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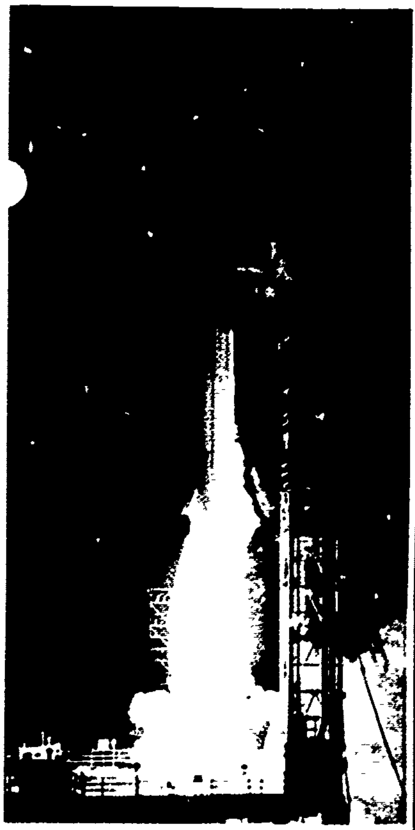
ABSTRACT

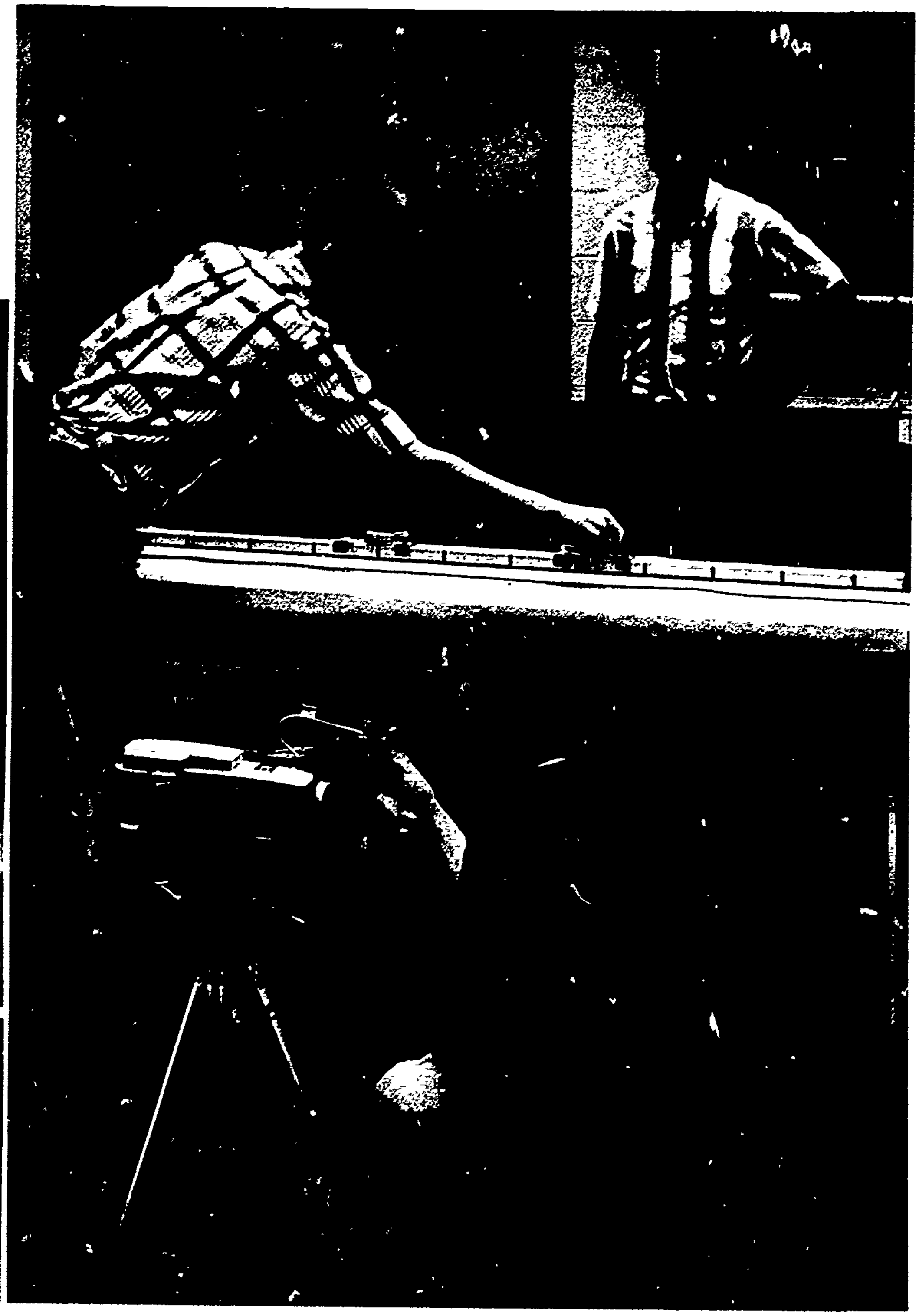
Ten experiments and 27 activities are presented in this handbook. The experiments are related to collisions, energy conservation, speed measurements, thermometry, calorimetry, gas properties, wave motions, and acoustic problems. The activities are concerned with stroboscopic photographs in collision, elastic impact, mass conservation, exchange of momentum, Heron's engine, gravitational acceleration, energy in a pendulum, Crooke's radiometer, mechanical equivalent of heat, gas theories, speed distribution, rockets, perpetual motion machines, "Least-Time" or "Least-Energy" situations, standing waves, Moire patterns, music and speech, and speed of sound. Demonstrations, construction projects, and self-directed instructions are stressed in these activities. The four chapters in the handbook are designed to correspond to the text, with complete instructions in each experiment. Some experiments and activities are suggested for assignment, and the remaining are used at student discretion. Besides illustrations and film loop notes for explanation use, a reprinted article concerning collateral reading is included. The work of Harvard Project Physics has been financially supported by: the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education, and Harvard University. (CC)

Project Physics **Handbook**

An Introduction to Physics

The Triumph of Mechanics





This handbook is the authorized interim version of one of the many instructional materials being developed by Harvard Project Physics, including text units, laboratory experiments, and teacher guides. Its development has profited from the help of many of the colleagues listed at the front of the text units.

The work of Harvard Project Physics has been financially supported by the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education and Harvard University.

