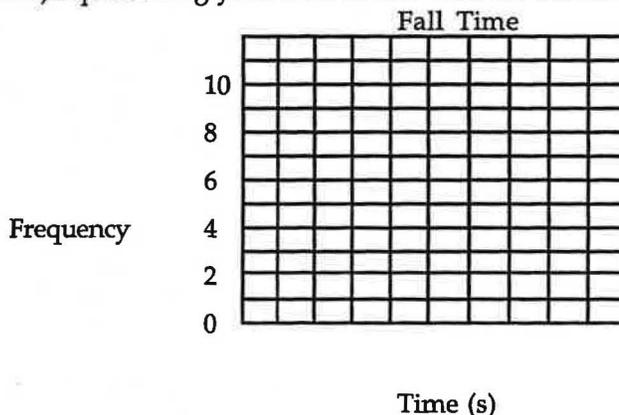
As an example, consider a very simple frequency distribution. Imagine that you have caught ten fish. Of these ten, four are 3" long, two are 4" long, and four are 5" long. The frequency distribution would appear as follows:



1.10 Exercise. Frequency Distribution for Your Time-of-fall Data

- Draw a frequency diagram (known as a histogram) representing your time-of-fall data for the ball in the grid below.

time (s)	frequency	time (s)	frequency



- Next, using a different color of pen or pencil sketch in the histogram above the results of the other group working at your lab table. To which of the three "distributions" pictured on the previous page does your distribution above most closely correspond?

How do the two distributions plotted above compare with each other?

Doing the Experiment

You should find the radiation monitor plugged into DG1 on the ULI, and the ULI plugged into the Power Mac. Be sure that the AC Adaptor for the ULI is plugged in and that the ULI's power switch (located on the back) is turned on. A green light will be illuminated on its front if it is turned on.

Lean the radioactive source up against a book and lay the radiation monitor on the lab table so that it points at the source and is about one centimeter away from it. Turn on the monitor and start with the counts switch in the "x1" position. If the needle goes beyond the end of the scale, change the counts switch to "x10".

On the Mac HD open the **Experiment data takers folder**, then open the **Event Counter folder**, and then open the **Event Counter** software.

When the Untitled-1 graph window appears make the following settings:

Drag down the **Collect** option in the menu bar to **Count Interval...** Set the count interval to 0.5 seconds.

Drag down the **Display** option in the menu bar and select (by releasing the mouse button when the option is highlighted) both **One Graph** and **Histogram**. (You can only select one at a time.)

Drag down the **Collect** option in the menu bar to **Run Time...** and set the run time to 10 seconds.

Click on the **Start** button at the bottom left of the graph window.

When the counting process has concluded click on the **Done** button at the bottom left of the graph window. Statistics showing the Mean (or average) and the Std. Dev. (e.g., standard deviation) will appear at the top of the graph window. If the Mean is less than 6 move the monitor a little closer to the radioactive source and repeat your 10 second reading. If the Mean is greater than 10 move the monitor a little farther away from the radioactive source, and repeat your 10 second reading. Continue this process until your Mean is between 6 and 10.

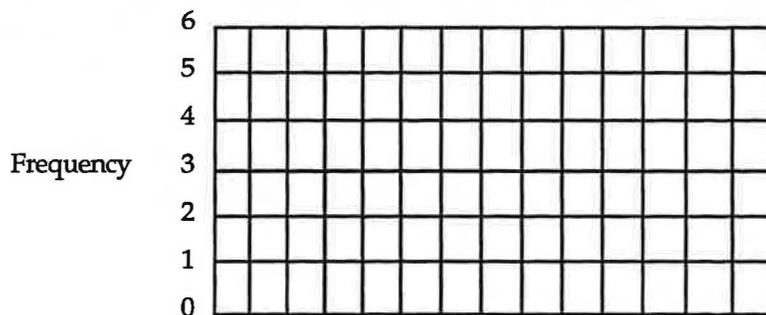
Once the Mean is between 6 and 10 do two things:

(1) draw a sketch of the histogram on the graph below;

(2) reset the **Run Time...** to at least 500 seconds (which is less than 9 minutes). If you have the time, you might consider setting the run time to 1000 seconds (which is still only a little over 16 minutes). Since you are getting 2 readings each second, a run time of 500 seconds will give you 1000 readings.

When everything is set up, click on **Start**.

Beta Decays (20 intervals)



counts per half-second

You will now let the computer plot the frequency distribution histogram for you automatically as it collects the data. This will allow you to obtain a frequency distribution for a thousand or more repeated counts/interval measurements.

Watch the process for awhile as the histogram is being produced. Do the readings appear in any predictable sequence?

Now answer the same questions for your histogram of 1000 or more readings of the radioactive beta decay process.

Does the histogram have a bell shape?

Does the peak coincide with the average value?

Determine, as best you can from your graph printout, the percentage of your readings that lie within $\pm\sigma_{sd}$ of the average. Show your calculations below. Are 68% of the readings within one standard deviation of the average?

Determine the percentage of your readings that lie within $\pm 2\sigma_{sd}$ of the average. Show your calculations below. Are 95% of the readings within two standard deviations of the average?

Can you conclude that the radioactive beta decay process is random? Explain.

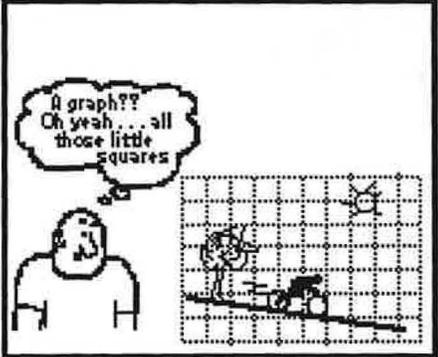
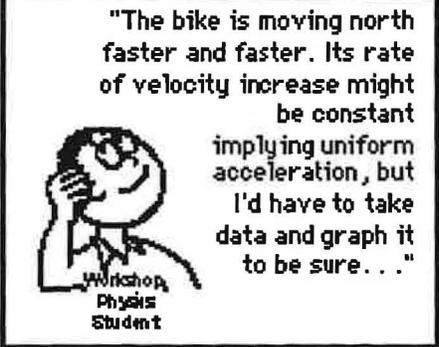
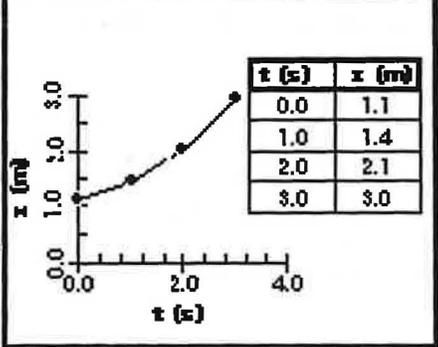
1.14. Commentary.

According to measurement theory, the inherent uncertainties present in any measurement process exhibit random behavior. That is why it is common practice to make a measurement several times and use the average as the best estimate of the measured quantity and to use the standard deviation as an estimate of the uncertainty. You can be sure that if you had dropped the ball in Experiment 1.2 1,000,000 times and plotted a frequency-of-reading histogram it would have the characteristic bell shape representative of a random process.

If you have any questions, discuss them with your teacher.

Lesson 2: Describing Motion with Words and Graphs

The focus in this lesson on kinematics is to be able to describe your position and velocity over time using words and graphs. You will use a motion detector attached to a computer to learn to describe one-dimensional motion.

	Describing Motion With Words . . .	Describing Motion With Graphs . . .										
Average Joe Schmoe	 <p>Uhh . . . the bike rolled down the hill.</p>	 <p>A graph?? Oh yeah . . . all those little squares</p>										
Physics Student	 <p>"The bike is moving north faster and faster. Its rate of velocity increase might be constant implying uniform acceleration, but I'd have to take data and graph it to be sure . . ."</p>	 <table border="1"> <thead> <tr> <th>t (s)</th> <th>x (m)</th> </tr> </thead> <tbody> <tr> <td>0.0</td> <td>1.1</td> </tr> <tr> <td>1.0</td> <td>1.4</td> </tr> <tr> <td>2.0</td> <td>2.1</td> </tr> <tr> <td>3.0</td> <td>3.0</td> </tr> </tbody> </table>	t (s)	x (m)	0.0	1.1	1.0	1.4	2.0	2.1	3.0	3.0
t (s)	x (m)											
0.0	1.1											
1.0	1.4											
2.0	2.1											
3.0	3.0											

For the investigations in this lesson you will need:

- a PowerMac computer
- a ULI laboratory interface
- a ULI motion detector (ultrasonic)
- MacMotion 4.5 software
- a number line on the floor

How does a position vs. time graph look when you move slowly? Quickly? What happens when you move toward the motion detector? Away? After completing the next few activities, you should be able to look at a position vs. time graph and describe the motion of an object. You should also be able to look at the motion of an object and sketch a graph representing that motion.

Note:

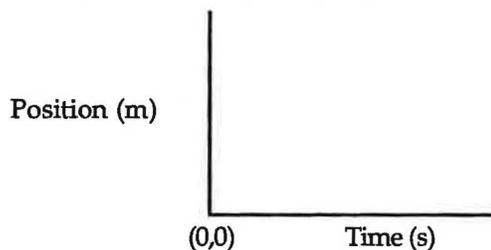
- "Position" means "distance from the motion detector."
- The motion detector is located at the origin of each graph.

To do the following experiments you will need the ULI motion detector plugged into Port 2 on the ULI, and the ULI plugged into the PowerMac. Be sure that the AC Adaptor for the ULI is plugged in and that the ULI's power switch (located on the back) is turned on. A green light will be illuminated on its front if it is turned on. Open the **Mac HD**, the **Physics Programs** folder, and the **MacMotion 4.5** software.

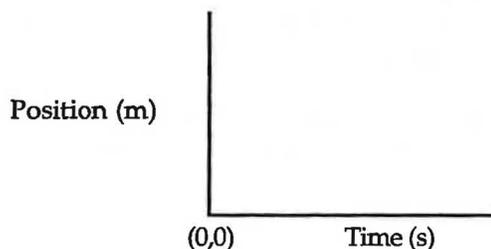
2.1 Experiment. Making Position vs. Time Graphs

Make position-time graphs for different walking speeds and directions by clicking on the start button at the bottom of the screen and walking in front of the motion detector at distances that are no closer than 0.5 m. Try the following motions and sketch the graph you observe in each case:

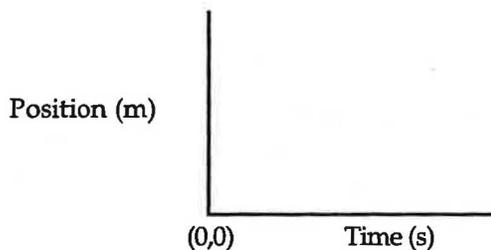
- (a) Start at 0.5 m walk away from the origin (i.e. the detector) slowly and steadily.



- (b) Walk away from the origin medium fast and steadily.

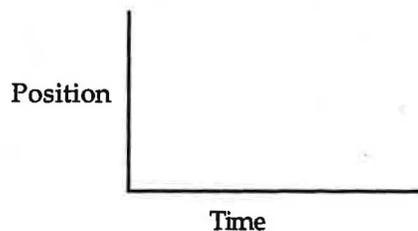


- (c) Walk toward the detector (origin) slowly and steadily. Sketch the graph.

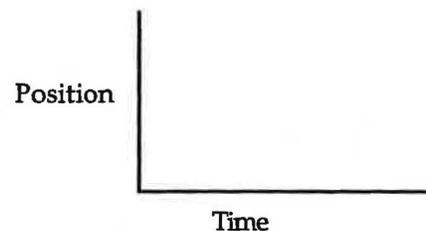


- (d) Describe the difference between the graph you made by walking away slowly and the one made by walking away more quickly.
- (e) Describe the difference between the graph made by walking toward and the one made walking away from the motion detector.

- (b) Describe in your own words how you plan to move in order to match this graph.
- (c) Move to match the **Position Match** graph on the computer screen. You may try a number of times. It helps to work in a team. Get the times right. Get the positions right. Do this for yourself. (Each person in your group should do his or her own match.) **You will not learn very much by just watching!**
- (d) What was the difference in the way you moved to produce the two differently sloped parts of the graph you just matched?
- (e) Now move your body in such a way as to make curved position vs. time graphs like those shown below. **Note:** Before trying to reproduce the shapes shown below, get rid of the graph you just matched by choosing **Hide Data B** from the **Data** option in the menu bar in the **MacMotion** software.



Graph 1

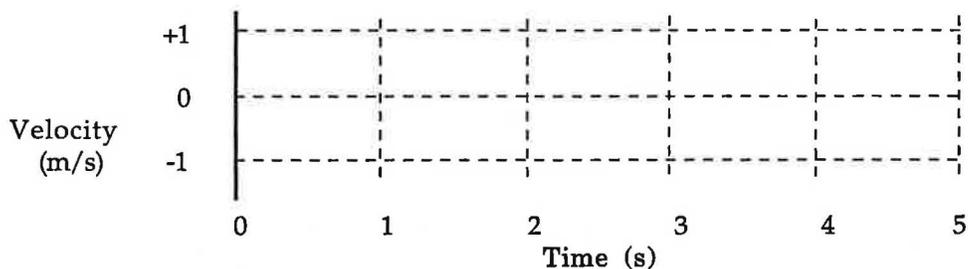


Graph 2

- (f) Describe how you had to move to produce a position vs. time graph with each of the shapes shown.
- Graph 1 answer:
- Graph 2 answer:
- (g) What is the general difference between motions which result in a straight line position vs. time graph and those that result in a curved-line position vs. time graph?

Discuss your results with your teacher.

(c) Make a velocity graph, walking toward the detector slowly and steadily. Sketch your graph below.



(d) What is the most important difference between the graph made by slowly walking away from the detector and the one made by walking away more quickly?

(e) How are the velocity vs. time graphs different for motion away and motion toward the detector?

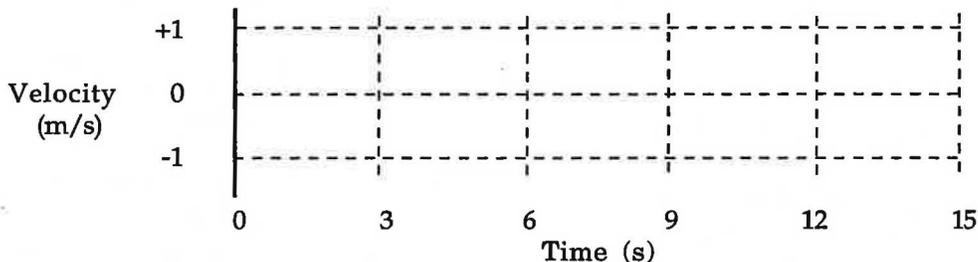
Discuss your results with your teacher.

2.5 Experiment. Predicting a Velocity vs. Time Graph Based on Words

Suppose you were to undergo the following sequence of motions:

1. walk away from the detector slowly and steadily for 6 seconds
2. stand still for 6 seconds
3. walk toward the detector steadily about twice as fast as before

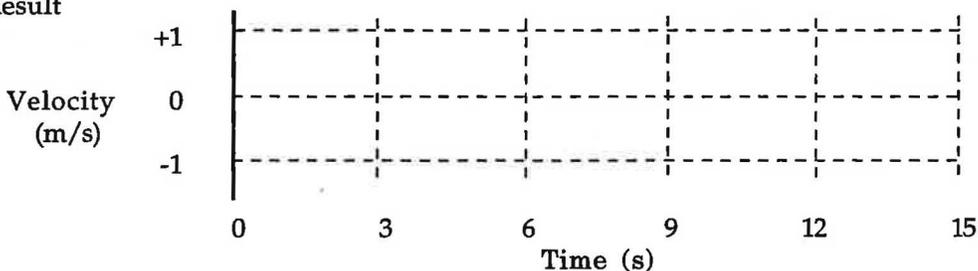
(a) Use a dashed line in the graph that follows to record your prediction of the shape of the velocity graph that will result from the motion described above.



(b) Compare predictions with your partners and see if you can all agree. Use a solid line to sketch your group prediction in the graph above.

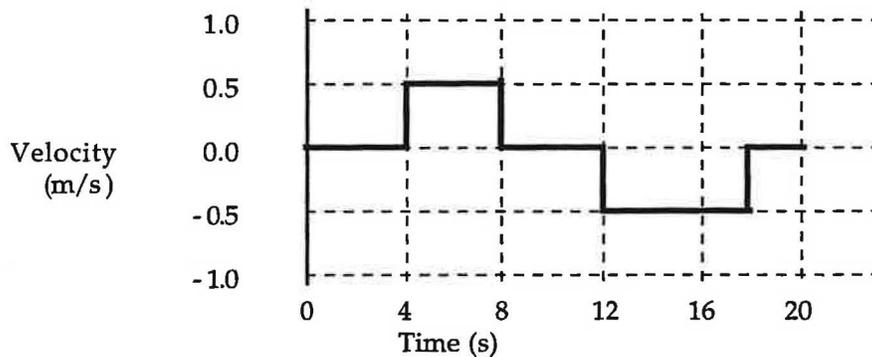
(c) Adjust the time scale to 15 s in the **MacMotion** software and then test your prediction. Repeat your motion until you are confident that it matches the description in words and then draw the actual graph on the axes below. Be sure the 6-second stop shows clearly.

Final Result



Velocity Graph Matching

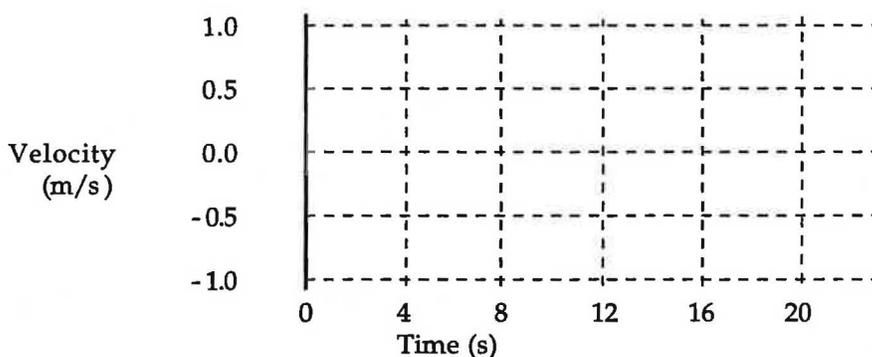
In the next experiment, you will try to move to match a velocity graph shown on the computer screen. This is often much harder than matching a position graph as you did in Experiment 2.3. Most people find it quite a challenge at first to move so as to match a velocity graph. In fact, some velocity graphs that can be invented cannot be matched! To do this activity **Open** (by double clicking on) the file **L1A2-2 (Velocity Match)** in the **RTP Experiment Files** folder in the **MacMotion** folder. The following velocity graph should appear on the screen.



2.8 Experiment. Matching a Velocity Graph

(a) Describe how you think you will have to move in order to match the given velocity graph.

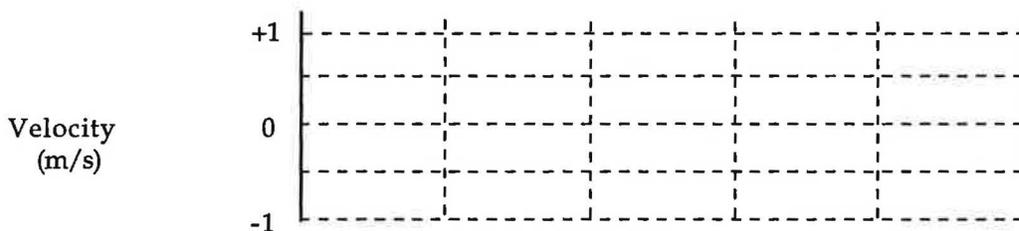
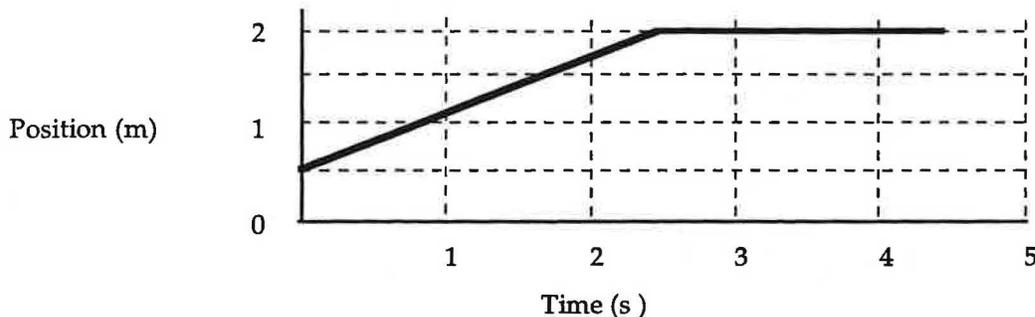
(b) Move in such a way that you can reproduce the graph shown. You may have to practice a number of times to get the movements right. Work as a team and plan your movements. Get the times right. Get the velocities right. You and each person in your group should take a turn. Then draw in your group's best match on the axes that follow.



(c) Describe how you moved to match each part of the graph.

2.10 Experiment. Predicting Velocity Graphs from Position Graphs

- (a) Carefully study the position graph shown below and predict the velocity vs. time graph that would result from the motion. Using a dashed line, sketch your prediction of the corresponding velocity vs. time graph on the velocity axes.



- (b) After each person in your group has sketched a prediction, test your prediction by matching the position vs. time graph shown. When you have made a good duplicate of the position graph, sketch your actual graph over the existing position vs. time graph.
- (c) Use a solid line to draw the actual velocity graph on the same graph with your prediction. (Do not erase your prediction).
- (d) How would the position graph be different if you moved faster? Slower?
- (e) How would the velocity graph be different if you moved faster? Slower?

Estimating and Calculating Velocity

In this exercise, you will estimate an average velocity from the velocity graph you created in the previous experiment and then calculate an average velocity using your position graph.

2.11 Exercise. Average Velocity Calculations

- (a) Find your average velocity from your velocity graph in the previous activity. Select **Analyze Data A** in the **Analyze** menu, read a number of values (say ten) from the portion of your velocity graph where your velocity is relatively constant, and use them to calculate the average (mean) velocity. The velocity values will show along the bottom of the graph.

Velocity values from graph (m/s) _____

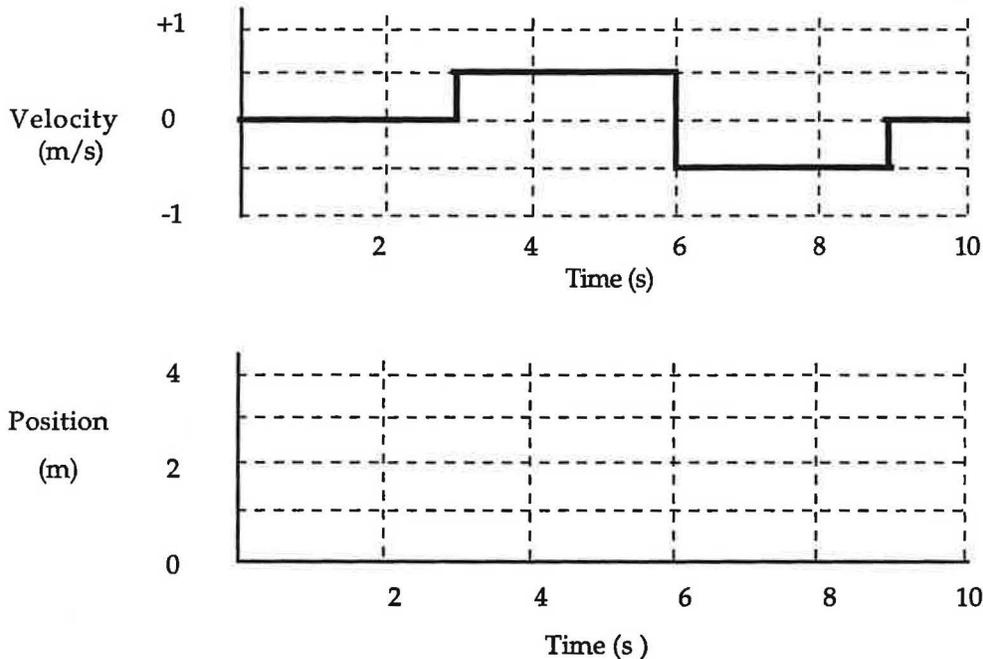
Average value of the velocity: _____ m/s

Predicting Position Graphs from Velocity Graphs

The final challenge is to be able to produce position vs. time graphs from velocity graphs. In order to do this successfully, you need to know the position of the person or object of interest for at least one of the times.

2.12 Experiment. Finding Position from a Velocity Graph

- (a) Carefully study the velocity graph that follows. Using a dashed line, sketch your prediction of the corresponding position graph on the bottom set of axes. (Assume that you started at the 1-meter mark.)



- (b) After each person has sketched a prediction, do your group's best to duplicate the top (velocity vs. time) graph by walking. (Reset the Time axis to 0 to 10 sec before you start.) When you have made a good duplicate of the velocity vs. time graph, draw your actual result over the existing velocity vs. time graph.
- (c) Use a solid line to draw the actual position vs. time graph on the same axes with your prediction. Do not erase your prediction.
- (d) How can you tell from a velocity vs. time graph that the moving object has changed direction?
- (e) What is the velocity at the moment the direction changes?
- (f) Is it possible to actually move your body (or an object) to make vertical lines on a position vs. time graph? Why or why not? What would the velocity be for a vertical section of a position vs. time graph?

Lesson 3: Changing Motion

Velocity and Acceleration Graphs

Body motions can be very jerky and irregular. We are interested in having you learn to describe some simple motions in which the velocity of an object is changing. In order to learn to describe motion in more detail for some simple situations, you will be asked to observe and describe the motion of a cart on a flat ramp. Although, graphs and words are still important representations of these motions, you will also be asked to draw velocity vectors which are arrows that indicate both the direction and speed of a moving object. Thus, you will also learn how to represent simple motions with velocity diagrams.

In the last lesson, you looked at position vs. time and velocity vs. time graphs of the motion of your body as you moved at a "constant" velocity. The data for the graphs were collected using a motion detector. Your goal in this lesson is to learn how to describe various kinds of motion in more detail. It is not enough when studying motion in physics to simply say that "the object is moving toward the right" or "it is standing still."

You have probably realized that a velocity vs. time graph is better than a position vs. time graph when you want to know how fast and in what direction you are moving at each instant in time as you walk. When the velocity of an object is changing, it is also important to know how it is changing. The rate of change of velocity is known as the acceleration.

In order to get a feeling for acceleration, it is helpful to create and learn to interpret velocity vs. time and acceleration vs. time graphs for some relatively simple motions of a cart on a ramp. You will be observing the cart with the motion detector as it moves at a constant velocity and as it changes its velocity at a constant rate. For the activities in this session you will need:

- a PowerMac computer
- a ULI laboratory interface
- a ULI motion detector
- MacMotion 4.5 software
- a cart with very little friction
- a smooth, level ramp which is 1.2 meters long
- a battery operated fan cart
- 4 fresh C-size batteries

IMPORTANT NOTE ON SAVING YOUR FILES: You may be asked to use the data collected using the motion software in some of the exercises for mathematical analysis in future lessons. For each experiment please save the graph sets and associated data on your group's personal data disk. We recommend that you identify your files by the lesson number and experiment number for later reference along with your group initials. Thus, if Smith, Kim, and Garcia work together on the Lesson 3 activities, the file names might be, for example, L3E1-1(SKG), L3E1-2(SKG), etc.

Graphing a Constant Velocity Cart Motion

Let's start by giving a frictionless cart a push along a smooth ramp and graphing its motion.



- (f) Display the acceleration graph of the cart and use a solid line to sketch it on the axes on the previous page. Note: To display an acceleration graph in the motion software hold the mouse button down on the Position label on your graph and select Acceleration.

Finding Accelerations

To find the average acceleration of the cart during some time interval (the average time rate of change of its velocity), you must measure its velocity at two different times, calculate the difference between the final value and the initial value and divide by the time interval.

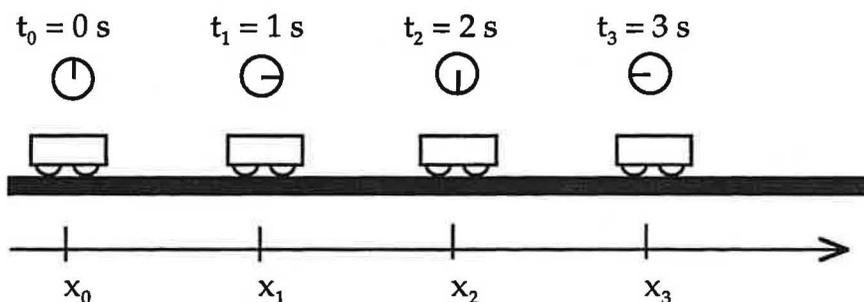
To find the acceleration vector from two velocity vectors, you must first find the vector representing the change in velocity by subtracting the initial velocity vector from the final one. Then you divide this vector by the time interval.

For example, if a car speeds up between time t_1 and t_2 , from a velocity v_1 to a velocity v_2 , then the change in the velocity is $\Delta v = v_2 - v_1$. And finally the average acceleration is given by

$$\langle a \rangle = \Delta v / \Delta t = (v_2 - v_1) / (t_2 - t_1)$$

3.2 Exercise. Representing Acceleration

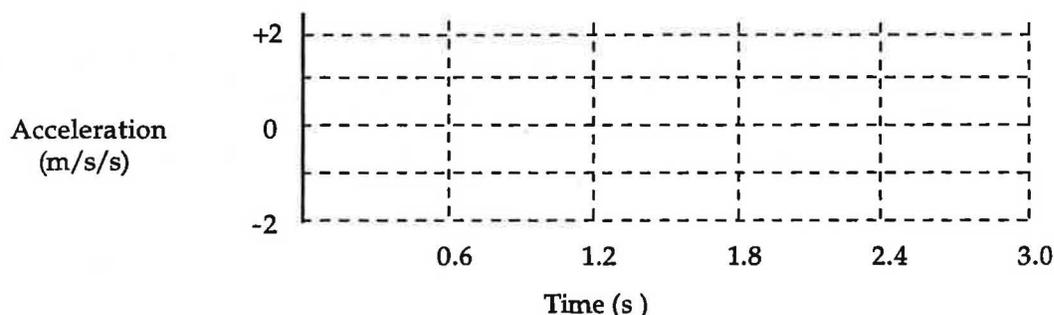
- (a) Does the acceleration vs. time graph you observed agree with this method of calculating acceleration? Explain. Does it agree with your prediction?
- (b) The diagram below shows the positions of the cart at equal time intervals. (This is like taking snapshots of the cart at equal time intervals.) At each indicated time, sketch a vector above the cart which might represent the velocity of the cart at that time while it is moving at a constant velocity away from the motion detector.



- (c) Explain how you would find the vector representing the change in velocity between the times 1.0 s and 2.0 s in the diagram above. From this vector, what value would you calculate for the acceleration? Explain. Is this value in agreement with the acceleration graph you obtained in Experiment 3.1?

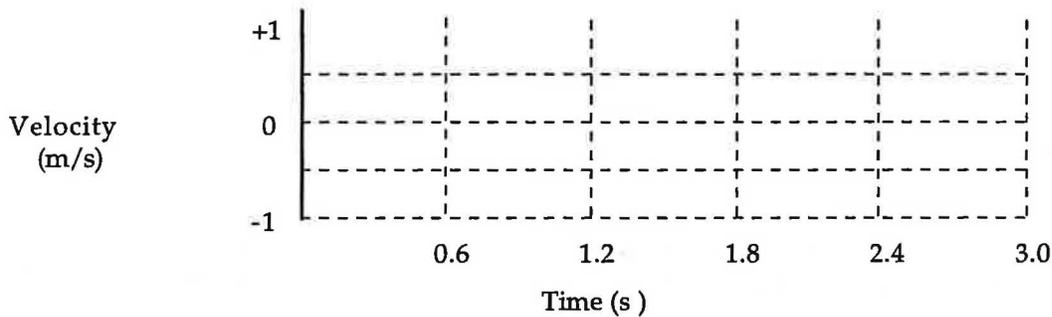
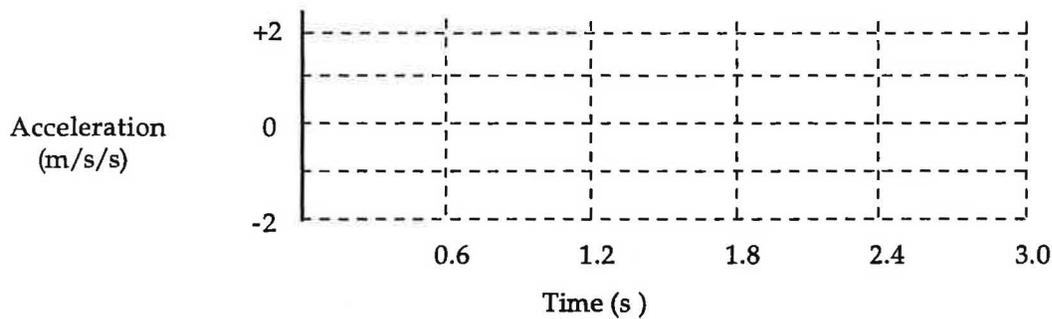
Discuss your results with your teacher.

- (c) How does your position graph differ from the position graphs for steady (constant velocity) motion?
- (d) What feature of your velocity graph signifies that the motion was away from the detector?
- (e) What feature of your velocity graph signifies that the cart was speeding up? How would a graph of motion with a constant velocity differ?
- (f) Change the Position display to Acceleration. Adjust the acceleration scale so that your graph fills the axes. Sketch your graph on the acceleration axes that follow.



Experimental Results of Speeding Up Moderately

- (g) During the time that the cart is speeding up, is the acceleration positive or negative? How does speeding up while moving away from the detector result in this sign of acceleration? Hint: Remember that acceleration is the rate of change of velocity. Look at how the velocity is changing.
- (h) How does the velocity vary in time as the cart speeds up? Does it increase at a steady rate or in some other way?
- (i) How does the acceleration vary in time as the cart speeds up? Is this what you expect based on the velocity graph? Explain.



(b) List 10 of the typical recorded accelerations of the cart . To find these values select the Acceleration vs. Time graph and then select **Analyze Data B** from the **Data** menu. Scroll along with the mouse to display the values at different times. (Only use values from the portion of the graph after the cart was released and before you stopped it.)

Reading #	1	2	3	4	5	6	7	8	9	10
Acceleration (m/s/s)										

(c) Calculate the average value of the acceleration.

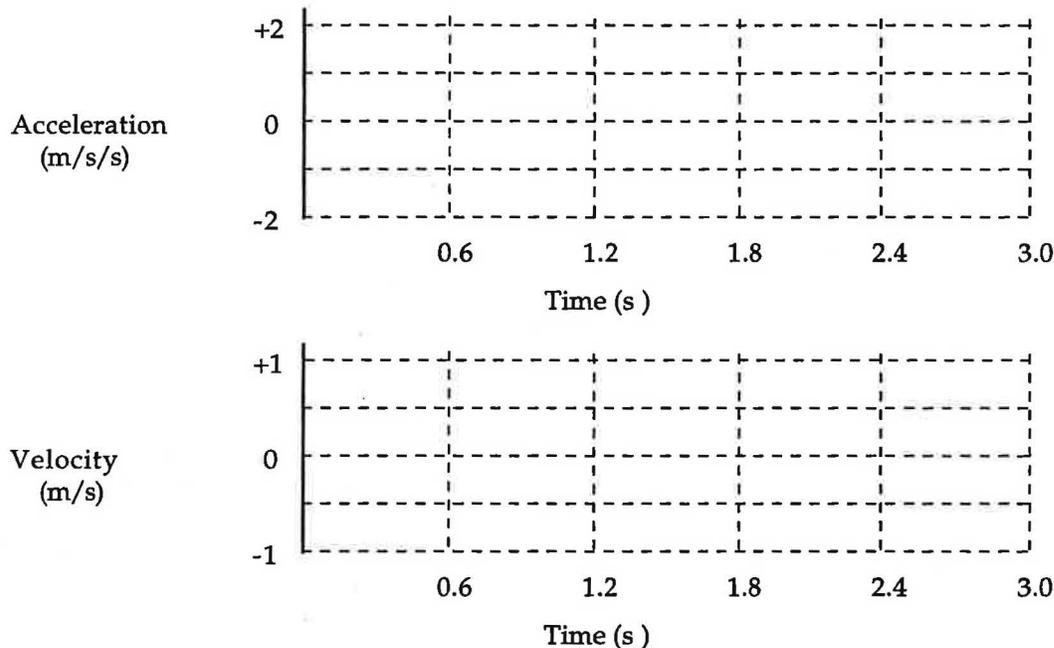
Average acceleration (mean): _____ m/s/s

(d) Since the average acceleration during a particular time period is defined as the change in velocity divided by the change in time, this is the average rate of change of velocity. By definition, the rate of change of a quantity graphed with respect to time is also the slope of the curve. Thus the (average) slope of an object's velocity vs. time graph is the (average) acceleration of the object.

Find the data needed to calculate the approximate slope of your velocity graph. Use **Analyze Data B** to read the velocity and time coordinates for two typical points on the velocity graph. For a more accurate answer, use two points as far apart in time as possible but still during the time the cart was speeding up.

	Time (s)	Velocity (m/s)
Point 1		
Point 2		

- (b) In the previous set of axes, use a dashed line or another color to sketch your predictions for the general graphs that depict a fan cart running under more power (i.e., the four batteries). Exact predictions are not expected. We just want to know how you think the general shapes of the graphs will change.
- (c) Test your predictions by accelerating the fan cart with the switch set on HIGH. Repeat if necessary to get nice graphs and then sketch the results in the axes that follow. Use the same scale as you did for the sketch of the graph with the switch set on LOW. (Remember to save your data on your data disc.)



Experimental Results of Speeding Up Rapidly

- (d) Did the general shapes of your velocity and acceleration graphs agree with your predictions? How is the greater magnitude (size) of acceleration represented on a velocity vs. time graph?
- (e) How is the greater magnitude (size) of acceleration represented on an acceleration vs. time graph?

3.7 Video Exercise

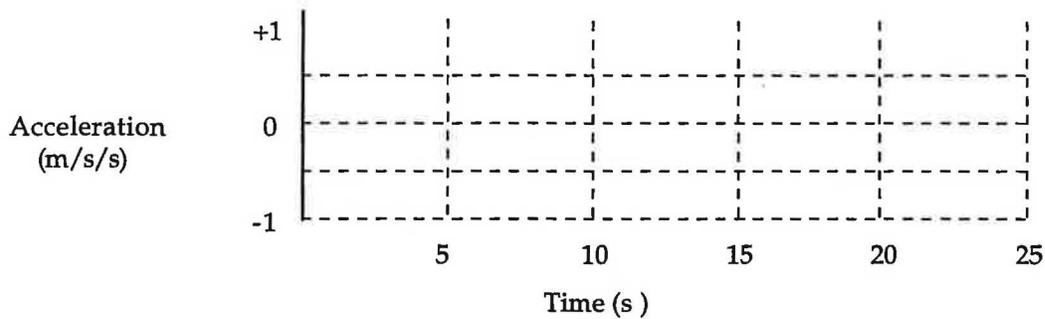
Go to the videodisc set-up and watch the following segment, following the instructions below.
Physics: Cinema Classics, Side A, Chapter 53 "Cart Trip". Set the audio to ANALOG 2/R.

Press the DISPLAY button, either on the front of the videodisc player or on the remote, to display the frame numbers. Follow the directions in the video and stop at frame 35732.

Before proceeding, draw a sketch (on the axes drawn on the next page) of the position vs. time graph produced in the video.

Use the Δv vectors to predict the average acceleration during each of the intervals during which the velocity was changing.

Using a dashed line sketch your prediction for the acceleration vs. time curve on the axes below.



Now watch the next portion of the video segment (frames 35760 - 36388).

Sketch the actual acceleration vs. time curve (using either a different color or a solid line) on the axes above.

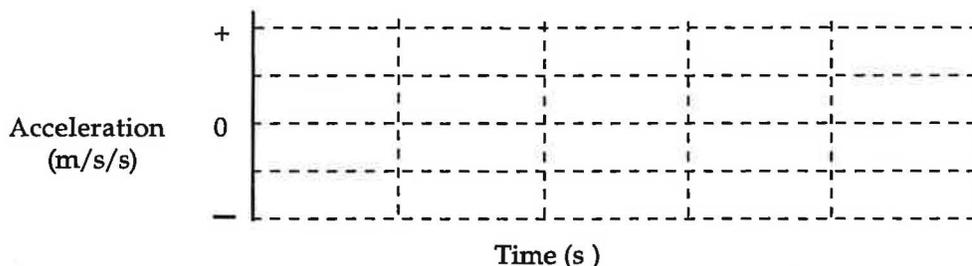
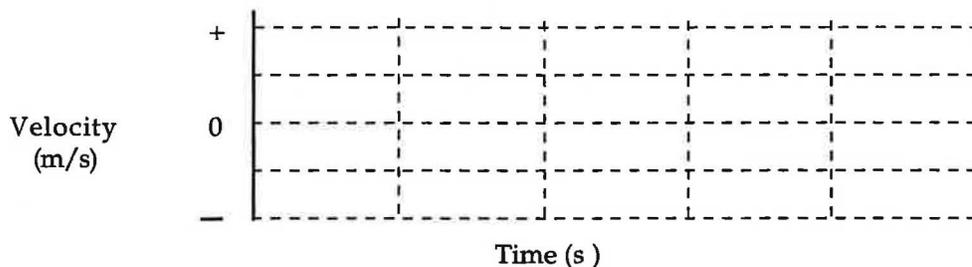
Explain the sign and location (along the time axis) of each acceleration event.