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Project Physics **Handbook**

An Introduction to Physics **3 The Triumph of Mechanics**

Authorized Interim Version 1968-69

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Chapter 9 Conservation of Mass and Momentum

Experiments

Activities

Chapter 10 Energy

Experiments

Activities

Chapter 11 The Kinetic Theory of Gases

Experiments

Activities

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Activities

Film Loop Notes

Appendix

This Student Handbook is different from laboratory manuals you may have worked with before. There are far more things described in this handbook than any one student can possibly do. Only a few of the experiments and activities will be assigned. You are encouraged to pick and choose from the rest any of the activities that appear interesting and valuable for you. A number of activities may occur to you that are not described in the handbook and that you would prefer to do instead. You should feel free to pursue these in consultation with your teacher.

There is a section corresponding to each chapter of the text. Each section is composed of two major subsections—Experiments and Activities.

The Experiments section contains complete instructions for the experiments your class will be doing in the school laboratory. The Activities section contains suggestions for demonstrations, construction projects and other activities you can do by yourself. (The division between Experiments and Activities is not hard and fast; what is done in the school laboratory and what is done by the student on his own may vary from school to school.)

The Film Loop Notes give instructions for the use of the film loops which have been prepared for this course.

Chapter 9 Conservation of Mass and Momentum

EXPERIMENT 22 Collisions in One Dimension

Some of the most powerful physical laws deal with quantities that are conserved. For example, you already know that mass is such a quantity, at least within the accuracy of your measuring instruments. In this experiment you will investigate the interaction of two objects which exert forces on one another as they collide. As you do the experiment, you will look for quantities which remain the same after the collision as they were before—that is, quantities that are conserved.

Your experimental collisions may seem artificial and unlike the ones you see around you. This is because, as in many scientific experiments, it has been possible to simplify the situation so as to make it easier to make meaningful measurements and to discover patterns in the observed behavior.

Three different procedures for observing collisions are described here, all leading to similar results. You will probably follow only one of them. Whichever procedure you do follow you should handle your results as described in the final section: Analysis of data.

Procedure I—the air track

The air track allows you to observe collisions between objects that move with almost no friction. The reason for reducing friction is so that the velocities of the objects, called gliders, will remain practically uniform as they travel, making it much easier for you to measure them.

The air track has three gliders: two small ones with the same mass, and a larger one which has just twice the mass of a small one. A small and a large glider can be coupled together to make

one glider so that you can have collisions between gliders whose masses are in the ratio of 1:1, 2:1 and 3:1. You can also arrange to have the gliders bounce apart after they collide (elastic collision) or stick together (inelastic collision).

You will take stroboscopic photographs of the gliders either with the xenon strobe or by using the rotating disc in front of the camera.

If you add light sources to the gliders their masses will no longer be in the same simple ratios. You can find the masses from the measured weights of the glider and light source.

Technique is important if you are to get good results. Before taking any pictures try out a variety of mass ratios with both elastic and inelastic collisions. Then, when you have chosen one to analyze, rehearse with your partners each step of your procedure before you go ahead.

From a good photograph you can find the speeds of both carts before and after they collide. Since you are interested only in relative speeds before and after each collision, use distance units measured directly from the photograph (in millimeters) and use time units equal to the time between strobe images. The speeds recorded in your notes are therefore in mm/interval.

Remember that you can get data from the negative of your Polaroid picture as well as from your positive print.

Alternative procedure II — dynamics carts

With the dynamics carts you can measure the velocities of masses that fly apart after an "explosion." To create the explosion put a compressed spring between two carts on the floor or on a smooth table (Fig. 1). When

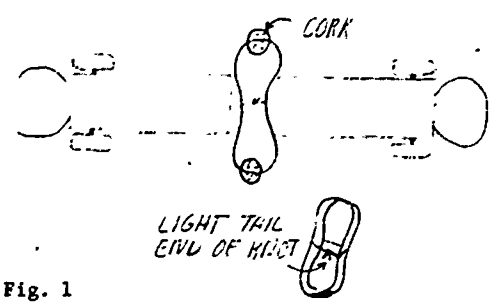


Fig. 1

you release the spring by burning the thread the carts fly apart with velocities that you can measure from a strobe photograph or from dots marked on ticker tape.

Load the carts with a variety of weights so as to create simple ratios of masses. Take data for as great a variety of explosions as time permits.

Since you are interested only in relative speeds, use relative distance units measured directly from the film close to the point of the explosion. Remember, too, that you can get data from the negative of a Polaroid picture as well as from the positive print.

Alternative procedure III — film loops

Several film loops show collisions that you cannot actually perform in the laboratory. Since they are shown in slow motion you can make measurements directly from the pictures projected onto graph paper and analyze your data in the same way as do others in the laboratory who may be using the other procedures.

Each film loop has a set of notes printed elsewhere in this handbook; read them before taking your data.

Analysis of data

Assemble all your data in a table such as Fig. 2. It should have column headings for the mass of each object, m_A and m_B, the velocities before the collision, v_A and v_B (for explosions, $v_A = v_B = 0$) and the velocities after the collision, v_A' and v_B'.

m_A	m_B	v_A	v_B	v_A'	v_B'

Fig. 2

Examine your table to answer the following questions about each collision:

Q1 Is <u>speed</u> a conserved quantity? That is, does the quantity ($v_A + v_B$) equal the quantity ($v_A' + v_B'$)?

Q2 Consider the direction as well as the speed, defining velocity to the right as positive and velocity to the left negative. Is <u>velocity</u> a conserved quantity?

Q3 If neither speed nor velocity is conserved, how about a quantity which combines the mass and velocity of each cart? Compare $m_A\vec{v}_A + m_B\vec{v}_B$ with $m_A\vec{v}_A' + m_B\vec{v}_B'$ for each collision. In the same way compare m/v, m^2v, etc. before and after the collision.

You should be able to find one quantity that is conserved in all your experiments and in all your classmates' experiments as well. In fact it is conserved in all collisions in nature as far as we can tell, whether between molecules, football players, or galaxies, whether elastic or inelastic.

Use your knowledge of this conservation law to answer the following questions.

Q4 A boy with a mass of 50 kg is in a canoe with a mass of 25 kg. What will happen to the canoe if the boy, moving parallel to the canoe's length, steps toward the shore with a speed of 1 m/sec?

Q5 If the same boy stepped at the same speed to the dock from an ocean liner that has a mass of 8×10^7 kg and is free to move, by how much would the ship's velocity be changed?

Q6 The mass of a bowling ball is about 7 kg and that of a pin about 2 kg. If a ball with an initial speed of 2 m/sec hits a pin head-on and slows down to 1 m/sec, what will happen to the pin?

In all the interactions so far friction has been neglected because its effect was so small.

Q7 Does your conservation law hold when frictional forces are acting on the colliding objects?

Q8 Defend your answer to Question 7 by discussing the example of a wooden block sliding to a stop as it coasts across the floor.

EXPERIMENT 23 Collisions in Two Dimensions

Collisions in the real world around us rarely occur in one dimension, i.e., along a straight line. In billiards, basketball and tennis the ball usually rebounds at an angle to its original direction; and ordinary explosions (e.g., collisions in which initial velocities are all zero) send pieces flying off in all directions.

This experiment shows you collisions that occur in two dimensions—that is, on a flat surface—instead of along a single straight line. It assumes that you know what momentum is and understand what is meant by "conservation of momentum" in one dimension. (See text Sec. 9.3.) In this experiment you will discover a new rule (a modified form of the rule for one dimension) that applies to the conservation of momentum in cases where the parts of the system move in two (or three) dimensions.

Again the experiment involves several parts of which you will probably do only one.

Procedure I — colliding pucks

On a carefully leveled glass tray covered with a sprinkling of Dylite spheres, you can make pucks coast with almost uniform speed in any direction. Put one puck motionless in the center of the table and shoot a second similar one towards it a little off-center. You can get excellent pictures of the resulting two-dimensional glancing collision with a camera mounted directly above the surface.

To be able to measure the speeds the photograph should be taken with light from the xenon stroboscope on one side of the glass tray. Each puck's location is made clearly visible in the photograph by a small white styrofoam hemisphere or steel ball stuck to its center.

Two people are needed to do the experiment. One experimenter, after some preliminary practice shots, launches the projectile puck while the other experimenter operates the camera. The resulting picture should consist of a series of white dots lying along a letter Y.

You can double and triple the masses, of course, by using the heavier pucks and by stacking discs one on top of the other and fastening them together with tape.

From your picture, measure and record all the speeds before and after collision. Record the masses in each case too. You can simplify your work if you record speeds in mm/dot instead of trying to work them out in cm/sec. You can also use the "puck" instead of the kilogram as your unit of mass.

Q1 Why are these more convenient units going to lead to the same findings as the "real" ones?

Now go on to the section below headed "Analysis of data."

Procedure II — colliding disc magnets

Disc magnets will also slide freely on the glass tray set-up described in Procedure I.

The difference here is that the magnets, if they repel each other, need never touch during the collision. Instead the projectile magnet follows a

curving path until it is sufficiently beyond the range of force exerted on it by the target. Is momentum conserved in this sort of interaction?

Following the procedure described above for air pucks, photograph one of these "collisions." Again small styrofoam hemispheres or steel balls attached to the magnets should show up in the strobe picture as series of white dots. Be sure the tracks you photograph are long enough so that the ends form straight lines rather than curves.

From your photo, measure and record the speeds and record the masses. You can simplify your work if you record speeds in mm/dot instead of working them out in cm/sec. You can use the "disc" instead of the kilogram as your unit of mass.

Q2 Why are these more convenient units going to lead to the same findings as the "real" ones?

Then go on to the section below headed "Analysis of data."

Procedure III—film loops

There are several film loops that show two-dimensional collisions which you cannot conveniently reproduce in the laboratory. After reading the film notes at the end of Chapter 9 in this handbook, project one of the loops onto the blackboard or onto a sheet of graph paper. Trace the paths of the moving objects. Record their masses and measure all the speeds. Then go on to the analysis described in the next section below.

Analysis of data

Whichever procedure you used you should analyze your results in the following way.

Get the mass of each member of the "system" involved in the collision. Then determine the speed of each member and multiply the mass of each member by its speed.

Do the same thing for each of the masses in the system after the collision, and add these "after-the-collision" products together.

Q3 Does their sum equal that of the "before-the-collision" products of mass and speed?

If the "collision" you observed was an explosion of a cluster of objects at rest, the total quantity mass-times-speed before the explosion will be zero. But surely the mass-times-speed of each of the flying fragments after the explosion is more than zero! Thus, if we think of momentum as "mass-times-speed," then momentum is not conserved in an explosion. You probably found it wasn't conserved in the experiments with pucks and magnets, either. You may already have suspected that we ought to be taking some account of the directions of motion.

To see what is conserved, proceed as follows.

From your measurements construct a drawing like Fig. 1 in which you show the directions of motion of all the objects both before and after the collision. There is no motion at all before the explosion, and hence no diagram to draw.

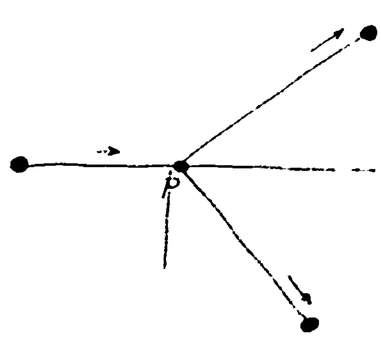


Fig. 1

Have all the direction lines meet at a single point in your diagram. The actual paths in your photographs may not do so, because the pucks and magnets are large objects instead of points, but you can still draw the directions of motion as lines through the single point, P.

On this diagram draw a vector whose magnitude (length) is proportional to the mass times the speed of the projectile before the collision. In Fig. 2(a) this vector is marked $m_A\vec{v}_A$.

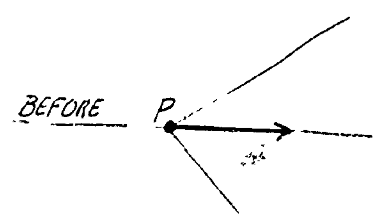


Fig. 2(a)

Below your first diagram draw a second one in which you once more draw the directions of motion of all the objects exactly as before. On this second diagram construct the vectors for mass-times-speed for each of the objects leaving P after the collision. For the collisions of pucks and magnets your diagram will resemble Fig. 2(b).

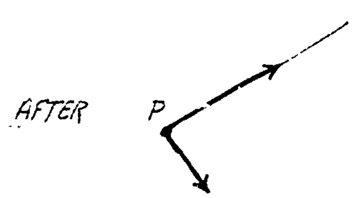


Fig. 2(b)

Q3 Does the sum of the vectors before the collision equal the sum of the vectors after the collision?

To find out, construct the vector sum and draw it on your "after-the-collision" figure.

Q4 How does it compare with the vector on your "before-the-collision" figure?

If the vectors are equal it means that the quantity represented by your vectors is conserved in the collision. The length of each of your vectors is given by the product of mass and speed. Since the arrows are drawn in the direction of the velocity, the vectors represent the products of mass and velocity, $m\vec{v}$.