Be sure you understand how the actual curve was obtained from the velocity vs. time curve.

Discuss your results with your teacher.

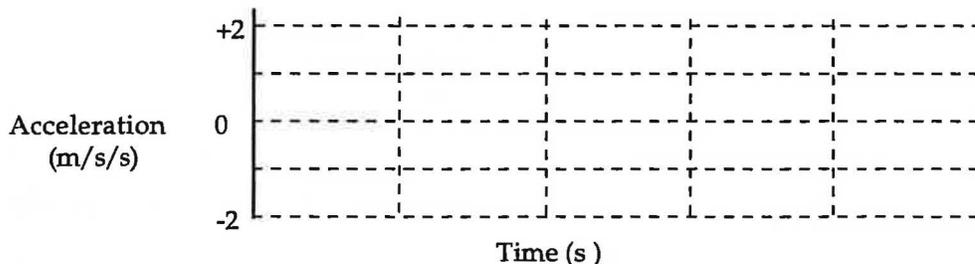
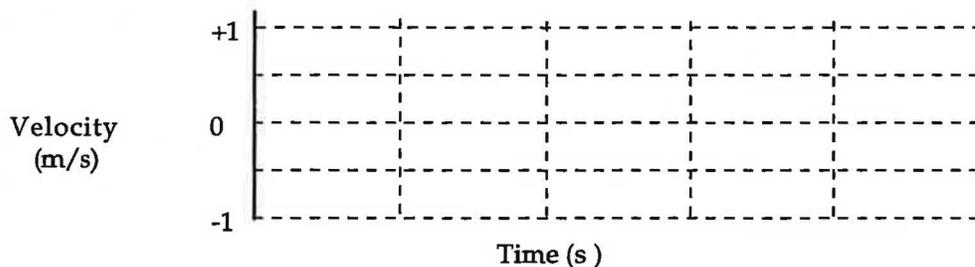
4.1 Experiment. Graphs Depicting Slowing Down

- (a) If you give the cart a push away from the motion detector and release it, will the acceleration be positive, negative or zero (after it is released)? Sketch your predictions for the velocity vs. time and acceleration vs. time graphs on the axes below.



- (b) To test your predictions open the experiment **L2A3-1 (Slowing Down)** (in the **RTP Experiment Files** folder in the **MacMotion** folder) to display the velocity vs. time and acceleration vs. time graphs. Then locate the cart 0.5 m from the detector, turn on its fan, click on the **Start** button in the graph window, and push the cart away from the motion detector once it starts clicking. Graph velocity first. Catch the cart before it turns around. Be careful of the fan blades!

Draw the results on the axes that follow. You may have to try a few times to get a good run. Don't forget to change the scales on the graphs in the graph window if this will make your graphs clearer; before making the sketch, also change the scale on the axes shown below, if needed.



Slowing Down Moving Away

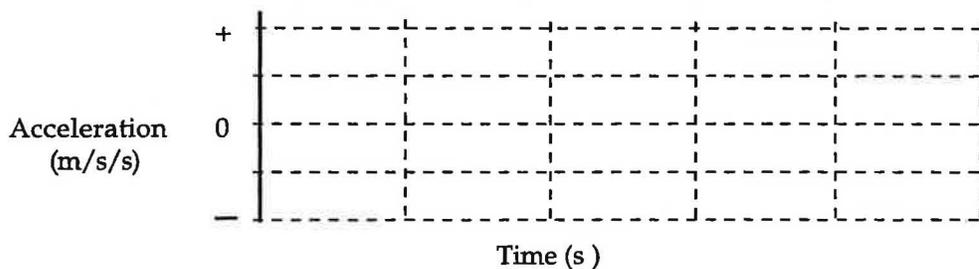
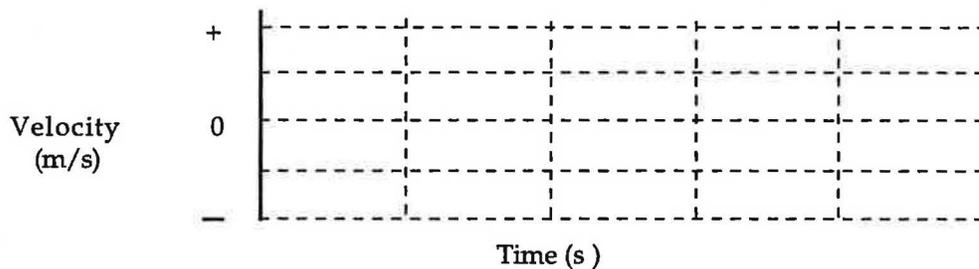
- (b) Show below how you would find the vector representing the change in velocity between the times 1 s and 2 s in the diagram above. Based on the direction of this vector and the direction of the positive x -axis, what is the sign of the acceleration? Does this agree with your answer to Question (f) in Experiment 4.1?
- (c) Based on your observations in this exercise and in the last lesson, state a general rule to predict the sign and direction of the acceleration if you know the sign of the velocity (i.e. the direction of motion) and whether the object is speeding up or slowing down.

Speeding Up Toward the Motion Detector

Let's investigate another common situation. Suppose the cart is allowed to speed up when traveling toward the motion detector. What will the direction of the acceleration be? Positive or negative?

4.3 Experiment. Graphs Depicting Speeding Up

- (a) Use the general rule that you stated in Exercise 4.2 to predict the shapes of the velocity and acceleration graphs. Sketch your predictions using the axes that follow.

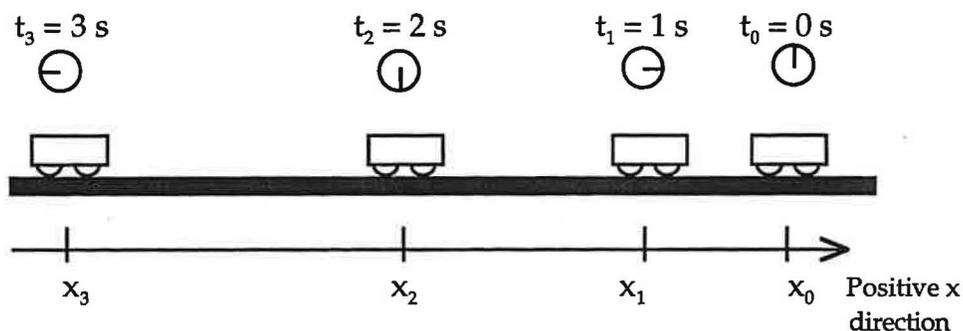


Constructing Acceleration Vectors for Speeding Up

Let's consider a diagrammatic representation of a cart which is speeding up and use vector techniques to figure out the direction of the acceleration.

4.4 Exercise. Vector Diagrams for Speeding Up

- (a) The diagram that follows shows the positions of the cart at equal time intervals. (This is like taking snapshots of the cart at equal time intervals.) At each indicated time, sketch a vector above the cart which might represent the velocity of the cart at that time while it is moving toward the motion detector and speeding up.



- (b) Show below how you would find the vector representing the change in velocity between the times 1 s and 2 s in the diagram above. Based on the direction of this vector and the direction of the positive x -axis, what is the sign of the acceleration? Does this agree with your answer to Question (d) in Experiment 4.3?

- (c) Was the general rule you developed in Exercise 4.2 (c) correct? If not, modify it and restate it here.

Moving Toward the Detector and Slowing Down

There is one more possible combination of velocity and acceleration for the cart, that of moving toward the detector while slowing down.

4.5 Experiment. Slowing Down Toward the Detector

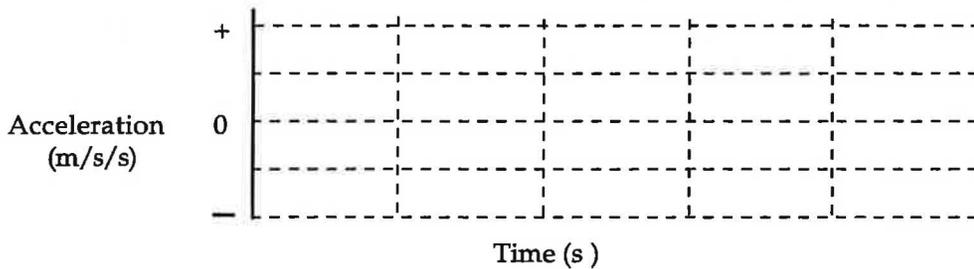
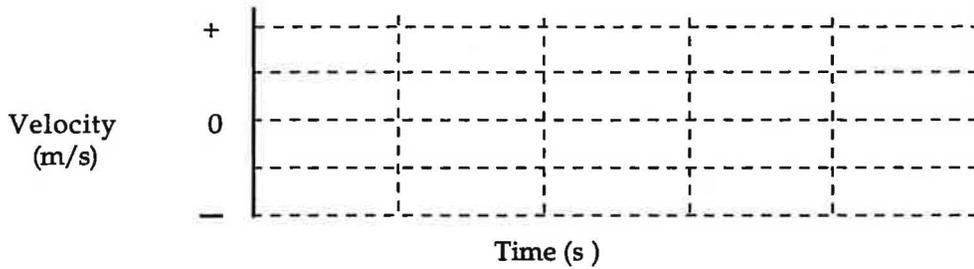
- (a) Use your general rule to predict the direction and sign of the acceleration when the cart is slowing down as it moves toward the detector. Explain why the acceleration should have this direction and this sign in terms of the velocity and how the velocity is changing.

4.5 Experiment. Reversing Direction

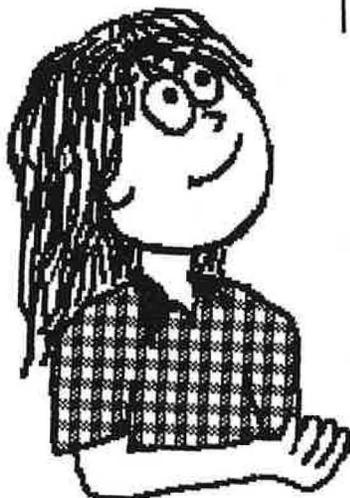
- (a) For each part of the motion—away from the detector, at the turning point, and toward the detector, predict in the table that follows whether the velocity will be positive, zero or negative. Also indicate whether the acceleration is positive, zero or negative.

	Moving Away, Slowing Down	Turning Around	Moving Toward, Speeding Up
Velocity			
Acceleration			

- (b) Sketch the predicted shapes of the velocity vs. time and acceleration vs. time graphs of this entire motion on the axes that follow.



- (c) To test your predictions set up the velocity and acceleration axes as shown below. (Open the experiment **L2A3-1 (Slowing Down)** if it is not already opened.) Use procedures that are similar to the ones you used in the slowing down and speeding up activities. You may have to try a few times to get a good run. Don't forget to change the scales if this will make your graphs clearer. When you get a good run, sketch both graphs on the axes on the next page.



Tossing a Ball

Suppose you throw a ball up into the air. It moves upward, reaches its highest point and then moves back down toward your hand. What can you say about the directions of its velocity and acceleration at various points?

4.6 Exercise. The Rise and Fall of a Ball

(a) Consider the ball toss carefully. Assume that upward is the positive direction. Indicate in the table that follows whether the velocity is positive, zero or negative during each of the three parts of the motion. Also indicate if the acceleration is positive, zero or negative. **Hint:** Remember that to find the acceleration, you must look at the change in velocity.

	Moving Up After Release	At Highest Point	Moving Down
Velocity			
Acceleration			

(b) In what ways is the motion of the ball similar to the motion of the cart which you just observed?

Note: Mathematically, “change in” (represented by Δ) is defined as the final value of something minus the initial value of something.

$$\Delta \equiv \text{“change in”} \equiv (\text{final value}) - (\text{initial value})$$

Remember that velocity is defined as the rate of change of position, which means the change in position divided by the change in time (e.g., the time interval over which the change in position occurred).

The above “word” statement should be consistent with the “equation” you wrote on the previous page. This statement is an operational definition of average velocity. It defines average velocity in terms of the operations that need to be performed to determine the average velocity, namely:

- (1) measure the distance something moves, noting the direction of the motion,
 - (2) measure the time interval required,
 - (3) divide the distance moved (e.g., change in position) by the time interval (e.g., change in time).
- The direction of the average velocity is the same as the direction of the motion (which is indicated by the direction of an arrow pointing from the initial position to the final position).

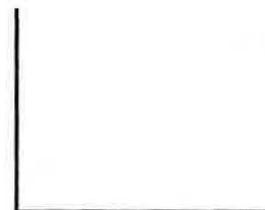
Instantaneous Velocity

Instantaneous velocity is the velocity at an instant of time, rather than the average over a time interval. A serious problem arises mathematically if the Δt in the denominator of the equation for the average velocity shrinks smaller and smaller to represent an “instant”.

5.2 Video Exercise

On the axes at the right draw a sketch of a position vs. time graph for an object moving with constant velocity?
What property of the graph indicates constant velocity?

In this case, does the instantaneous velocity at any time differ from the average velocity for the entire time? Explain.



Consider your results from Experiment 3.3. Draw a sketch of the position vs. time graph for this motion.
In this experiment was the velocity constant?
How do you know?



How would you describe the position vs. time graph?

The average velocity for some time interval on the graph can still be obtained by determining the slope of a straight line drawn from the position (x_1) at the beginning of the time interval (t_1) to the position (x_2) at the end of the time interval (t_2). But how could you determine the velocity at precisely the beginning of the time interval? In other words, how could you determine the instantaneous velocity (v_1) at that specific time (t_1)?

Go to the videodisc set-up and watch the following video segments:

The Mechanical Universe, Program 3 “Derivatives”, frame numbers 15022 - 16385, and 19065 - 21885.

5.4 Exercise. Calculating Average Velocities and Average Accelerations from Position vs. Time Data

The following data represents the position of an object as a function of time. You used this data in Lesson 1.

Time (s)	Position (cm)
0.000	0.00
0.033	2.50
0.067	6.10
0.100	10.75
0.133	16.45
0.167	23.25
0.200	31.15
0.233	40.10
0.267	50.10
0.300	61.25
0.333	73.40
0.367	86.70

Open a spreadsheet in ClarisWorks and enter the above data (including titles and units) in columns A and B. Select this data by positioning the arrow in cell A1 and holding the mouse button down while dragging down and to the right to cell B14. From the **Edit** menu select **Copy**.

Open the Graphical Analysis software (in the Graphical Analysis folder on the Mac HD) and click in the space to the right of the 1 and under the X. Then select **Paste** under the **Edit** menu.

Describe the graph that is produced.

Go back to the spreadsheet and enter the title "Average Velocity" in cell C1, and the units "(cm/s)" in cell C2.

In cell C4 enter the equation " $=(B4-B3)/(A4-A3)$ ". This is the equation for average velocity,

$$\langle v \rangle = (x_2 - x_1)/(t_2 - t_1)$$

and will calculate the average velocity during each time interval of 0.033 s.

Show one sample calculation of average velocity.

Click in cell C4 and drag down to cell C14 to highlight these cells. Under the **Calculate** menu select **Fill Down**. This copies the equation from cell C4 into each of the other cells, but changes the cell addresses so that the equation always recognizes the data in the cells immediately to its left as the final values of position and time and the contents of the cells in the next row up as the initial values. Click on any of the cells in column C to see the equation in that cell, which you will see displayed in the equation line at the top of the spreadsheet.

Select cells C1 through C14 and select **Copy** under the **Edit** menu. Paste this data into the Y column in the Data Set window in Graphical Analysis. Describe the resulting graph.

Under the **Analyze** menu select **Automatic Curve Fit...** Record the equation of the line in the space below. Based on this equation, what is the acceleration for this motion?

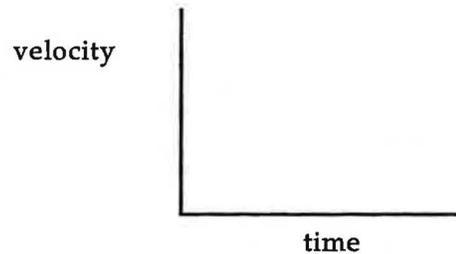
If we use the simplifying assumption that the initial time t_1 has a value of zero (i.e., the time when the clock starts), then we can drop the subscript on the final time, can change the subscript on the initial velocity from "1" to "0" (to represent velocity at time zero) and drop the subscript on the final velocity. The result will be:

$$v = v_0 + at$$

Complete the following sentence to express this equation in words:

For the case of constant acceleration, the final velocity after time t is ...

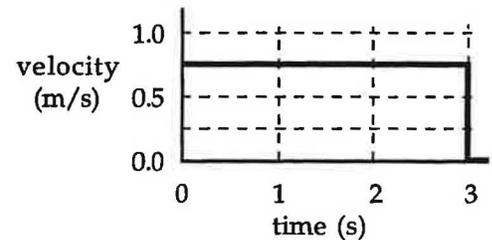
Draw a sketch of a velocity vs. time graph for a motion that has constant acceleration and an initial velocity v_0 .



Rearrange the equation for the average velocity (see Exercise 5.1) to obtain an equation for the final position of the object. Again make the simplifying assumption that the initial time t_1 has a value of zero (i.e., the time when the clock starts), and modify the equation as was done above with the equation for the final velocity.

Unfortunately we cannot replace the average velocity $\langle v \rangle$ with an instantaneous velocity because the instantaneous velocity is continually changing. However we can determine a simple expression for the average velocity in the case that the acceleration is constant.

Consider the constant velocity graph drawn at the right. What is the result of multiplying the height of the rectangle, v_0 , by the length of the rectangle, t ?



Notice that the units of your answer are meters. What quantity is measured in meters?

Now answer the question: "How far do you move in 3 s, walking at a constant velocity of 0.75 m/s?"

Based on these results, what general conclusion can you draw about the meaning of the area under a velocity vs. time graph?

Discuss your conclusion with your teacher.

We now have produced the following set of kinematic equations:

$$\langle v \rangle \equiv \Delta x / \Delta t \quad \langle a \rangle \equiv \Delta v / \Delta t \quad v = v_0 + at \quad x = x_0 + v_0 t + (a/2)t^2$$

The first two are definitions of average velocity and average acceleration and are valid under any circumstances, but the last two are derived and are valid only for motion with constant acceleration. The third equation tells how the velocity of an object changes with time; it is a linear equation, and a graph of it will always produce a straight line. The fourth equation tells how the position of the object changes with time; it is a quadratic equation, and a graph of it will always produce a curve called a parabola (unless the acceleration is zero).

5.6 Exercise. The Parabolic Nature of the Position Graph

Mathematicians usually give the equation for the parabola as follows:

$$f(x) = c_1 x^2 + c_2 x + c_3$$

where c_1 , c_2 , and c_3 are constants. Although all parabolas have the same basic shape, some are skinny, some are fat, some start one place on a coordinate axis and some start another place. Some parabolas are even upside down! The magnitudes of the constants and whether they are positive or negative determine how a given parabola looks.

In the study of kinematics a different notation is used for the parabolas and each coefficient represents a physical quantity. Thus, using the kinematic equation we derived in Exercise 5.5 we get:

$$x = (a/2)t^2 + v_0 t + x_0$$

Thus, we say that position, x , is a function of the elapsed time, t . What kind of parabolas do we get for various values of acceleration (a), initial velocity (v_0), and initial position (x_0) for a uniformly accelerated object? Plotting some parabolas using computer software should provide you with some quick answers to this question. Most of the parabolas you will plot will only be half parabolas. Can you figure out why?

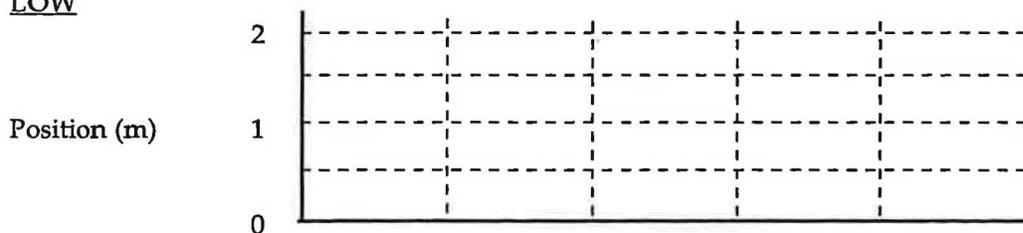
Parabolas for Different x_0 Values

- (a) By examining the equation, predict what you think the effect of the initial position will be on the graph of x vs. t . Explain the reasons for your prediction.
- (b) Test your prediction by drawing some graphs. To do this you will use two pieces of software: **Graphical Analysis** and **ClarisWorks**. Both are located in their respective folders on the **Mac HD**. Open **Graphical Analysis**; under the **Graph** menu select **Point Protectors**, **Connecting Lines**, and **Background Grid**. Then hold the mouse button down on the **Graphical Analysis** icon at the top right of the screen and pull down to **Finder**. Find the **ClarisWorks 4.0 Folder** and open **ClarisWorks**, select **Spreadsheet** in the **New Document** window, and set up the spreadsheet as follows:
- enter "time (s)" in cell A1 and "position (m)" in cell B1;
 - enter "a (in m/s/s) =" in cell C1, "v0 (in m/s) =" in cell C2, and "x0 (in m) =" in cell C3;
 - enter the values 0, .1, .2, .3, .4, .5, .6, .7, .8, .9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6 in cells A2 through A18;
 - enter "= D\$1/2*A1^2+D\$2*A1+D\$3" in cell B2 (this is the equation " $= (a/2)t^2 + v_0 t + x_0$ "); The \$ symbols in the cell address tells the computer to go always to that cell to get data.
 - click on cell B2 and drag down to cell B18, then select **Fill Down** in the **Calculate** menu.

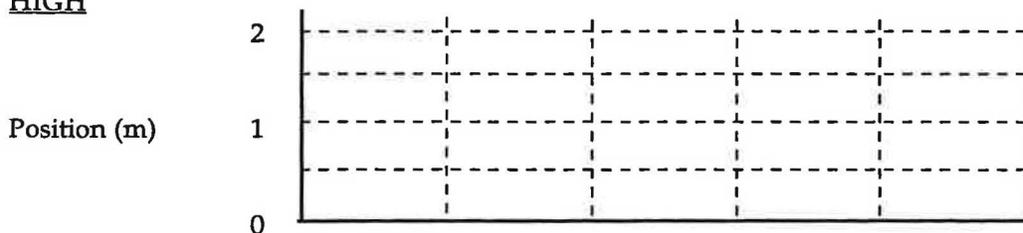
For each case, sketch the results below and then explain how changing a in various ways affects the shape of the parabolas you get. Label each sketch with its value of a .

- (c) Does the nature of the change agree with your observations in Lesson 3 when you used a motion detector to record the positions of a fan cart speeding up (Experiment 3.3) and when you repeated the experiment with the fan cart speeding up even faster (Experiment 3.6)? Explain. Resketch the two graphs you observed.

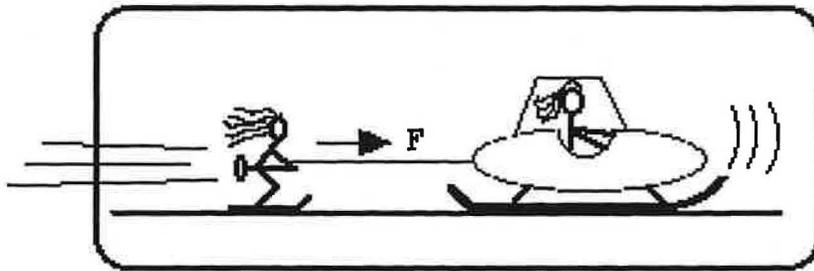
LOW



HIGH



Unit 3: ONE DIMENSIONAL FORCES, MASS, AND MOTION



*Nature and Nature's laws lay hid at night:
God said, "Let Newton be!" and all was light.*

Alexander Pope

OBJECTIVES

1. To learn to use an electronic force probe to measure forces with a microcomputer-based laboratory system.
2. To understand the relationship between the force applied to an object and its motion in the absence of significant friction.
3. To develop a definition of mass in terms of an object's motion under the influence of a force.
4. To understand how different forces can act together to make up a combined force. To establish a definition of combined force as that which causes motion.
5. To pull all of the observations together and develop Newton's First and Second Laws of Motion for motion along a straight line.
6. To devise a way to account for friction in formulating Newton's First and Second Laws of Motion.

Lesson 6: Combining Forces

For this lesson you will need the following:

- a PowerMac computer
- **MacMotion** software
- a force probe
- a ULI motion detector
- a Universal Laboratory Interface (ULI)
- a low-friction cart
- 2 spring scales with a maximum reading of 5 or 10 N
- a smooth track 1.2 m long
- a low friction pulley and string
- a variety of small hanging masses (10 - 50 grams)
- 2 fan carts (each with 4 C size batteries)
- table clamp, rod and rod clamp

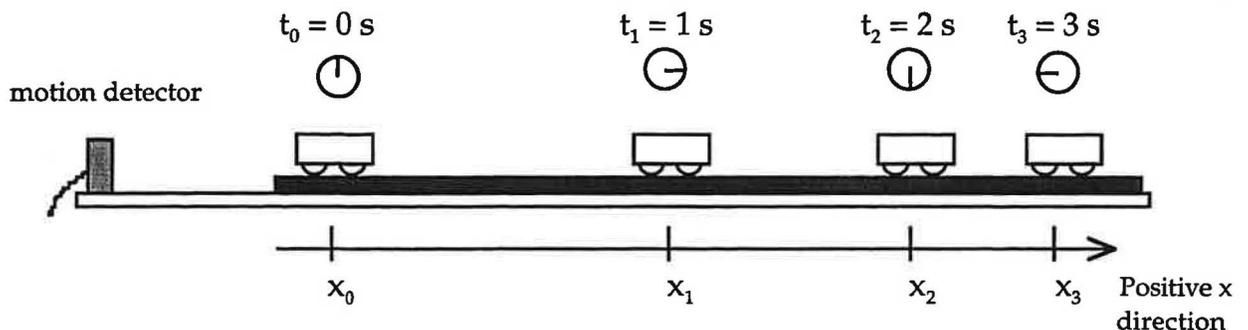
6.1 Experiment. Slowing Down while Moving Away from the Motion Detector

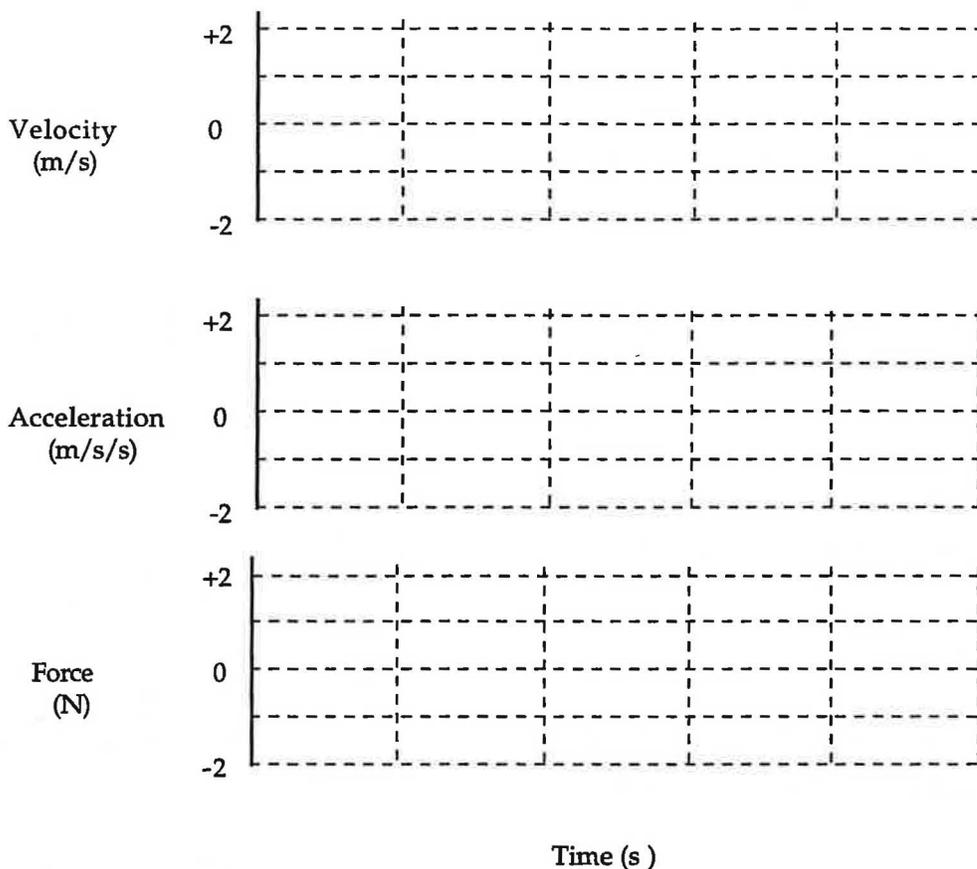
1. Set up the cart, track, pulley, hanging mass, force sensor, and ULI motion detector as shown. You may need to position the motion detector slightly off to the side of the pulley so that it sees the cart and not the string. The force probe should be fastened securely to the cart, and plugged into port 1 of the ULI. The motion detector should be plugged into port 2. (The cable of the force probe must not interfere with the motion of the cart.)

Now when you give the cart a push away from the motion detector, it will slow down after it is released. In this activity you will examine the acceleration and the applied force.



2. In Lesson 4 you learned to draw arrows (vectors) to represent velocity and acceleration. Arrows are also used to represent forces. Suppose that you give the cart a push toward the right and release it. Draw below arrows which represent your prediction of the velocity and acceleration of the cart, and the force acting on the cart, at each time after it is released and is moving toward the right. Be sure to mark your arrows with v , a , or F as appropriate.





Question 1: Did the signs of the velocity, force and acceleration agree with your predictions? If not, can you now explain the signs?

Question 2: Did the velocity and acceleration both have the same sign? Explain these signs based on the relationship between acceleration and velocity.

Question 3: Did the force and acceleration have the same sign? Were the force and acceleration in the same direction? Explain.

Question 6: Which of the signs--velocity, force and/or acceleration are the same as in the previous activity--where the cart was slowing down and moving away, and which are different? Explain any differences in terms of the differences in the motion of the cart.

Question 7: Based on your observations, draw below vectors which might represent the velocity, force and acceleration for the cart at the same instant in time.

Velocity

Force

Acceleration

Do these agree with your predictions? If not, can you now explain the directions of the vectors?

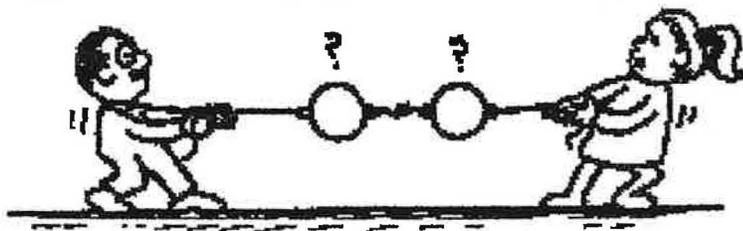
Question 8: Write down a simple rule in words which describes the relationship between the direction of the applied force and the direction of the acceleration for any motion of the cart.

Question 9: Is the direction of the velocity always the same as the direction of the force? Is the direction of the acceleration always the same as the direction of the force? In terms of its magnitude and direction, what is the effect of a force on the motion of an object?

Discuss your results for Experiments 1 and 2 with your teacher.

If you have more time, carry out Extension A now to more carefully explore the signs of velocity, acceleration and force. You will find Extension A at the end of this lesson.

6.3 Commentary. Net Force: Combining Applied Forces

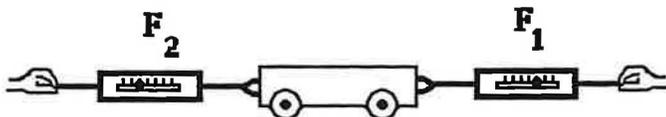


Vectors are mathematical entities which have both magnitude and direction. Thus a one-dimensional vector can have a direction along the positive x-axis or along the negative x-axis. Vectors pointing in the same direction add together and vectors pointing in opposite directions subtract from each other.

Quantities which have vector behavior are often denoted by a letter with a little arrow above it or by a

Question 13: Draw arrows next to the diagram above that represent a scale drawing of the magnitudes and directions of F_1 , F_2 , and F .

3. Observe what kind of motion results when two spring scales are hooked to opposite ends of the cart and extended in a horizontal direction so that each of their forces is equal to 1.0 N in magnitude but they are opposite in direction.



Question 14: Does the cart move? If so how? What do you think the combined or net applied force on the cart is equal to in this situation?

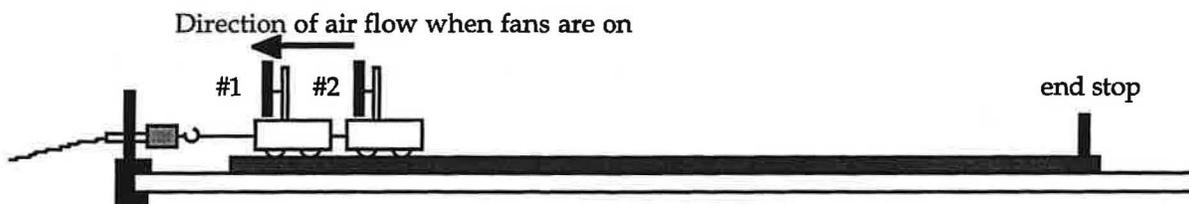
Question 15: Draw arrows next to the diagram above that represent a scale drawing of the magnitudes and directions of the forces you are applying. Let 5.0 centimeters of arrow length represent each newton of force. Label each arrow appropriately with an F_1 or an F_2 .

Question 16: Do one-dimensional forces seem to behave like one dimensional vectors? Why or why not?

Pulling carts with spring scales is awkward and takes practice to do well. In the rest of this investigation you will use fan carts to apply forces, and the motion detector to measure the resulting velocities and accelerations of the carts.

6.5 Experiment. Cooperating Fan Units

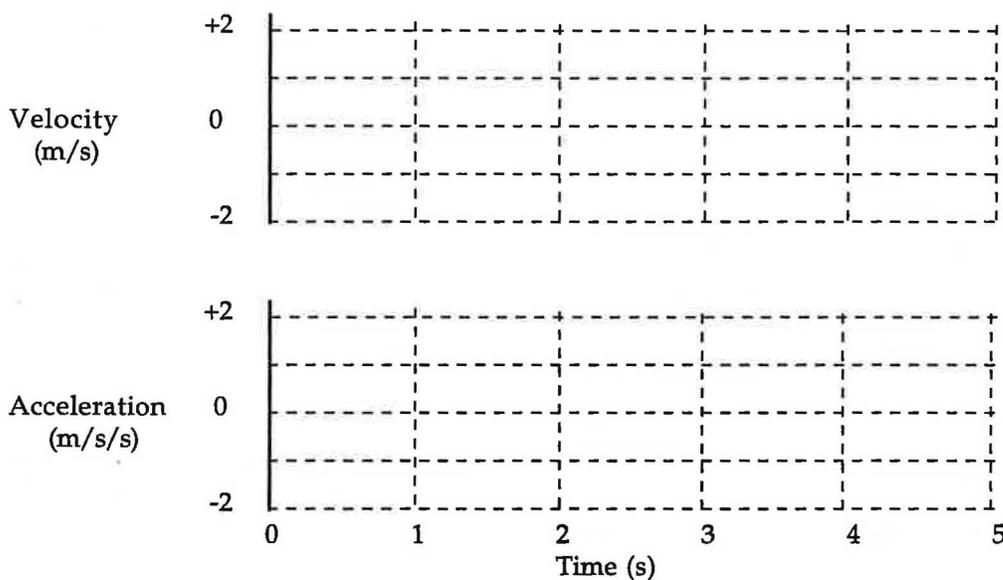
1. Connect two fan carts end-to-end so that each cart tends to move toward the right when its fan is on.
2. Set up the force probe in the rod clamp as shown.
3. Calibrate the force probe with a 2 N pull from a spring scale.



4. Use the force probe to measure the average force applied when only fan #1 is turned on. You may use the experiment L4A2-2a (Cooperating Fan Units) to display appropriate axes. **To save the batteries, be sure to only keep the fan turned on during the time when you are actually making measurements.**

(To find the average force, select **Analyze Data A** from the **Analyze** menu, highlight the desired part of your graph using the mouse and then select **Statistics . . .** from the **Analyze** menu.)

Record your result in the table on the next page.



8. Find the average accelerations for fan #1 alone pushing the carts (**Data B**) and for fan # 2 alone pushing the carts (**Data A**), using **Analyze Data A** and **Analyze Data B** and **Statistics . . .** under the **Analyze** menu as you did for the forces. Only use the portions of the acceleration graphs where the accelerations are nearly constant.

Record these values in the table on the previous page.

Suppose that you turned on both fans at the same time. What do you suppose would be the effect of the combination of the two forces on the motion of the carts? In your **prediction**, compare the velocity and acceleration graphs you expect with those you made above.

9. Test your prediction. Set up the motion detector and graph velocity and acceleration with both fans pushing the carts toward the right. Determine the average acceleration as before, and record it in the table.

Question 20: Was your prediction correct? How does the motion of the carts with the combination of forces compare with the motion with the single force? Is the acceleration constant? Do one-dimensional forces seem to behave like one dimensional vectors? Why or why not?

Comment: In this experiment you have examined the effects of combining the forces applied by fans, looking at the motion of the carts with either of two fans pushing alone, and with both pushing together in the same direction. You first tested the idea that forces can be combined by the same rules as one-dimensional vectors. Then you saw that the acceleration of an object depends on the combined force acting on it. In other words, it is the combined force which should be used to determine the acceleration.

In the next experiment you will carry this investigation further and look at the motion of the cart when the two fans push in opposite directions, i.e., when the forces on the carts combine to cancel each other.

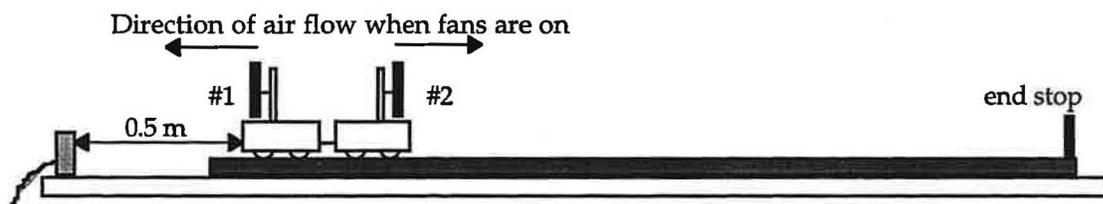
Motion at a Constant Velocity

In the previous experiment, you used the force probe to measure two individual forces applied to the carts in the same direction, and also the combination of the two forces. Then you used the motion detector to investigate the motion of the carts. You saw that it is the combined force (the vector sum of the two forces) which determines the acceleration of the carts.

In the next experiment you will examine what happens when the two forces applied to the carts push in opposite directions. What is the acceleration then? You will also answer the question: "What combined force will keep the carts moving at a constant velocity?"

6.6 Experiment. Dueling Fans

1. Set up the track, two fan carts and motion detector as shown below so that the two fans will now push the carts in opposite directions. Be sure that the track is level.



Suppose that each fan pushed on the carts with the same magnitude force. What do you predict would be the combined force acting on the cart? What do you predict would be the acceleration of the cart? Given your prediction for the acceleration, how do you predict the velocity would change?