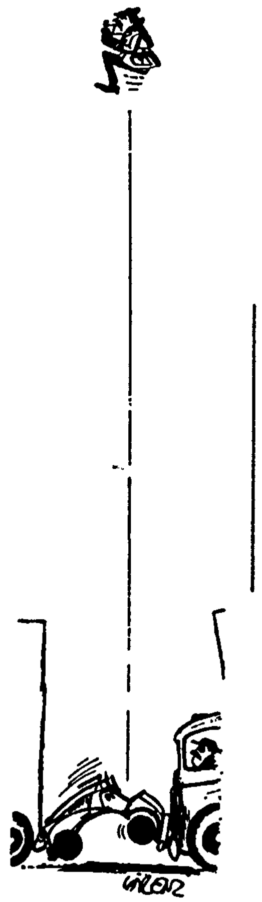
When momentum is defined in this way you should find that it is conserved within the limits of uncertainty of your measurements. (Defined as simply "mass-times-speed" without regard to direction, it is not conserved, as you have probably found already.)

Use this refinement of the conservation principle (i.e., the principle of conservation of momentum in two dimensions) to answer the following questions.

Q5 Is the principle of conservation of momentum for one dimension different from that for two, or merely a special case of it? How can the principle of conservation of momentum be extended to three dimensions? State it. Give examples.

Q6 A bowling ball whose mass is 7 kg is traveling at 2 m/sec when it strikes a pin whose mass is 2 kg. The pin flies off to an angle of 45° to the original line of motion of the ball. The ball is deflected by 30° on the opposite side of the original direction. By a construction similar to the one in your laboratory exercise, find the speeds of the ball and the pin.

A fourth-of-July skyrocket at the top of its trajectory explodes into eight fireballs. Seven yellow ones have a mass of 100 g each, and the eighth one, a red one, has a mass of 50 g. All eight are projected horizontally and symmetrically—one northward, one northeastward, one eastward, etc. If all the yellow fireballs have the same speed just after their separation, what is the velocity of the red one?



*Stroboscopic Photographs of One-Dimensional Collisions

Introduction

The following pages contain stroboscopic photographs showing three different examples of one dimensional-colisions. They are useful both in Chapter 9 for studying momentum and again in Chapter 10 for studying kinetic energy.

You should read sections I and II before analyzing any of the events, to find out what measurements to make and how to make them. Section III gives a description of how the collisions were produced.

Following sections I, II, and III are special discussions and questions for each event.

I. Material Needed in Addition to these Notes.

A metric ruler marked in millimeters, preferably of the clear plastic see-through variety, and of good quality.

II. The Measurements You Will Make.

In these Notes you will find a photographic record of a collision between two balls. Some discussion of this collision is given below under Section IV. You will find that you must make measurements (directly on the photograph) of displacements experienced by moving balls in given time intervals. To make such a measurement, place some mark on the ruler as exactly as possible against the left, or right, edge of the ball in one of the two positions and now read the ruler at the same edge of the ball in the other position. You will find it possible, by careful viewing, to estimate the nearest tenth of the millimeter between the neighboring millimeter marks on the ruler.

Here are some questions you should consider before you decide on the measuring procedure. Which of the following three possibilities (a), (b), or (c) is the best?

(a) Place the zero end of the ruler against the edge of the ball's picture in one position and read the ruler for the same edge of the ball in the next position.

(b) Place one of the thick centimeter rulings somewhere in the middle of the ruler against the edge of the ball's picture in one position and then read the ruler for the same edge in the next position.

(c) Place any of the thin millimeter rulings somewhere in the middle of the ruler against the edge of the ball's picture in one position and proceed as in (a) and (b).

Now consider the following additional questions.

(d) Is one such measurement for any given displacement sufficient? Should you take several? If you had a partner, should you and your partner each take, say, at least two such readings? How do you find the final best value of your measurements?

III. How the Collision was Produced.

Figure 1 shows schematically that the colliding balls were hung from very long wires. The balls were released

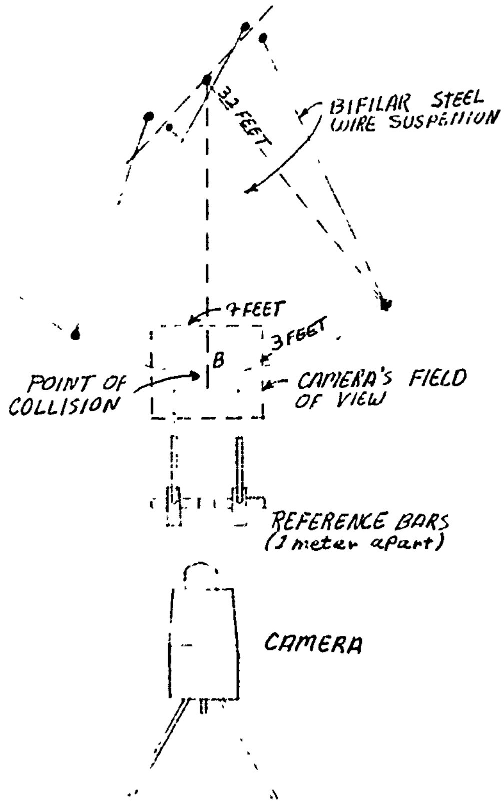


Figure 1

from rest and collided in the center. Stroboscopes illuminated the 3 by 4 ft. rectangle which was the field of view of our camera. The stroboscopes are not shown in Figure 1.

Notice the two rods whose tops reach into the field of view. These rods were 1 meter ± 2 millimeters apart, measured from top center of one rod to top center of the other. The tops of these rods are visible in the photographs on which you will make your measurements, so your measurements could be converted to actual distances.

The balls speed up as they move into the field of view. Likewise, as they leave the field of view, they should slow down. Therefore, successive displacements on the stroboscopic photograph, each of which took exactly the same time, will not necessarily be equal in length. Check this with your ruler.

Before you decide on the displacement to measure a ball's speed before or after collision, you may have to make a choice. Figure it out yourself!

Event 1 (Also shown in Film Loop 18, first example.)

a) Discussion of Event 1.

Figure 2 shows that ball A came in from the right and that ball B was at rest initially. Both moved off to the left. The balls are made of case-hardened steel.

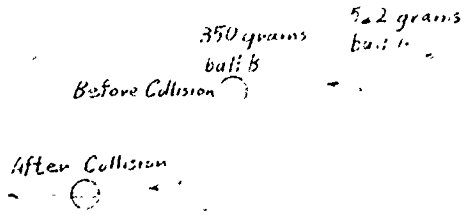


Figure 2

You can now proceed to the photograph and actually number the positions of each ball at successive flashes of the stroboscope. During which time interval did the collision occur? Which time interval is the best choice for finding the velocity of ball A before collision? Which is best for finding the velocities of both balls after collision?

b) Questions about Event 1.

What are your values for the total momentum of the system of two balls before collision and after? What are your values for the total kinetic energy before collision, and after?