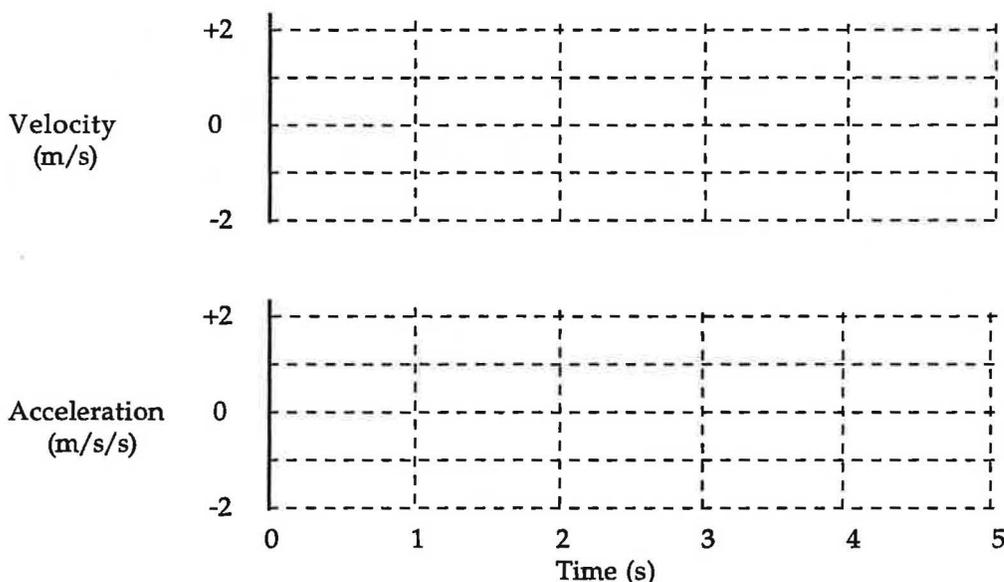
Suppose the cart is moving with the velocity which is shown on the velocity vs. time graph on the next page. Sketch on the accompanying axes your prediction for the acceleration vs. time graph of the carts, and the force vs. time graph of the combined force after the carts begins moving.

Explain the reasons for your predictions.

3. Test your predictions. Turn on both fans. If the carts tends to move in one direction or the other, exchange batteries between the fan carts until they remains at rest with both fans turned on.

Question 24: When both fans are turned on, but the carts have no tendency to move, what is the combined (net) force exerted by both fans on the carts? How do you know?

4. Prepare to graph velocity and acceleration. Open the RTP Experiment Files folder and open the experiment called L4A3-1 (Dueling Fan Units) to display the velocity and acceleration axes shown below.



5. Now turn on both fans, and **Start graphing**. Give the carts a small push toward the right. Move the graphs to Data B for comparison. Then sketch them on the axes above, or print them.

Question 25: Indicate with an arrow on the graphs the time when you stopped pushing the carts. How do the portions of these graphs after the carts were released compare to those for the motions in Experiment 6.5 where the fans both pushed in the same direction?

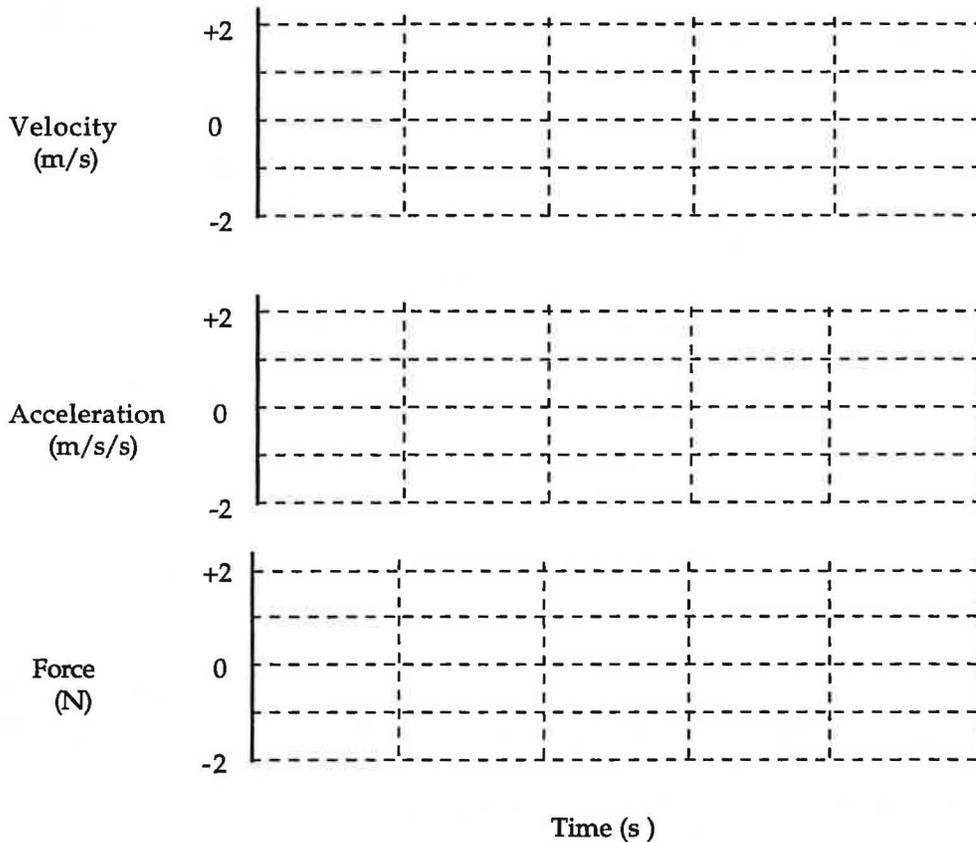
6. Turn on both fan units and give the cart a bigger push to the right. Sketch the graphs with dashed lines on the axes above, or print and affix over the axes.

Question 26: Compare the graphs to those with the smaller push (Data B). Are there any differences in the velocity graphs? In the acceleration graphs?

Extensions for Lesson 6: Combining Forces**Extension A: Reversing Direction**

Suppose that you use the same setup as in Experiments 6.1, but now you give the cart a push away from the motion detector, release it and let it move away, reverse direction and head back towards the motion detector. Sketch on the axes below with dashed lines your **predictions** for the velocity, acceleration and force after the cart leaves your hand and before you stop it. Mark on your prediction the time at which the cart reverses direction.

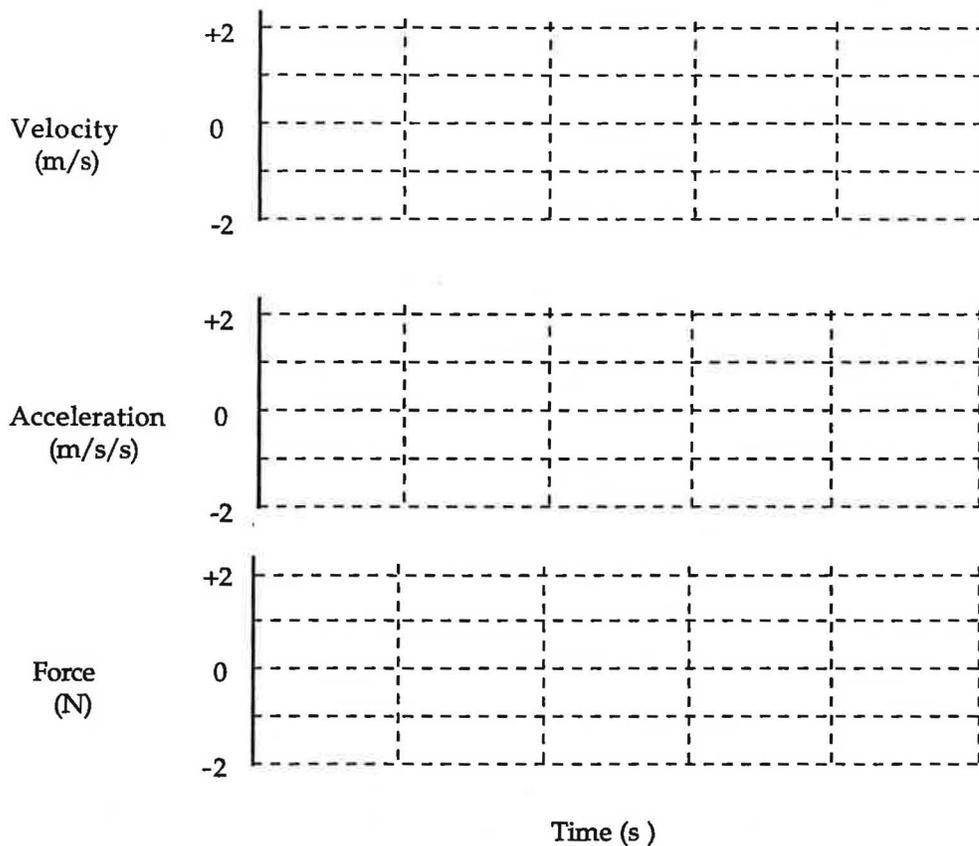
Also describe the velocity, acceleration and force in words in the space below the axes.



Carry out this observation. You may use the same experiment file as in Experiment 6.1--L4A1-1 (**Slowing Down**). Sketch your observed graphs with solid lines on the axes above, or print the graphs and affix them over the axes. Mark on your graphs the time at which the cart reverses direction.

Question 1: Compare your observations with your predictions. Describe the force and acceleration at the moment when the cart reverses direction.

Question 2: Based on your knowledge of acceleration and force, explain why the force and acceleration have the sign they have at this moment.



For this lesson you will need the following:

- a PowerMac computer
- MacMotion software
- a force probe
- a ULI motion detector
- a Universal Laboratory Interface (ULI)
- a low-friction cart
- a spring scale with a maximum reading of 5 or 10 N
- a smooth track 1.2 m long
- a low friction pulley and string
- a variety of small hanging masses (10 - 50 grams)
- table clamp, rod and rod clamp
- a variety of masses to increase the mass of the cart, totaling 2-3 times the mass of the cart
- a triple-beam balance and an electronic scale

Part 1

7.1 Experiment. Acceleration and Mass

You can easily change the mass of the cart by attaching masses to it, and you can apply the same force each time by using appropriate hanging masses. By measuring the acceleration of different mass carts, you can find a mathematical relationship between the acceleration of the cart and its mass, with the applied force kept constant.

1. Set up the track, pulley, cart, string, motion detector and force probe as shown below. Be sure that the track is level.

The force probe should be fastened securely to the cart, and plugged into port 1 of the ULI. The motion detector should be plugged into port 2. (Be sure that the handle of the forceprobe does not extend beyond the end of the cart. The cable must not interfere with the motion of the cart, and must not be seen by the motion detector.)

2. We will define a mass scale in which the unit is the mass of the cart (including the force probe), called one cart mass. A triple-beam balance can be used to assemble a combination of masses equal to one cart mass. If this combination of masses is divided in half, each half is 0.5 cart mass.

Use the balance in this way to determine a combination of masses which you can add to the cart to make the cart's mass equal to 1.5, 2.0, 2.5 and 3.0 cart masses. Keep track of the combinations required to give the correct amounts.



Be sure that the force probe handle does not extend beyond the back of the cart, and tape the cable back along the handle to assure that the motion detector "sees" the cart.

3. Now add masses to make the cart's mass 2.0 cart masses.
4. Be sure that the cart's friction is minimum.
5. Find a hanging mass which will accelerate the cart across the track from away from the motion detector in about 2-3 seconds after the mass is released.

Record the value of this mass: _____ kg

Mass of Cart (cart masses)	Average Applied Force (N)	Average Acceleration (m/s/s)
1.0		
1.5		
2.0		
2.5		
3.0		

7.2 Experiment. Accelerating a Cart Having a Different Mass

Suppose that you halve the mass of the cart back to 1.0 cart masses, and accelerate it with the same applied force. Predict how the acceleration would compare with that of the larger mass cart used in Experiment 7.1

1. Test your prediction. Remove the masses you added in Experiment 7.1 to doubled the mass of the cart to 2.0 cart masses.

Comment: You want to accelerate the cart with the same applied force. As you may have noticed, the force applied to the force probe by the string decreases once the cart is released. (You will examine why this is so in a later lesson.) This decrease depends on the size of the acceleration. Therefore, in order to keep the applied force constant, you may need to change the hanging mass.

2. **Zero** the force probe with nothing pulling on it. Adjust the hanging mass until the force probe reading while the cart is accelerating is the same as the force you recorded in the third row of the table above. When you have found the correct hanging mass, graph the motion of the cart. (Don't forget to **Zero** the force probe first.) Measure the average force and average acceleration of the cart during the time interval when the force and acceleration are nearly constant and record these values in the first row of the table above.

Question 1: Did the acceleration agree with your prediction? Explain.

3. Now make the mass of the cart 1.5 cart masses, and accelerate it again with the same size force. (Don't forget to adjust the hanging mass, if necessary.) Measure the average force and acceleration of the cart, and record these values in the table.
4. Repeat step 3 for masses of 2.5 and 3.0 cart masses.

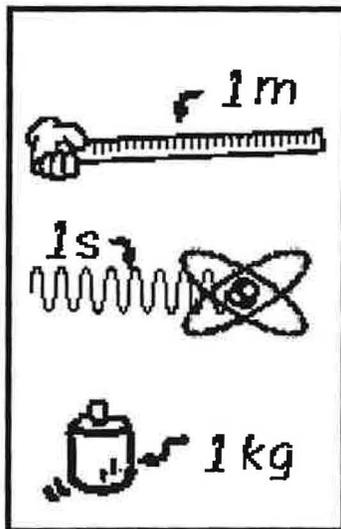
Question 3: What appears to be the relationship between acceleration and mass of the cart, when the applied force is kept constant?

Question 4: In Lesson 6, you found that the acceleration of the cart was proportional to the combined applied force, when the mass of the cart was not changed. State in words the general relationship between the applied force, the mass and the acceleration of the cart which you have found in these two lessons. If the combined force is ΣF , the mass is m and the acceleration is a , write a mathematical relationship which relates these three physical quantities. This relationship was first determined by Issac Newton and is known as Newton's Second Law.

Part 2

So far you have been measuring force in standard units based on the pull exerted by a spring scale calibrated in newtons. Where does this unit come from? By contrast, we have our own private units for measuring mass-cart masses. If one group were using a large wooden cart in their force and motion experiments, and another group were using a small aluminum cart with smaller mass, they would have different values for mass, and would observe different accelerations for "one cart mass pulled by one newton." It's time to discuss standard units for force and mass.

It would be nice to be able to do a mechanics experiment in one part of the world and have scientists in another part of the world be able to replicate it or at least understand what actually happened. This requires that people agree on standard units. In 1960 an international commission met to agree upon units for fundamental quantities such as length, time, mass, force, electric current, pressure, etc. This commission agreed that the most fundamental units in the study of mechanics are length, time, and mass. All other units (including force, work, energy, torque, rotational velocity, etc.) which you encounter in your study of mechanics can be expressed as a combination of these basic quantities. The fundamental International System or SI units along with the standard unit for force are shown in the boxes below.



FUNDAMENTAL UNITS FOR MECHANICS

Length: A meter (m) is the distance traveled by light in a vacuum during a time of $1/299,792,458$ second.

Time: A second (s) is defined as the time required for a cesium-133 atom to undergo 9,192,631,770 vibrations.

Mass: A kilogram (kg) is defined as the mass of a platinum-iridium alloy cylinder kept at the International Bureau of Weights and Measures in Sévres France. It is kept in a special chamber to prevent corrosion.

7.4 Exercise. Calculating One "cart mass" in Standard Units

- In Part 1 of this lab, you measured the force applied to a cart and the acceleration of the cart with 1.0, 1.5, 2.0, 2.5 and 3.0 cart masses. Turn back to your table of information from that experiment on page 86, and copy the values of average force and average acceleration into the second and third columns of the table below.

Mass of Cart (cart masses)	Average Applied Force (N)	Average Acceleration (m/s/s)	Ratio of F / a (calculated mass)	Mass of cart measured with balance (kg)
1.0				
1.5				
2.0				
2.5				
3.0				

In the discussion above, the mass in standard units was calculated using Newton's second law by taking the ratio of the combined (net) force on the object in newtons to the acceleration of the object measured in meters per second per second.

- For each row in the table, calculate the ratio of the force to acceleration and record it in the fourth column.

Question 4: According to the discussion, the values you just calculated should be the mass of the object in kilograms. Do your numbers seem to make sense? What do you get for the value of 1.00 cart masses in kilograms? What do you get for the value of 2.00 cart masses in kilograms?

Comment: Physicists call the quantity you have just calculated--the ratio of combined (net) force on an object to its acceleration--the inertial mass of the object.

You could continue to determine and compare masses by accelerating them and taking force to acceleration ratios, but this process is pretty tedious.

A simpler approach is to use an electronic scale or a mechanical balance that has already been calibrated in kilograms using a standard mass by somebody who is intelligent and knowledgeable! (The details of why such devices can give us correct masses in kg will not be easy to understand fully until after gravitational forces are studied in a later lesson.)

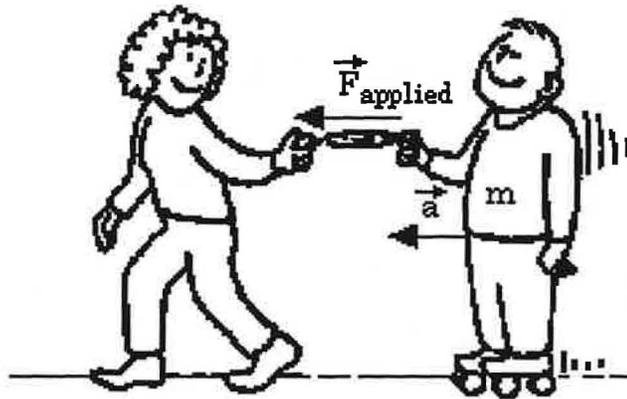
- Compare your inertial mass calculations for 1.0, 1.5, 2.0, 2.5 and 3.0 cart masses with the values you get by placing your cart on an electronic scale or mechanical balance. Record these values in the last column of the table.

Question 5: Are your inertial masses reasonably consistent with your scale masses?

Question 7: A force of 5.4 N is applied to an object, and the object is observed to accelerate with an acceleration of 3.0 m/s/s. If friction is so small that it can be ignored, what is the mass of the object in kg? Show your calculation.

Question 8: An object of mass 39 kg is observed to accelerate with an acceleration of 2.0 m/s/s. If friction is negligible, what is the force applied to the object in N? Show your calculation.

Comment: The main purpose of Lessons 6 and 7 has been to explore the relationship between the forces on an object, the object's mass, and its acceleration. You have been trying to develop Newton's First and Second Laws of Motion for one-dimensional situations in which all forces lie in a positive or negative direction along the same line.



7.6 Exercise. Newton's Laws in Your Own Words

Question 9: Express Newton's First Law (the one about constant velocity) in terms of the combined (net) force applied to an object in your own words clearly and precisely.

Question 10: Express Newton's First Law in equations in terms of the acceleration vector, the combined (net) force vector applied to an object, and its mass.

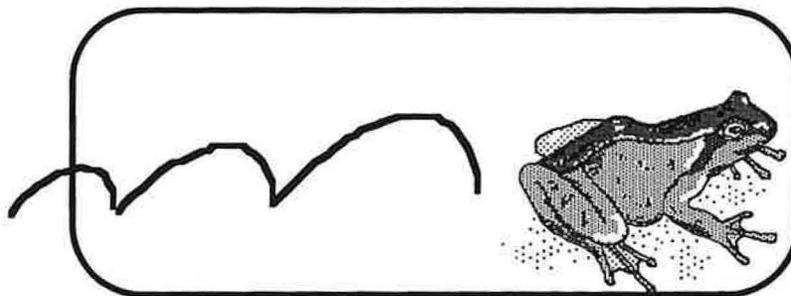
If $\Sigma F =$

then $a =$

and $v =$

Question 11: Express Newton's Second Law (the one relating force, mass, and acceleration) in terms of the combined (net) force applied to an object in your own words clearly and precisely.

Lesson 8: Gravitational Forces

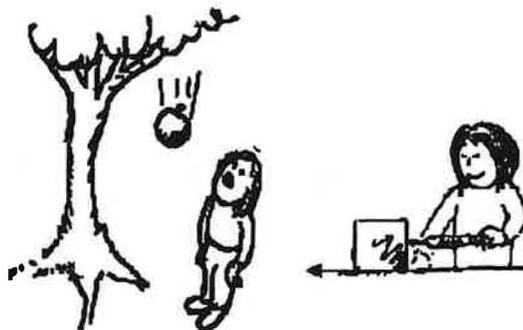


"And thus Nature will be very conformable to herself and very simple, performing all the great Motions of the heavenly Bodies by the attraction of gravity . . ."

Isaac Newton (1730)

OVERVIEW

You started your study of Newtonian Dynamics in Lesson 6 by developing the concept of force. Initially when asked to define forces most people think of a force as an obvious push or pull such as a punch to the jaw or the tug of a rubber band. By studying the acceleration that results from a force when little friction is present, we came up with a second definition of force as that which causes acceleration. These two alternative definitions of force do not always appear to be the same. Pushing on a wall doesn't seem to cause the wall to move. An object dropped close to the surface of the earth accelerates and yet there is no visible push or pull on it.



The genius of Newton was to recognize that he could define net force or combined force as that which causes acceleration, and that if the obvious applied forces did not account for the degree of acceleration then other "invisible" forces must be present. A prime example of an invisible force is the gravitational force--the attraction of the earth for objects.

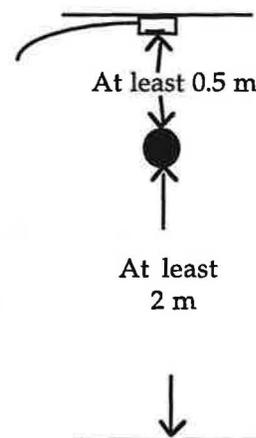
When an object falls close to the surface of the earth there is no obvious force being applied to it. Whatever is causing it to move is invisible. Most people rather casually refer to the cause of falling motions as the action of "gravity." What is "gravity"? Can we describe its effects mathematically? Can Newton's Laws be interpreted in such a way that they can be used for the mathematical prediction of motions that are influenced by "gravity"?

In this lesson you will first study vertical motion and the gravitational force. Then you will look at the motion of an object along an inclined ramp. You will also explore the relationship between mass and weight, and the meaning of mass.

Later you will examine the mechanism for normal forces--passive forces which often oppose the gravitational force to keep objects from moving.

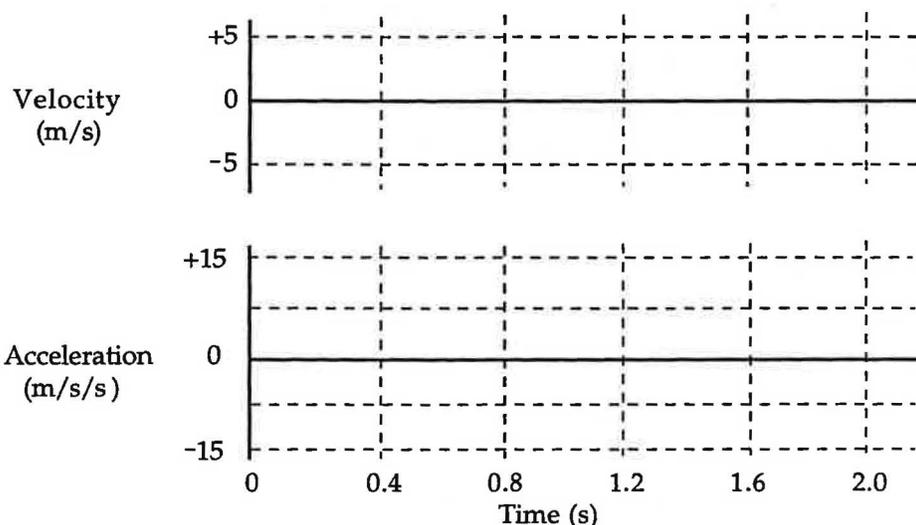
You have previously used the motion detector to examine the motion of your body and of a cart. The motion of a falling ball takes place much faster. While you can use the motion detector to measure position, velocity and acceleration, you will have to collect data at a faster rate than you have before. The easiest way to examine the motion of the falling ball is to mount the motion detector as high up as you can, and to use a large ball (like a basketball). It is essential to keep your hands and the rest of your body out of the way of the motion detector after the ball is released. This will be difficult, and may take a number of tries. It also will take some care to identify which portion of your graph corresponds to the actual downward motion of the ball, and which portions are garbage.

3. Tape the motion detector to a light fixture or something else as high above the floor as possible, with the detector looking downward, as shown on the right. Plug the cable of the motion detector into Port 2 of the ULI. Turn the power switch ON that is located on the back of the ULI.
4. Set up the axes shown below by opening experiment L6A1-1 (**Falling Ball**), which you will find in the **RTP Experiment Files** folder in the **Physics Programs** folder on the Mac HD. This will also set the data collection to a faster rate than has been used before (30 points/sec). Because the motion detector is pointing downward--in the negative y-direction--the software has been set up to call distance away from the detector negative. You can check this by looking in **Configure Distance Probe . . .** on the **Collect** menu.



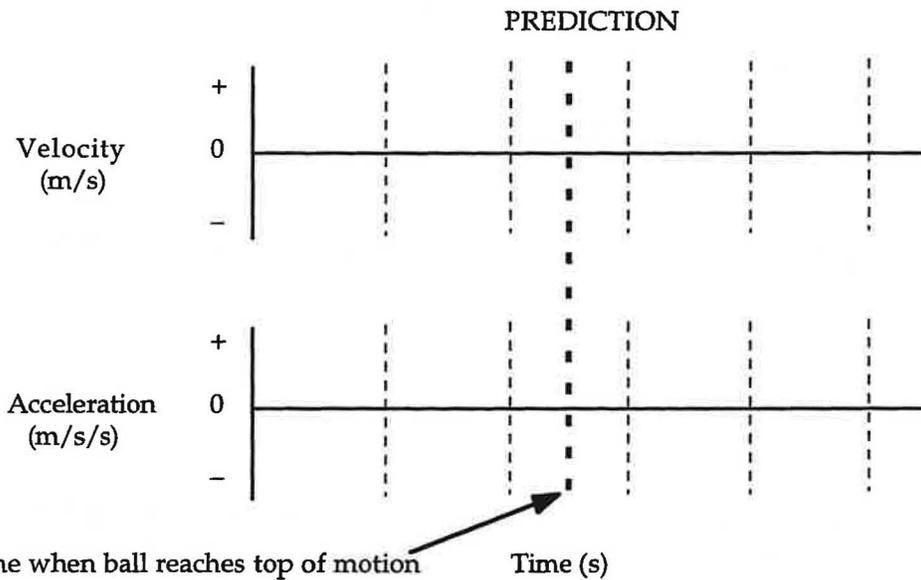
5. Hold the ball at least 0.5 m directly below the motion detector, and at least 2 m above the floor. Remember that your hands and body must be completely out of the path of the falling ball, so the detector will see the ball--and not your hands or body--the whole way down.
6. When everything is ready, click on **Start** and release the ball as soon as you hear the clicks from the motion detector.
7. Change the axes if necessary to display the velocity and acceleration as clearly as possible. Move the graphs to **Data B** (using **Data A -> Data B** under the **Data** menu) for comparison in Experiment 8.3. Save your data on your group's data disc. You may use it in a later lesson. Sketch your graphs on the axes below, or print them and affix them over the axes.
8. Mark with arrows on your graphs the time interval during which the ball was falling.

FINAL RESULTS



8.3 Experiment. Motion Up and Down

- Suppose that you toss a ball upward, and analyze the motion as it moves up, reaches its highest point and falls back down. Is the acceleration of the ball the same or different during the three parts of the motion—moving upward, momentarily at the highest point and moving downward? Explain.
- Sketch on the axes below your predictions of the velocity vs. time and acceleration vs. time graphs for the entire motion of the ball from the moment it leaves your hand until it returns to your hand. Assume that the positive direction is upward.



Throwing the ball upward and keeping it in the range of the motion detector is harder to do than dropping the ball. Try to throw it directly up toward the motion detector. It may take a number of tries. **Again be sure that your body is not seen by the motion detector.**

- The same experiment **L6A1-1 (Falling Ball)** used in Experiment 8.1 should work in this experiment as well. If necessary, move the graphs from Experiment 8.1 from Data A to Data B for later comparison.
- When everything is ready, **Start**, and when you hear the clicking begin, toss the ball up toward the motion detector. Toss the ball as high as you can, but remember that it should never get closer than 0.5 m from the detector. A short quick throw will work best. Repeat until you get a throw where you are sure the ball went straight up and down directly below the detector. When you get a good run, sketch the portion of your graphs corresponding to the ball's up and down motion on the axes on the next page, or print the graphs and affix them over the axes. Label this portion of the printed graphs. Save your data on your group's data disc. You may use it in a later lesson. Also label with an arrow the instant in time when the ball reached its highest point.

8.4 Exercise. How a Ball Actually Rises

1. Examine the portion of the graph in Experiment 8.3 which represents the upward motion of the ball. Using the convention that on the y-axis up is positive and down is negative, is the acceleration of the tossed object positive or negative as it rises (i.e. in what direction is the magnitude of the velocity increasing)?

2. If you think the object is undergoing a constant acceleration, use the modeling technique you used in Unit 2, Exercise 5.7 to find an equation that describes y as a function of t as the ball rises.
 - (a) Begin by selecting the portion of the velocity vs. time graph for which the slope is constant and the velocity is positive. Remember that this is done with the **Analyze Data A** option under the **Analyze** menu by highlighting the region of interest by dragging the vertical line from the beginning to the end of the region.
 - (b) View the position vs. time graph for this motion by clicking on the vertical axis label "Velocity" and selecting "Position". Describe the shape of the position vs. time graph for the upward part of the ball's motion.
 - (c) Select **Data A Table** under the **Windows** menu and copy ONLY the time and position values of the highlighted region. Paste that data into the **Untitled: Data Set 1** window in the **Graphical Analysis** software. Under the **Analyze** menu select **Automatic Curve Fit...** When the Automatic Curve Fit selection window appears, select **Polynomial** and set the **degree** at 2, and click **OK**. Write the equation of motion in the space below. **Hint:** Since you are dealing with the second dimension (i.e. the vertical dimension), you should replace x with y and x_0 with y_0 . Below the graph you will see a window titled "Automatic Curve Fit:". Use the coefficients listed there to find the values of a , v_0 and y_0 with the appropriate units. **Note:** Since the acceleration is caused by gravity, our notation for it will be a_g rather than just a .

The equation of motion with proper units is:

$$y =$$

The acceleration with proper sign and units is: $a_g =$

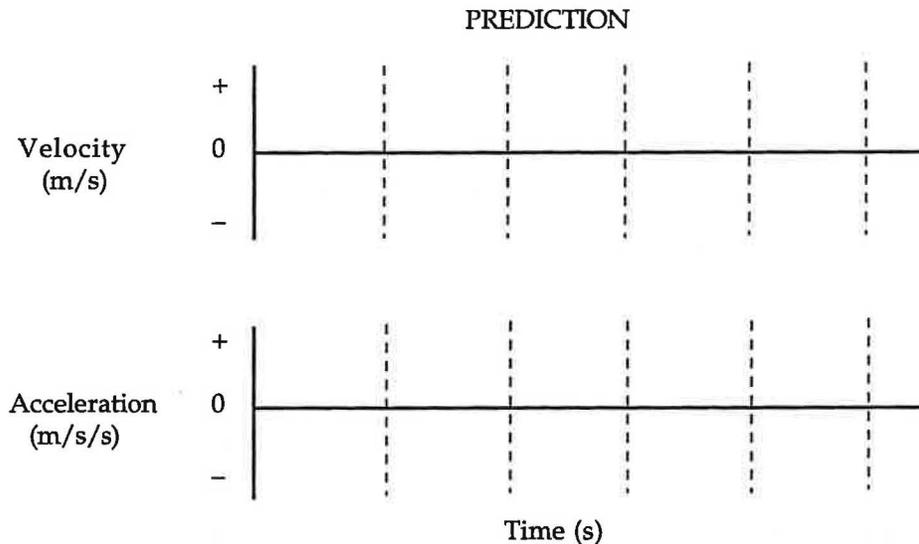
The initial velocity with proper sign and units is: $v_0 =$

The initial position with proper sign and units is: $y_0 =$

8.5 Exercise. How a Ball Actually Falls

1. Examine the portion of the graph in Experiment 8.3 which represents the downward motion of the ball. Using the convention that on the y-axis up is positive and down is negative, is the acceleration of the tossed object positive or negative as it falls (i.e. in what direction is the magnitude of the velocity increasing)?

1. Suppose that you have a very low friction cart and an inclined track, as shown above. The cart is given a push up the ramp and released, and its motion is graphed using the motion detector at the top of the ramp. (The direction toward the motion detector is positive.) Sketch on the axes below your predictions of the velocity vs. time and acceleration vs. time graphs for the motion of the cart.



2. What would be your prediction of the magnitude of the acceleration of the cart compared to the acceleration you determined in Exercise 8.2 for a ball falling straight downward? Explain.
3. Set up the track on a long board with the motion detector at the top of the board, 0.5 m away from the top end of the track. The end of the board with the motion detector should be elevated 10 cm or so. Be sure that the motion detector sees the cart over the whole length of the track.
4. Open the experiment **L6A1-4 (Inclined Ramp)** --in the **RTP Experiment Files** folder--to display the axes on the next page. As before, the software has been set up to consider motion toward the detector positive, so the positive direction of motion is up the track.
5. Hold the cart at the bottom of the track and **Start graphing**. When you hear the clicks of the motion detector, give the cart a push up the track and release it. The graph should include all three parts of the motion--up the track, at its highest point and on its way down. Repeat if necessary.
6. When you have good graphs, sketch them on the axes below or print and affix them over the axes. Mark on both graphs the instant when the cart was at its highest point along the track.
7. Measure the average acceleration of the cart during the time interval after it was released and before it was stopped at the bottom of the track. (Use **Analyze Data A ...** and **Statistics ...** on the **Analyze** menu.)
Average acceleration: _____ m/s/s

8.8 Exercise. Describing Gravity

First, you should describe the nature of the force that could cause the acceleration you observed.

1. Use the electronic scale (but not the spring scale) to determine the mass of the rubber ball in kg, and write it in the space below.

$$m = \text{_____ kg}$$

Question 10: Suppose the ball was floating in outer space (away from the gravity of the earth, friction, or any other influence) and that Newton's Second Law holds. Calculate the force in newtons that you would have to apply to the ball so it would move with an acceleration of the magnitude that you just observed in Experiment 8.1 towards the earth.

Question 11: What would the direction of the force need to be? How do you know?

Question 12: If Newton's Second Law is to be used in the situation where you dropped the ball in the classroom (on the earth) with no visible applied force on it, what force do you need to invent* to make Newton's Second Law valid? Is the force constant or varying during the time the ball is falling? What is its magnitude? Its direction?

So far you have studied the motion of just one object under the influence of the gravitational force you invented or discovered. You should have observed that the acceleration of the falling ball was constant so that the gravitational force was constant. This doesn't tell the whole story. How does the mass of the falling object affect its acceleration? Is the gravitational force constant--independent of the mass of the falling object just the way a horizontal push or pull with your hand on a cart might be constant?

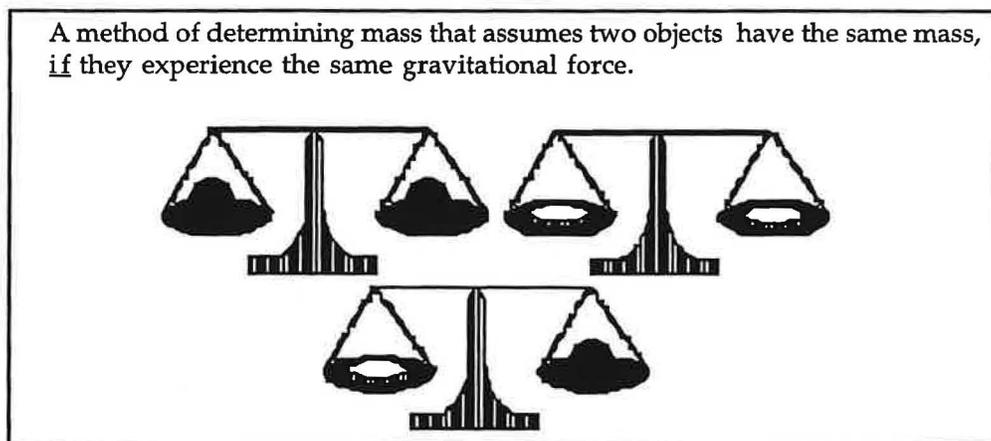
- * If you already believe Newton's Second Law is a fundamental law of nature then you might prefer to say you discovered the gravitational force. If you feel you and Newton have been constructing this law on the basis of some interplay between your minds and nature's rules then you could say you are inventing the idea of the gravitational force.

8.9 Experiment. Gravitational Force and Acceleration When Different Masses Fall

1. If you were to drop a massive steel ball and a not very massive rubber ball at the same time, would they fall with the same acceleration? Explain the reasons for your prediction.
2. Release the two objects from the same height at the same time, and observe when they hit the floor. Repeat several times.

Question 13: Did one object take significantly longer than the other to reach the floor, or did they both hit at about the same time?

But suppose we have two objects that have different shapes and are made of different stuff, such as a small lead pellet and a silver coin. To compare their masses we can put them on a balance, and when they balance each other we say that the "force due to gravity" or the force of attraction exerted on each of them by the earth is the same, so they must have the same mass.



Actually, if we balance gravitational forces as the method of determining mass, we are only determining a gravitational mass. Gravitational mass is proportional to the force of attraction exerted by the earth on the mass.

Another approach to determining mass that we used in Lesson 7 is to apply a constant force to an object, measure its acceleration, and calculate the mass as the ratio F/a . This method is used to determine inertial mass. Inertial mass is a measure of the resistance of an object to acceleration.

It is not obvious that these two definitions of mass—gravitational and inertial—should yield the same results. This equivalence is assumed in both Newton's theory of gravity and Einstein's general relativistic modifications of it. Mass can be measured with modern techniques to about 1 part in 10^{11} . Sophisticated experiments have shown that within these limits of experimental uncertainty, there is no difference between the two types of mass.

What is Force? Force can be defined several ways which seem to happily turn out to be consistent.

- (1) It can be defined as a push or pull and measured in terms of the stretch of a rubber band or spring, or the reading of a force probe.
- (2) Alternately the net or combined force on an object can be defined as the cause of motion. In this case we use Newton's Second Law to define net force by considering what happens to a standard mass. Suppose we extend a spring just enough so that a mass of "exactly" one kilogram will accelerate by exactly 1 m/s^2 when this force is applied to it. That force is defined as 1 newton. (An apple like that which Newton is supposed to have contemplated in free fall feels a gravitational force of about a newton.)
- (3) Finally we can define force in terms of the pull exerted on a mass by the earth as determined by the stretch of a spring when a mass is hanging from it. Thus, force is both a push or a pull and the cause of motion (for a non-zero net force).

Is There a Difference Between Mass and Weight?

Weight is a measure of the gravitational force, F_g , on a mass m and mass represents the resistance to motion. Many individuals confuse the concepts of mass and weight. Now that you understand Newton's Laws, you should know the difference.

8.13 Experiment. Normal forces

In this investigation you will consider the characteristics of another "invisible" type of force--normal force--that must be taken into account for the application of Newton's Laws to problems of real interest. A book resting on a table does not move, neither does a person pushing against a wall. According to Newton's First Law the combined (net) force on the book and on the person's hand must be zero, since neither is moving. We have to invent a type of force to explain why books don't fall through tables and hands don't usually push through walls. Since the forces exerted by a surface always seem to act in a direction perpendicular to the surface, such forces are called normal forces. Normal forces are examples of passive forces because they seem to act in response to active forces like pushes and gravitational forces. (Other forces characterized as passive are tension and frictional forces.)

To investigate some attributes of normal forces you will need the following apparatus:

- an embroidery hoop with elastic rubber diaphragm
- an embroidery hoop with stiffer (less flexible) material such as several layers of cloth
- 50 g and 100 g masses

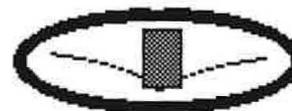
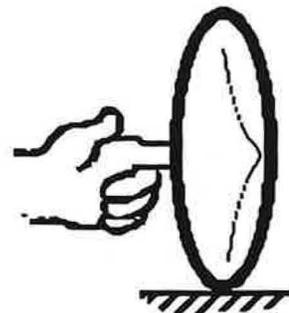
1. In the diagram at the right, a book is sitting on the table. The book is not moving, so the net force on it must be zero.



If the mass of the book is m , what is the magnitude of the gravitational force on the book?

What is the direction of this force?

2. If the net force on the book is zero according to Newton's First Law, then what magnitude force must the table exert on the book? What is the direction of this force?
3. By applying forces perpendicular to flexible surfaces with different degrees of stiffness you can discover a mechanism for the passive normal forces which crop up in reaction to forces applied to a surface.
 - (a) Hold the embroidery hoop with elastic rubber vertical and press in the center perpendicular to the rubber surface. Observe and describe what happens.
 - (b) Press harder in the center. Observe and describe what happens this time.
4. Repeat steps (a) and (b) using the stiffer (less flexible) hoop. Try to apply pushes of about the same magnitude as in steps (a) and (b), and observe how much the surface is displaced and how hard the surface pushes back on your finger.
5. Do a similar set of investigations using the same hoops held horizontally with 50g, then 100g, and finally 150 g masses placed at the centers of the surfaces. Record your observations below.