Was momentum conserved? Was kinetic energy conserved? If not, why not? If one or the other of these quantities was not conserved, explain why not.

Event 2 (Also shown in Film Loop 18, second example.)

a) Discussion of Event 2.

Figure 3 shows that ball B came in from the left and that ball A was at rest initially. The collision reversed the direction of motion of ball B and sent ball A off to the right. The balls are made of case-hardened steel.

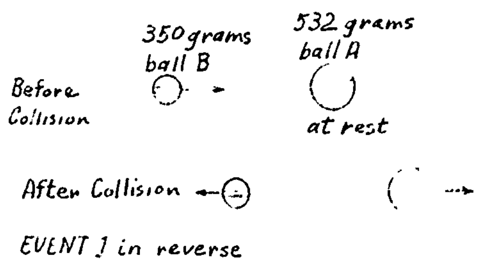


Figure 3

We photographed this event in parts, as you will notice, from the prints provided with these Notes. The first print shows conditions before collision, the second print after collision. Had we taken the picture with the camera shutter open throughout the motion, it would have been difficult to tell apart the successive positions of ball B because B retraces its path. You can actually number the position of each ball at successive stroboscope flashes in either photograph.

Which time interval is the best choice for finding the velocity of ball B before collision? Which is best for finding the velocities of both balls after collision?

b) Questions about Event 2.

Why is the direction of motion of ball B reversed by the collision?

Calculate the momentum of each ball before collision and then after collision. What is the total momentum of the system of two balls before collision? Next, find the total momentum of the system of two balls after collision.

When making this latter calculation, keep in mind that momentum is a vector quantity. It is the product of a mass (a scalar quantity) and velocity (a vector quantity). Oppositely directed momenta counteract each other.

Is momentum conserved in this collision?

Next, calculate the total kinetic energy of the system of two balls before and after collision. Here it is important to keep in mind that kinetic energy is not a vector, but a scalar quantity. And that it is never negative. (Why not?)

Was kinetic energy conserved?

If one or the other of these quantities was not conserved, where did it go?

Ball B is very slow after collision, and you probably had trouble getting a precise value for its speed then. This means that your value for this speed is the least reliable. Nevertheless, this fact has only small influence on the reliability of your value for the total momentum after collision. Can you explain why this should be so?

c) Further Questions (if you have also studied Event 1).

Notice that the same balls were used in Events 1 and 2. Check your velocity data, and you will find that the initial speeds were roughly equal. Thus, Event 2 is the reverse of Event 1.

Why, then, was the direction of motion of ball A in Event 1 not reversed while that of ball B was reversed in Event 2?

Use your data to calculate the percentage of kinetic energy conserved for each event. The two percentages will not differ by much. The percentage is somewhat higher for Event 2 than for Event 1. Can you think of an explanation? If not, discuss this question with other students or your teacher. You may learn a bit about the forces during collision and about the imperfect elasticity of the balls. (Hint: the harder we hit a ball, the more we deform it.)

Event 4 (Also shown in Film Loop 19, second example.)

a) Discussion of Event 4.

Figure 4 shows that two balls come in from the left, that ball A is far more massive than ball B and that ball A is moving faster than ball B before collision. The collision occurs when A catches up with B, increasing B's speed at some expense to its own speed. The balls are made of case-hardened steel.

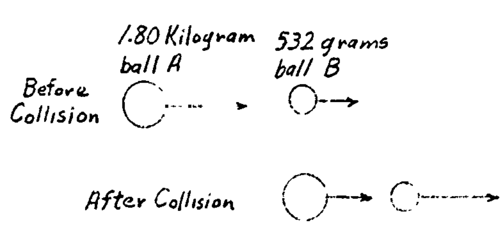


Figure 4

Each ball moves across the camera's field from left to right on the same line. In order to be able to tell successive positions apart on a stroboscopic photograph, we took the picture twice. A print of each picture is provided with these Notes. The first photograph shows only the progress of the large ball A because ball B has been given a thin coat of black paint (of negligible mass). Ball A was painted black when the second picture was taken. You can actually number white-ball positions at successive stroboscope flashes in each picture.

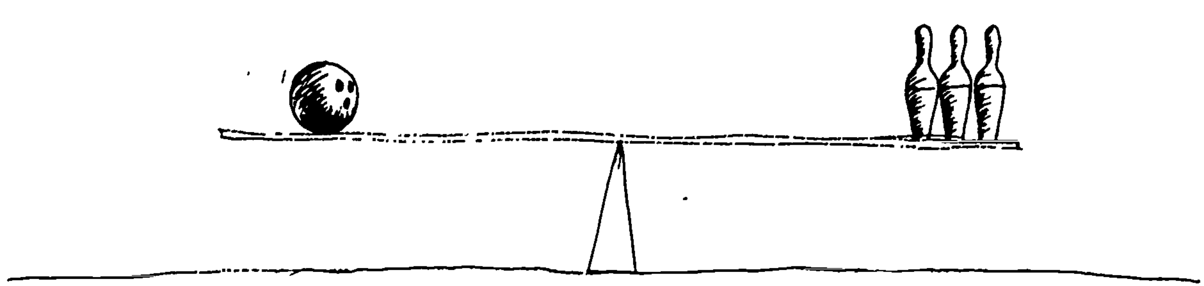
During which time interval did the collision occur in each picture? Which time intervals are adequate choices for the measurement of ball A's speed before collision and after? In the other picture, which intervals are good choices for the speeds of ball B before and after collision?

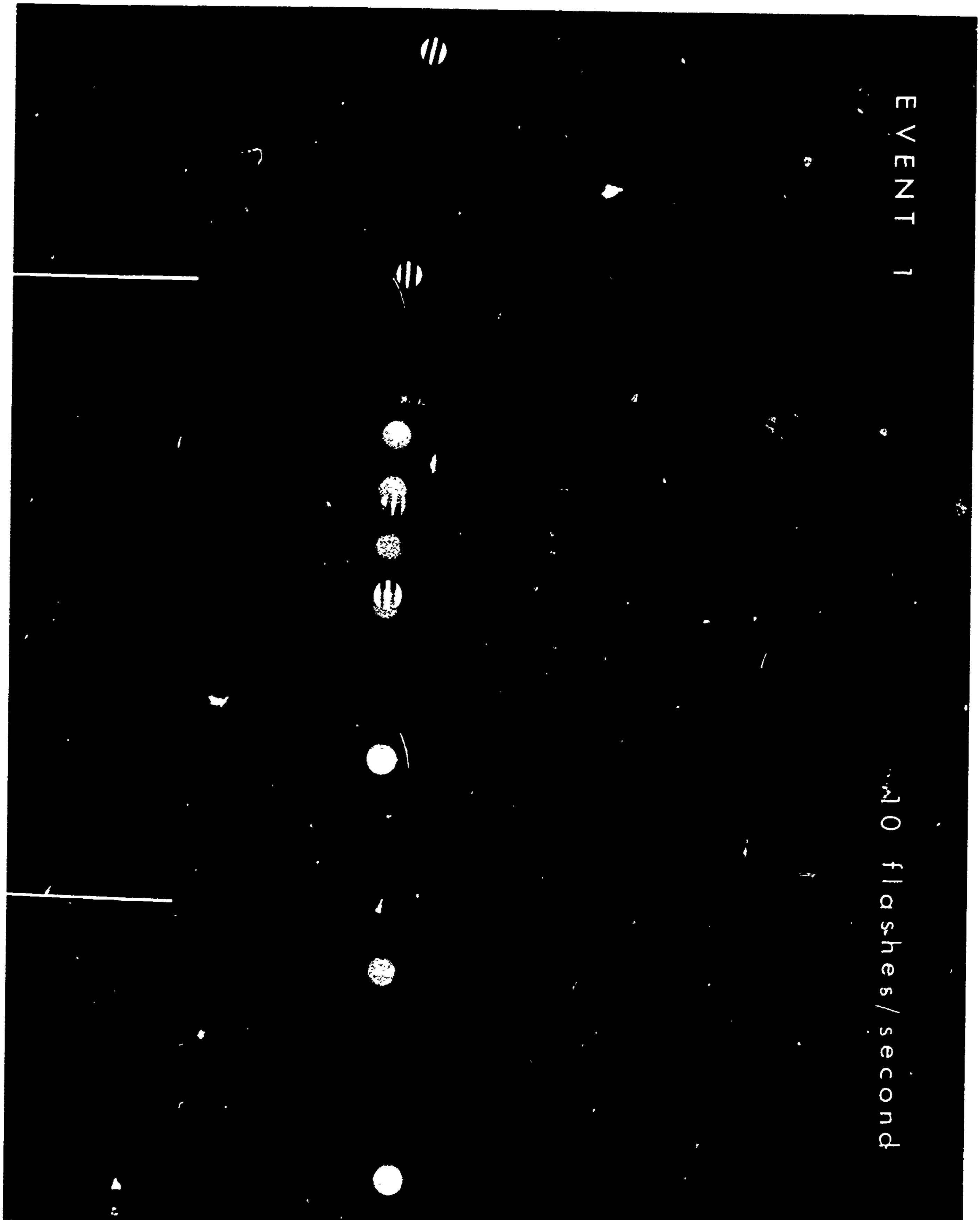
V. Questions about Event 4.

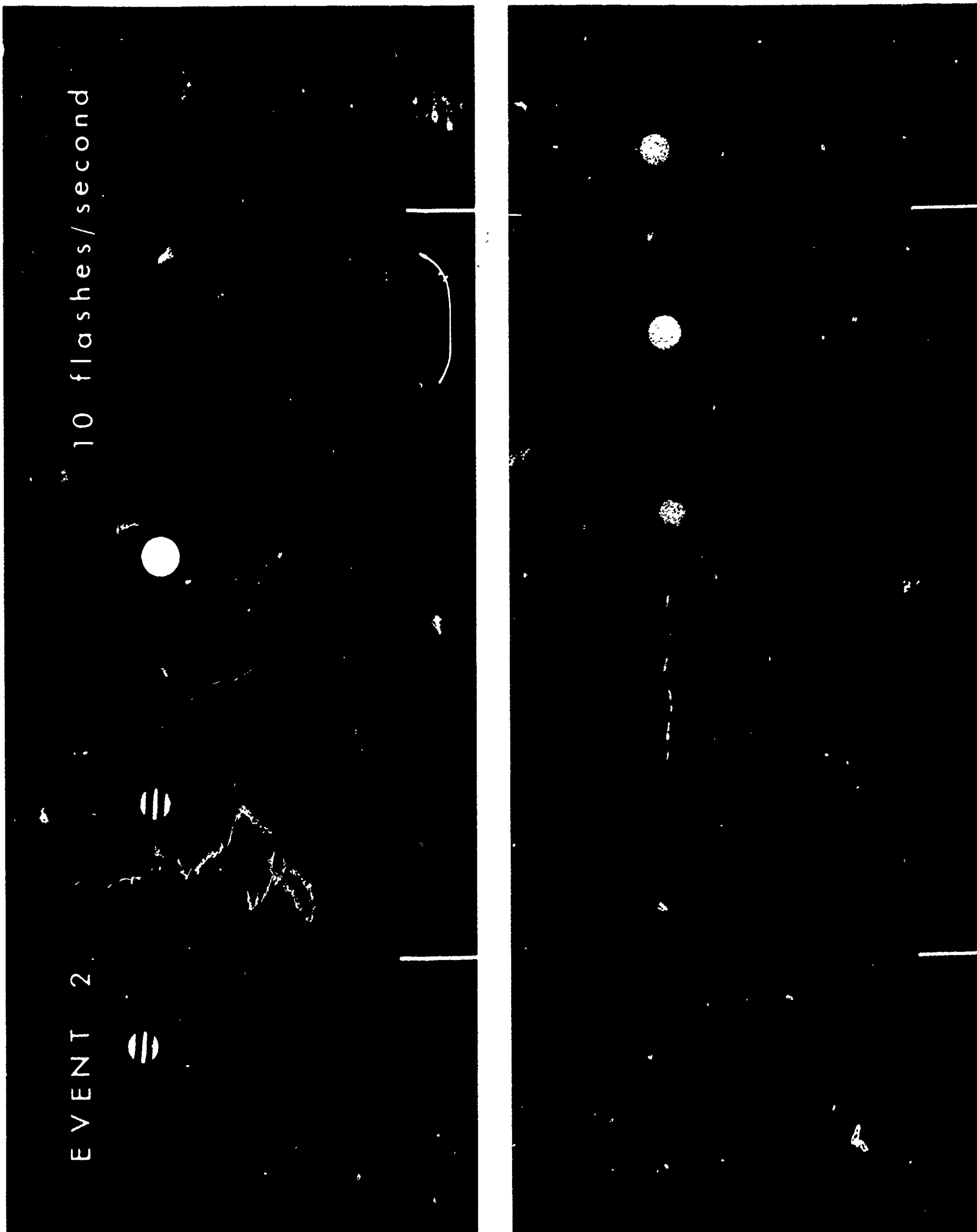
What are your values for the total momentum of the system of two balls before collision and after? Was momentum conserved?