Extension A. Vertical Motion with Air Resistance

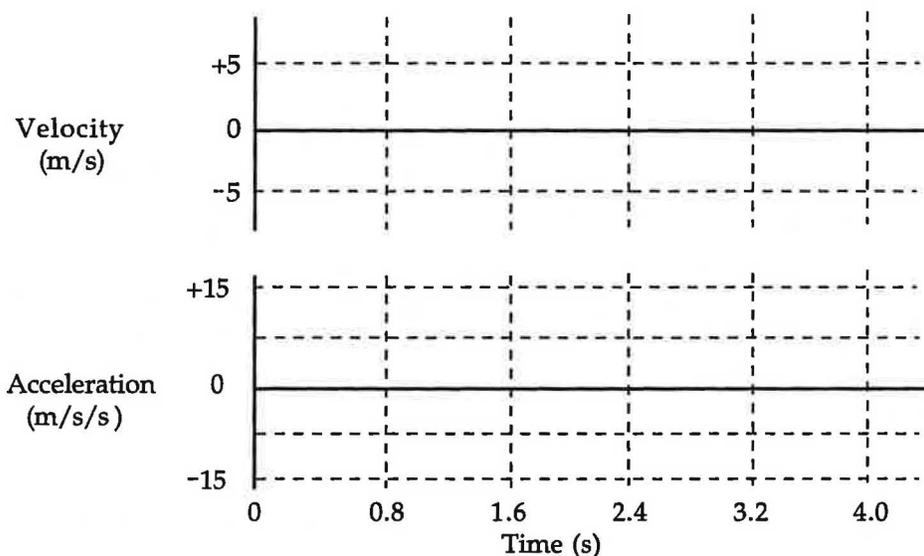
In this Extension you will use the motion detector to examine the motion of a paper coffee filter falling from rest. In addition to the setup in Experiment 8.1 you will need:

- a paper coffee filter--the type with a flat bottom and folds along the sides

Use the same experiment file as in Experiment 8.1, **L6A1-1 (Falling Ball)**. Increase the time range if necessary to record the complete motion of the filter, and change the velocity and distance axes if necessary to display the graphs more clearly.

Be sure to keep your body out of the way of the motion detector.

Sketch the graphs on the axes below, or print and affix them over the axes.



Question 1: Compare the graphs to those for the falling ball. Does the filter appear to fall with a constant acceleration? If not how would you describe the motion? Describe in terms of the acceleration and how the velocity is changing as the filter falls.

Question 2: Based on Newton's Laws of Motion, do you think that the gravitational force is the only one acting on the filter? If there is another force, what is its direction and how does its magnitude compare to the gravitational force? Explain.

Lesson 9: Newton's Third Law and Passive Forces

In this lesson you will consider the characteristics of several "invisible" forces that must be taken into account during the comprehensive application of Newton's laws to problems of real interest. These forces, friction and tension in strings, are known as passive forces because they only act in response to other forces. The normal force, examined in the last lesson, was also presented there as an example of a passive force.

In addition you will be introduced to the third of Newton's laws and will study a small portion of its extensive application.

An Introduction to Newton's Third Law

In order to apply Newton's laws to real life situations, we need to consider a third force law formulated by Newton having to do with the forces of interaction between two objects. In order to "discover" some simple aspects of the third law, you should make some straightforward observations using the following equipment:

- 2 spring balances (range = 20 N)
- a cart



Figure 9.1: Ways to test Newton's third law

9.1 Experiment. Newton's 3rd Law—Forces of Interaction

Set up the situations shown in the figure above and see if there are any circumstances in which the object that is pulling and the object that is being pulled exert different forces on each other. Describe your conclusions below. **Note:** You can use a skater, a skate board, a person riding on a large cart, etc. for your dynamic observations.

In order to investigate the nature of tension forces you will need the following apparatus:

- a rubber band
- 2 short lengths of string (approx. 6") w/ small loops at each end
- 2 long lengths of string (approx. 24") w/ small loops at each end
- 2 matched spring scales w/ 20 N max readings
- 2- 1000 g masses
- 2 frictionless pulleys
- clamps, stands, and rods to hold strings, pulleys, and masses

A. Mechanisms for Tension and the Direction of Forces

For these observations you should stretch a rubber band and then a string between your hands as shown in the diagram below. First, just feel the directions of the forces. Then add the spring scales and both feel and measure the forces.



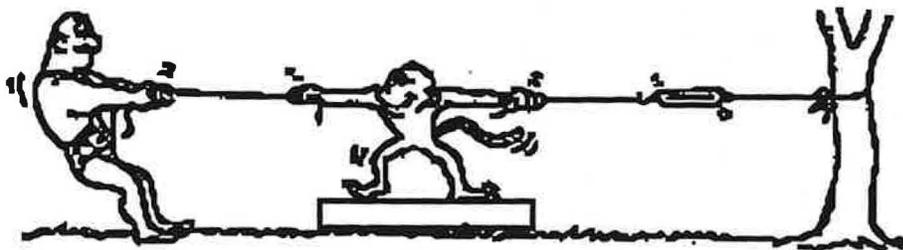
Figure 9.3: Stretching a string

9.2 Experiment. Tension Mechanisms & Force Directions

1. Pull on the two ends of a rubber band. (Forget about the spring scales for now). Does the rubber band stretch? What is the direction of the force applied by the rubber band on your right hand? On your left hand?
2. Does the magnitude of the forces applied by the rubber band on each hand feel the same?
3. Repeat this activity with a string instead of a rubber band. This time, use a spring scale at each end to measure the forces at the ends of the string. Does the string stretch? (Look carefully!)
4. If you pull by the same amount on the string as you did on the rubber band, does substituting the string for the rubber band change anything about the directions and magnitudes of the tension forces exerted on each hand?
5. If the forces caused by the string on your left and right hands respectively are given by F_{T1} and F_{T2} , what is the equation that relates these two forces?
6. What is a mechanism that might cause a rubber band or a string to develop tension in response to a force that you apply?

Discuss your answers with your teacher.

2. Based on Newton's third law and the observations you just made, answer the following questions using vector notation. If the muscle man in the diagram below is pulling to the left on a rope with a force of $F = -150 \text{ N}$, (the negative sign indicates that the direction of the force is to the left)



- What is the magnitude and direction of the force that the rope is exerting on the man?
 - What force is the left-hand rope exerting on the monkey's right arm (the one closest to the man)?
 - What force is the spring scale experiencing on its left end?
 - What force is the spring scale experiencing on its right end?
 - What is the reading on the spring scale?
 - What force is the rope exerting on the tree?
 - What force is the tree exerting on the rope?
3. Summarize what your observations reveal about the nature of tension forces everywhere along a string.

C. Can a String Support Lateral Forces?

Take a look at the diagram on the next page. Can the strongest member of your group stretch a string or rope so that it is perfectly horizontal when a 2 kg mass is hanging from it? In other words, can the string provide a force that just balances the force exerted by the mass?

Applying Tension Concepts to the Atwood's Machine

Sometime before 1780, a physicist at Cambridge University named George Atwood devised a marvelous machine for measuring the acceleration of a falling mass without the aid of high speed timers, motion detectors or video cameras. It consists of two masses connected to each other by means of a light string passing over a relatively frictionless light pulley, as shown in the diagram below.*

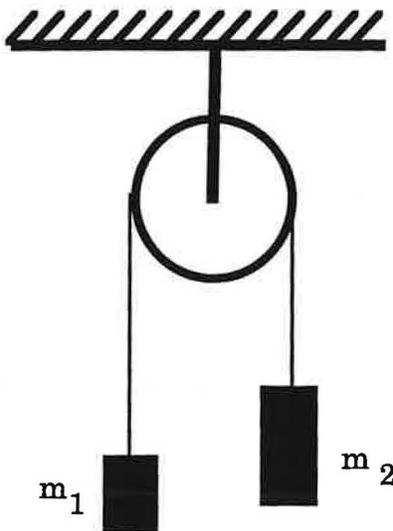


Figure 9.7

Atwood's machine is not only historically important but it allows us to practice applying Newton's laws and the kinematic equations to the analysis of motion. In order to make observations of the motion of the masses on an Atwood's machine you will need:

- a frictionless pulley
- a smooth length of string
- 2 identical 50 g mass hangers
- clamps and rods to support the pulley
- various small masses

9.5 Experiment. Behavior of the Atwood's Machine

1. Assume that the two masses are equal. If you pull down gently on one of them, what motion do you predict will result? Explain your reasoning.

2. Set up the Atwood's Machine with combinations of equal masses, pull on one of them gently, and describe what you observe. How does your observation compare with your prediction?

3. Suppose that m_2 is greater than m_1 . What do you expect to observe and why?

4. Set up the Atwood's Machine with combinations of unequal masses, and describe what you observe. How do your observations compare with your prediction?

* The meaning of "light": In referring to a "light" pulley and string, we mean that the mass of these items is very small compared to the masses of the falling weights. Thus, the masses of the string and pulley can be neglected in any calculations. Physicists are often kidded about their massless strings and pulleys!

The Bricklayer's Song

Dear sir, I write this note to you to tell you of my plight,
For at the time of writing it I'm not a pretty sight;
My body is all black and blue, my face a deathly gray,
And I write this note to say why I am not at work today.

While working on the 14th floor, some bricks I had to clear,
But tossing them down from such a height was not a good idea.
The foreman wasn't very pleased; he is an awkward sort
He said I had to cart them down the ladders in me hod.
Well, clearing all these bricks by hand – it was so very slow,
So I hoisted up a barrel and secured a rope below.
But in me haste to do the job, I was too blind to see
That a barrel full of building bricks was heavier than me.

And so when I untied the rope the barrel fell like lead,
And clinging tightly to the rope, I started up instead.
I shot up like a rocket and to my dismay I found
That halfway up I met the bloody barrel coming down.

Well, the barrel broke me shoulder as to the ground it sped,
And when I reached the top I banged the pulley with me head.
But I clung on tightly, numb with shock, from this almighty blow,
While the barrel spilled out half its bricks, some 14 floors below.

Now when these bricks had fallen from the barrel to the floor
I then outweighed the barrel, and so started down once more.
But I clung on tightly to the rope, me body racked with pain
And half way down I met the bloody barrel once again.

The force of this collision half way down the office block
Caused multiple abrasions and a nasty case of shock,
But I clung on tightly to the rope as I fell towards the ground,
And I landed on the broken bricks the barrel scattered 'round.

Well as I lay there on the floor I thought I'd passed the worst,
But the barrel hit the pulley wheel and then the bottom burst.
A shower of bricks rained down on me; I didn't have a hope,
As I lay there bleeding on the ground I let go the bloody rope.

The barrel now being heavier, it started down once more.
It landed right across me as I lay there on the floor.
It broke three ribs and my left arm, and I can only say
I hope you'll understand why I am not at work today!

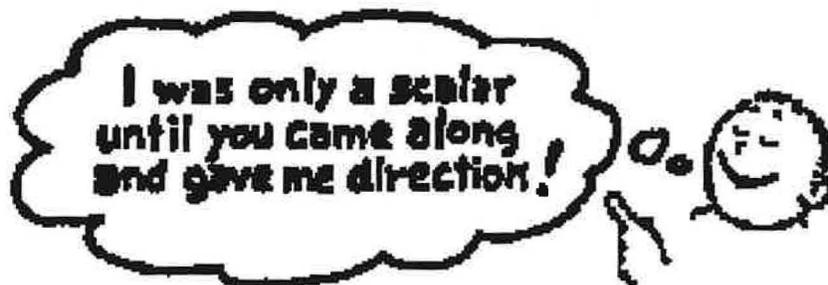
Unit 4: TWO DIMENSIONAL MOTION

OBJECTIVES

1. To learn to describe positions, velocities, and accelerations using vectors.
2. To understand the experimental and theoretical basis for describing projectile motion as the superposition of two independent motions: (1) a body falling in the vertical direction, and (2) a body moving in the horizontal direction with no forces.
3. To explore circular motion and determine the relation between the motion and the forces producing the motion.

OVERVIEW

In Lesson 10 you will prepare for the mathematical description of two dimensional motion by learning about some properties of two dimensional vectors, which can be used to describe positions, velocities and accelerations. You will then apply that to the specific example of projectile motion, in which an object accelerates in one dimension and moves at a constant velocity in the other. In Lesson 11 you will study uniform circular motion, in which an object continuously accelerates yet moves with constant speed.





10.2 Demonstrations. Independence of Vertical and Horizontal Motion for a Projectile

- A. Suppose a ball riding on a moving cart (with negligible friction in the wheel bearings) is launched straight up in the air. Will the ball fall behind the cart, in front of the cart, or in the cart when it lands?
- Describe what you think will happen when a ball is tossed straight up from a moving cart by sketching the path you think an observer at rest in the laboratory will see.
 - Explain the reasons for your prediction.
 - Observe the demonstration and describe what happens.
 - Suppose the cart is moving at 3 m/s. What is the initial horizontal velocity of the ball according to an observer in the laboratory? What is its horizontal velocity a few moments later when it lands on the cart?
 - What happens to the vertical velocity of the ball according to an observer in the laboratory?
 - Do the horizontal and vertical motions seem to be independent?
- B. Suppose two balls are launched simultaneously from the same elevation, ball A is dropped from rest and falls straight down and ball B is launched horizontally.
- Draw a sketch of the motion of each ball.



A vector has two key attributes that can be represented by an arrow pointing in space. These attributes are magnitude and direction. The **magnitude** of a vector can be represented by the **length of the arrow** and its direction can be represented by angles between the arrow and the coordinate axes chosen to help describe the vector. Suppose we want to represent the position of an object as shown in Figure 10.1. To answer questions about the magnitude and direction of vector **R** you will need:

- a ruler
- a protractor

10.3 Exercise. Vector Magnitude and Direction

1. What is the magnitude of the position vector in the x, y coordinate system shown in Fig. 10.1 (b)?
2. What angle does the vector make with the x -axis in the same coordinate system?
3. What is the magnitude of the vector in the x', y' coordinate system shown in Fig. 10.1 (c)? How does this compare to the magnitude of the vector in the x, y coordinate system?
4. What angle does the vector make with the x' -axis? Is this the same as the angle with respect to the x -axis?

VECTOR NOTATION

There are two common ways to indicate that a quantity is a vector: one is to represent it as a letter with an arrow over it; the other is to print the symbol in boldface. In this set of lessons symbols such as **R**, **v**, **a**, and **F** all represent quantities which have magnitude and direction. To represent only the magnitude of a vector quantity it is customary to either use italics or normal print (without the arrow or the boldface). Thus, either $R, v, a, \text{ and } F$ or $R, v, a, \text{ and } F$ represent only the magnitudes of those vectors. **Note:** You should always place an arrow over vector quantities, since you would have a difficult time designating a vector by making its symbol boldface.

There are a variety of ways to represent vectors. One common method is to use the idea of components. Figure 10.2 shows a position vector **R**.

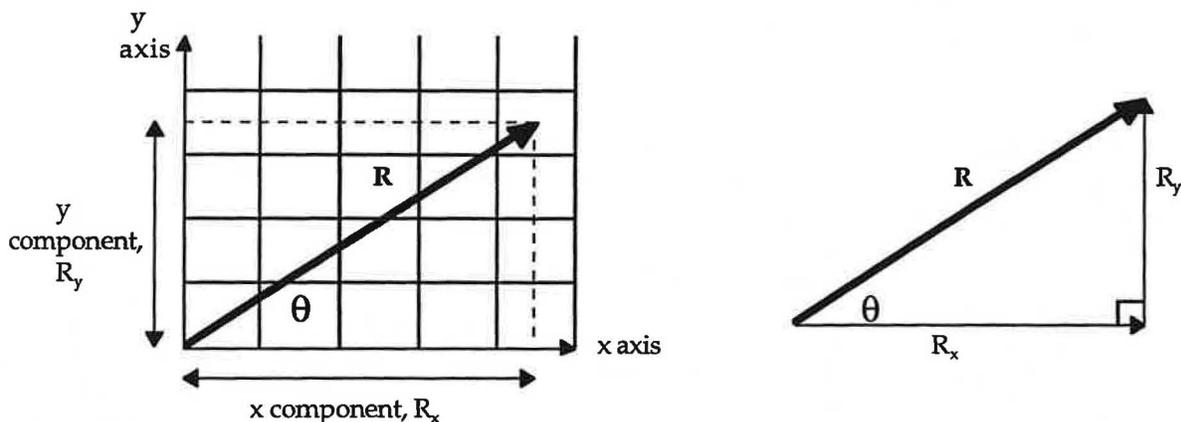


Figure 10.2

- (a) Under the **Setup** menu select **Calibrate....** Follow the directions in the **Video Calibrate** window. A white one-meter stick is lying on the countertop in the movie. Use it to perform the calibration. Be sure the **Actual size** information entered in the window is 1.00 meters. It is important to do a careful job of drawing the line the same length as the meter stick. Also make sure there is a check in the box labeled **Read times from the movie.**
 - (b) Under the **Setup** menu select **Set Single Origin.** The cursor becomes a box containing a cross when it is over the movie window. The actual point you pick as the origin is not important, but all measurements will be made relative to the point you pick. Possibilities include the initial position of the ball, a point on the countertop beneath the ball's original position, either end of the meter stick, etc.
 - (c) Under the **View** menu select **Magnifier.** Starting at the beginning of the movie, position the magnifier over some point on the ball and click the mouse button. This action should place a yellow square marker at that ball position and advance the movie one frame. Repeat the process for each new ball position, until its motion is complete. You must be careful to continue using whatever point on the ball you picked to begin with.
3. Describe the path of the ball.

How does it compare with your prediction in Exercise 10.1?

4. Under the **View** menu select **Velocity Vector.** Describe the change that this makes in the movie window. How do the velocity vectors change from one ball position to the next? (e.g., do they change in magnitude? do they change in direction?)

Try to explain the reason for any changes that occur in the velocity vectors.

5. Under the **View** menu you can also choose to see either the x-component of the velocity vector (Horizontal Velocity) or its y-component (Vertical Velocity). All three can be viewed separately or together. Examine the vectors to convince yourself that any given velocity vector does correspond to the components indicated for it. Are the vertical velocity components changing? Why or why not? Explain in terms of the forces acting on the ball.

Are the horizontal velocity components changing? Why or why not? Explain in terms of the forces acting on the ball.

10. Under the **Analyze** menu select **Automatic Curve Fit...** and determine an equation for the curve. (**Hint:** Is the curve shaped like any you have examined before?) In the space below write the equation of the curve, using proper symbols. Identify and explain the significance of each constant in the equation in terms of the properties of the motion (y_0 , v_{0y} , a_y). Type a graph title into the **Untitled:Text Window**, move things around on the screen so that the graph, the data, and the text window are all visible and then select **Print Screen...** under the **File** menu. Print a copy for each team member and affix one to the top of this page.
11. From your results in steps 6 and 10 you should have obtained values for the horizontal and vertical components of the ball's initial velocity. Using those values calculate the magnitude of the initial velocity vector. Show your calculated result (with units) below.
12. Switch back to the VideoGraph software, close the data table, and click in the movie, if necessary, to make it the active window. Under the **Measure** menu select **Angle Between Lines**. Follow the directions in the text box that appears and measure the initial launch angle of the ball. Position the vertex at the initial position of the ball and drag the vertical axis down until it is tangent to the curve. Record (in the space below) the angle measurement displayed in the text box; then click **Done**.

$$\theta = \underline{\hspace{2cm}}$$

Using the equations for the horizontal and vertical components of a vector given in step 4 of Exercise 10.4, calculate the horizontal and vertical components of the initial velocity. How do they compare with the values you determined from your graphs?

Discuss your results and conclusions from Exercise 10.6 with your teacher.

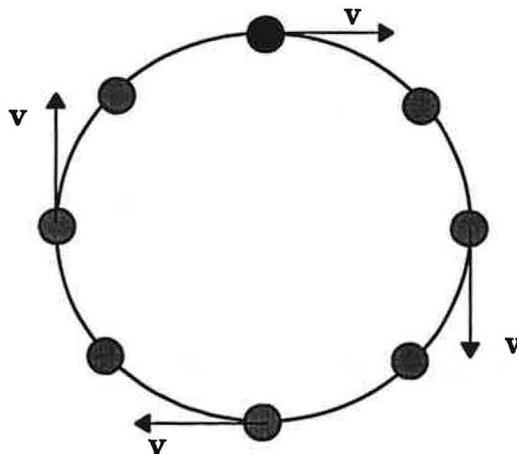
10.7 Demonstration/Discussion. The Monkey and the Hunter

10.8 Video

If time permits, the following other examples of projectile motion are available for viewing:

- in the **VideoGraph** software open the movie **Snowmobile and Flare**,
- on the videodisc Physics: Cinema Classics, Side B, the following chapters:
 - Vertical and Horizontal Motion
 - Horizontal Ballistics
 - Ballistics
 - Ping Pong Ball Model
 - Air Table and Shotputter
 - Airplane and Flare
- on the Saunders Physics videodisc, chapter 1 contains seven demonstrations, many of which are shown again in slow motion.

Lesson 11: Uniform Circular Motion



OVERVIEW

In the last lesson you studied the application of Newton's laws to projectile motion. In this lesson you are going to consider the application of Newton's laws in another phenomena in two dimensions, uniform circular motion, in which an object moves at a constant speed in a circle. Since Newton's laws can be used to predict types of motion or the conditions for no motion, their applications are useful in many endeavors including human body motion, astrophysics, and engineering.

In particular, you will develop a mathematical description of centripetal acceleration and the force needed to keep a massive object moving in a circle.

Moving in a Circle at a Constant Speed

When a race car speeds around a circular track, or when David twirled a stone at the end of a rope to clobber Goliath, or when a planet like Venus orbits the sun, they undergo uniform circular motion. Understanding the forces which govern orbital motion has been vital to astronomers in their quest to understand the laws of gravitation.

But we are getting ahead of ourselves, for as we have done in the case of linear and projectile motion we will begin our study by considering situations involving external applied forces that lead to circular motion in the absence of friction. We will then use our belief in Newton's laws to see how the circular motions of the planets can be used to help astronomers discover the laws of gravitation.



Figure 11.1: Uniform circular motion. A ball moving at a constant speed in a circle of radius r .

2. Hang the rotating mass back on the string, allow it to hang freely and adjust the position of the rod supporting the mass until the mass hangs directly over the radius indicator.
- (a) Describe the forces that act on the mass in its present position while at rest, giving both the magnitude and direction of each one. Also draw an arrow representing each force on the sketch of the rotating mass at the right.
- (b) For each force listed in part (a), describe the force that arises because of Newton's third law --the force that is equal in magnitude, acts in the opposite direction, and acts on a different body. Specify what each "third law" force acts on.
3. Attach the spring to the rotating shaft and to the rotating mass.
- (a) What is the net force acting on the mass now (while it is at rest)? How do you know?
- (b) Identify each force acting on the mass and draw arrows representing each force on a diagram at the right.
- (c) For the spring force listed in part (b), describe the force that arises because of Newton's third law -- the force that is equal in magnitude, acts in the opposite direction, and acts on a different body. Specify what this "third law" force acts on.
4. To the other side of the mass attach a string and drape it over the pulley. (The apparatus should be located close to the edge of the table so that the pulley extends past the edge.) Hang a mass hanger on the other end of the string. Add masses to the mass hanger until the rotating mass is once again positioned exactly over the radius indicator.
- (a) What is the net force acting on the mass now? How do you know?
- (b) On the diagram at the right draw arrows to represent each force acting on the stationary rotating mass.
- (c) For the new force listed in part (b), describe the force that arises because of Newton's third law -- the force that is equal in magnitude, acts in the opposite direction, and acts on a different body. Specify what this "third law" force acts on.



11.3 Experiment. The Velocities

In this experiment you will make the necessary measurements to calculate the speed (magnitude of the velocity vector) of the rotating mass as it undergoes uniform circular motion. You will do this at the three radius values measured in Exercise 11.2. At one of those radius values you will also change the value of the rotating mass.

1. Begin with the rotating mass in the location you studied in Step 8 of Exercise 11.2. If necessary remove any slotted masses from on top of the rotating mass.

Rotate the vertical shaft at the correct speed to keep the rotating mass moving over the top of the radius indicator as accurately and steadily as possible. While maintaining this motion measure the time for 10 continuous rotations. **Caution:** Be extremely careful that you count 10 rotations accurately! Make this measurement three times and record each measurement in the table on the following page. If any of your measurements differs from the others by more than 0.3 s you should repeat measurements. Also record in the table the other data requested.

2. Move the radius indicator to its farthest position from the central shaft. **Caution:** Be sure to reposition the supporting rod so that the rotating mass hangs freely over the top of the newly positioned radius indicator when the spring is not attached. Repeat the measurements of Step 1.
3. Move the radius indicator to its closest position from the central shaft. **Caution:** Be sure to reposition the supporting rod so that the rotating mass hangs freely over the top of the newly positioned radius indicator when the spring is not attached. Repeat the measurements of Step 1.
4. Add a 100 g slotted mass to the top of the rotating mass and repeat the measurements of Step 1.
5. Add another 100 g slotted mass to the top of the rotating mass and repeat the measurements of Step 1. If you can't add 100 g, add 50 g.

Step #	radius (m)	rotating mass (kg)	time for 10 rotations (s)				magnitude of the velocity (m/s)
			1	2	3	average	
1							
2							
3							
4							
5							

6. For each step in this exercise, calculate (a) the average time measurement, and (b) the magnitude of the velocity vector, and record them in the table above. **Caution:** remember to use the time for ONE rotation when calculating the magnitude of the velocity vector.

$$v = 2\pi r / t$$

11.4 Exercise. The Accelerations

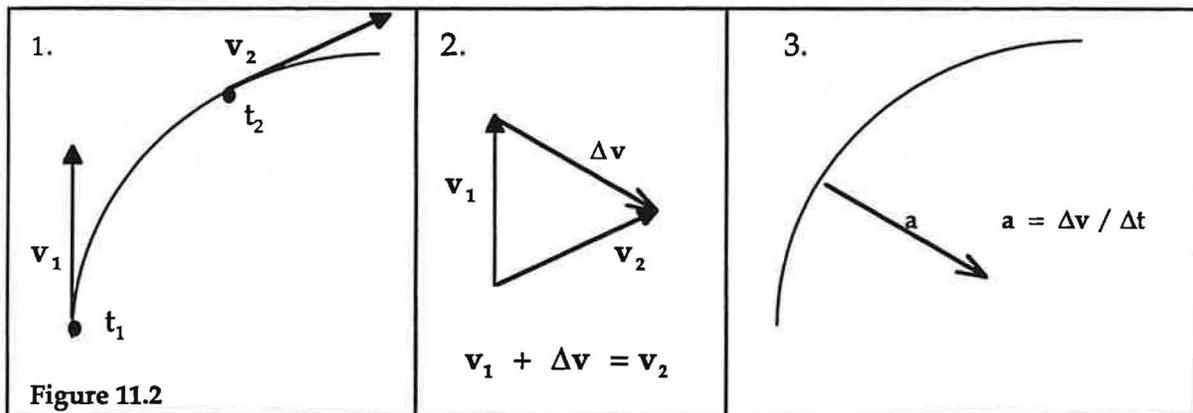
1. (a) On the diagram at the right draw arrows representing the forces acting shaft on the rotating mass when it is experiencing the uniform circular motion of Step 1 in Experiment 11.3.
 (b) Describe each force, specifying its magnitude and direction.



Describe the curve obtained with these four data points. Does its shape give you a hint regarding the exponent n ? (Remember the [Introduction to the Macintosh Computer](#) lesson.) Use the **Manual Curve Fit...** option under the **Analyze** menu, select the **Power** curve fit, set the constant B at a value consistent with your observations of the shape of the curve, and find the value of A that gives the best fit. Print a copy of your graph, attach it to the top of this page, and write the equation of the "best fit" curve on the graph.

11.5 Exercise. Using Vectors to Determine the Direction of Acceleration for Uniform Circular Motion

By now you should have concluded from your experimental results that the direction of the acceleration is inward, and that it is a result of the constantly changing direction of motion of the ball. We would like you to figure out how to determine the direction of the acceleration using what we know about the velocity vector. In order to use vectors to find the direction of velocity change in circular motion, let's review some rules for adding velocity vectors.



- 1. Velocities:** Draw an arrow representing the velocity, \mathbf{v}_1 , of the object at time t_1 . Draw another arrow representing the velocity, \mathbf{v}_2 , of the object at time t_2 .
- 2. Velocity Change:** Find the change in the velocity $\Delta\mathbf{v} = \mathbf{v}_2 - \mathbf{v}_1$ during the time interval $\Delta t = t_2 - t_1$. Start by using the rules of vector sums to rearrange the terms so that $\mathbf{v}_1 + \Delta\mathbf{v} = \mathbf{v}_2$. Next place the tails of the two velocity vectors together halfway between the original and final location of the object. The change in velocity is the vector which points from the head of the first velocity vector to the head of the second velocity vector.
- 3. Acceleration:** The acceleration equals the velocity change $\Delta\mathbf{v}$ divided by the time interval Δt needed for the change. Thus, \mathbf{a} is in the same direction as $\Delta\mathbf{v}$ but is a different length unless ($\Delta t = 1$). Thus, even if you do not know the time interval, you can still determine the direction of the acceleration because it points in the same direction as $\Delta\mathbf{v}$.

The acceleration associated with uniform circular motion is known as centripetal acceleration. You will now use the vector diagram technique to find its direction.

- Determine the direction of motion of the ball shown on the next page if it is moving counter-clockwise at a constant speed. Note that the direction of the ball's velocity is always tangential to the circle as it moves around. Draw an arrow representing the direction and magnitude of the ball's velocity as it passes the dot just before it reaches point A. Label this vector \mathbf{v}_1 .

11.6 Exercise. How Does a_c Depend on r ?

1. Do you expect the centripetal acceleration to be or larger or smaller for an object moving at a given magnitude of velocity but rotating in a smaller circle? In other words, would the magnitude, a_c , have to increase or decrease as r decreases if circular motion with the same speed is to be maintained? Explain.

Discuss your prediction with your teacher.

2. You have already determined (Exercise 11.4) that the centripetal acceleration is proportional to the square of the magnitude of the velocity vector. That means that the equation in Exercise 11.4 can be written as

$$a_c = c r^m v^2$$

Based on your prediction in Step 1, should the exponent m be positive or negative?

To determine m , divide each of the acceleration values from Steps 1, 2, and 3 of Exercise 11.4 by their respective values of v^2 . Record the results in the table below.

Step #	radius (m)	magnitude of velocity (m/s)	magnitude of acceleration (m/s/s)	a_c / v^2 (?)
1				
2				
3				

What are the units of for a_c / v^2 ? Does this give you a clue for the value of the exponent m ?

The equation from Exercise 11.4 has been transformed into $a_c / v^2 = c r^m$. Using the Graphical Analysis software, plot a_c / v^2 vs. r , with a_c / v^2 along the Y axis. Describe the resulting curve.

2. Use the **Automatic Curve Fit...** option under the **Analyze** menu to find the best fit through your data points. Select the **Power** option. If the constant B (the exponent in the power relation) is not an integer, force it to be an integer by adjusting its value in the Automatic Curve Fit window below the graph. (This action will change the curve fit method to Manual Curve Fit.) Then adjust the value of the constant A to give the best fit (e.g., the smallest value for the Mean Square Error).

Print a copy of your graph, attach it to the top of this page, and write the equation of the "best fit" curve on the graph.

11.7 Exercise. Final Results

1. Based on your results from Exercises 11.4 and 11.6, what is the final equation for the magnitude of the centripetal acceleration vector for uniform circular motion in terms of the radius and velocity?

The image of Newton having this idea as a sudden insight while sitting under an apple tree is probably mythical. However, it leads to some interesting modern facts. Nabisco now distributes both Fig and Apple Newtons. Near the surface of the earth the force on an average sized apple is about one newton. Think of this the next time you eat Apple Newtons!

You have now completed a series of observations which hopefully have led you to reconstruct Newton's three laws of motion and to understand some of their ramifications for yourself. In summary the laws are:

TABLE 11-1: Summary of Newton's Laws

First: If the net force acting on an object is zero its acceleration is zero. Or, an object at rest tends to remain at rest and an object in motion tends to continue moving with constant velocity, unless acted upon by a non-zero net force.

$$[\text{If } \Sigma \mathbf{F} = 0 \text{ then } \mathbf{a} = 0, \text{ so that } \mathbf{v} = \text{constant or zero.}]$$

Second: The net force on an object can be calculated by multiplying its mass times its acceleration. The direction of the acceleration vector is the same as the direction of the net force vector.

$$[\Sigma \mathbf{F} = m\mathbf{a}]$$

Third: Any two objects that interact exert forces on each other which are equal in magnitude and opposite in direction. These two forces never act on the same object; hence they cannot cancel.

$$[\mathbf{F}_{21} = -\mathbf{F}_{12}]$$

These three laws are incredibly powerful because an understanding of them allows you to either: (1) use a complete knowledge of forces on a system of objects to predict motions in the system or (2) identify the forces on a system of objects based on observations of its motions. In fact, you have already used a belief in Newton's laws to identify several active and passive "invisible" forces". The forces identified so far are shown in the table below.

TABLE 11-2: Forces Studied and Notation

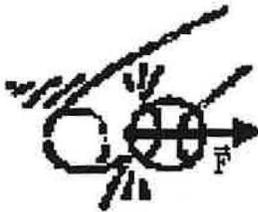
Active Forces:

- | | |
|------------------------------------|---|
| •External Forces (pushes or pulls) | \mathbf{F}_{ext} |
| •Gravitational Force (weight) | $\mathbf{F}_g = m \mathbf{a}_g$ |
| •Centripetal Force | $\mathbf{F}_c = m \mathbf{a}_c = m v^2 / r$ |

Passive Forces:

- | | |
|-------------------------|--|
| •Tension Force | \mathbf{F}_T |
| •Normal Force | \mathbf{F}_{norm} |
| •Static Friction Force | $\mathbf{F}_{f, \text{stat}} \leq \mu_{f, \text{stat}} \mathbf{F}_{\text{norm}}$ |
| •Kinetic Friction Force | $\mathbf{F}_{f, \text{kin}} = \mu_{f, \text{kin}} \mathbf{F}_{\text{norm}}$ |

OVERVIEW



In this unit we will explore the forces of interaction between two or more objects and study the changes in motion that result from these interactions. We are especially interested in studying collisions and explosions in which interactions take place in fractions of a second or less. Early investigators spent a considerable amount of time trying to observe collisions and explosions, but they encountered difficulties.

This is not surprising, since the observation of the details of such phenomena requires the use of instrumentation that was not yet invented (such as the high speed camera). However, the principles of the outcomes of collisions were well understood by the late seventeenth century, when several leading European scientists (including Sir Isaac Newton) developed the concept of quantity -of-motion to describe both elastic collisions (in which objects bounce off each other) and inelastic collisions (in which objects stick together). These days we use the word momentum rather than motion in describing collisions and explosions.

We will begin our study of collisions by exploring the relationship between the forces experienced by an object and its momentum change. It can be shown mathematically from Newton's laws and experimentally from our own observations that the area under of graph showing the force experienced by an object over time is equal to its change in momentum. This time-force product is defined as a special quantity called impulse, and the statement of equality between impulse and momentum change is known as the impulse-momentum theorem.

Next you will study the one-dimensional interaction forces between two colliding and exploding objects. By combining the results of this study with the impulse-momentum theorem, you can prove theoretically that momentum ought to be conserved in any interaction. It can be verified experimentally that whenever an object explodes or whenever two or more bodies collide, the momentum of the bodies before the event and their momentum after the event remain the same as long as no net external force acts on them. At the conclusion of this study you will have the opportunity to use video analysis to verify the Law of Conservation of Momentum.

When the Law of Conservation of Momentum and the impulse-momentum theorem are applied to the study of collisions between two or more objects, physicists can learn about the interaction forces among them. There is no way to make direct measurements of the tiny forces of interaction between the various particles that are the fundamental building blocks of matter. Contemporary physicists working in accelerator laboratories bombard materials with tiny, rapidly moving particles and collect data on the momentum changes that occur during the collisions. This provides them with an indirect way to learn about fundamental forces of interaction. Those of you who will continue the study of physics will revisit these relationships between momentum changes and forces many times.

Just to double check your reasoning, you should have come to the conclusion that momentum is defined by the vector equation

$$\mathbf{p} \equiv m\mathbf{v} \quad [\text{Eq. 12-1}]$$

where the symbol \equiv means "defined as."

12.2 Commentary. Re-expressing Newton's Second Law Using Momentum

Originally Newton did not use the concept of acceleration or velocity in his laws. Instead he used the term "motion", which he defined as the product of mass and velocity (the quantity we now call momentum). Let's examine a translation from Latin of Newton's first two laws (with some parenthetical changes for clarity).

Newton's First Two Laws of Motion ^{1,2}

1. Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed on it.
2. The (rate of) change of motion is proportional to the motive force impressed: and is made in the direction of the right line in which that force is impressed.

The more familiar contemporary statement of the second law is that the net force on an object is the product of its mass and its acceleration where the direction of the force and of the resulting acceleration are the same. Newton's statement of the law and the more modern statement are mathematically equivalent, as shown below.

- (a) The contemporary mathematical expression for Newton's second law relating net force to mass and acceleration is

$$\Sigma \mathbf{F} = m\mathbf{a}$$

where \mathbf{a} is the instantaneous acceleration.

- (b) The definition of average acceleration in terms of the rate of change of velocity is

$$\mathbf{a}_{\text{ave}} = \Delta \mathbf{v} / \Delta t$$

which is the slope of a velocity vs. time graph between two times t_1 and t_2 . To get the instantaneous acceleration at time t_1 (i.e., the instantaneous rate of change of velocity at time t_1) it was necessary to let Δt get smaller and smaller so that t_2 approached t_1 , and the line used to determine the slope of the graph became a tangent line, tangent to the curve at t_1 .

- (c) It can be shown that if an object has a changing velocity and a constant mass then

$$m\mathbf{a}_{\text{ave}} = m \Delta \mathbf{v} / \Delta t = \Delta(m\mathbf{v}) / \Delta t = \Delta \mathbf{p} / \Delta t$$

The left side of this equation is just the average net force over the time interval Δt , while the right side is the slope of the momentum vs. time graph for the same time interval. If the time Δt gets smaller and smaller, then the right side eventually becomes the slope of a tangent line, which is the instantaneous rate of change of momentum at time t_1 . This means that the left side has become the instantaneous net force at the same time.

In other words, at any instant the net force equals the instantaneous time rate of change of momentum:

$$\mathbf{F}_{\text{net}} = \Delta \mathbf{p} / \Delta t \quad [\text{Eq. 12.2}]$$

¹ I. Newton, *Principia Mathematica*, Florian Cajori, Ed. (U. of Calif. Press, Berkeley, 1934). p. 13.

² L.W. Taylor, *Physics the Pioneer Science*, Vol. 1 (Dover, New York, 1959). pp. 129-131

It would be nice to be able to use Newton's formulation of the second law of motion to find collision forces, but it is difficult to measure the rate of change of momentum during a rapid collision without special instruments. However, measuring the momenta of objects just before and just after a collision is usually not too difficult. This led scientists in the seventeenth and eighteenth centuries to concentrate on the overall changes in momentum that resulted from collisions. They then tried to relate changes in momentum to the forces experienced by an object during a collision. In the next activity you are going to explore the mathematics of calculating momentum changes.

12.4 Exercise. Calculating 1D Momentum Changes

1. Which object undergoes the most momentum change during the collision with a door – the clay blob or the super ball? Explain your reasoning carefully.
2. Let's check your reasoning with some formal calculations of the momentum changes for both inelastic and elastic collisions. This is a good review of the properties of one-dimensional vectors. Recall that momentum is defined as a vector quantity that has both magnitude and direction. Mathematically, momentum change is given by the equation

$$\Delta \mathbf{p} = \mathbf{p}_f - \mathbf{p}_i \quad [\text{Eq. 12-3}]$$

where \mathbf{p}_i is the initial momentum of the object just before and \mathbf{p}_f is its final momentum just after a collision.

- (a) Suppose a dead ball (or clay blob) is dropped on a table and "sticks". It has an initial momentum just before it hits of $\mathbf{p}_i = -p_i$ where the minus sign indicates that the direction of the momentum is downward, in the negative-y direction. Since it sticks, what is the final momentum of the dead ball?

$$\mathbf{p}_f =$$

- (b) According to Equation 12.3, what is the change in momentum of the clay blob as a result of its collision with the table?

$$\Delta \mathbf{p} =$$

What is the significance of the sign?

- (c) Suppose that a live ball (or a super ball) is dropped on a table and "bounces" on the table in an elastic collision so that its speed just before and just after the bounce are the same. Also suppose that just before it bounces it has an initial momentum of $\mathbf{p}_i = -p_i$ where the minus sign indicates that the direction of the momentum is downward, in the negative-y direction. What is the direction of the final momentum of the ball? **Hint:** Does the final \mathbf{p} vector point along the +y or -y axis? Write the final momentum in terms of the initial momentum.

$$\mathbf{p}_f =$$

- (d) What is the change in momentum of the ball as a result of the collision?

$$\Delta \mathbf{p} =$$

Applying Newton's Second Law to the Collision ProcessThe Egg Toss

Suppose somebody tosses you a raw egg and you catch it. In physics jargon, you would say (in a very official tone of voice) that "the egg and my hand have undergone an inelastic collision." What is the relationship between the force you have to exert on the egg to stop it, the time it takes you to stop it, and the momentum change that the egg experiences? You ought to have some intuition about this matter. In more ordinary language, would you catch an egg slowly or fast?