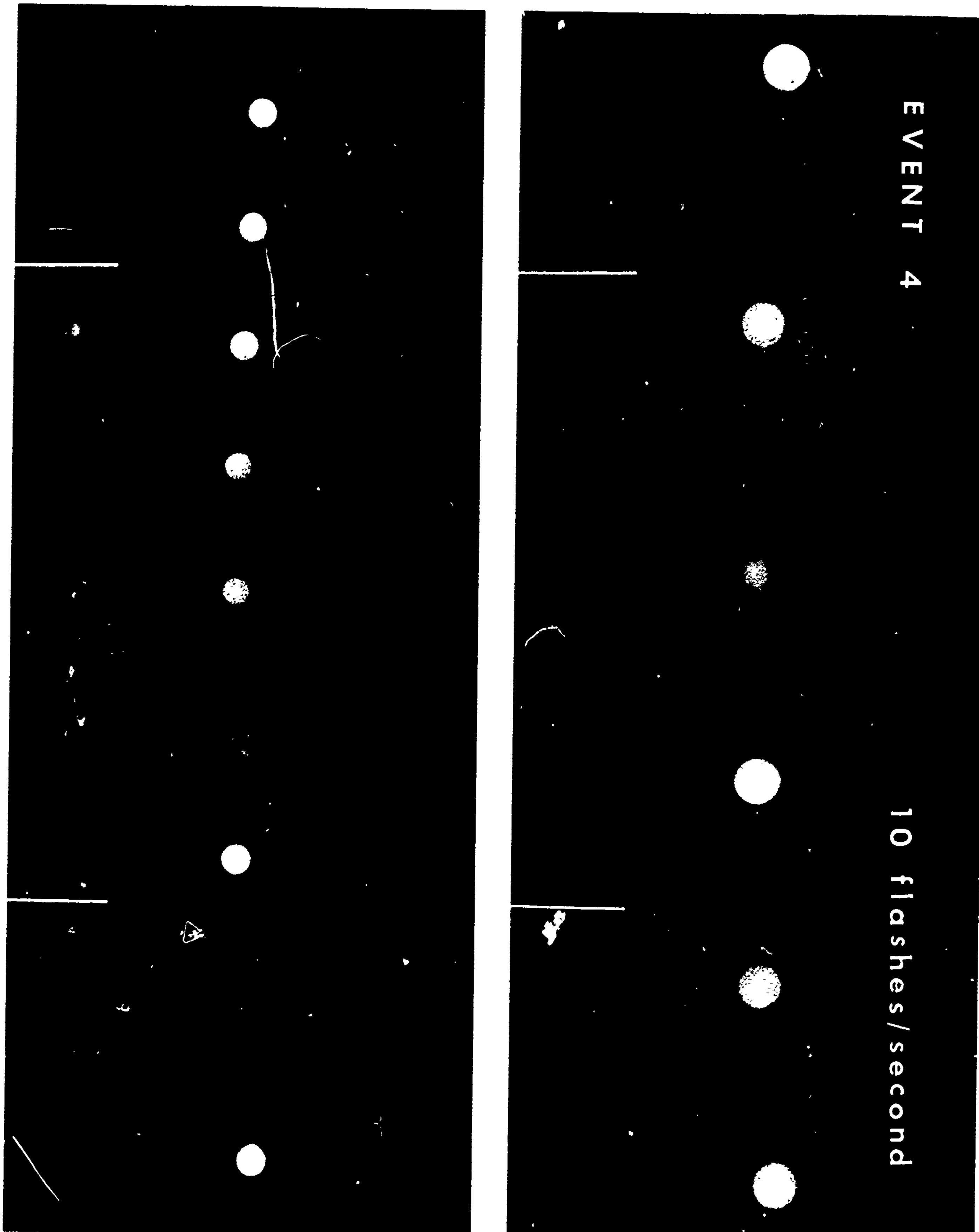
What are your values for the total kinetic energy of the system of two balls before collision and after? Was kinetic energy conserved?

Your answer to the last question should enable you to discuss the elastic properties of the collision. Do so!




EVENT 1
10 flashes/second


10 flashes/second
EVENT 2


EVENT 4
10 flashes/second

*Stroboscopic Photographs of Two-Dimensional Collisions

I. Material Needed in Addition to These Notes:

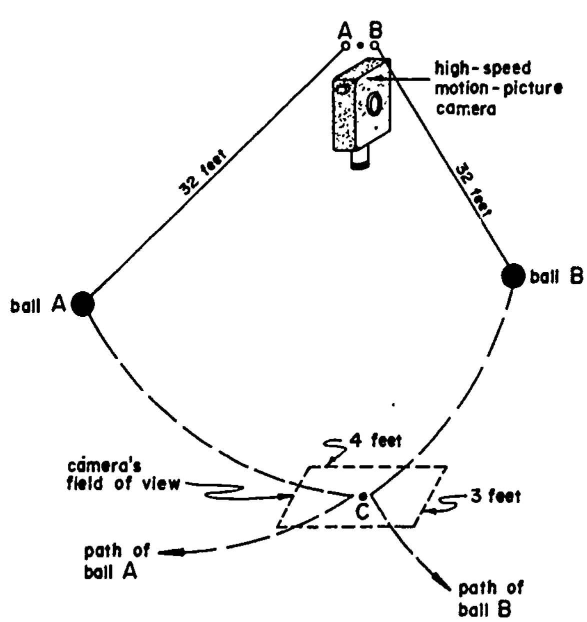
1. A transparent plastic ruler, marked in millimeters.

2. A large sheet of paper (at least 17" × 22") and cellophane (or masking) tape. Tape the photograph of the event you are analyzing to the upper right-hand corner of the paper. Leave room for a large vector diagram on the paper.

3. Two large triangles are useful for transferring direction vectors from the photographs to the vector diagrams.

II. How the Collisions Were Produced:

Balls were hung from 32-foot-long wires, as shown schematically in Fig. 1. When released, they collided at point C. A camera was placed directly below C, facing upward. Electronic strobe lights (not shown in Fig. 1) illuminated the 3 by 4 foot rectangle shown in each picture.



(This schematic diagram is not to scale)

Fig. 1

Two white bars are visible at the bottom of each photograph. These are rods which had their tips 1 meter ± 2 millimeters apart in the actual situation. You could determine the scale for the photograph, and convert your measurements to the actual distances.

NOTE: since the balls are pendulums, they move faster near the center of the photographs than near the edge. Do you understand why your measurements of displacements should be made near the center?

III. Sample Procedures for Vector Addition:

The purpose of Events 10, 13 and 14 is to demonstrate that momentum is conserved in two-dimensional collisions. You will see this by constructing vector diagrams, since momentum is a vector quantity having magnitude (mass of the ball times its speed) and direction (the direction of a ball's motion).