12.5 Exercise. Momentum Changes and Average Forces on an Egg

1. If you catch an egg of mass m that is heading toward your hand at speed v what is the magnitude of the momentum change that it undergoes?
2. Does the total momentum change differ if you catch the egg more slowly or is it the same?
3. Suppose the time you take to bring the egg to a stop is Δt . Would you rather catch the egg in such a way that Δt is small or large. Why?
4. What do you suspect might happen to the average force you exert on the egg while catching it when Δt is small?

You can now use Newton's second law to derive a mathematical relationship between momentum change, force, and collision times for objects. This derivation leads to the impulse-momentum theorem that we mentioned in the overview.

5. Write the mathematical expression for Newton's second law in terms of the net force and the time rate of change of momentum. (See Commentary 12.2, step (c) for details.)
6. Show that for a constant net force F the change in momentum is given by $\Delta p = F \Delta t$. Note that for a constant force, the term $F \Delta t$ is known as the impulse given to one body by another.

12.6 Demonstration. Egg Drop

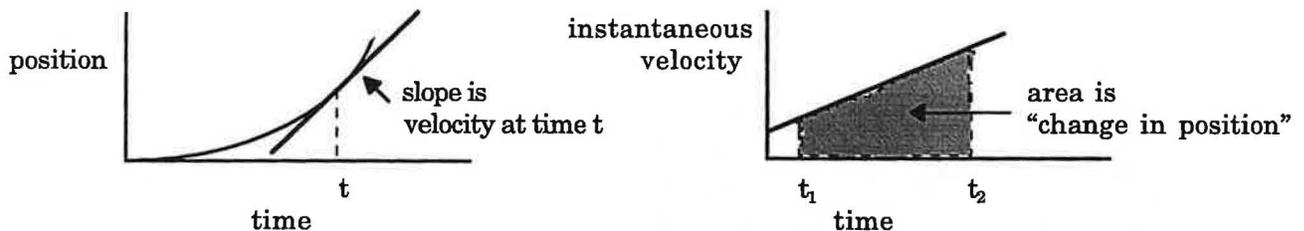
After observing the demonstration explain the application of the impulse relation (from step 6 in Exercise 12.5).

Lesson 13: Impulse, Momentum and Interactions

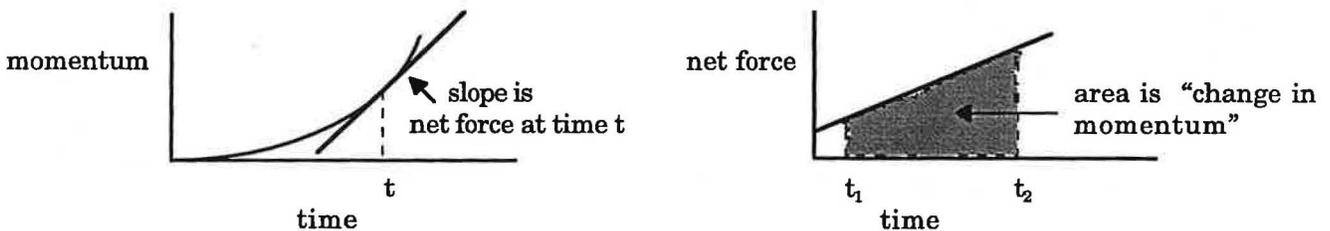
The Impulse-Momentum Theorem

Real collisions, like those between cars, eggs and hands, a ball and a racquet, or a falling ball and an electronic scale are tricky to study because Δt is so small and the collision forces are not really constant over the time the colliding objects are in contact. Thus, we cannot calculate the impulse as $F\Delta t$. Before we study more realistic collision processes, let's redo the theory for a variable force. In order to do this we will draw upon your earlier experience with the relations between distance, time, and velocity.

Recall from Exercise 5.5 in Lesson 5 that the area under a velocity vs. time graph represented the "change in position" of the moving object in the time interval from t_1 to t_2 . Earlier you learned that the slope of a position vs. time graph at a given time represented the instantaneous velocity at that time.



In the last lesson you learned that the slope of a momentum vs. time graph at a given time represented the instantaneous net force at that time. In agreement with the above results, the area of a net force vs. time graph is then the "change in momentum" experienced in the time interval from t_1 to t_2 .



Impulse is a vector quantity defined by the relation

$$\mathbf{J} \equiv \text{area under a net force vs. time graph}$$

By combining this definition with the understanding that the area under a net force vs. time graph represents the change in momentum, we can formulate the impulse-momentum theorem in which

$$\mathbf{J} = \Delta \mathbf{p} \quad [\text{Eq. 13.1}]$$

In cases where the net force is constant this relation can be expressed by the equation

$$\mathbf{J} = \mathbf{F} \Delta t \quad [\text{Eq. 13.2}]$$

Verification of the Impulse-Momentum Theorem

To verify the impulse-momentum theorem experimentally we must show that for an actual collision involving a single force on an object the equation

$$\Delta p = J = \text{the area under the curve of a graph of force vs. time}$$

holds.

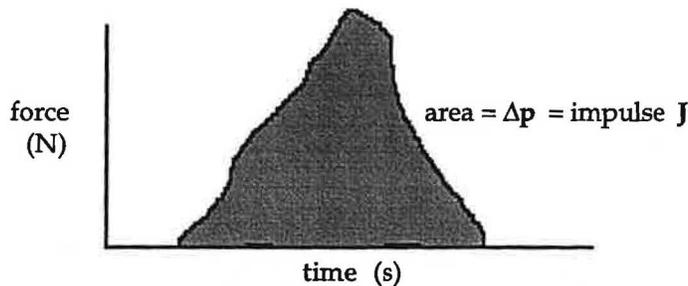


Figure 13.1: Evaluating the impulse as the area under the graph of force as a function of time.

By using a microcomputer-based laboratory system it is possible to measure changes in force as a function of time during actual collisions. An MBL force setup is shown for the case of a dynamics cart (with a force probe) colliding with a wall in the illustration below.

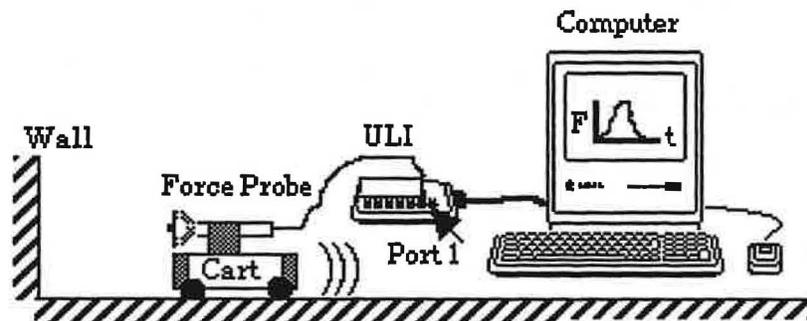


Figure 13.2: MBL apparatus for measuring collision forces on a force probe mounted on a cart and an "immovable object" in the form of a wall.

Your task is to see if you can set up a collision situation that will allow you to monitor the change of force as a function of time during the collision so that you can calculate the impulse experienced by the cart. At the same time, you must take measurements to allow you to determine the momentum before and after the collision and hence the momentum change of the object. You can then determine whether or not the impulse associated with the collision is equal (within the limits of experimental uncertainty) to the momentum change of the cart.

With an MBL force detection system that is capable of taking 1000 or more force readings a second, there are many ways to set up a verification experiment with the equipment available in a typical introductory physics laboratory. For this experiment we will focus on studying very gentle collisions between a dynamics cart and a force probe. The velocity of the cart can be measured with a ULI motion detector attached to a ULI laboratory interface hooked up to another computer. (Unfortunately, the computers are not fast enough to handle both force and motion readings simultaneously at the relatively rapid data collection rates needed to record an impulse curve during a short collision time.)

2. The ULI motion detector should be plugged into Port 2 on the other ULI interface at your lab table. Turn the ULI on using the switch at the right rear. Position the motion detector at the opposite end of the track from the force probe. Open the MacMotion software on the other computer. Display a graph of velocity vs. time. Set the time axis maximum at 5.0 s and the velocity axis minimum and maximum at -2 m/s and +2 m/s, respectively. Under the Collect menu select Motion + Force Data. Under the same menu set the Data Rate... at 30. Finally, again under the Collect menu, select Configure Distance Probe..., enter the correct room temperature and select Distance away is negative.
3. Describe the measuring techniques and calculation methods you are going to use to determine the change in momentum of your cart as a result of a collision with the force probe.

4. Do the experiment in which you determine both the velocity change and the impulse curve for the same gentle collision. Remember, the maximum force between the cart and the probe must be less than 20N. When you have a collision that you are satisfied with, you can use the Analyze feature associated with the MacMotion software to determine the approximate value of the area of the Force vs. time curve for the time between the start and end of your collision. Proceed as follows:
 - (a) Under the Analyze menu select Analyze Data A.
 - (b) Position the vertical line at the beginning of the collision, hold the mouse button down and drag across to the end of the collision, and release the mouse button. This action should highlight the area under the curve corresponding to the collision time interval.
 - (c) In calculus, the area under a curve (one for which the equation is known) is obtained by evaluating what is called the integral. It is also possible to use approximations to get the area under a more complicated curve for which the equation is not known. This is still referred to as the integral of the function. You can determine the area under your force vs. time curve by selecting **Integral** under the **Analyze** menu. Do so now and record below the resulting value displayed above the top of the graph.

integral (= area) = _____

What are the units for this area value?

- (d) Affix a printout of your impulse curve in the space below.
5. Use the **Analyze** feature of **MacMotion** to determine the velocity of the cart just before the collision and just after the collision. List the values below. Be careful of signs, and include units!

$v_i =$ _____ $v_f =$ _____

6. Measure the mass of the cart and record its value below.

$m =$ _____

- Click on **Start** on both computers and release the cart as soon as the motion detector begins emitting its clicking sound. Stop the cart before it reaches the end of the track.
- To analyze the data, examine both the force vs. time and velocity vs. time graphs and pick an initial time and a final time for which you can get accurate velocity measurements. Analyze the force vs. time graph as you did in Experiment 13.2 to get the area under the curve; be careful to use the same exact time interval corresponding to the interval between the initial and final velocities. Record the velocities and the area under the force vs. time curve in the space below.

$$v_i = \underline{\hspace{2cm}} \quad v_f = \underline{\hspace{2cm}} \quad \text{integral (= area)} = \underline{\hspace{2cm}}$$

- Measure the mass of the cart/force probe combination and record it below.

$$m = \underline{\hspace{2cm}}$$

- Calculate the change in momentum of the cart/force probe system, and compare it with the impulse (as determined in step 5) the applied force exerted on the system. Record your results below.
- Does the impulse-momentum theorem seem valid within the limits of experimental uncertainty for this experiment?

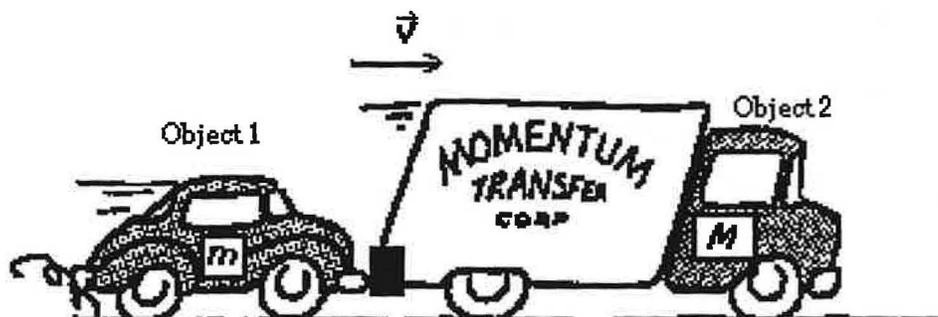
13.5 Experiment.

If time permits, repeat the experiment and analysis of Experiment 13.4, but this time begin with the hanging mass resting on the floor and the cart close to the pulley. Give the cart a push toward the motion detector. Gather data for the velocity and force as functions of time as the cart approaches the motion detector, stops, and moves away from the motion detector. You will probably have to increase the maximum value for the time axis for each graph before you gather the data.

Discuss your results for this lesson with your teacher.

3. Suppose the mass of object 1 is much less than that of object 2 and that it is pushing object 2 which has a dead motor so that both objects move in the same direction at speed v .

$$m_1 \ll m_2 \text{ and } v_1 = v_2$$

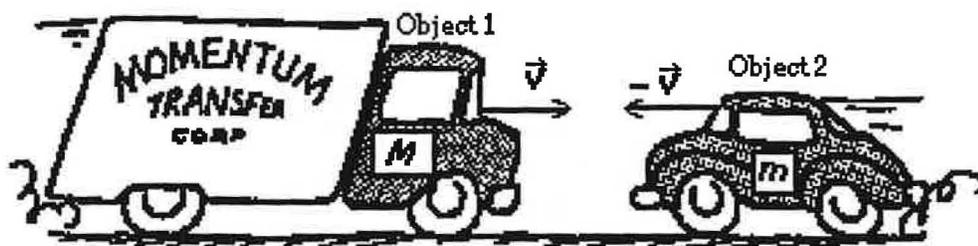


Predict the relative magnitudes of the forces between object 1 and object 2. Place a check next to your prediction.

- Object 1 exerts more force on object 2.
- The objects exert the same force on each other.
- Object 2 exerts more force on object 1.

4. Suppose the mass of object 1 is greater than that of object 2 and that the objects are moving toward each other at the same speed so that

$$m_1 > m_2 \text{ and } v_1 = -v_2$$



Predict the relative magnitudes of the forces between object 1 and object 2. Place a check next to your prediction.

- Object 1 exerts more force on object 2.
- The objects exert the same force on each other.
- Object 2 exerts more force on object 1.

7. Provide a summary of your predictions. What are the circumstances under which you predict that one object will exert more force on another object.

Measuring Mutual Forces of Interaction

In order to test the predictions you made in the last exercise you can study gentle collisions between two force probes attached to carts. You can attach additional masses to one of the carts to increase its total mass so it has significantly more mass than the other. To make these observations you will need the following equipment:

- a PowerMac computer
- Data Logger software (located in the Physics Programs folder)
- 2 force probes
- a spring scale (20 N) to calibrate the force probes
- 2 dynamics carts
- masses to place on one of the carts to triple its mass
- a level track for the carts

This apparatus should be set up as shown in the following diagram.

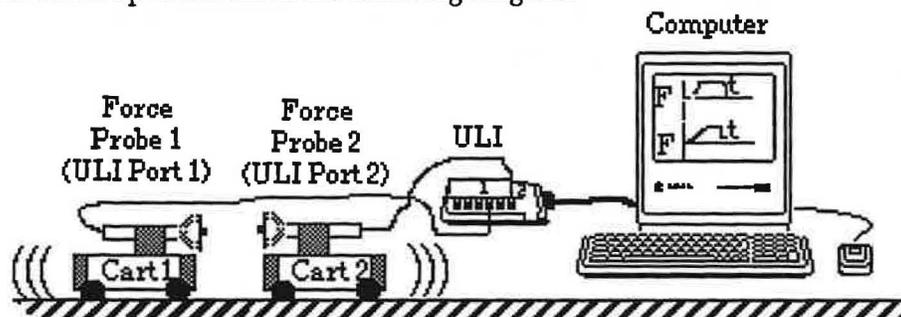


Figure 14.1: Setup for reading two forces at once during a gentle collision.

Setup and Calibration for the Measurement of Mutual Forces

SETUP

1. Plug one force probe into Port 1 of the ULI and the other into Port 2.
2. Turn the ULI on using the switch at the right rear.
3. Turn on the Macintosh and open the L9A1-1 (Collisions) experiment file, which is located in the RTP Experiment files folder. You should see two Force vs. Time axes, one for each force probe.

CALIBRATION OF THE PROBES FOR PUSH-PUSH

1. Select Calibrate Force from the Collect menu.
2. Position the probes horizontally with their heads lined up but not touching and follow the directions to calibrate with no force on the probes.
3. Connect the two probes together so each one experiences the same magnitude of pull (i.e. tension force). Use a spring scale to apply the tension to the aligned probes.
4. Enter the reading of the spring scale into the dialog box and follow the instructions on the screen.
5. Return to the main graph screen to do your experiments.

Note: Since the force probe output voltages change a bit in time, it is important to zero them frequently when you are taking measurements. This is done by clicking the mouse on the Zero box in the lower right hand corner of the graph screen. Be patient – it takes time for the computer to zero both probes.

6. If you think you might use the same probes again put a label on them and save the force probe calibration file on your data disk.

14.5 Experiment. Verifying Momentum Conservation in Inelastic Collisions

1. Measure and record below the mass of each cart and of the two extra masses.

cart 1 _____ cart 2 _____ mass 1 _____ mass 2 _____

2. Use 2 carts on the track with ULI motion detectors at opposite ends of the track. Remember that the carts need to be no closer than 0.5 m from the motion detectors. With this arrangement you will be able to measure the velocity of each cart both before and after a collision.



3. For this experiment face toward each other the ends of the carts equipped with Velcro. The speed of the carts should be small enough that the carts will stick together after a collision, producing an inelastic collision.
4. Carry out three or four types of collisions (see Exercise 14.1 for examples). For each collision use the **MacMotion** software to determine the initial and final velocity of each cart. Then calculate the initial and final momentum of each cart, and the total initial and final momentum values.

masses (kg)		initial velocity (m/s)		final velocity (m/s)		initial momentum (kg m/s)			final momentum (kg m/s)		
cart 1	cart 2	cart 1	cart 2	cart 1	cart 2	cart 1	cart 2	total	cart 1	cart 2	total

14.6 Experiment. Verifying Momentum Conservation in Elastic Collisions

1. For this experiment face toward each other the ends of the carts equipped with magnets. The speed of the carts should be small enough that the carts do not make physical contact during a collision. These will then be elastic collision.
2. Carry out three or four types of collisions (see Exercise 14.1 for examples). For each collision use the **MacMotion** software to determine the initial and final velocity of each cart. Then calculate the initial and final momentum of each cart, and the total initial and final momentum values.

masses (kg)		initial velocity (m/s)		final velocity (m/s)		initial momentum (kg m/s)			final momentum (kg m/s)		
cart 1	cart 2	cart 1	cart 2	cart 1	cart 2	cart 1	cart 2	total	cart 1	cart 2	total

Unit 6: WORK AND ENERGY



In order to understand the equivalence of mass and energy, we must go back to two conservation principles which ... held a high place in pre-relativity physics. These were the principle of the conservation of energy and the principle of the conservation of mass.

Albert Einstein

OBJECTIVES

1. To extend the intuitive notion of work as physical effort to a formal mathematical definition of work as a function of force and distance.
2. To understand the concept of power and its relationship to work.
3. To understand the concept of kinetic energy and its relationship to work as embodied in the work-energy theorem.
4. To relate experimentally determined kinetic energy loss to frictional loss.
5. To understand the concept of potential energy.
6. To investigate the conditions under which mechanical energy is conserved.

Lesson 15: Physical Work and Power

The Concept of Physical Work

Suppose you are president of the Moorhead Load 'n' Go Co. A local college has three jobs available and will allow you to choose which one you want before offering the other two jobs to rival companies. All three jobs pay the same amount of money. Which one would you choose for your crew?

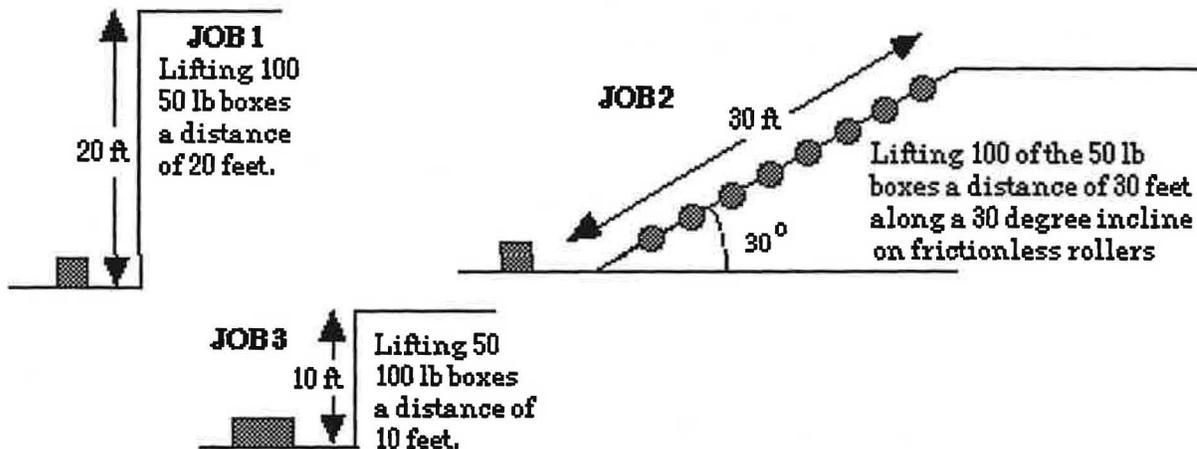


Figure 15-1: A description of jobs to bid on

Complete Exercise 15.1 and Experiment 15.2 before coming to class.

15.1 Exercise. Choosing Your Job

Examine the descriptions of the jobs shown in Figure 15-1. Which one would you be most likely to choose? Least likely to choose? Explain the reasons for your answer.

You obviously want to do the least amount of work for the most money. Before you reconsider your answers later in this unit, you should do a series of activities to get a better feel for what physicists mean by work and how the president of Load 'n' Go can make top dollar.

15.3 Commentary.

In physics, work is not simply effort. In fact, the physicist's definition of work is precise and mathematical. In order to have a full understanding of how work is defined in physics, we need to consider its definition in a very simple situation and then enrich it later to include more realistic situations.

A Simple Definition of Physical Work:

If an object that is moving in a straight line experiences a constant force in the direction of its motion during the time it is undergoing a displacement, the **work done by the external force**, F_{ext} , is defined as the product of the force and the displacement of the object.

$$W = F_{\text{ext}}\Delta x \quad [\text{Eq. 15-1}]$$

where W represents the work done by the external force, F_{ext} is the magnitude of the force, and Δx the displacement of the object. Work done by a force is always positive!

What if the force of interest and the displacement are in the opposite direction? For instance, what about the work done against the force of sliding friction, F_f , when a block slides down an inclined plane as a result of the gravitational force? In this case we refer to work done against a force. This is given by

$$W_{\text{against}} = -F_f\Delta x \quad [\text{Eq. 15-2}]$$

Work done against a force is always negative!

15.4 Exercise. Applying the Physics Definition of Work

- Does effort necessarily result in physical work? Suppose two guys are in an evenly matched tug of war. They are obviously expending effort to pull on the rope, but according to the definition of physical work, are they doing any physical work? Explain.



- A wooden block with a mass of 0.30 kg is pushed along a sheet of ice that has no friction with a constant external force of 10 N which acts in a horizontal direction. After it moves a distance of 0.40 m how much work has been done on the block by the external force?

How should work be calculated when the external force and the displacement of an object are not in the same direction? For this project you'll need:

- a 0-5 N spring scale
- a fairly smooth horizontal surface
- a wood block with hooks in it
- a set of kg weights

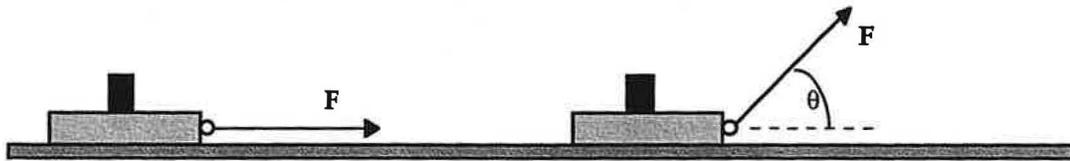


Figure 15-3: A block sliding on a one-dimensional surface

Before you make your simple force measurements, you should put some weights on your block so that it slides along a smooth surface at a constant velocity even when it is being pulled with a force that is 45° from the horizontal.

15.5 Experiment. Calculating Work

1. Hold the spring scale horizontal to the table and use it to pull the block a distance of 0.50 meters along the horizontal surface. Exert the minimum force needed to move the block at a constant speed. Record the force in newtons and the distance in meters in the space below and calculate the work done on the block in joules. (Note that there is a special unit for work – the joule or J for short. One joule is equal to one newton times one meter, i.e. $J = N \cdot m$)
2. Repeat the measurement, only this time pull on the block at a 30° angle with respect to the horizontal. First try to exert the same force as in Step 1. What do you observe?

Again find the minimum force needed to move the block at the same speed. Is the force needed larger or smaller than you measured in Step 1?

3. Repeat Step 2, only this time pull on the block at a 45° angle with respect to the horizontal. Again pull the block at the same speed. Is the force needed larger or smaller than you measured in Steps 1 and 2?

Assuming that the actual physical work done in Steps 2 and 3 are the same as the physical work done in Step 1 above, how can we enhance the mathematical definition of work so that the forces measured in Steps 2 and 3 could be used to calculate work? In other words, how can we find a mathematical equation that relates the physical work, W , to the magnitude of the applied force, F , the magnitude of the displacement, Δx , and the angle, θ , between F and Δx ?

The Concept of Power

People are interested in more than physical work. They are also interested in the rate at which physical work can be done. Average power, $\langle P \rangle$, is defined as the ratio of the amount of work done, ΔW , to the time interval, Δt , it takes to do the work, so that

$$\langle P \rangle = \frac{\Delta W}{\Delta t} \quad [\text{Eq. 15-4}]$$

If work is measured in joules and time in seconds then the fundamental unit of power is in joules/second (J /s) where 1 joule/second equals one watt (W). However, a more traditional unit of power is the horsepower, which represents the rate at which a typical work horse can do physical work. It turns out that

$$1 \text{ horsepower (or hp)} = 746 \text{ W} = 746 \text{ J /s.}$$



Those of you who are car buffs know that horsepower is a big deal in rating high performance cars. The hp in a souped-up car is in the hundreds. How does your lifting ability stack up? Let's see how long it takes you or one of your classmates to lift a heavy object like a dumbbell a distance of one meter. For this observation you'll need the following items:

- a meter stick
- a dumbbell
- a stop watch

15.8 Experiment. Rate the Horsepower in Your Arms

1. While one of your partners times you, lift a dumbbell through a known height as fast as possible. Feel free to adjust the weight of the dumbbell to make it both possible and a challenge for you. Try to do the lift while standing, without bending over. Record in the space below the time and height of the lift and compute the work done against the force of gravity.

2. Compute the average power, $\langle P \rangle$, you expended in hp. How does this compare to the horsepower of your favorite automobile? If you're not into cars, how do you stack up against a horse?

3. Calculate the work done by gravity during your lift. (Be careful of signs.)

Discuss your results with your teacher.

If you attach a brass spring to a force probe (that has been calibrated) as shown in the figure below, you will be able to measure the spring's distance from a motion detector and the force you are applying to it at the same time.

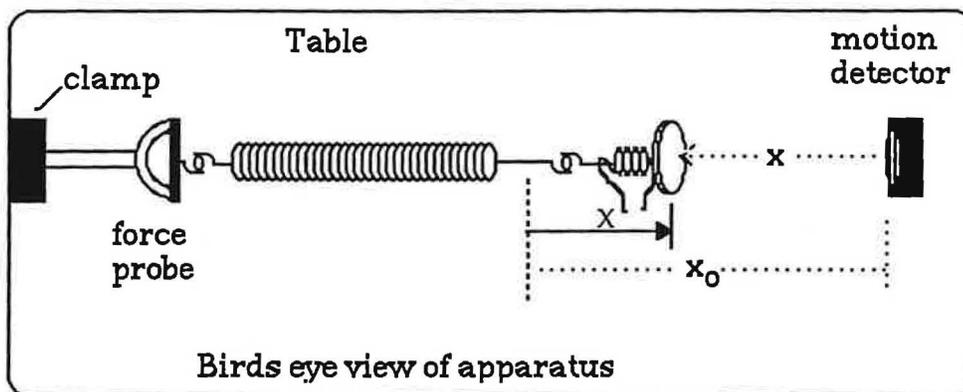


Figure 16.1: Schematic of the set-up for measuring spring forces. x_0 is the equilibrium position of the mass hanger at the end of the spring when there is no force on it. You may find it helpful to tape a 4" x 6" notecard to the bottom of the mass hanger to provide a larger reflecting surface.

You will have to figure out how to calculate the displacement of the spring from its equilibrium (unstretched) position.

16.2 Experiment. Force vs. Displacement for a Spring

- With the force probe plugged into Port 1 and the motion detector plugged into Port 2, turn on the ULI, open the MacMotion software, and calibrate the force probe. For a known force use a force of 8 N, pulling horizontally with the 0-20 N spring scale. Be sure the motion detector is at least 90 cm from the flat surface of the mass hanger when arranged as in Figure 16.1. Set up the MacMotion software to record **Motion + Force Data** (under the **Collect** menu), with a **Data Rate...** of 30 /s. Under **Display** select **Two Graphs**. Use graphs of **Distance vs. Time** and **Force vs. Time**, with the maximum time set at 5.0 s on each graph. Under the **Collect** menu select **Configure Distance Probe...**, enter the current room temperature, and select **Distance away is negative**.
- Make an initial measurement with no force exerted on the spring. (It might be wise to try to support the length of the spring so that its weight does not exert a force on the force probe.) Under the **Analyze** menu, select **Analyze Data A** and determine the distance and force values. Record these in the space below. Under the **Collect** menu again select **Configure Distance Probe...** and enter the negative distance you just measured into the **Offset the zero point by** **meters** box, as illustrated here. The effect of this will be to make future distance measurements positive and increasing as the spring is stretched.

distance = _____ m force = _____ N
- Click on **Start** and slowly but steadily stretch the spring by hand until it has been stretched about 30 cm, being careful to keep the bottom flat surface of the mass hanger facing the motion detector. Examine the two graphs and describe them below.

Discuss your graphs with your teacher before proceeding.

Note: Any restoring force on an object which is proportional to its displacement is known as a Hooke's Law Force, named after an erratic, contentious genius named Robert Hooke who was born in 1635. He played with springs and argued with Newton.

We would like to expand the definition of work so it can be used to calculate the work associated with stretching a spring and the work associated with other forces that are not constant. A helpful approach is to plot the average force needed to move an object for each successive displacement Δx as a bar graph like that shown in Figure 16.2 below.

Note: The bar graph below is intended to illustrate mathematical concepts. Any similarity between the values of the forces in the bar graph and any real set of forces is purely coincidental. In general, the force causing work to be done on an object is not constant.

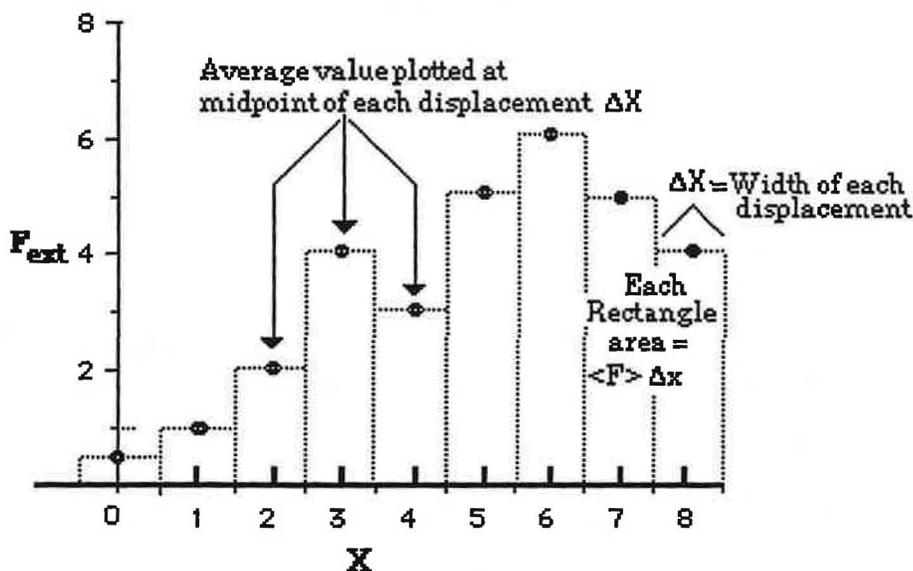


Figure 16.2: A bar graph representing the average applied force causing each unit of displacement of an object. This example graph does represent a force that is not constant but not the force vs. displacement of a typical spring.

In the graph in Figure 16.2, the displacement for each interval is 1.0 cm. With the data you recorded in the table on the previous page, you used a displacement for each interval of 3.0 cm .

2. Replot your spring data in a bar graph format on the next page. After plotting the force vs. distance data points, draw in the boundaries of the 3.0 cm wide displacement intervals using dashed lines.

Defining Kinetic Energy and Its Relationship to Work

What happens when you apply an external force to an object that is free to move and has no friction forces on it? Obviously it should experience an acceleration and end up being in a different state of motion. Can we relate the change in motion of the object to the amount of work that is done on it?

Let's consider a fairly simple situation. Suppose an object is lifted through a distance s near the surface of the earth and then allowed to fall. During the time it is falling it will experience a constant force as a result of the attraction between the object and the earth – called the force of gravity. You can use the theory we have already developed for the gravitational force to compare the velocity of the object to the work done on it by the gravitational field as it falls through a distance y . This should lead naturally to the definition of a new quantity called kinetic energy, which is a measure of the amount of "motion" gained as a result of the work done on the mass.

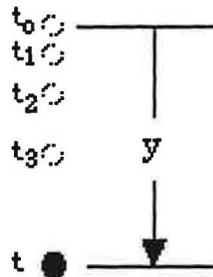


Figure 16.3: Diagram of a ball which has fallen a distance y in a time t under the influence of a constant gravitational force.

16.4 Exercise. Equations for Falling v vs. y

1. An object of mass m is dropped near the surface of the earth. What is the magnitude and direction of its acceleration a_g , assuming air resistance is not a factor?
2. If the object has no initial velocity and is allowed to fall for a time t under the influence of the gravitational force, what kinematic equation describes the relationship between the distance the object falls, y , and its time of fall, t ? Assume $y_0 = 0$. (Hint: review Exercise 5.5.)
3. Do you expect the magnitude of the velocity to increase, decrease or remain the same as the distance increases? **Note:** This is an obvious question!!
4. Write down a relationship between v , the constant acceleration a_g , and time t . (Hint: review Exercise 5.5.)
5. Combine the equations you obtained in Steps 2 and 4 to describe how the velocity, v , of the falling object depends on the distance, y , through which it has fallen.

You have just proven an example of the work-energy theorem which states that the change in kinetic energy of an object is equal to the net work done on it for all the forces acting on it.

$$\Delta E_{\text{kin}} = W \quad [\text{Work-Energy Theorem}]$$

Although you have only shown the work-energy theorem for a special cases where no friction is present, it can be applied to any situation in which the net force can be calculated. For example, the net force on an object might be calculated as a combination of applied, spring, gravitational, and friction forces.

16.7 Video Exercise. Work - Energy Theorem

1. Go to the videodisc set-up and watch the following segment:
Physics: Cinema Classics, Side E, Chapter 14 "Work and Kinetic Energy".
Set the audio at ANALOG 2/R.
2. Use frame number 12320 to analyze the graph and calculate the area under the graph to get the work done by the system.
3. Use the data for m , Δx , and Δt contained in the last few frames to calculate the change in kinetic energy of the cart.
4. How do the work done and change in kinetic energy compare? Do you feel this substantiates the work - energy theorem? Explain.

16.8 Application Exercise

1. How would the expression for the work done by gravity derived in Step 2 of Exercise 16.6 change if the object moved upwards a distance y , rather than downwards?
2. What would happen to the kinetic energy of an object that is thrown upwards, once it leaves your hand?
3. Is the work - energy theorem still valid? Explain.

Discuss your results for the last three activities with your teacher.

The $(1/2)mv_f^2$ is a measure of the motion resulting from the fall. If we define it as the energy of motion, or, more succinctly, the kinetic energy, we can define a work-energy theorem for falling objects:

$$W = \Delta E_{\text{kin}} = E_{\text{kin},f} - E_{\text{kin},i} \quad [\text{Eq. 17-5}]$$

or, the work done on a falling object by the earth is equal to the change in its kinetic energy as calculated by the difference between the final and initial kinetic energies.

If external work is done on the mass to raise it through a height y (a fancy phrase meaning "if some one picks up the mass"), it now has the potential to fall back through the distance y , gaining kinetic energy as it falls. Aha! Suppose we define potential energy to be the amount of external work, W_{ext} , needed to move a mass at constant velocity through a distance y against the force of gravity. Since this amount of work is positive while the work done by the gravitational force has the same magnitude but is negative, this definition can be expressed mathematically as

$$E_{\text{pot}} = W_{\text{ext}} = -W_g = -mgy \quad [\text{Eq. 17-6}]$$

Note that when the potential energy is a maximum, the falling mass has no kinetic energy but it has a maximum potential energy. As it falls, the potential energy becomes smaller and smaller as the kinetic energy increases. The kinetic and potential energy are considered to be two different forms of mechanical energy. What about the total mechanical energy, consisting of the sum of these two energies? Is the total mechanical energy constant during the time the object falls? If it is, we might be able to hypothesize a law of conservation of mechanical energy as follows: In some systems, the sum, E_{tot} , of the kinetic and potential energy is a constant. This hypothesis can be summarized mathematically by the following statement.

$$E_{\text{tot}} = E_{\text{kin}} + E_{\text{pot}} = \text{constant} \quad [\text{Eq. 17-7}]$$

The idea of mechanical energy conservation raises a number of questions. Does it hold quantitatively for falling masses? How about for masses experiencing other forces, like those exerted by a spring? Can we develop an equivalent definition of potential energy for the mass-spring system and other systems and re-introduce the hypothesis of conservation of mechanical energy for those systems? Is mechanical energy conserved for masses experiencing frictional forces, like those encountered in sliding?

17.2 Exercise. Is Mechanical Energy Conserved for a Falling Mass?

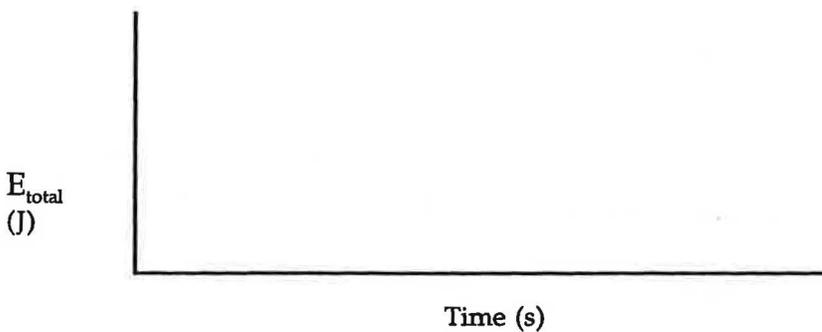
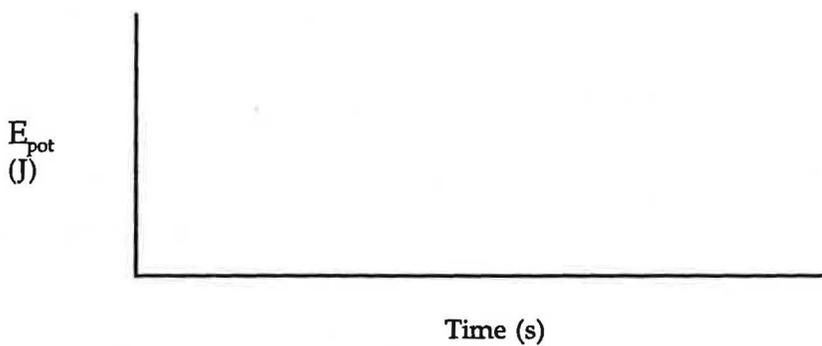
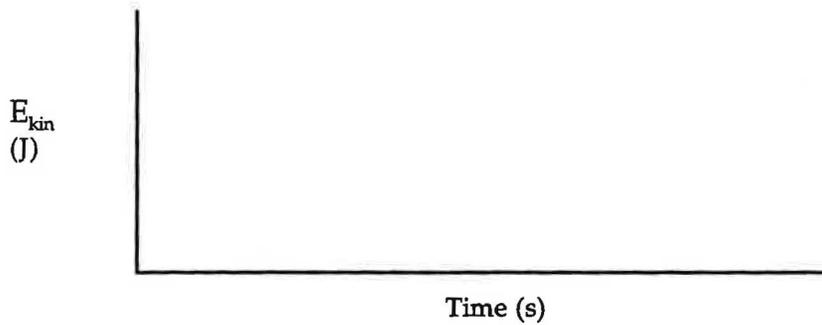
Is the mechanical energy conservation hypothesis stated above valid for a falling mass? In other words, is mechanical energy conserved within the limits of uncertainty? In Lesson 8 of Unit 3 you recorded data for the vertical position of a ball that was dropped in the laboratory as a function of time. In Lesson 10 of Unit 4 you analyzed the motion of a projectile. Either of these data sets should give you the information you need to calculate the vertical position and average vertical velocity of the ball as a function of time. You can then calculate the kinetic and potential energy for the tossed ball as a function of time and see if there is any relationship between them.

Note: If you didn't save previous data for the position as a function of time of a tossed ball you can quickly obtain new data using the following software and digital movie:

- software entitled VideoGraph
- a movie entitled "conservation of energy movie"

The speed of the movie is 18 frames/s and the mass of the ball is 7.27 kg.

3. Copy your spreadsheet data, open the **Graphical Analysis** software, and **Paste** the data into the **Graphical Analysis Data** window. Label the columns with correct titles and units. Create three graphs, E_{kin} , E_{pot} and E_{total} , as a function of time and roughly sketch the graphs in the space below.



4. Do the maximum and minimum values for each agree with what you predicted?
5. Is the sum of E_{kin} and E_{pot} what you predicted?
6. Is the mechanical energy of this system conserved according to your results? Explain.

Discuss your results with your teacher.

5. Under the **Display** menu select **Two Graphs**, and create a Velocity vs. Time graph to compare with the Distance vs. Time graph. Describe each graph. How do they compare with your predictions?

Record below three times for which the velocity is zero and three times for which the velocity is a maximum (either positive or negative).

velocity is zero at _____ and _____ and _____.

velocity is maximum at _____ and _____ and _____.

From the Distance vs. Time graph, where in its motion is the mass at the times when the velocity is zero?

From the Distance vs. Time graph, where in its motion is the mass at the times when the velocity is maximum?

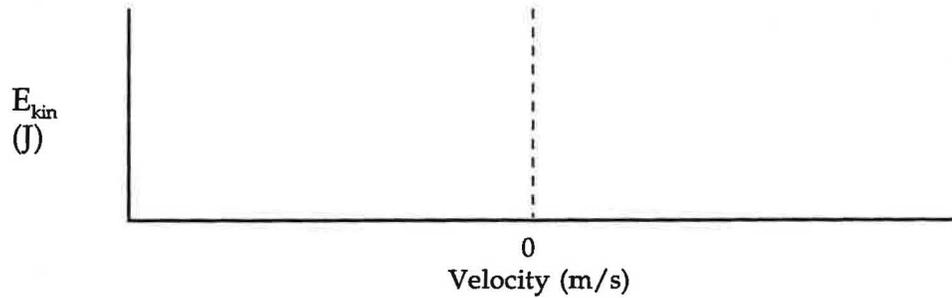
6. Under the **Windows** menu select **Data A Table**. Highlight the data in the first three columns (time, distance, and velocity) and select **Copy** under the **Edit** menu. Open the **Physics 1** folder on the **Mac HD**. In it you will find a file titled "Vibrating Spring SS (Lesson 17)". Open that file. Click in Cell A9 on the spreadsheet, and select **Paste** under the **Edit** menu. Measure the mass of the spring and of the hanging mass suspended from the spring and enter those values (in kilograms) into the appropriate cells on the spreadsheet (B3 and B4, respectively). Equations have been entered into the cells in this spreadsheet to calculate the kinetic energy, the potential energy, and the sum of those energy values for the vibrating system. Pick a time and do one set of calculations yourself (in the space below) to verify the accuracy of the equations and your understanding of their use. (Mathematical analysis shows that one-third the mass of the vibrating spring should be added to the hanging mass suspended from the spring when determining the total mass of the vibrating system.)
The equations used are:

$$E_{\text{kin}} = (1/2)m_{\text{total}} v^2 = (1/2)(m_{\text{hanging}} + m_{\text{spring}}/3)v^2$$

$$E_{\text{pot}} = m_{\text{total}} a_g h = (m_{\text{hanging}} + m_{\text{spring}}/3)a_g h$$

$$E_{\text{sum}} = E_{\text{kin}} + E_{\text{pot}}$$

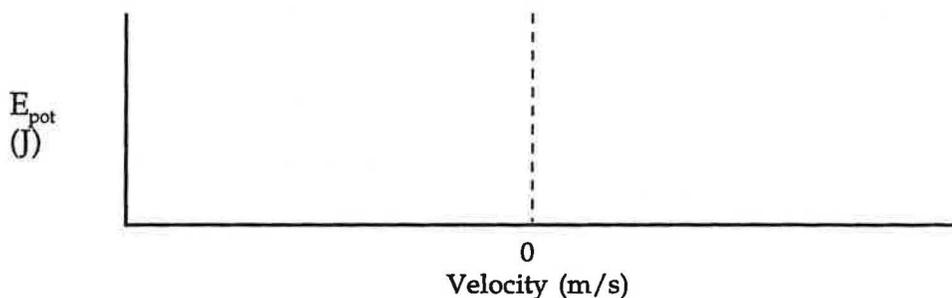
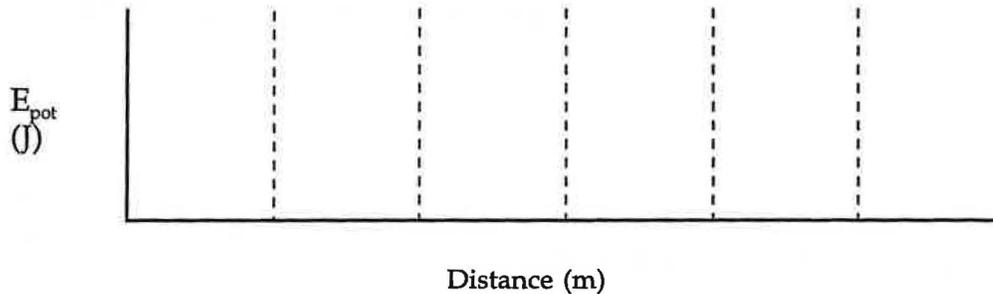
7. Click in Cell A9 and drag to the lower right corner of the data to select and highlight all the data you have entered and calculated for t , y , v , E_{kin} , E_{pot} , and E_{sum} . Select **Copy** under the **Edit** menu. Open the **Graphical Analysis** software, located in the **Graphical Analysis** folder on the **Mac HD**. Paste the data into the **Untitled:Data Set 1** window. Type and enter correct titles and units for the six columns.



- (b) Create, in turn, each of the above graphs using the **Graphical Analysis** software. To change the quantity plotted along the horizontal axis just click on that axis label and select the desired quantity from the pop-down menu. Using a different color, sketch the actual graphs resulting from the data in the graphs above. Label them to distinguish them from your predictions.

Describe any differences between the actual graphs and your predictions. Be sure you understand the appearance of the actual graphs.

10. (a) Now predict the graphs that would result if you plotted E_{pot} vs. Distance, and E_{pot} vs. Velocity. Draw your predictions on the following graphs.



- (b) Create, in turn, each of the above graphs using the **Graphical Analysis** software. Using a different color, sketch the actual graphs resulting from the data in the graphs above. Label them to distinguish them from your predictions.

17.4 Video (If time permits.)

Go to the videodisc set-up and watch the following segments:

Physics: Cinema Classics, Side E, Chapter 21 "Swinging Bowling Ball", Chapter 22 "Flying Acrobats", Chapter 23 "Water Wheel", Chapter 24 "Roller Coaster". Set the audio to ANALOG 1/L.

Discuss any questions with your teacher.

An additional video resource is:

The Mechanical Universe, Program 13 "Conservation of Energy" (26 minutes long). It contains a small amount of calculus, but you should have no difficulty understanding the overall presentation.

OVERVIEW

Any motion that repeats itself regularly is known as harmonic or periodic motion. The pendulum in a grandfather clock, molecules in a crystal, the vibrations of a car after it encounters a pothole on the road, and the rotation of the earth around the sun are examples of periodic motion. In this unit we will be especially interested in a type of periodic motion known as Simple Harmonic Motion, which is often called SHM. SHM involves a displacement that changes sinusoidally in time.

SHM is so common in the physical world that your understanding of it will help you understand such diverse phenomena as the behavior of the tiniest fundamental particles, how clocks work, and how pulsars emit radio waves. Pendula and masses on springs are merely two examples of thousands of similar periodic systems that oscillate with simple harmonic motion.

In this unit we will continue to study a mass and spring system. We will then apply SHM concepts to the understanding of waves, after which we will examine the unique behavior patterns of waves. You will need to devise some ways to describe oscillating systems in general and then apply these descriptions to help you observe periodic oscillations. There are several questions you must address in following lessons: What is periodic motion and how can it be characterized? What mathematical behavior is required of a periodic system to qualify its motion as harmonic?

There is a strong link between SHM and the motion of a wave. Waves are a familiar part of every day life. Most of us have seen ocean waves, ripples on a pond, and vibrating guitar strings. All of us have heard sound waves. We have experienced the benefits of TV and radio waves even though we cannot detect their presence with any of our five senses. Some waves travel through material mediums, while others can travel through empty space. Physicists define waves as disturbances that travel through space. Sounds like a pretty vague description, huh? In this unit we will study mechanical waves and electromagnetic waves.

In the following lessons you will study wave characteristics (amplitude, frequency, speed), wave types (longitudinal, transverse, torsional), and wave behavior (reflection, diffraction, interference, resonance, polarization).

18.3 Experiment. Relating Period and Frequency

Two of the definitions given above, frequency and period, are related to each other. You could find a mathematical equation that relates the frequency of a given oscillating system to its period by observing any one of the systems demonstrated above. However, you will make observations using the same set-up you used in Experiment 17.3 to study the energy of a mass-spring system. To get the necessary data you can vary the amount of mass hanging on the spring.

1. After opening the **MacMotion** software to display a graph of Distance vs. Time, set the maximum time on the horizontal scale to 15 s. Under the **Collect** menu, set the **Data Rate...** to 50. Don't forget to configure the distance probe (under the **Collect** menu). When doing so, select **Distance away is positive**.
2. Varying the total mass hanging on the spring over the range from 250 g to 650 g, take measurements of the position of the system as a function of time for each mass. Pull the mass down about 5 cm and release it, and then click on Start. As you watch the mass oscillating on the spring you can see the mass going from a maximum displacement to no displacement and then to a maximum displacement in the opposite direction.

Once the measurements for a given mass have been obtained, use the **Analyze Data A** option under the **Analyze** menu to determine the period and the time for 10 or more complete oscillations. To get the period, position the vertical line at one of the top peaks of the Displacement vs. Time curve and note the time displayed at the bottom of the window. Then move the vertical line to the next top peak and note the time for it. The difference gives a value for the period. To determine the frequency divide the total number of cycles you measure by the total time in seconds. Record your data and calculations in the table below.

Mass (g)	Period (s)	# of Cycles	Time (s)	Frequency (Hz)

3. Can you spot the mathematical relationship between period and frequency by examining the period and frequency values listed in the table? Open the **Graphical Analysis** software and enter the period and frequency data. Remember to change the X and Y column labels to their correct values and to enter their units. Sketch the shape of the graph. What mathematical relationship is associated with this shape?

Discuss your results with your teacher.

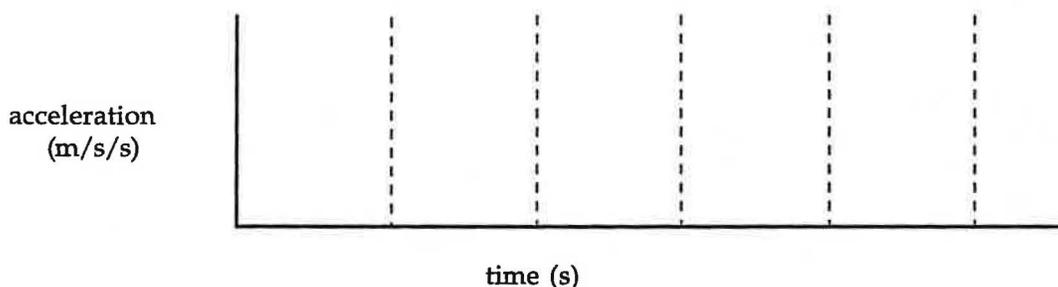
18.4 Experiment. Graphing Periodic Motion Using a Motion Detector

1. In Step 4 of Experiment 17.3 you saved on your data disc the data for the motion of the spring-mass system you studied in that experiment. You will now use that data to learn more about this example of harmonic motion. On the axes on the next page, draw a sketch of the Distance vs. Time graph you obtained in that study. On your sketch draw a horizontal line at the location of the equilibrium position of the mass (e.g., the position of the mass when the displacement is zero).

select **Two Graphs** under the **Display** menu. If necessary, change the range of the scale values along each axis to make comparison with the Distance vs. Time graph easier.)

At what displacements from equilibrium is the velocity of the oscillating mass a maximum? A minimum? At what displacements is the velocity of the mass zero? (For instance, is the velocity a maximum when the displacement is a maximum? is zero? or what?)

4. Try now to predict the shape of the Acceleration vs. Time graph for the harmonic motion of the mass-spring system. Draw your prediction on the axes below. It might be helpful to first think in terms of Newton's second law and consider the forces acting on the mass as a function of distance since the forces will determine the acceleration. For comparison draw a sketch of the Distance vs. Time graph too.



5. Now sketch the actual Acceleration vs. Time graph on the same axes used in Step 1, above. Use yet a different color of pen or pencil for the acceleration graph. (To see the original Acceleration vs. Time graph just click on the word Velocity along the vertical axis of the Velocity vs. Time graph and select Acceleration from the pop-up list. If necessary, change the range of the scale values along each axis to make comparison with the Distance vs. Time graph easier.)

At what displacements from equilibrium is the acceleration of the oscillating mass a maximum? A minimum? At what displacements is the acceleration of the mass zero? (For instance, is the acceleration a maximum when the displacement is a maximum? is zero? or what?)

6. Based on your observations in the previous step, what general conclusions can you draw about the relationship between acceleration and displacement for harmonic motion? Can you express the relationship mathematically? (Hint: you might try changing the Acceleration vs. Time graph in **MacMotion** to an Acceleration vs. Distance graph to get a clear picture of the relationship.)

Discuss your conclusions with your teacher.

Explain in words the relationship between the acceleration and the displacement for Simple Harmonic Motion, according to Eq. 18.2.

What does the negative sign tell you about the directions of the acceleration and displacement vectors?

- Using the **MacMotion** software, change the Acceleration vs. Time graph for your mass-spring system to an Acceleration vs. Distance graph by clicking on the word Time along the horizontal axis and selecting Distance from the pop-up menu. Describe the graph. Does it match the pattern determined in Step 2 (i.e., is it a linear graph with a negative slope)?
- On the basis of your Distance vs. Time and Acceleration vs. Distance graphs, do you think your spring-mass system underwent simple harmonic motion? Why or why not?

18.7 Exercise. The Period of SHM

- You saw in Experiment 18.3 that changing the mass of the vibrating system changed the period (and frequency) of the motion. What other characteristic(s) of the system do you think will affect the period?
- In Experiment 16.2 you discovered that the one dimensional force exerted by a spring has the form $F = -kx$, where k is the spring constant. The negative sign tells us that the direction of the spring force is always opposite to the direction of its displacement. You also determined the value of the spring constant k for the spring. Since you should be using the same spring in this lesson as you did in Lesson 16, look up your spring constant value and record it here.
 $k = \underline{\hspace{2cm}} \text{ N/m.}$

According to Newton's second law, $F = ma$. Combining these two expressions gives: $ma = -kx$, or

$$a = - (k/m) x \quad \text{[Eq. 18.3]}$$

where k is the spring constant of the spring and m is the mass of the vibrating mass-spring system. Combine Eq. 18.3 with Eq. 18.2 to get an equation relating the frequency to m and k .

Lesson 19: Wave Motion

Waves are thoughts on Wings.
Anon

We will confine our study of waves in this lesson to mechanical waves because they can be sensed and studied in more concrete ways. In a later lesson we will study electromagnetic waves that travel through empty space (light, radio waves and TV waves are examples of such). A mechanical wave is defined as a wave that travels from one place to another through a material medium causing the medium to be temporarily disturbed without the medium itself moving from one place to another.

The study of mechanical waves is vitally important to the understanding of most physical phenomena because the mathematical description of mechanical waves and of all other waves is very similar. Although we will not delve much into the mathematical description of waves, we will examine the main features of wave behavior. Discoveries in the early part of the 20th century, when quantum mechanics and relativity replaced Newtonian mechanics, have convinced physicists that all matter is best described, ultimately, in terms of waves. "It's all a matter of waves."

19.1 Demonstrations/Video. One Dimensional Traveling Wave Pulses

1. Several different wave pulses will be shown, some "live" and some on film. Take a look at the different wave pulses being demonstrated. Describe two aspects of each type of wave pulse – first, the medium through which it is traveling, and second the direction of the disturbance of that medium relative to the direction of travel of the wave. You may find it helpful to take a mental picture of each wave and sketch it.

(a) Slinky Wave Type 1: Physics: Cinema Classics, Side C, Frames 02174-02328. Set audio to ANALOG 2/R.

(b) Slinky Wave Type 2: Physics: Cinema Classics, Side C, Frames 06645-06985. Set audio to ANALOG 2/R.

(c) Demonstration of Long Coiled Spring

(d) Wave Machine

(e) Video of Water Wave Tank

2.
 - (a) Measure the wave pulse speed using either a long coiled spring or a slinky. Try a couple of amplitudes to check its affect.
 - (b) Also measure the tension in the spring (using a combination of spring scales in parallel).
 - (c) Measure the mass of 10 coils of the spring and then estimate the linear density of the spring by counting the number of coils per meter in the stretched spring.
 - (d) Repeat these three measurements for a variety of three spring tensions. Record your measurements and calculation results below.

3. Based on your results in Step 2, how accurate are your predictions in Step 1? Explain.

19.5 Demonstration/Experiment. Reflection of Wave Pulse

When a wave pulse reaches the end of its path (or a boundary between the medium it is traveling in and another medium in which the pulse would travel at a different speed), some of the wave energy is reflected. What determines whether or not the reflected wave is inverted?

1. Demo with coiled spring.
 - (a) Far end fixed in position
 - (b) Far end free
2. Demo with wave machine.
 - (a) Far end fixed in position
 - (b) Far end free
 - (c) Far end connected to other half of wave machine

19.6 Experiment. Harmonic Waves

A harmonic wave train is one that is driven with a sinusoidal oscillation such as that produced by a vibrating object (an oscillating mass on a spring or pendulum swinging at a small amplitude are examples).

1. Harmonic vibrations are characterized by such properties as frequency f and period T .
 - (a) How are T and f related for Simple Harmonic Motion?

2. Place the microphone, which is attached to the computer, about 10-15 cm from the speaker. Click on the red **Record** button on the **Sample Editor** screen. When the pop-up window appears, click on **Start Recording**. Click on **Stop** after 2 or 3 s, and then turn off the function generator. You should see patterns produced in the **Main View** and **Overview** windows. Both patterns will be highlighted. Click anywhere in the **Main View** window to turn off the highlighting. In the **Overview** window, click in the space above the pattern and drag to the right to select a small region of the pattern. Be sure your selection rectangle extends above and below the pattern and is about 2 or 3 mm wide. Once accomplished this should produce an enlarged detailed view of the wave pattern associated with the sound you recorded. Draw a sketch of the detailed wave pattern picture you obtained. On your sketch label one wavelength of the wave pattern.

3. By counting the number of complete wave patterns in a given time interval, determine the period and frequency of the sound wave. Record your measurements and calculation results below. Check the accuracy of your results with your teacher before proceeding!

4. Under the **Edit** menu choose **Select All**, and then under the **Exit** menu again, select **Clear**. Turn the function generator back on and turn the Amplitude way down. Repeat Step 2, but this time turn the amplitude up a lot during your 3 s recording.. Describe any changes in the wave pattern. Did the period and frequency of the sound you recorded change while the amplitude was changing?

What physical property of the sound is associated with the amplitude?

5. Repeat Step 2 with the frequency set at a different value. Describe any changes in the recorded wave pattern.

6. Try recording other sound sources (your voice when humming or whistling, for instance). Describe the wave pattern you produced. Is it a sine wave?

2. Why does the frequency of a plucked guitar or violin string increase as its tension is increased?
3. What do you expect to happen to the wave speed of a one dimensional wave if the number of coils per meter on a slinky or the thickness of a string is increased? Explain.
4. Which strings on a guitar or violin have the most mass per unit length—the ones that vibrate at low frequencies or the ones that vibrate at high frequencies?
5. If the wave length is a constant, what does the frequency have to do with wave speed?

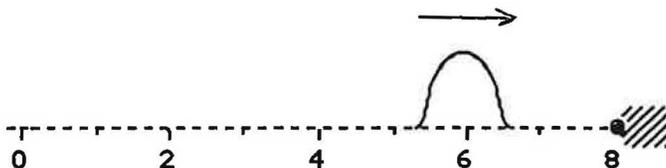
20.2 Experiment. Superposition (Addition of Waves)

What happens when different wave pulses or wave trains are sent through a medium and encounter each other? Take a few minutes to make some observations with your own spring. You and one of your partners should hold opposite ends of the spring so that it is stretched with a reasonable tension (i.e., not just hanging loose). Each of you should then move your end of the spring to either produce short pulses or continuous traveling waves. After some thinking and discussion, write down a principle of superposition.

Discuss your principle of superposition with your teacher.

20.3 Exercise. 1D Reflection from a Fixed Boundary

1. If a wave pulse is traveling at 8 cm/s from left to right along a string that is fixed at its right end, as shown in the picture below, sketch its shape and location one second later and indicate its direction of travel.



20.5 Commentary. Terminology of Standing WavesAntinode: position of maximum displacementNode: position of minimum displacementLoop: distance between two neighboring nodes (or between two neighboring antinodes)Wavelength: length of two loops

Draw a sketch of a standing wave containing at least 2 loops and label each of the above quantities.

20.6 Demonstration/Video/Experiment. Observing Resonance

Standing waves are stimulated only at certain "resonant" frequencies. You can observe resonance in several systems which only vibrate at certain frequencies as a result of reflected traveling waves setting up "allowed" frequencies of standing waves. Observe and record wavelengths and frequencies, when possible, for the following:

1. Singing rods (demonstration).
2. Vibrating 2-meter stick (demonstrations: both ends free, one end free).
3. Wave machine (demonstration).
4. Vibrating wire (video- Physics: Cinema Classics, Side C, Frames 26921-27277. Set audio to ANALOG 1/L.).
5. Soap films (video- Physics: Cinema Classics, Side C, Chapter 44. Set audio to ANALOG 1/L.).
6. Coupled pendulums (demonstration)
7. Tuning fork and resonance boxes (demonstration).
8. Standing sound waves (demonstration using function generator, speaker, air column, microphone and oscilloscope).
9. Vibrating spring (experiment). Working with a partner, produce standing wave patterns consisting of 1 loop, 2 loops, and 3 loops. Measure and record the loop lengths, wavelengths, and frequencies for each case.

	loop length (m)	wavelength (m)	time for 10 oscillations (s)	frequency (Hz)
1 loop				
2 loops				
3 loops				

4. If the frequency is now turned up a little, the standing wave pattern will shrink in amplitude and maybe disappear altogether. Why?
5. How many loops will the next resonance mode (standing wave pattern) of the vibrating cord contain?
How will the wavelength compare to the wavelength for the first resonance mode produced in Step 2?

Write down your prediction of the frequency of vibration needed to produce the next resonance mode. Explain why you made that prediction.

6. Proceed now to turn up the frequency and produce resonance modes (i.e., standing wave patterns) containing 2, 3, 4, 5, 6, 7, and 8 loops. Always be careful to achieve as large an amplitude at the antinodes as possible. Do not change the amplitude setting on the function generator! For each case record the frequency in the table below.

# of loops	1	2	3	4	5	6	7	8
frequency (Hz)								
length of one loop (m)								
wavelength (m)								
wave speed (m/s)								

7. Fill in the remaining blanks in the table above by calculating the length of one loop, the wavelength, and the wave speed for each case, using your measurement for the length of the single loop obtained in Step 2 as your starting value.
8. (a) Is there any pattern in the frequency values? Can you write a mathematical expression for the frequency for n loops in terms of the frequency for 1 loop?
- (b) Is there any pattern in the wave speeds? Is this what you expected? Explain.
9. (a) Predict how the required frequency for a standing wave pattern with 4 loops would change if the tension in the cord is reduced. Explain your prediction.

21.4 Experiment. Diffraction and Interference of Light.

For the following experiment you will use:

- a force table/spectroscope
- an incandescent light bulb(with socket) as a white light source
- a 300 lines/mm diffraction grating (the distance between two adjacent slits is 3333 nm)
- a tripod and right angle clamp

1. Suppose a white-light source was incident upon a diffraction grating. White light consists of many wavelengths, ranging from the short waves of the color violet (≈ 400 nm) to the long waves of the color red (≈ 700 nm). [The metric prefix nano, represented by the symbol n, equals 10^{-9} .]

All the colors passing through the grating will undergo constructive interference in the central direction ($\theta = 0$) because for every wavelength the path length difference is zero in that direction. Will all colors also undergo the next constructive interference at the same angle? If not, which color will appear closest to the central point of constructive interference? Explain.

2. Follow the verbal instructions given by the teacher for adjusting the spectroscope and setting up the apparatus. While looking through the eyepiece, start it at the zero degree position. Then swing at all the way clockwise and then all the way counter-clockwise to see the diffraction/interference pattern produced. Describe your observations in a sketch below. Use colored pencils to show the relative positions of the six basic colors: red, orange, yellow, green, blue, and violet. How many sets of these colors were visible on each side? Were the colors distinct in each set?

Note: each set of colors is called a spectrum and is designated by an order number. The central spectrum, which looks white, is called the zero order spectrum, because the path length difference is zero for light arriving there from adjacent slits in the grating. The first spectrum outward in both directions from the central one is labeled the first order spectrum. For it the path length difference is 1 wavelength for light arriving from adjacent slits in the grating.

3. Measure the smallest angle from the zero order spectrum at which you can see light in both of the first order spectrums. Also measure the largest angle from the zero order spectrum at which you can see light in both of the first order spectrums. Using the equation you recorded in Step 2(f) of Demonstration 21.3, calculate the wavelength of the light seen in these measurements. Record your measurements and calculated results in the table below. In the equation, the distance between two point sources is replaced by the distance between two adjacent slits in the grating.

	smallest angle from the center ($^{\circ}$)	calculated wavelength (nm)	largest angle from the center ($^{\circ}$)	calculated wavelength (nm)
clockwise first order				
counter-clockwise first order				
color				

Lesson 22: Resonance States in Atoms

22.1 Commentary/Video.

In the CASTLE material you discovered that atoms contain particles called electrons. They are negatively charged, and have very little mass. For a time scientists believed in the "plum pudding" model of the atom. In this model the atom was believed to be a spherical mass of positive charge with the negative electrons embedded within the atom in some sort of symmetrical arrangement, like raisins in a plum-pudding. An experiment, called the Rutherford Experiment disproved that notion, and led instead to the "nuclear" model of the atom. In this model all the positive charge and the vast majority of the mass of the atom is contained in an extremely small "nucleus", with the electrons outside the nucleus. This led to the "planetary" model, in which the negative electrons were believed to be traveling in circular orbits around the nucleus. The electrostatic attractive force between the negative electron and the positive nucleus would hold the electron in its orbit, in the same way that the attractive gravitational force holds the planets in their orbits around the sun, or satellites in their orbits around the earth.

There is, however, a major problem with this model. Any object moving in a circular path has a centripetal acceleration due to the continual changing of direction of its velocity vector. Other experimental results done with electrons had shown that accelerating electrons always radiate electromagnetic energy. (Recall the microwave demonstrations done in Lesson 21.) Yet it is obvious that atoms do not continually radiate electromagnetic energy. And if they did, the energy of the electron-nucleus system would continually decrease, causing the electrons to spiral into the nucleus, resulting in the collapse of the atom, just like a satellite orbit decays if it loses energy due to friction with the upper atmosphere. Obviously there is an inconsistency.

The following video segment covers these ideas:
The Mechanical Universe, Program 49 "Atoms", Chapters 15-21.

22.2 Exercise. Orbital Energies

From what you have already learned in the module on electricity and in this module on mechanics you can derive an expression for the energy of the electron-nucleus system. The electron will have both kinetic energy and electrical potential energy. Since the nucleus attracts the electron, there is electrical potential energy associated with their separation (just like the gravitational potential energy associated with the separation - or elevation - of a mass relative to the surface of the earth).

The equation for the electrical potential energy is $E_{\text{pot}} = -\frac{ke^2}{r}$, where e is the charge on the electron,

k is the constant in Coulomb's law, and r is the distance between the electron and the nucleus. This equation is valid for the smallest atom, hydrogen, which has only one electron and has a nucleus with only one unit of positive charge.

1. Complete the following equation by plugging in expressions for kinetic and potential energy:

$$E_{\text{total}} = E_{\text{kin}} + E_{\text{pot}} =$$

2. We now need something to relate v and r . When a mass moves in a circular orbit the net force acting on

it is called a centripetal force and is given by the equation $F = m \frac{v^2}{r}$. In this case the only force acting on the electron is the electrostatic force between it and the nucleus, which is given by

$$F = \frac{ke^2}{r^2}. \text{ Equate these two force equations and rearrange them to get an equation for } mv^2.$$

22.5 Commentary. How the Atom Radiates Energy

You teacher will discuss the Bohr theory of energy levels and energy level transitions and the photon theory of light.

Notes:

22.6 Experiment. The Hydrogen Spectrum

For this experiment you will need:

- a force table/spectroscope
- a hydrogen spectrum source and power supply
- a 600 lines/mm diffraction grating (the distance between two adjacent slits is 1667 nm)

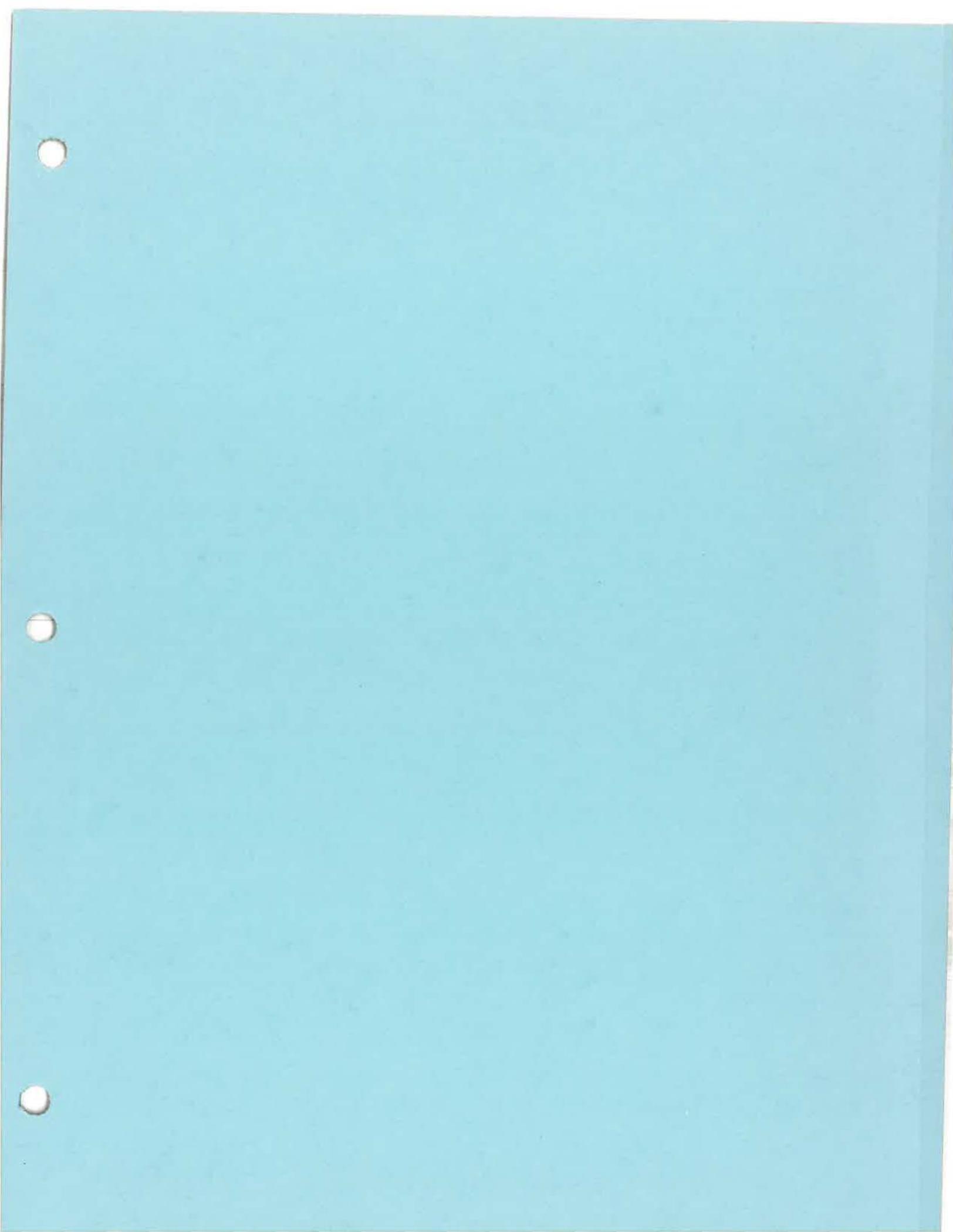
1. Follow verbal instructions given by your teacher to adjust the spectroscope and to arrange the apparatus.

It is important that the central zero order spectrum be bright and be located at zero degrees.

2. Measure the angular position (to the nearest 0.1°) of each line in both the first order spectrum and the second order spectrum as you swing the eyepiece counter-clockwise from the zero degree position. Record your measurements in the table below.

color	order number	angle ($^\circ$)	calculated wavelength (nm)	accepted wavelength (nm)	percent difference
red	1			656.3	
blue	1			486.1	
violet	1			434.1	
violet	1			410.2	
violet	1			397.0	
red	2				
blue	2				
violet	2				
violet	2				
violet	2				

3. Using the diffraction equation, $n\lambda = d \sin\theta$, calculate the wavelength of each line observed. Then calculate the percent difference between your values and the accepted values. Record your calculation results in the table.



LIGHT AND OPTICS

The following material has been taken from *Physics by Inquiry*, Volumes I and II, by Lillian C McDermott, with Peter S. Shaffer and Mark L. Rosenquist and the Physics Education Group at the University of Washington.
Copyright © 1996, by John Wiley & Sons, Inc.
Reprinted by permission of John Wiley & Sons, Inc.
Modified by Tom Smith for use at Mt San Antonio College.

TABLE OF CONTENTS

page	
	PART A: LIGHT AND SHADOWS
2	Lesson 1. Introduction to Light
9	Lesson 2. Light Sources, Masks, and Screens
15	Lesson 3. Shadows
	PART B: PLANE MIRRORS AND IMAGES
19	Lesson 4. Introduction to Reflection
25	Lesson 5. Image Formation in a Plane Mirror
	PART C: LENSES AND IMAGES
32	Lesson 6. Introduction to Refraction
38	Lesson 7. Law of Refraction: Snell's Law
44	Lesson 8. Image Formation by Convex Lenses
50	Lesson 9. Image Formation, Ray Diagrams, and the Thin Lens Equation
60	Lesson 10. Using the Thin Lens Equation, and Image Formation by Concave Lenses
72	Lesson 11. Applications of Geometrical Optics
76	Additional Homework Problems for Light and Optics

Part A: Light and Shadows

We begin our investigation of light by making observations using flashlights, masks, and screens. We use the ideas that we develop in this context to account for more complicated phenomena, such as the formation of images and shadows from extended sources.

Lesson 1. Introduction to Light

1.1 Experiment

This experiment should be performed in a darkened room.

You will need a small round bulb, a socket, two batteries, a battery holder, connecting wires, and a bulb cover. Connect the bulb to two batteries in series so that the bulb shines brightly. Complete the circuit only during the time you need the light.

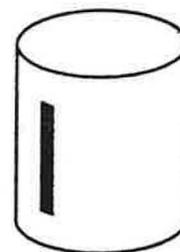
- A. Look at the lighted bulb. Note that you can see it from many places.

Cover for the bulb with the cover provided, as shown at right. If necessary place an opaque piece of paper over the top of the cover.

Can you still see the bulb from many different places? If not, where must you place your eye to see the bulb?

Rotate the cover. Now where must you place your eye to see the bulb?

Draw a top view diagram (a picture of what someone would see when looking down from above) to show where you need to place your eye in order to see the bulb. Do this for at least two different positions of the slit.



Describe the arrangement of bulb, slit, and your eye that is necessary for you to be able to see the lighted bulb.

- B. Obtain a chalkboard eraser that has chalk dust on it. Have your partner hold the eraser near the slit in the tube and strike the eraser several times with a ruler. What do you observe? What do you think makes it possible for you to see the light from the bulb without satisfying the conditions listed above in A?
- C. People often speak of a beam of light. Why do you think people use this word to describe light?

1.3 Experiment

A. Look at an unlighted bulb. Notice that even though the bulb is not lighted, you can still see it. Suppose you took the bulb into a very dark closet. Would you still be able to see it? Explain.

B. Place the cover that you used in Experiment 1.1 over the unlighted bulb. Where do you have to place your eye to see the bulb?

Use a flashlight with a mask to produce a beam of light.

How do you have to aim the flashlight to make the bulb inside the cover more easily visible?

C. When you are not aiming a flashlight at the bulb, does light from anywhere else strike the bulb? Explain.

D. Discuss this experiment and Experiment 1.2 with your teacher.

1.4 Exercise

A. Consider the following statement by a student:

"At night it is dark, but during the day it is bright because the sun lights up objects. When objects are lit up I can see them."

Do you agree with the statement by this student? Would you change the statement in any way to make it more correct?

B. Summarize the conditions necessary for you to be able to see an object.

1.5 Video

Go to the videodisc set-up and watch the following segment:

Physics: Cinema Classics, Side D, Chapter 34 "Scattering - Light". Set AUDIO to 1/L.

How do the smoke particles make the light visible?

Is this related to the experiment in part 1.1 B? In what way?

1.8 Experiment

This experiment should be performed in a darkened room.

A round bulb, a screen made of white paper, and a mask are arranged as shown. The mask is a sheet of paper with a hole in it that is about 3 mm wide.

- A. Predict what you will see on the screen when the bulb is lighted. Explain.

Set up the equipment and check your prediction.

- B. Predict how what you see on the screen would change if the bulb were moved upward, downward, or side to side. Explain.

Check your predictions.

How does the direction that the bright spot moves compare to the direction that the bulb moves?

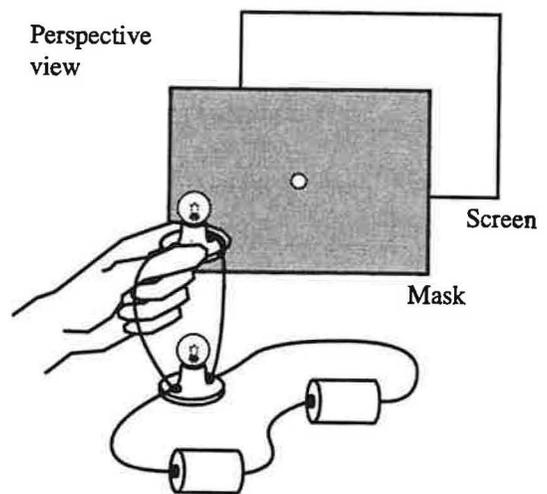
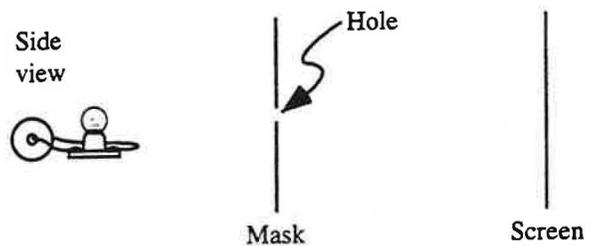
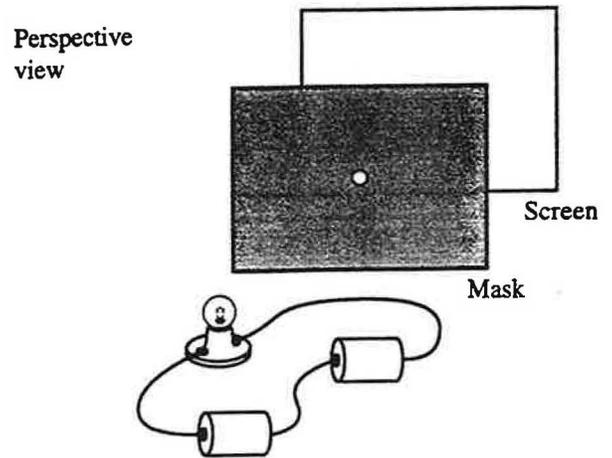
Draw a diagram to account for what you observe.

- C. Predict how placing a second bulb above the first would affect what you see on the screen.

Predict how moving the top bulb upward slightly would affect what you see on the screen.

Connect a second round bulb in parallel with the first bulb and check your predictions.

- D. What do your observations suggest about the path taken by light from the bulb to the screen?



1.11 Video

Go to the videodisc set-up and watch the following segment:

Physics: Cinema Classics, Disc 2, Side C, Chapter 18 "Light", stop at frame 10431. Set VIDEO to 1/L.

What are the students attempting to show in the first sequence with the light source and masks?

Are the conclusions drawn from this demonstration consistent with those you have arrived at based on the experiments you have done?

Draw a diagram to show the relationship between the location of the red and blue light sources, the hole in the wall, and the red and blue images on the wall inside the darkroom.

Why is the image of the girl inverted?

- (2) Compare the angles in the two triangles.
How do the corresponding angles of the triangles compare?

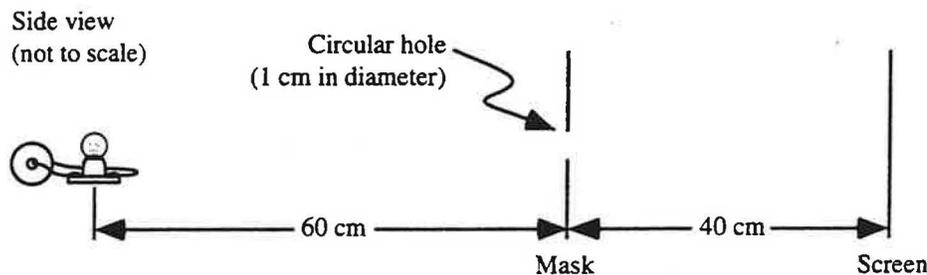
What is the ratio of corresponding angles in the two triangles?

- C. Triangles such as the two that you have drawn, where one is a scaled version of the other, are called similar triangles. Suppose that you were given two triangles. Describe a method by which you could determine whether or not the triangles are similar.

It is not always possible to make a full-size diagram of a physical setup. For example, if a bulb and screen are very far apart, it may be necessary to make a sketch that is smaller than life-size. A diagram in which each distance is shown reduced or enlarged by the same multiplicative factor is called a scale diagram.

2.2 Experiment

A bulb is placed in front of a mask and screen as shown below.



- A. Use the properties of similar triangles to write an equation that you can use to determine the height, h , of the bright region on the screen.

Calculate h . What are the units of h ?

Is the height of the bright region on the screen greater than, less than, or equal to the diameter of the hole in the mask? Explain how you can tell from your equation and how you can tell from the diagram.

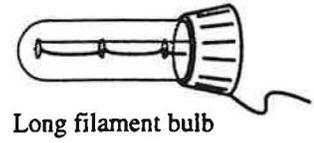
Set up the apparatus and check your prediction for the height of the bright region on the screen.

- B. Write an equation for the height, h , of the bright region on the screen in terms of the diameter, d , of the hole in the mask.

Check your equation by substituting 1 cm for the diameter of the hole. You should obtain the same answer as in part A.

Suppose that the diameter of the hole in the mask were doubled. Would the height of the bright region on the screen also double? Explain how can you tell from your equation.

- C. Predict what you would see on the screen if you were to replace the three small bulbs by a long filament bulb. Explain your reasoning.



Obtain a bulb with a long filament and check your prediction.

Describe how your observation is consistent with the idea that we can consider a long filament bulb as a string of closely spaced small bulbs.

- D. Predict what you would see on the screen when two long filament bulbs are arranged to form a T-shaped light source. Use a diagram to help explain your prediction.

Check your prediction. Draw a side view diagram and a top view diagram to account for your observation.

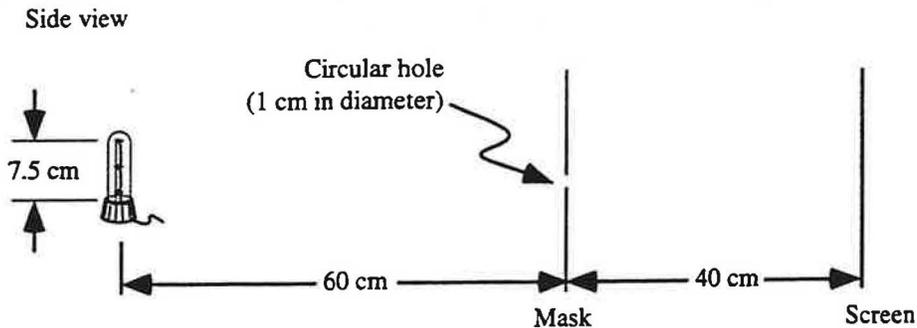
- E. Predict what you would see on the screen when two long filament bulbs are arranged to form an L-shaped light source. Use a diagram to help explain your prediction.

Check your prediction. Draw a side view diagram and a top view diagram to account for your observation.

Discuss your results with your teacher.

2.5 Experiment

Consider the situation pictured below. Except for the hole in the mask, the diagram has been drawn to scale.



If the diameter of the hole in the mask were halved, would the height of each bright region on the screen also halve? Explain your reasoning.

If the diameter of the hole in the mask were halved, would the width of each bright region on the screen also halve? Explain your reasoning.

Check your predictions. If any of your predictions were incorrect, resolve the inconsistency.

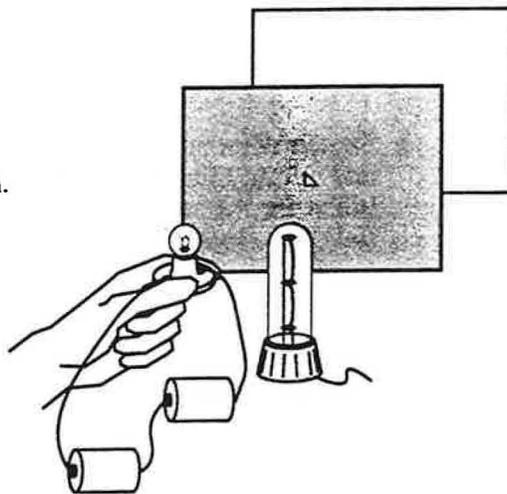
Discuss your results with your teacher.

2.6 Experiment

This experiment should be performed in a darkened room.

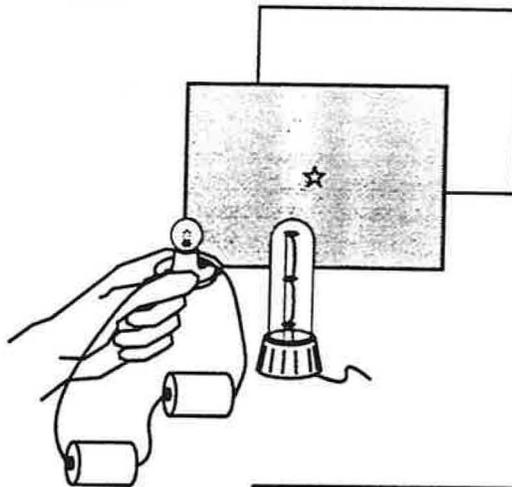
In this experiment, you will be making several predictions. If you find that your predictions are incorrect, try to find the error in your explanation before continuing to the next prediction.

- A. Predict what you would see on the screen when a small bulb is held near the top of a long filament bulb, and both are held in front of a mask with a triangular hole as shown at right. Explain your reasoning.



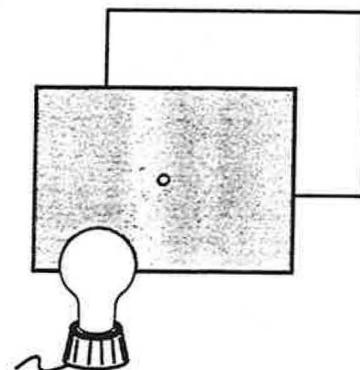
Check your prediction.

- B. Predict what you would see on the screen if instead the hole in the mask were star-shaped. Explain your reasoning.



Check your prediction.

- C. Predict what you would see on the screen if an ordinary frosted bulb were placed in front of a mask with a circular hole. Explain.



Check your prediction.

- B. Suppose the bulb is held 20 cm above the tabletop and 15 cm horizontally from the nail. Predict the length of the shadow that is cast on the table by the nail.

Set up the equipment and check your prediction.

Check your results with your teacher.

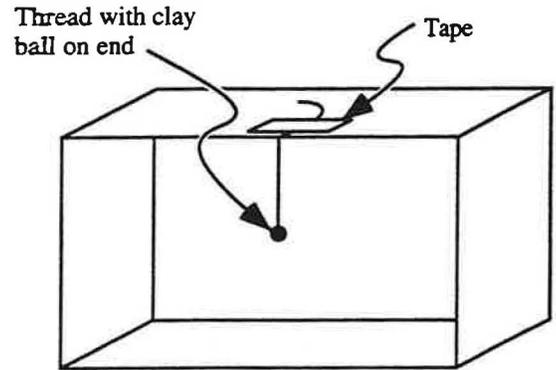
3.3 Experiment

This experiment should be performed in a darkened room.

In this experiment, you will use a shadow box. You will need a small round light bulb set-up, clay, thread, tape, and a box.

Suspend a small ball of clay, about 1 cm in diameter, from thread as shown.

- A. Hold a small lighted bulb in front of the clay ball.



Describe what you observe. Draw a diagram to help you account for your observation.

- B. For each of the following situations, first predict how the shadow will change, then check your prediction. Use diagrams and the ideas developed thus far to explain your predictions and observations.

- (1) The clay ball is made larger.

prediction

observation

- (2) The clay ball is made smaller.

prediction

observation

- (3) The clay is formed into a triangular shape.

prediction

observation

- D. In Lesson 2, we treated the long filament bulb as though it consisted of a line of point sources. Explain how that idea can be used to explain your observations in this experiment.

3.5 Experiment

Perform this experiment in a darkened room. In this experiment, you will be making several predictions. If you find that a prediction is incorrect, try to resolve any inconsistencies before continuing to the next prediction. Hang a clay ball about 1 cm in diameter in the shadow box as you have done before.

- A. Predict what you will see in your shadow box when two long filament bulbs are used to make a T-shaped light source. Use diagrams to explain your prediction.

Check your prediction.

- B. Predict what you will see in your shadow box when two long filament bulbs are used to make an L-shaped light source.

Check your prediction.

- C. Predict what you will see in your shadow box when the clay is made into a triangular shape (the light source is still L-shaped).

Check your prediction. If your prediction is incorrect, try to resolve the inconsistency.

Discuss your results with your teacher.

- (1) Use the mask with a single slit (3 mm wide) to produce a beam of light. Examine the effect of putting one or both mirrors in the path of a beam of light. Describe your observations.

Describe the path of the light when the beam is aimed (a) at an angle toward the mirror and (b) straight toward the mirror.

- (2) Place the two-slit mask on the light box. Is it possible to make the two beams cross using only one mirror? If so, draw a sketch that illustrates your answer.

- (3) Place the single-slit mask on the light box and turn off the light. Make an X on the paper in a location that is not directly in front of the light.

Decide where you need to place one or both mirrors so that the beam will pass over the X. Talk to a staff member if you need additional equipment. Explain how you determined your answer.

Turn on the light box and check your answer.

- (4) Ask a partner to look away while you place one or two mirrors in the path of a beam of light. Mark the resulting path on the sheet of paper, then remove the mirrors and turn off the light box.

Ask the partner to predict where to place the mirrors in order to have the light follow your marked path.

Turn on the light box and check your partner's answer.

Make sure each of you can correctly perform this operation.

4.3 Experiment

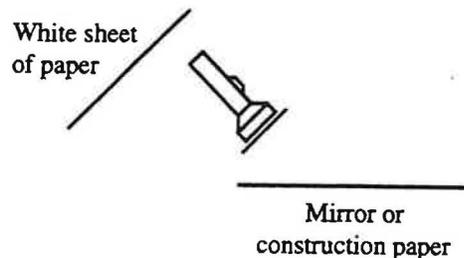
Place a mirror on a clean sheet of paper and draw a line along the front of the mirror to mark its location.

- A. Using the single-slit mask on the light box, aim the beam so it reaches the mirror at an angle. Use a ruler to mark the path of the light both toward and away from the mirror by drawing a line along the center of the beam.

Use a protractor to measure the angle at which the beam strikes the mirror and the angle at which it leaves the mirror.

How do the two angles compare?

- C. Imagine that you were to place the sheet of white paper at the location shown at right.



Predict what you would see on the white sheet of paper if the flashlight were aimed at:

- (1) a mirror?
- (2) construction paper?

Check your predictions.

- D. Compare and contrast how light is reflected by mirrored surfaces and by non-mirrored surfaces.

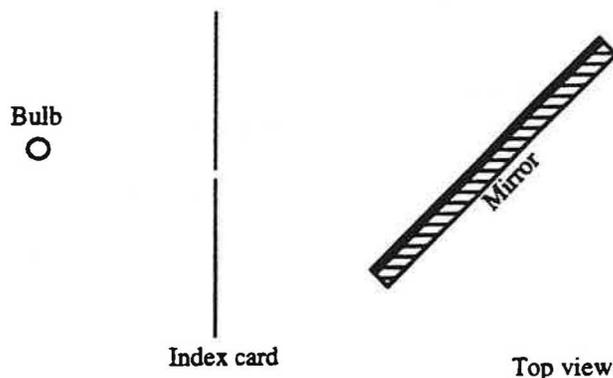
Recall the rule that you wrote in Experiment 4.3 to predict the path of a beam of light that is aimed toward a mirror. Does this rule also describe the behavior of a light beam that is reflected by a non-surface? Explain your reasoning.

Discuss your results with a staff member.

4.5 Experiment

For this experiment you will need a mirror, a small round bulb and two batteries, an index card (or other piece of heavy paper) containing a narrow slit, a nail, and a large sheet of white paper.

On the large sheet of paper, set up the lighted bulb, slit, and mirror as shown.



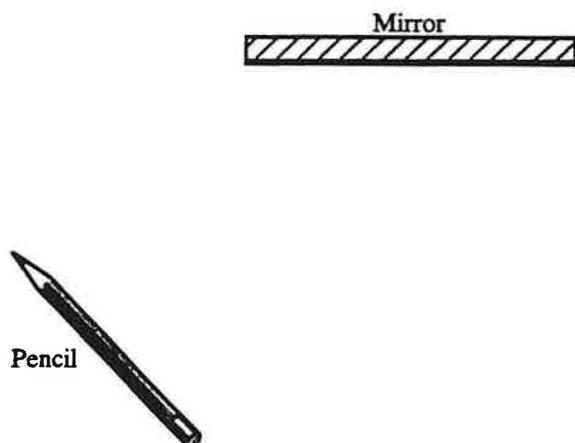
- A. Describe the path of the light through the slit. Sketch the path on the paper. Show the beams that are incident on and reflected from the mirror. Draw arrow heads to indicate the direction the light travels.

Where must you place your eye to see the light bulb in the mirror?

The bulb that you see in the mirror is called the image of the bulb.

4.7 Experiment

Consider a pencil near a mirror as shown in the top view diagram below.



- A. Indicate the region in front of the mirror where an observer could see:
- (1) the image of the tip of the pencil
 - (2) the image of the eraser
 - (3) the entire image of the pencil
- B. Choose a point from which the observer could see the entire image of the pencil. Indicate the directions in which that observer would have to look to see:
- (1) the image of the tip
 - (2) the image of the eraser
- C. Place a mirror on your ray diagram and check your results for parts A and B. (If necessary, use paper to mask a larger mirror to make it the correct size.)

Discuss this experiment with your teacher.

4.8 Video

- A. Reflection is a behavior of all waves, of which light is just one example. A water surface supports waves, a fact which allows for simple demonstrations of many wave phenomena, such as reflection.

Go to the videodisc set-up and watch the following segments:

Physics: Cinema Classics, Side C, Chapter 53 "Water - Plane Surfaces". Set audio at ANALOG 2/R.

Physics: Cinema Classics, Side C, Chapter 54 "Water - Curved Surfaces".

In these video segments a "ripple tank" is used to create visual images of water waves as the waves cast shadows.

- B. Infra-red radiation also behaves as a wave and, consequently, can also be reflected. Watch the following video segment for interesting demonstrations of the reflection of infra-red radiation.
- Principles of Physics Videodisc, Side 1, Chapter 47 "Thermal Radiation: Focused Transmission using Parabolic Mirrors".

Notice that in two of these video sequences the reflecting surfaces are curved rather than flat. Does the law of reflection still apply? What evidence is given in these two video to suggest that it does?

In the previous experiment, you observed that there is an apparent change in the relative location of the two pencils when you move your head from side to side. This effect is said to be due to parallax.

5.3 Experiment

- A. Describe how you can use parallax to determine which of two objects is closer to you. Draw a ray diagram to illustrate your answer.

How must the two objects be located relative to one another if you observe no effect of parallax when you move your head from side to side?

- B. Explain how you could use parallax in Experiment 5.1 to tell whether your finger is (1) directly over the piece of paper, (2) in front of the piece of paper or (3) behind the piece of paper.

Repeat Experiment 5.1 and test the method that you have devised.

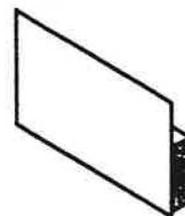
- C. Have your partner hold two pencils in front of you as in part A of Experiment 5.2. Close one eye and use the method of parallax to direct your partner as to which direction to move the upper pencil until it is directly above the lower pencil.

Discuss your reasoning with your teacher.

Return now to your larger groups for the remainder of the lesson.

5.4 Experiment

Obtain two identical nails and a mirror that is shorter than the nails. Place one nail upright on a sheet of paper about 10 cm in front of the mirror. We will call this nail the "object nail."



- A. Place your head so that you can see the image of the object nail. Then move your head from side to side. Describe what you observe.

Where does the image appear to be located?

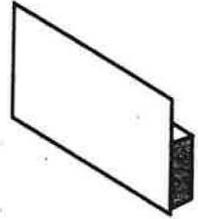
Does the image stay in the same location or does it change location as you move your head?

Repeat the procedure above to mark lines of sight from three other vantage points, then remove the nail.

How can you use the lines of sight that you drew to determine where the nail was located?

What is the smallest number of lines of sight necessary to determine the location of an object?

- B. Turn the paper over (or use a fresh sheet). Place a mirror and nail on top of the paper as shown at right. Draw a line on the paper to mark the location of the mirror.



- (1) Place your head near the surface of the table and look at the image of the nail. Push two pins into the corkboard so that, from your location, they appear to be in line with the image of the nail. Use a ruler to draw your line of sight to the image.

Can you tell the location of the image from the single line of sight that you have drawn? Explain.

Repeat the procedure above from several different eye locations.

How can you use the lines of sight that you drew to determine the location of the image of the nail?

Would all observers who can see the image of the nail agree on its location? Explain.

- (2) Use the method of parallax to determine the location of the image of the nail.

Does the method of parallax yield the same image location as you found in part (1) above?

- (3) Discuss how the methods in part (1) and part (2) for determining image location are related.

- C. Move the nail and use the intersecting lines of sight method developed above to find the new location of the image. Do this for several different nail locations including: a location close to the mirror, a location far from the mirror, and a location off to the side of the mirror. Use a different sheet of paper for each case.
- D. Based on your observations, describe the relationship between the object location, the image location, and the location of the mirror.

You will need the sheets of paper from part C for the next experiment.

In this course, when you are asked to use ray tracing to determine the location of an image, always draw at least two rays. Use a solid line with an arrow head (\longrightarrow) to represent the actual path of a ray of light. Use a dashed line (- - - - -) to extend a ray behind a mirror to indicate a path that light only appears to take.

5.7 Exercise

As you may have noticed in your experiments thus far, the image of an object in a plane mirror is located as far behind the mirror as the object is in front. Use geometry to prove this fact. (Hint: Start with a ray diagram that shows the location of an image and look for similar triangles. You may find it necessary to draw additional lines or rays.)

5.8 Exercise

A. Draw a ray diagram to determine the location of the image of each of the two objects in the diagram below.



B. Determine the region in which you could stand and see the images of both objects at the same time.

C. Describe how you could use a ray diagram to determine the location of the image of an extended object, such as a pencil or brick.

Part C: Lenses and Images

In Part C of *Light and Optics*, we study the behavior of light as it passes from one material to another, such as from air to glass or from air to water. We develop a technique for drawing ray diagrams that enables us to determine the location and size of an image formed by a lens. We then apply the model in constructing optical instruments, such as a simple telescope and microscope.

Lesson 6. Introduction to Refraction

6.1 Experiment

- A. Obtain a laser and two clear glass beakers. Fill the beakers with water to a level that is higher than the beam of light coming from the laser. A few drops of milk in the water should make the light beam visible as it passes through.

Place the laser and beakers on a sheet of white paper. Turn on the laser and explore what happens when one or both of the beakers are placed into the beam of light.

Describe some of your observations, both in words and in diagrams (showing the arrangements of the beakers and laser and the effect on the path of the light). Record the path of the beam through the water, also.



- B. As part of your explorations, try to answer the following questions:
Does light follow a straight path in water the way it does in air?

How does the path of a beam that passes through a beaker of water differ from the path through an empty beaker?

Can you use a single beaker of water to make the beam bend:

- (1) left then left again?
- (2) left then right?
- (3) right then right again?
- (4) only once either left or right?
- (5) not at all?

6.3 Exercise

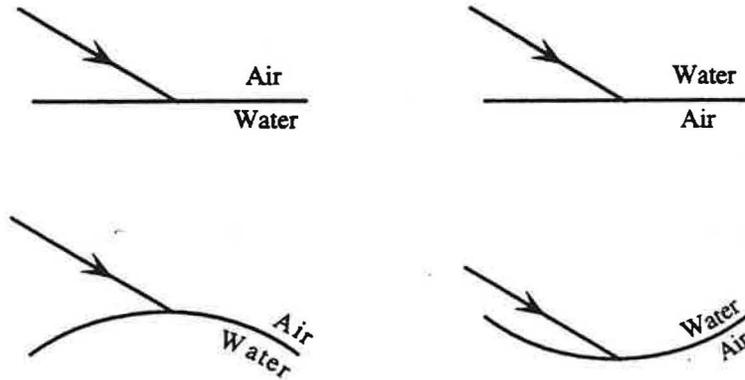
The beam inside a beaker may be considered as both a transmitted beam and an incident beam: it is the transmitted beam where light enters the beaker and it is the incident beam where light leaves the beaker.

Examine several of your diagrams from Experiments 6.1 and 6.2. For each diagram, identify the incident, transmitted, and reflected beams. Clearly label the beams that are both incident and transmitted beams.

6.4 Exercise

In each top view diagram below, the path of a beam of light is shown incident on the side of a transparent container filled with water. Only part of each container is shown.

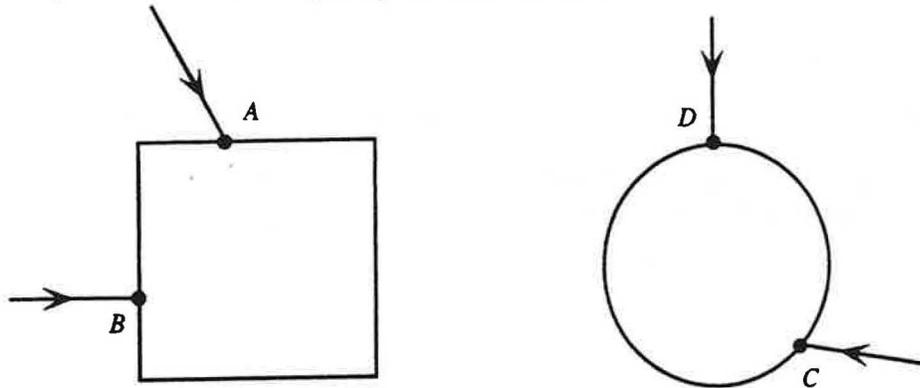
Sketch the approximate path of the beam in the second material. Using a dashed line, also draw the path that the beam would have taken had it continued without bending. Be sure that your rays are consistent with your observations. Make additional observations if necessary.



6.5 Exercise

A. Each of the top view diagrams below illustrates two rays of light incident on a transparent container filled with water.

Make a sketch that shows the approximate directions of the corresponding transmitted rays. Draw the rays so that they are consistent with your prior observations.



B. Draw a line through point A that makes a 90° angle with the side of the container. Repeat for point B.

These lines are said to be perpendicular or normal to the container. Such a line is called the normal to the container at the point it intersects the container.

Draw the normal at point C and at point D on the beaker. Explain what it means for a line to be normal to a curve.

6.7 Experiment

A. Obtain two flat pieces of glass, one thick and one thin (e.g., a microscope slide and a thick glass block).

Place each piece, in turn, into a beam of light and examine the effect on the beam. Try various orientations of the glass. Sketch diagrams to record your observations.

Does one of the pieces of glass seem to affect the beam to a greater extent? If so, which one? Describe the experiment(s) that allows you to determine your answer.

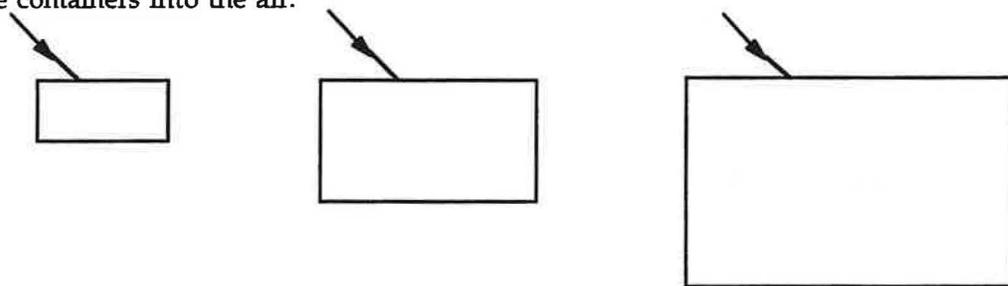
B. In Experiment 6.1 you examined the path of light through a beaker of water. You determined whether the glass from which a beaker is made plays a large role in refracting light.

Are your observations in part A above consistent with your conclusion in Experiment 6.1? Explain.

6.8 Exercise

The top view diagrams below show beams of light incident on one side of transparent containers filled with water. The beams are all incident on the containers at the same angle.

Sketch the transmitted beams in each case and show the direction of each beam when it passes back out of the containers into the air.



How do the directions of the beams inside the containers compare? Explain your reasoning.

How do the directions of the beams once they have left the containers compare? Explain your reasoning.

In each case, how does the direction of the beam that has exited the container compare to the direction of the beam incident on the container?

Obtain several containers of water and check your answers.

Lesson 7. Law of Refraction: Snell's Law

7.1 Experiment

Place a semi-cylindrical dish of water onto a sheet of paper, and aim a beam of light from a laser at the dish. If necessary, adjust the height of the laser and/or the dish to ensure that the light beam passes through the water. (**Hint:** The path of the laser beam can be accurately determined by drawing a vertical line on a note card and holding the note card in the beam so that it is centered on the vertical line.)

A. View the dish from above and slowly rotate it through 360° . Describe your observations.

Make three or four sketches for various configurations of the dish and incident beam. On your diagrams show not only the incident beam, but any reflected and transmitted beams.

B. For this part of the experiment, orient the dish so that the beam always strikes the flat side of the dish first.

(1) Examine what happens when the beam strikes the dish at different locations along the flat side and at different angles. Sketch several arrangements of the dish and beam.

(2) Find orientations of the beam and dish in which the beam is first incident on the flat side of the dish and behaves as follows:

- the beam bends at both the flat side and the curved side of the dish
- the beam does not bend at either side of the dish
- the beam bends at the flat side of the dish, but not at the curved side
- the beam bends at the curved side of the dish, but not at the flat side

Record several examples of each case (unless a particular behavior occurs for only one orientation of the incident beam).

In the remainder of this section we examine the relationship between the angle of incidence and the angle of refraction for light passing from one material to another.

7.2 Experiment

- A. Based on your results from Experiment 7.1, parts D and E:
can total internal reflection occur when a light beam in water is incident on air?

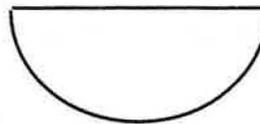
can total internal reflection occur when a light beam in air is incident on water?
- B. Devise and perform an experiment to answer the following question. Record your results.
Does total internal reflection occur for a single angle of incidence or for a range of angles? Find the angle or range of angles.

Check your results from Experiments 7.1 and 7.2 with your teacher.

7.3 Experiment

In this experiment we conduct a qualitative investigation of the relationship between the angle of incidence and the angle of refraction for a light beam that passes from air to water.

- A. The top view diagram at right shows a semi-cylindrical dish of water. Sketch the path of a beam of light that strikes the flat side of the dish and passes through the dish without bending at either side of the dish.



Before continuing, check your diagram with your teacher.

- B. Aim the beam from your laser at the semi-circular dish of water at the angle you illustrated in part A. Gradually increase the angle of incidence by rotating the dish, keeping the beam aimed at the same point on the flat side of the dish. Describe your observations.

As the angle of incidence increases, does the angle of refraction increase, decrease, or stay the same?

7.4 Experiment

In this experiment we conduct a quantitative investigation of the relationship between the angle of incidence and the angle of refraction for a light beam that passes from air to water.

Place a semi-cylindrical dish on a sheet of polar graph paper with the center of the flat side at the center of the paper. Arrange the light beam and dish as you did in part B of the preceding experiment, e.g., with the beam incident on the center of the flat side. Concentrate on the incident and refracted beams at the flat side of the dish. Record your measured values in the table on the next page.

- (1) If the angle of incidence is 0° , what is the angle of refraction?
- (2) Aim the incident beam at the center of the flat side so that the angle of incidence is 10° . Measure and record the angle of refraction for this case.
- (3) When the angle of incidence is doubled to 20° , does the angle of refraction double? Check your answer experimentally.

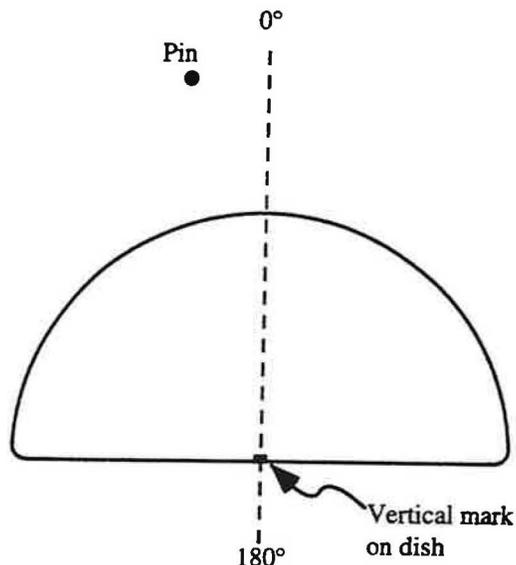
7.6 Experiment

Reverse the orientation of the semi-cylindrical dish on the polar graph paper as shown at right.

- A. Devise a method for using the equipment in Experiment 7.5 to measure the angle of refraction for various angles of incidence for light passing from water to air.

(Hint: How could you modify your method from part C of Experiment 7.5 to do this?)

Explain why your method gives correct values of these angles for light passing from water to air when the pin is in air, not in water.



- B. Use the method you devised in part A to complete the table at right.
- C. Compare the results you obtained in this experiment to those you obtained in Experiments 7.4 and 7.5.

Describe any similarities and differences.

- D. Earlier, you found that under certain circumstances light is totally internally reflected. Use your method from part A to find the range of angles for which total internal reflection occurs.

Check your results from this experiment with your teacher.

Light passing from water to air

Angle of incidence	Angle of refraction
-----	-----
-----	-----
-----	-----
-----	-----
-----	-----
-----	-----
-----	-----
-----	-----

7.7 Exercise

Suppose you were to use your data from Experiment 7.4 to graph the angle of incidence versus the angle of refraction for light passing from air to water.

Would you expect the graph to be a straight line? Explain.

Graph your data and check your prediction. You may either do the graph by hand or use the graphing software on the computer.

Check your answers with your teacher.

7.8 Exercise

Your results so far indicate that the relationship between the angle of incidence and the angle of refraction is more complicated than just a linear one. Since we are dealing with angles, let us look for an algebraic relationship between these angles that involves trigonometric functions such as $\sin \theta$, $\cos \theta$, and $\tan \theta$.

- A. Use your results from Experiment 7.4 to make a graph of $\sin \theta_i$ versus $\sin \theta_r$, where θ_i represents the angle of incidence (in air) and θ_r represents the angle of refraction (in water). You may find it helpful to use the spreadsheet software and the graphing software on the computer.

Lesson 8. Image Formation by Convex Lenses

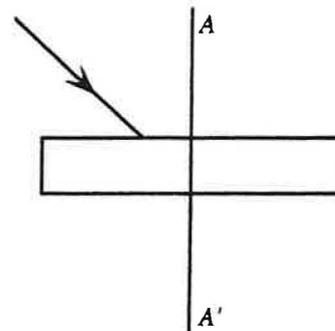
8.1 Exercise – to be done before coming to class

- A. At right is a diagram of a light ray incident on a thin rectangular plate of glass. The line AA' is perpendicular to the plate.

Sketch the continuation of the ray through the glass and into the air.

How does the angle between the emergent ray and AA' compare to that between the incident ray and AA' ? Explain.

How would your answer change if the plate were thicker or thinner than the one shown above? Explain.

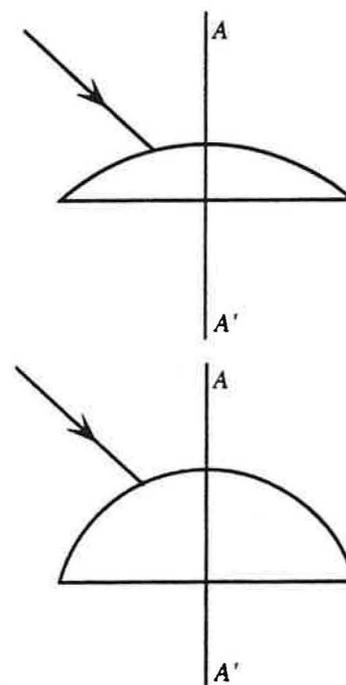


- B. At right is a diagram of a light ray incident on a piece of glass with one spherical surface and one plane surface.

How does the angle between the emergent ray and AA' compare to that between the incident ray and AA' ? Explain.

- C. Suppose that the spherical surface in the diagram in part B were replaced by a spherical surface with a smaller radius of curvature as shown.

How would the angle between the emergent ray and AA' compare to the corresponding angle in part B? Explain.



- D. Suppose that the glass in part B were made of a type of glass with a greater index of refraction.

How would the angle between the emergent ray and AA' compare to the corresponding angle in part B? Explain.

- E. What factors determine the ability of a piece of transparent material, such as glass, to change the direction of an incident ray? Explain your reasoning.

8.3 Experiment

For this experiment you will need the larger diameter lens from the preceding experiment. You will find at your workstation a one-meter stick, two supports, a lens holder, and a few other accessories.

- A. Stand a nail on its head on a lab jack stand and place it at the end of the one-meter stick. Place the larger diameter lens in the lens holder and position the lens holder on the meter stick so that it is 50 cm from the nail. Adjust the height of the nail so that its elevation is even with that of the lens. Place your eye about 30 cm from the lens and look through the lens at the nail.

Describe the image of the nail.

Does the location of the image seem to differ from the actual location of the nail?

Would you say that the image of the nail is closer to you, farther from you, or the same distance from you as the nail? Explain how you can tell from your observations.

- B. Take a second nail that is identical to the first. Use the method of parallax to place the second nail at the location of the image of the first nail.

Does the image appear to be larger or smaller than the nail appears without the lens?

Is the location of the image consistent with your answer in part A? If not, how can you resolve the inconsistencies? (Hint: Can you determine the location of the image solely on the basis of the size of the image?)

Remove the second nail.

- C. Place the lens about 5 cm from the first nail. Look at the nail through the lens with your eye about 30 cm from the lens. Use the method of parallax to determine the location of the image.

Is the image closer to you, farther from you, or the same distance from you as the nail?

Does the image appear to be larger or smaller than the nail appears without the lens? Can you use the apparent size of the image as a clue as to whether the image is closer to you than the nail?

- D. Turn the lens around. Does the location of the image depend on which side of the lens is toward the nail?

Discuss this experiment with your teacher.

8.4 Experiment

For this experiment use several convex lenses of different sizes and shapes.

- A. Place a lens in the lens holder on the meter stick and arrange it so that light from a brightly lit distant source (e.g., an outdoor scene) passes through the lens and falls on a screen mounted on the meter stick. Move the screen back and forth until a clear image of the object appears on the screen.

Describe the appearance of the image. Is it erect or inverted? Is it larger or smaller than the object?

Measure the distance from the lens position to the screen position when the image is sharp.

Turn the lens around. Describe what happens to the image. Has the distance to the screen changed?

Move the screen back and forth. Describe what happens to the image.

C. Repeat part B for each of the following locations for the lighted bulb. Record your observations and the four measured positions in the spaces below.

(1) at a distance between 1 m and $2f$ from the lens

(2) at a distance $2f$ from the lens

(3) at a distance between $2f$ and f from the lens

(4) at a distance f from the lens

(5) at a distance between f and $f/2$ from the lens

(6) at a distance $f/2$ from the lens

(7) at a distance less than $f/2$ from the lens

Do the two methods for determining the location of the image always work? If not, note which method fails and when it fails.

Place the lighted bulb as close to the lens as possible. Describe the image in this case. Record your observations.

D. Summarize your observations in words by answering the following questions:

As an object is moved toward a lens from a large distance away, how does the location of the image vary?

As the object is moved toward the lens, how does the apparent size of the image vary?

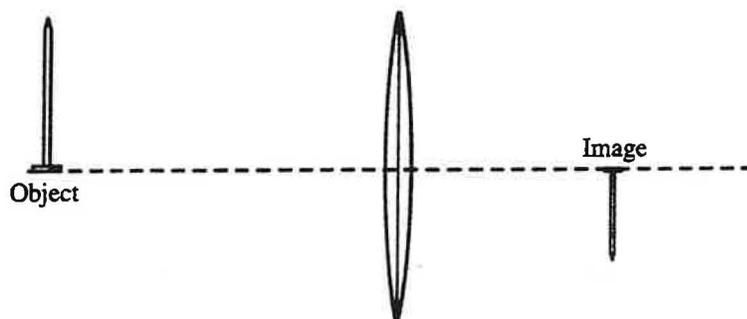
Lesson 9. Image Formation, Ray Diagrams, and the Thin Lens Equation

In this section, we develop an algorithm, or a set of rules, for predicting the position and appearance of the image formed by a convex lens. This procedure, which is based on the tracing of light rays through a lens, is a powerful tool that we will apply and extend throughout our study of geometrical optics.

Work through Exercises 9.1, 9.2, 9.3, and 9.4 before coming to class. Discuss your results with your partners.

9.1 Exercise

The diagram below shows a nail near a convex lens. The image formed by the lens is shown on the diagram.



- A. From the tip of the nail, draw several rays, some of which pass through the lens.

Show by a sketch how you can use these rays to account for the formation of the image of the tip of the nail. Explain.

- B. Draw similar sketches for two other points on the nail.
- C. Explain how you decided to draw the rays in the way that you did in parts A and B.
- D. A convex lens is often called a converging lens.

Is this term appropriate? Explain why or why not.

9.2 Exercise

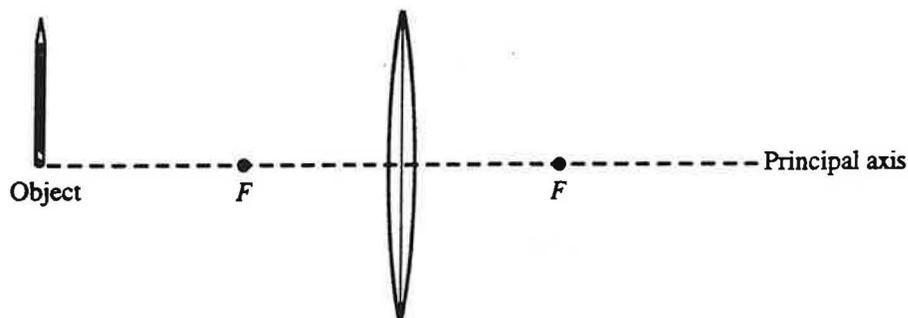
A lens is held at a very great distance from a tall building so that a clear image of the building is formed on a piece of paper. Consider two points on the building, P and Q. P is on the principal axis, Q is directly above it at the top of the building.

- A. Draw a diagram that shows several rays from point P that reach the lens.

The location of the image for any object can be found through the use of a ray diagram. Analysis of the preceding experiments and exercises suggests a method for tracing the path of light rays from a point on an object, through a lens, to a corresponding image point. Below, we apply this technique to the construction and interpretation of the image formed by a convex lens.

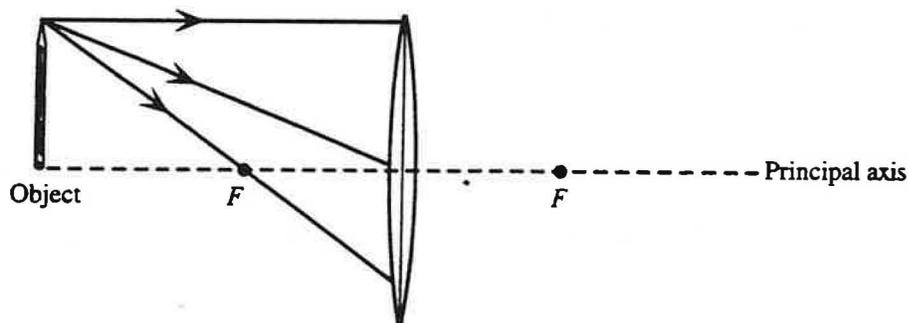
9.5 Exercise

In drawing a ray diagram for a lens, we begin by showing the lens, the principal axis, and the locations of the two focal points. A simple sketch of the object is then drawn at the proper distance from the center of the lens, usually on the left side of the lens.



As we found in Exercise 9.1, we can think of all the rays from a single point on the object that pass through the lens as converging at a single corresponding image point.

There are three special rays from each object point for which it is particularly easy to determine the path through the lens. These are shown in the following sketch.



A. Do you expect these three rays to intersect after they pass through the lens? Explain.

Draw the continuation of each of these rays on the other side of the lens. In each case, explain your reasoning.

How would you interpret the intersection of these three rays?

These three rays, which are called principal rays, are only a few of the infinitely many that we might draw from one point on the object.

- B. Which observer(s) can see the image of the pencil tip? Explain.
- C. Which observer(s) can see the image of the eraser? Explain.
- D. Which observer(s) can see the entire image of the pencil? Explain.
- E. Suppose that you were to place your eye at the location of an observer who can see the entire image of the pencil.

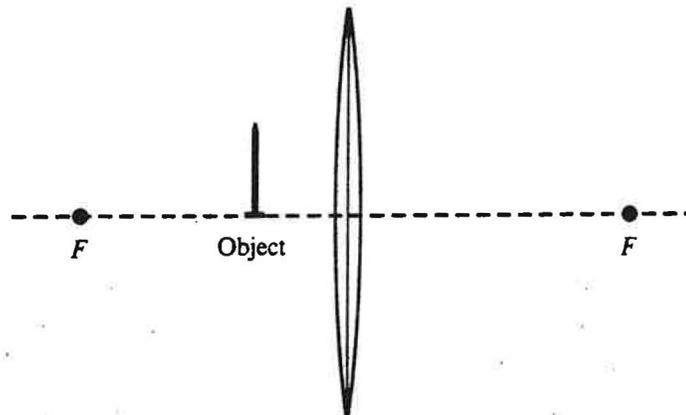
Which would appear to be larger to the observer: the image of the pencil (with the lens in place) or the pencil (with the lens removed)? Explain how you can tell from the ray diagram.

If you were to use a ruler to measure the length of the pencil and the length of the image, which would be larger? Explain how you can tell from the ray diagram.

Discuss your reasoning with your teacher.

9.8 Exercise

In Exercise 9.5, we developed a procedure for drawing ray diagrams for situations in which a convex lens forms a real image. In this exercise, we extend this procedure to include the case that the image is virtual.



- A. Draw the three principal rays from the tip of the nail to the lens. Do these rays intersect on the right side of the lens?

Would an observer on the right side of the lens see an image? If so, where is the image located? (Hint: Consider your observations using convex lenses in Lesson 8.)

Explain how you would find the location of the image by using the principal rays. Recall that it is customary to use dashed lines to indicate the extension of a ray into a region in which the light does not pass.

- B. Is the image erect or inverted? Is the image larger or smaller than the object? Explain how you can tell from the ray diagram.

In which cases would the image of the object (with the lens in place) appear to be larger to an observer than the object (with the lens removed)? Explain how you can tell.

- C. Compare your results for the image locations in part A with your observations in part C of Experiment 8.6. Are they consistent? If not, resolve any discrepancies.

9.10 Experiment

In this experiment, be sure to make all predictions before performing the experiments. Draw ray diagrams to justify your predictions.

Assume that you use a long filament bulb as an object, the convex lens you used in part C of Experiment 8.6 mounted in a lens holder on a meter stick, and a screen mounted on the meter stick, with the screen located so that a sharp image of the bulb is on it. The bulb is elevated so that it is at the same level as the lens.

- A. Predict what would happen to the image if the top half of the lens were covered by a mask. Explain your reasoning.

Does it matter on which side of the lens the mask is placed?

- B. Predict what would happen to the image if a mask with a small hole in the center (smaller than the object) were placed in front of the lens.

How would your answer differ if the hole were moved so it is not at the center of the lens

- C. Perform each of the above experiments and check your predictions. If your predictions were incorrect, draw new ray diagrams that are consistent with what you observe. (Was it necessary to move the screen to a new position to get the sharpest image when the mask with a small hole was used? If so, why?)

- D. In turn cover the lens with a red filter and then a blue filter and determine the position of the screen to get the sharpest image. Are the positions different?

What does that tell you about the index of refraction of glass?

Discuss your observations with your teacher.

B. A convenient way to graph your results is to use new variables, x and x' . Let $x = s - f$, and $x' = s' - f'$.

What physical interpretation can you give to the variables x and x' ?

Where is the object when x is positive?

When x is negative?

When x is zero?

Where is the image when x' is positive?

When x' is negative?

When x' is zero?

(1) Enter values for x and x' corresponding to each value of s and s' in your table.

(2) Graph x as a function of x'

(3) As your graph indicates, the relationship between x and x' is clearly not linear. You might guess from your study of mathematics that the resultant curve is a hyperbola.

To test whether the curve is a hyperbola, plot a graph of x as a function of $1/x'$.

Is the relationship between x and $1/x'$ linear? Explain how you can tell from your graph.

Find the slope of the graph and call it K .

Write an equation relating x , x' and K .

The constant K is related to the focal length, f . Make an educated guess as to this relationship, by considering the units of K . Check your guess.

Write an equation relating x , x' and f .

Check your reasoning with your teacher.

The equation that you derived in the preceding exercise is known as the Newtonian form of the thin lens equation. This form of the thin lens equation is seldom used. The Gaussian form, which is given in the following exercise, is more useful in practice.

Lesson 10: Using the Thin Lens Equation, and Image Formation by Concave Lenses

Do the following two exercises before coming to class. Compare your results and conclusions with your partners.

10.1 Exercise

- A. Use the thin lens equation to find the image location s' , for an object placed at the following values of s :
 $s = 4f, 2f, 3f/2, f, 3f/4, f/2, f/4$.
Show your work in each case.

- B. Not all of the values of s in part A result in a positive value for s' .

How would you interpret negative value for s' ?

How would you interpret the failure of the equation to yield a number for s' ? (Hint: Draw on your experience in working with lenses in the laboratory and on your experience in drawing ray diagrams.)

10.2 Exercise

- A. We now have three ways of finding the location of an image formed by a thin convex lens: by using parallax, by using a screen, and by using an equation.

Discuss which of the methods work for finding the image locations for each of the images in the preceding exercise. You have used the first two of these methods in Experiment 8.6.

If one of the methods fails for some of the object distances, discuss why that method fails.

In the remainder of this lesson, we examine the behavior of concave lenses. Concave lenses have at least one surface that curves inward and are thinner in the middle than at the edge.

10.4 Experiment

Obtain two concave lenses of different diameters.

- A. Look at a coin through the lens with the larger diameter. Hold the coin at arm's length in front of you so it is upright when you are looking at it without the lens. Place the lens directly in front of the coin, then move it slowly toward your eye. Keep the coin fixed in place as you move the lens. Describe your observations in words and with sketches.

Where, if at all, can you hold the lens so that the coin appears to be:

- (1) upside down?
 - (2) right side up?
 - (3) larger than it is in real life?
 - (4) smaller than it is in real life?
 - (5) the same size as it is in real life?
- B. Hold the lens fixed in place about 20 cm from your eye. Place a coin behind the lens and very close to it. Slowly move the coin as far from the lens as you can. Describe your observations in words and with sketches.

Repeat the procedure above for the other lens. Do you notice any differences between the two lenses?

10.5 Experiment

For this experiment you will need the larger diameter lens from the preceding experiment. You will find at your workstation a one-meter stick, two supports, a lens holder, and a few other accessories.

- A. Stand a nail on its head on a lab jack stand and place it at the end of the one-meter stick. Place the larger diameter lens in the lens holder and position the lens holder on the meter stick so that it is 40 cm from the nail. Adjust the height of the nail so that its elevation is even with that of the lens. Place your eye about 10 cm from the lens and look through the lens at the nail.

Describe the image of the nail.

Does the location of the image seem to differ from the actual location of the nail?

In a previous section, we developed a method for determining the location of the focal point and focal length of a convex lens. The focal point is the point of intersection of the principal axis and the image of a very distant object. In the following experiment, we determine the focal length of a concave lens.

10.8 Experiment

Find the focal length for both sides of each lens from Experiment 10.7. (Hint: Since, for a concave lens, the image of a very distant object is virtual, how can you determine the location of the image? Review your operational definition of virtual image in Exercise 10.2 B.)

Is there a focal point on each side of the lens? If so, how does the focal length on one side of the lens compare with that on the other? Explain how you can tell from your observations.

It is customary to use a single symbol f to denote the focal length of a lens. Explain why two symbols, one for each focal point, are not necessary.

Discuss Experiments 10.7 and 10.8 with your teacher.

For a convex lens, the image of a distant object is on the opposite side of the lens from the object. As you have seen, for a concave lens, the distant object and its image are both on the same side of the lens. The following sign convention is consistent with our observations and also with the sign convention for s and s' .

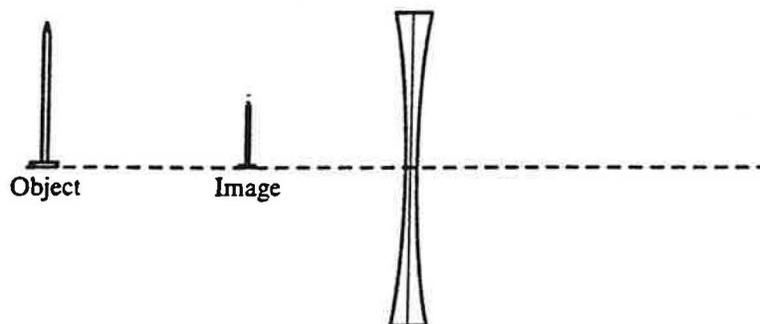
Algebraic sign convention for the focal length of a lens

When a distant object and its image are on opposite sides of the lens, the focal length is considered positive. (e.g., a convex lens)

When a distant object and its image are on the same side of the lens, the focal length is considered negative. (e.g., a concave lens)

10.9 Exercise

The diagram below shows a nail near a concave lens. The image formed by the lens is also shown.



- A. From the tip of the nail, draw several rays. Some of the rays that you have drawn should pass through the lens.

Do the rays that you have drawn actually intersect at a point, or do they only appear to have passed through the same point? Explain.

- D. Trace a third ray from the tip of the object that is initially directed toward the focal point on the far side of the lens.

Continue the ray through the lens and out the other side. Explain how you determined the direction of the ray on the other side.

How does the direction of the continuation of this ray compare to the orientation of the principal axis?

The three rays that you have drawn are called principal rays. Although tracing principal rays is a convenient tool for determining the location of an image formed by a lens, these rays are only a few of the infinitely many that we might draw from one point on the object.

- E. Trace a fourth ray from the tip of the object to the lens. Continue this ray through the lens and out the other side of the lens. Explain how you determined the direction in which this ray continues on the other side.

Discuss your reasoning with your teacher.

10.11 Exercise

For this exercise you will need your ray diagram from the preceding exercise.

- A. Choose a point on the object other than the tip of the object. On the ray diagram, trace rays from this point to determine where the image of this point is located. (You may want to use ink of a different color.) Explain the reasoning you used in determining your answer.
- B. Consider a point on the object that lies on the principal axis. Trace rays to show where the image of this point is located.
- C. Sketch the entire image of the object at the appropriate location on your diagram.

Discuss your completed ray diagram with your teacher.

- (2) at a distance $2f$ from the lens
- (3) at a distance between $2f$ and f from the lens
- (4) at a distance f from the lens
- (5) at a distance between f and $f/2$ from the lens
- (6) at a distance $f/2$ from the lens
- (7) at a distance less than $f/2$ from the lens

Place the lighted bulb as close to the lens as possible. Describe the image in this case. Record your observations.

- D. Summarize your observations in words. If necessary, make additional observations to answer the following questions:

As an object is moved toward a concave lens from a large distance away, how does the location of the image change?

As the object is moved toward the concave lens, how does the apparent size of the image change?

For what range of object locations, if any, is the image erect? For what range of object locations, if any, is the image inverted?

Where, if anywhere, must the object be located in order for the image to be on the same side of the lens as the object? Where, if anywhere, must the object be located in order for the image to be on the opposite side of the lens as the object?

Discuss your results with your teacher.

C. Write an equation relating s , s' , and f .

Compare the equation that you obtain for diverging (concave) lenses with the thin lens equation that you derived for converging (convex) lenses.

Can the same equation be used for both types of lenses? As part of your answer, discuss the critical importance of our conventions for the algebraic signs of s , s' , and f .

Discuss your results with your teacher.

The following two exercises can be done as homework assignments, to be completed before our next class meeting. Compare your results with those of your partners.

10.15 Exercise

An object is placed near a concave lens along the principal axis.

A. For each of the following distances from the object to the lens, draw a ray diagram to determine the location of the image:

(1) greater than $2f$

(2) at $2f$

(3) between $2f$ and f

(4) at f

(5) between f and $f/2$

(6) at $f/2$

(7) less than $f/2$

Lesson 11. Applications of Geometrical Optics

The phenomena of reflection and refraction are the basis of a number of optical instruments. In this section, we investigate several common optical instruments.

11.1 Experiment

Imagine that you wanted to be able to see over the top of the crowd lined up in front of you at a parade. How could you use two mirrors and a cardboard tube to create a periscope, a device that you could use to see over the crowd?

Design (and construct, if you have suitable materials at home) such a device.

11.2 Experiment

A magnifying glass is a convex lens used to make an object appear larger than it is.

A. Use a convex lens as a magnifying glass.

Is the image erect or inverted? Is it real or virtual?

Does the lens make the object appear closer to you or farther from you? Use parallax to determine where the image is located.

B. Sketch a ray diagram to illustrate a lens used as a magnifying glass. The diagram need not be drawn to scale but should show the correct object and image locations with respect to the lens and its focal points.

Does a magnifying glass simply make objects appear closer? If not, what does it do?

Discuss your answers with a staff member.

11.3 Exercise

In a camera, light from an object reaches a piece of film and exposes it.

A. Describe how to use a convex lens to make a simple camera. Does it matter whether the image is real or virtual?

- B. In order to focus on objects that are at various distances, the focal length of the lens in the eye can change, while the distance between the lens and the retina is relatively unchanged.

How does this situation differ from that for a camera?

If you were to focus on something farther away than the words on this page, would the focal length of your lens increase or decrease? Draw ray diagrams to support your answer.

Estimate the focal length of the lens in your eye when you are viewing a distant object. (Assume the retina is at the back of the eyeball, and assume a reasonable diameter for the eyeball.)

- C. Not everyone can focus on distant objects. In a farsighted eye, light from distant objects converges too far from the lens; in a nearsighted eye, too close.

Obtain a paper screen to represent a retina, a convex lens to represent a lens, and a lighted bulb to represent a distant object. Use these materials to illustrate a normal eye viewing a distant object.

Change your arrangement to illustrate: (1) a farsighted eye viewing a distant object and (2) a nearsighted eye viewing a distant object. Draw sketches of the arrangements you use, indicating how they differ from that used for "normal" eyesight.

- D. Do you think you would be able to correct farsightedness using glasses made from a convex lens? Test your answer by using the equipment from part C and a second convex lens.

Do you think you would be able to correct farsightedness using glasses made from a concave lens? Test your answer by using the equipment from part C and a concave lens.

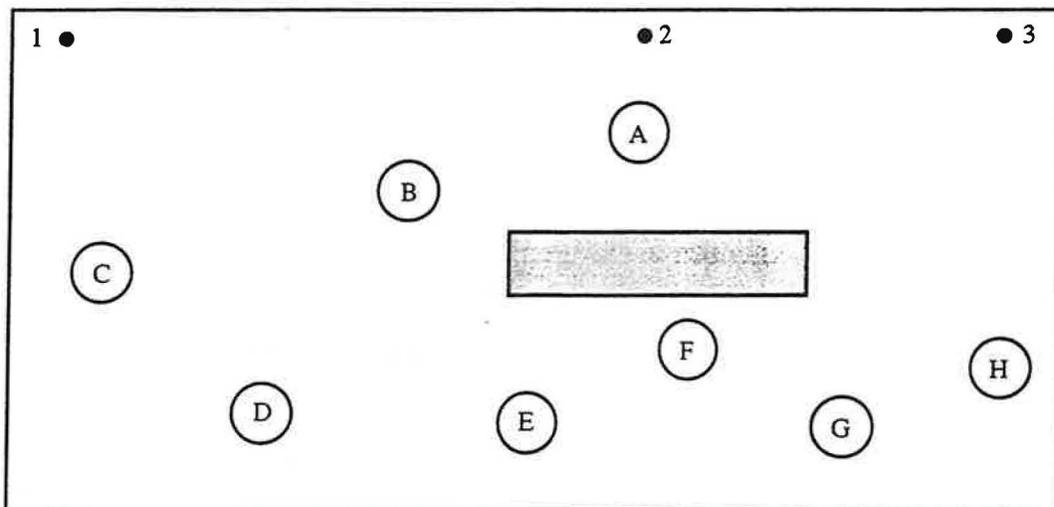
- E. Repeat part D, attempting to correct nearsightedness.

- F. Describe an experiment you could perform to determine whether a pair of eyeglasses corrects for farsightedness or nearsightedness. If you or your partner wears eyeglasses, test your experiment.

Additional Homework Problems for Light and Optics

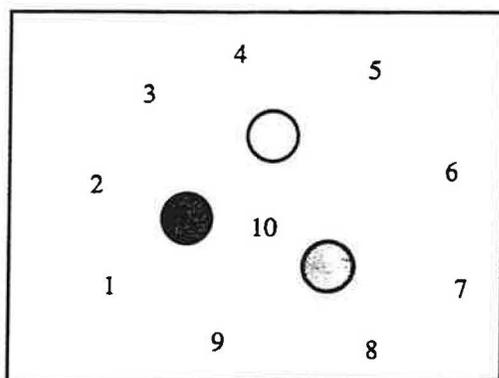
Problem 1.1

The diagram below is a top view diagram of a room containing eight pillars (A-H), three observers (1, 2, and 3) and a wall. Are all of the pillars visible to each observer? For each observer, draw a diagram that shows what the observer would see. Label the objects in your diagram. Explain your reasoning using the ideas developed in Lesson 1.

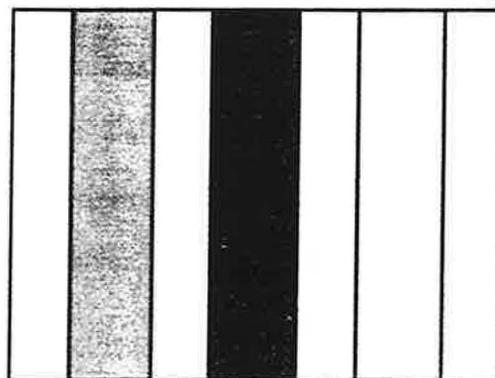


Problem 1.2

A student was standing in a room containing three pillars. The diagram below left is a top view diagram of the room. The student made a rough sketch of her view of the pillars from where she was standing. Her sketch is below right. On which numbered spot was she standing to see this view of the pillars? Explain how you can tell.



Top view diagram of room



Sketch

Problem 2.1

A. Draw both a top view diagram and a side view diagram of an upright soda can on a table.

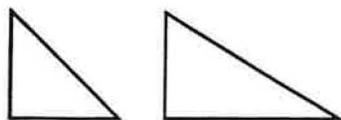
B. Draw a top view diagram of the apparatus used in part A of Experiment 2.4.

Problem 2.2

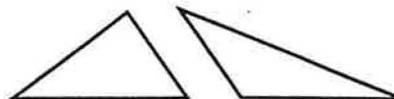
A. What is the relationship between corresponding angles in similar triangles?

What is the relationship between corresponding sides in similar triangles?

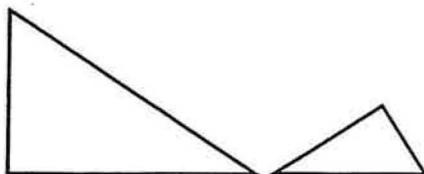
B. Which of the following pairs of triangles are similar triangles? Explain your reasoning. You may use a ruler or protractor to help you answer these questions.



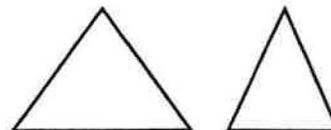
(1)



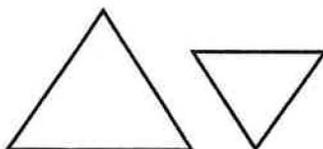
(2)



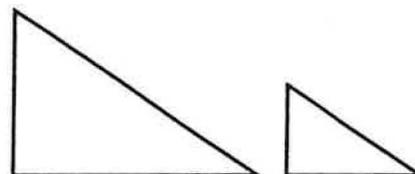
(3)



(4)



(5)



(6)

C. Was it necessary in part B to have both a ruler and a protractor? Would either one have been sufficient? Explain your reasoning.

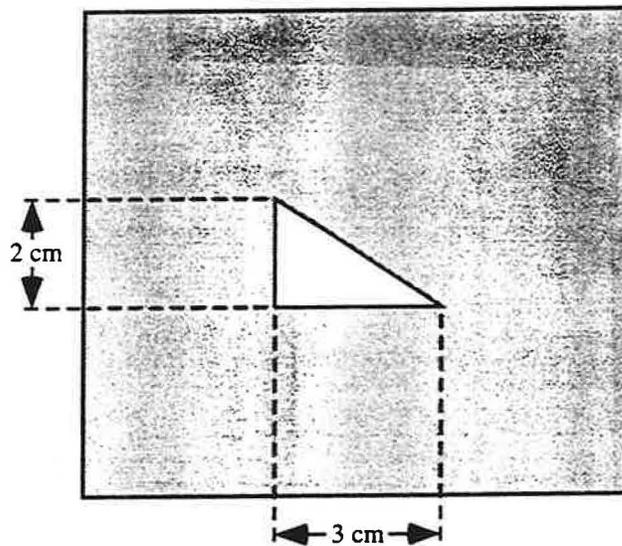
Problem 2.5

A mask with a circular hole is placed between a small lighted bulb and a screen. How would each of the following changes affect the size of the bright region on the screen? In each case, explain your reasoning, and draw sketches to support your answer.

- A. The screen is moved closer to the mask (without moving the bulb or mask).
- B. The mask is moved closer to the screen (without moving the screen or bulb).
- C. The bulb is moved farther from the mask and screen (without moving the mask or screen).

Problem 2.6

A small bulb is placed in front of the mask shown below. The bulb is level with the bottom of the hole in the mask. When viewed from the top, the bulb is aligned with the left side of the hole in the mask. A screen is placed 20 cm behind the mask. The bright region on the screen is 15 cm tall.



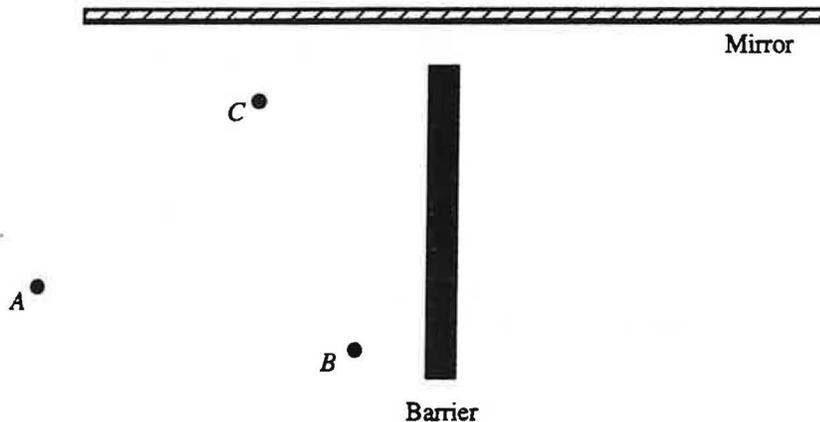
- A. Draw a picture of the bright region that you would see on the screen.
- B. Determine the width of the bright region at the widest part. Explain your reasoning in each step.
- C. How far is the bulb from the mask? Explain your reasoning.

Problem 4.1

A barrier is placed in front of, but not touching, a plane mirror. The barrier is perpendicular to the mirror. Suppose you have a flashlight that projects a narrow beam of light. A target is placed successively at positions A, B, and C on the left side of the barrier.

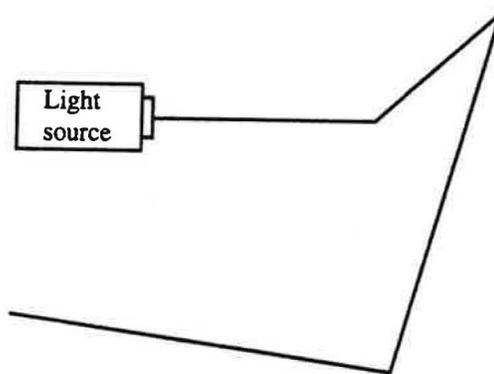
- A. For target locations A and B, indicate a location on the right side of the barrier where the flashlight could be placed in order to hit the target with light. Explain how you determined these locations.

- B. For target location C, determine the entire region on the right side of the barrier in which a flashlight could be placed in order to hit the target with light. Explain how you determined the region.



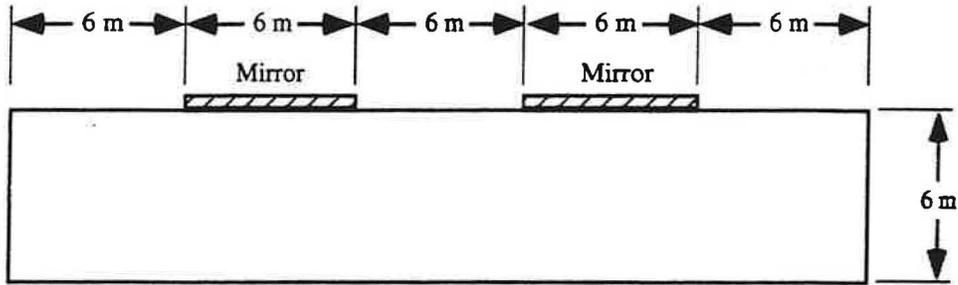
Problem 4.2

After class one day, you find a sheet of paper on the floor with the following drawing on it. Evidently, a student was doing an experiment that used mirrors and a light source, but the student apparently forgot to indicate the locations of the mirrors on the paper. On the diagram, indicate the locations and orientations of the mirrors and explain how you determined the arrangement of the mirrors used by the student.



Problem 4.4

The ballroom shown below has two large mirrors mounted on the ceiling.



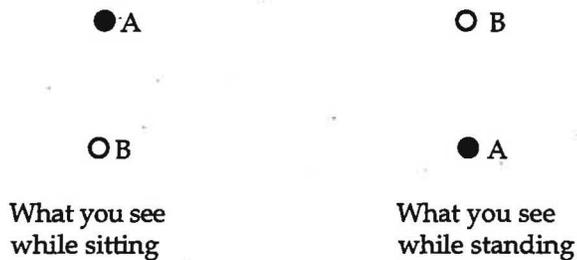
- A. In what region of the floor could a small mouse be located so that when it looks at the mirrors it could see another mouse on the floor at either end of the room? Explain your reasoning.

- B. Is there anywhere on the floor that a mouse could be located and see the entire ballroom floor in the mirrors? Again, explain your reasoning.

- C. Would your answer to part B differ if the ceiling were higher, but the length of the room didn't change? Explain.

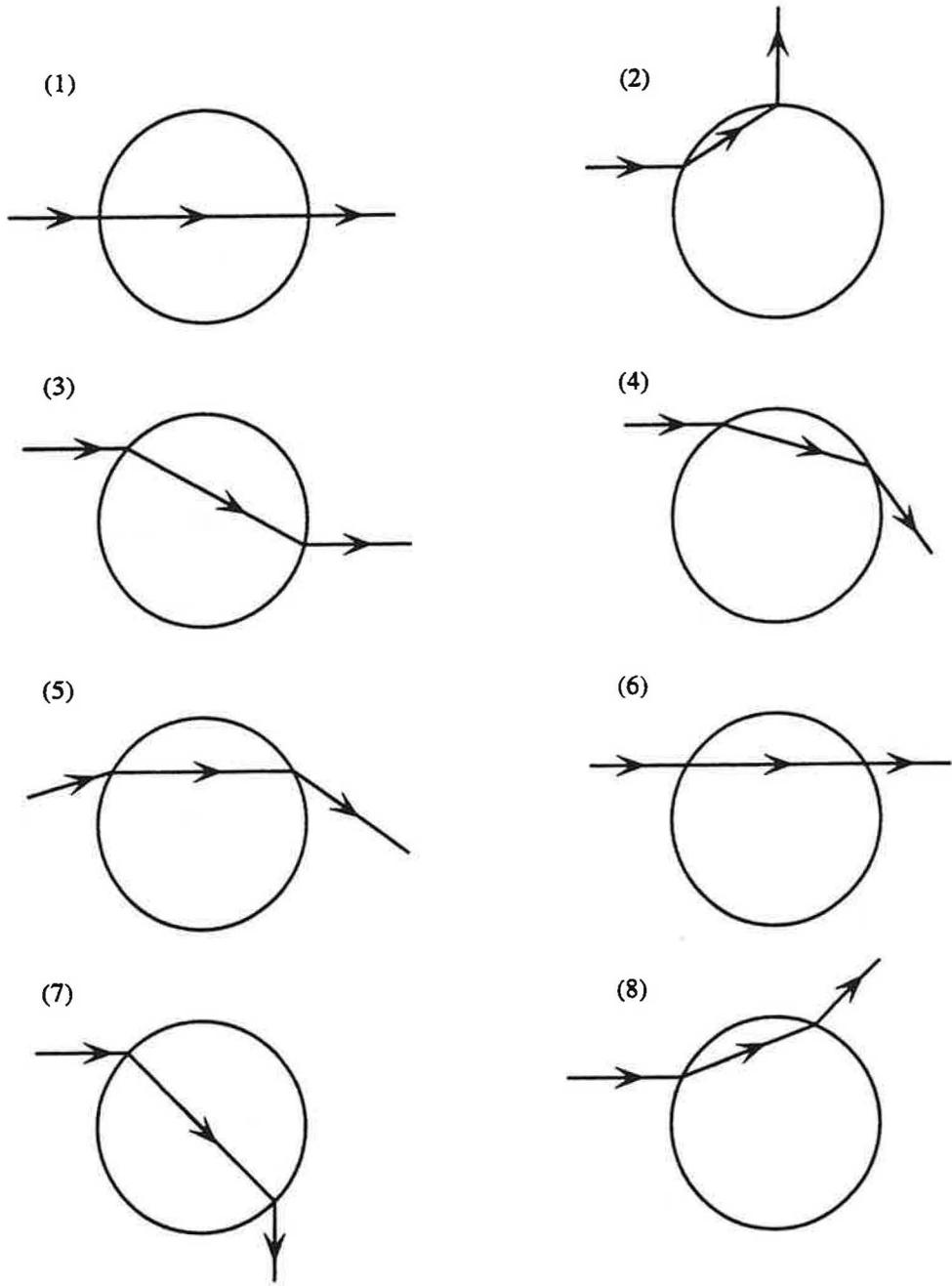
Problem 5.1

When you are sitting in a chair, it appears to you that object A is above object B. When you stand up, object A appears to be below object B. Which of the two objects is farther away from you? Draw a diagram showing the locations of the two objects and your eye, and explain these observations.



Problem 6.1

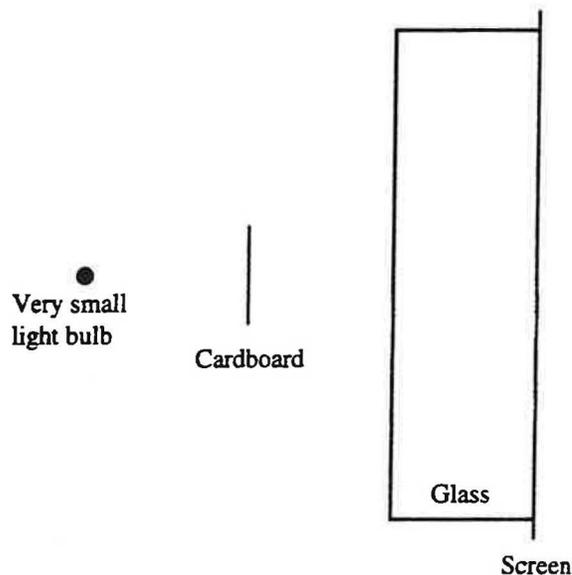
The following are top view diagrams of a beaker of water. Some of the diagrams represent qualitatively correct paths for light through a beaker of water and some do not. Which diagrams have "flaws"? Briefly explain the flaw in each case.



Problem 6.3

A piece of cardboard is placed between a very small light bulb and a screen. A block of glass is placed in front of the screen as shown in the side view diagram at right.

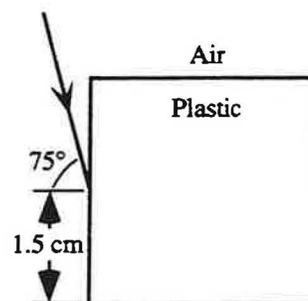
If the glass were removed, would the size of the shadow on the screen increase, decrease, or stay the same? Explain your reasoning, and support your answer with a clear, qualitatively correct ray diagram.



Problem 7.1

A beam of light enters a plastic cube of side 3 cm from the center of the left side as shown in the diagram at right. The angle of incidence is 75° . The index of refraction of the plastic with respect to air is 1.5.

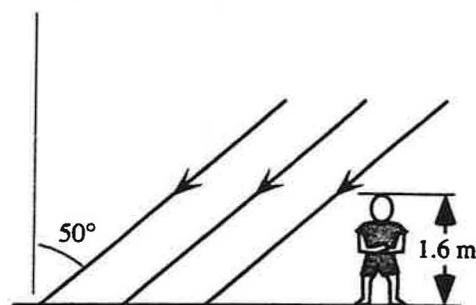
- From which side of the cube will the ray emerge?
Draw a diagram to support your answer.
- At what angle will the ray emerge?



Problem 7.2

One day, a student determines that light from the sun strikes the ground at an angle of 50° from the vertical. The student is 1.6 m tall.

- What is the length of the student's shadow?
Explain.
- The student then goes completely underwater on the bottom of the deep end of a large swimming pool. The surface of the pool is still and the bottom of the pool is level. What is the length of the student's shadow? Show your work.

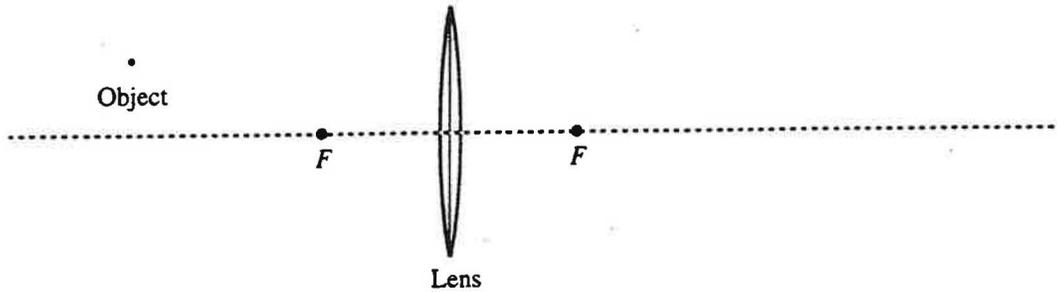


Problem 8.1

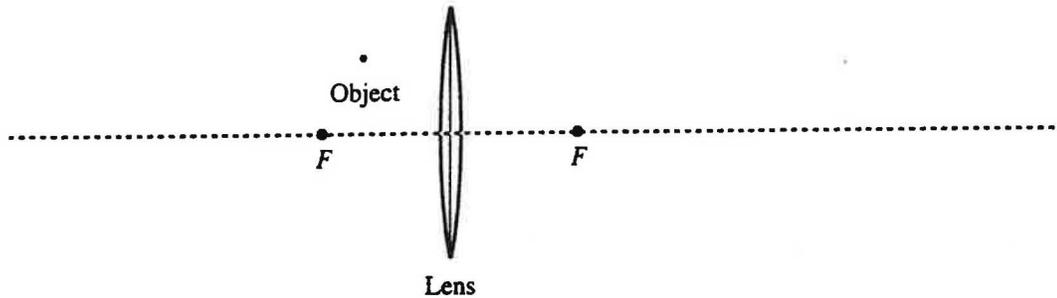
You have two convex lenses: one with focal length f and one with focal length $10f$. Which lens would you say is "stronger"? Explain your reasoning.

Problem 9.2

- A. A small object is placed in front of a convex lens as shown below. Draw an accurate ray diagram using all principal rays to determine the location of the image. Explain how you determined the image location. Label each of the rays, and in words, explain how you decided to draw each ray in the way that you did.



- B. Repeat part A for the object closer to the lens as shown below.



Problem 9.3

An object is placed in front of a convex lens. The focal length of the lens is 20 cm.

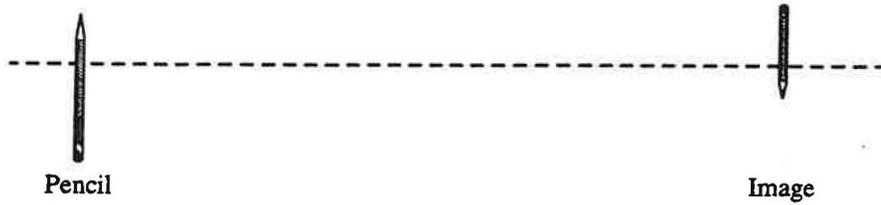
- A. Suppose the object is 60 cm from the lens. On a sheet of graph paper, draw a ray diagram to find the location of the image.

Use the thin lens equation to calculate the location of the image. Is your answer consistent with your ray diagram? If not, resolve any discrepancies

Is the image real or virtual? Explain.

Problem 9.6

A convex lens is used to create a real image of a pencil. The locations of the pencil and its image are shown below. The lens, however, is not shown.

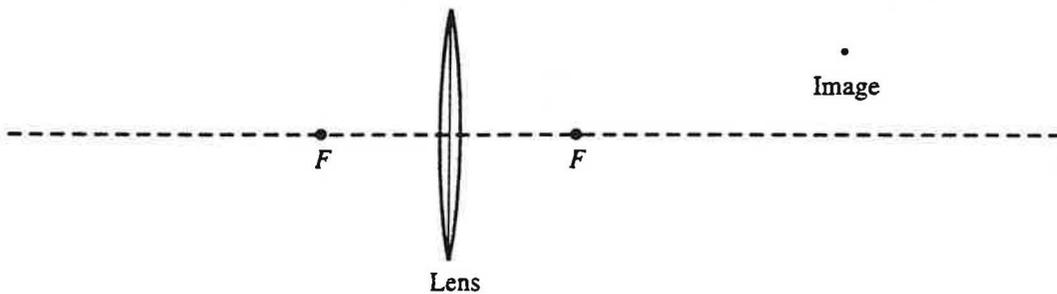


A. Where is the lens located? Explain how you determined your answer.

B. Where are the focal points of the lens located? Explain how you determined your answer.

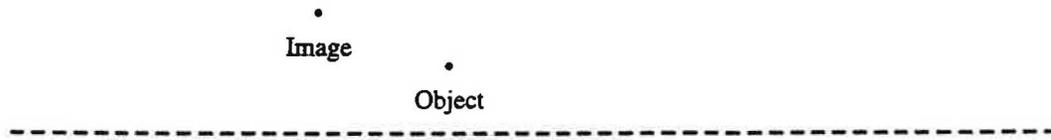
Problem 9.7

A convex lens is used to create a real image of a small object. The diagram below shows the locations of the lens, its focal points, and the image. Determine the location of the object. Explain how you determined your answer. Treat the object as a point source of light.



Problem 10.3

- A. The diagram below shows a small object and its image, which is virtual. The principal axis of the lens is shown, however the lens is not. Treat the object as a point source of light.



Is this situation possible?

If so: Is the lens concave, convex, or is either type possible? Determine the locations of the lens and its focal points. Explain how you determined your answers.

If not: Explain why not.

- B. Suppose the object and image locations from part A were reversed.



Is this situation possible?

If so: Is the lens concave, convex, or is either type possible? Determine the locations of the lens and its focal points. Explain how you determined your answers.

If not: Explain why not.