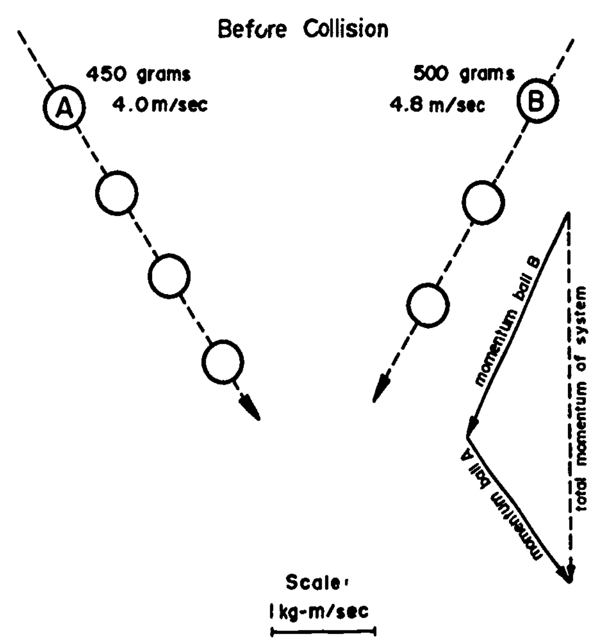


Fig. 2 Two balls moving in a plane. Their individual momenta, which are vectors, are added together vectorially in the diagram on the lower right. The vector sum is the total momentum of the system of two balls.
(Note: Your vector drawings should be at least twice as big.)

Let us consider an example; in Fig. 2, a 450 g and a 500 g mass are moving toward each other. Ball A has a momentum of 2.4 kg-m/sec, in the direction of the ball's motion. Using the scale shown, we draw a vector 2.4 units long parallel to the direction of motion of A. Similarly, for ball B we draw a momentum vector of 1.8 units long, parallel to the direction of motion of B.

The "system" of two balls has a total momentum before the collision equal to the vector sum of the two momentum vectors for A and B.

The total momentum after the collision is also found the same way, by adding the momentum vector for A after the collision to that for B after the collision (see Fig. 3).

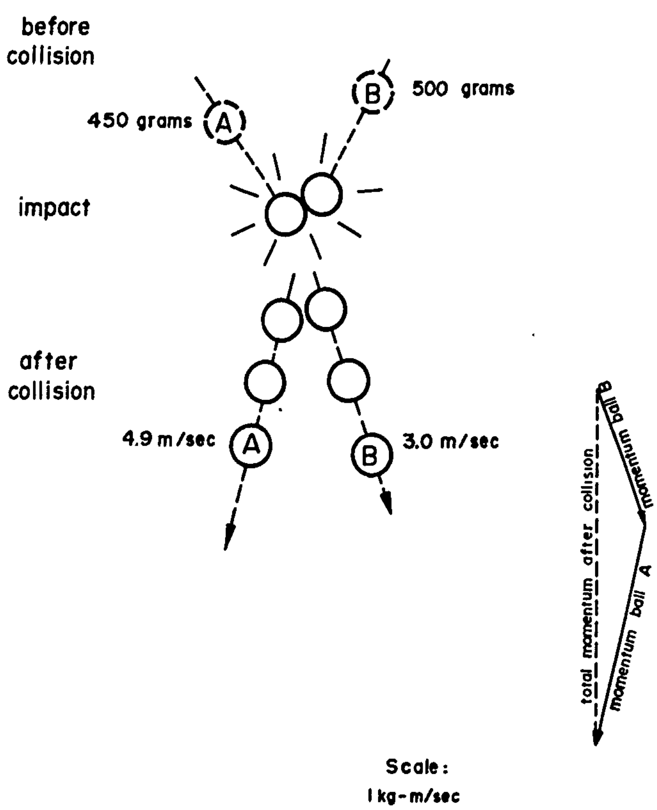


Fig. 3 The two balls collide and move away. Their individual momenta after collision are added vectorially. The resultant vector is the total momentum of the system after collision.

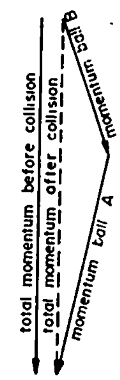


Fig. 4 Comparison of total momentum before and after collision. Momentum is conserved.

This same basic procedure is used for any event you analyze. Determine the momentum (magnitude and direction) for each object in the system before the collision, then graphically add them. Then do the same thing for each object after the collision. You could convert your measurements on the photograph to actual distances.

Event 10

Event 10 shows an elactic collision between two steel balls of equal mass. A white arrow indicates the direction of motion of each ball. The mass of each ball and the flash rate are also given on the photograph.

Event 13

(Note: Event 13 is also shown as the second example in film loop 23.)

Event 13 shows inelastic collisions between two plasticene balls of equal mass which stick together and move off as one compound object after the collision.

Caution: you may find that the two objects rotate slightly about a common center after the collision. For each picture after the collision, you should make marks halfway between the centers of the two objects. Then determine the velocity of this "center of mass," and multiply it by the combined mass to get the total momentum after the collision.

Event 14

Do NOT try to analyze event 14 unless you have done at least one of the simpler events

(Note: Event 14 is also shown in film loop 24.)

Figure 5 shows the setup used in photographing the scattering of the cluster. The photographer and camera are on the floor, and four electronic stroboscopes are on tripods in the lower center of the picture.

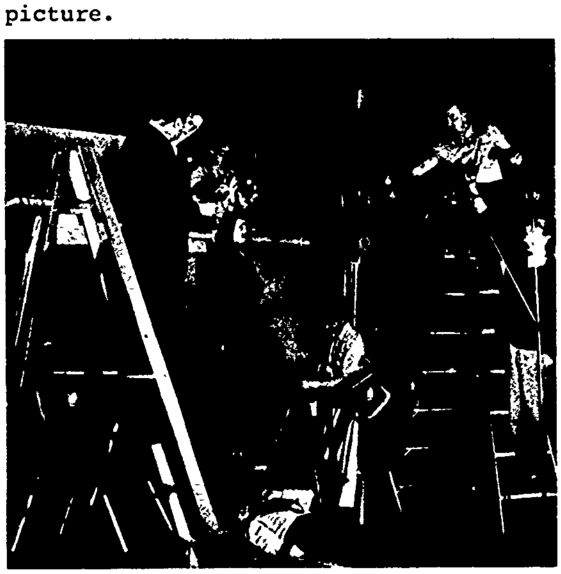


Fig. 5. Catching the seven scattered balls to avoid tangling in the wires from which they hang. Photographer and camera on the floor. The four stroboscopes are seen on tripods in lower center of the picture.

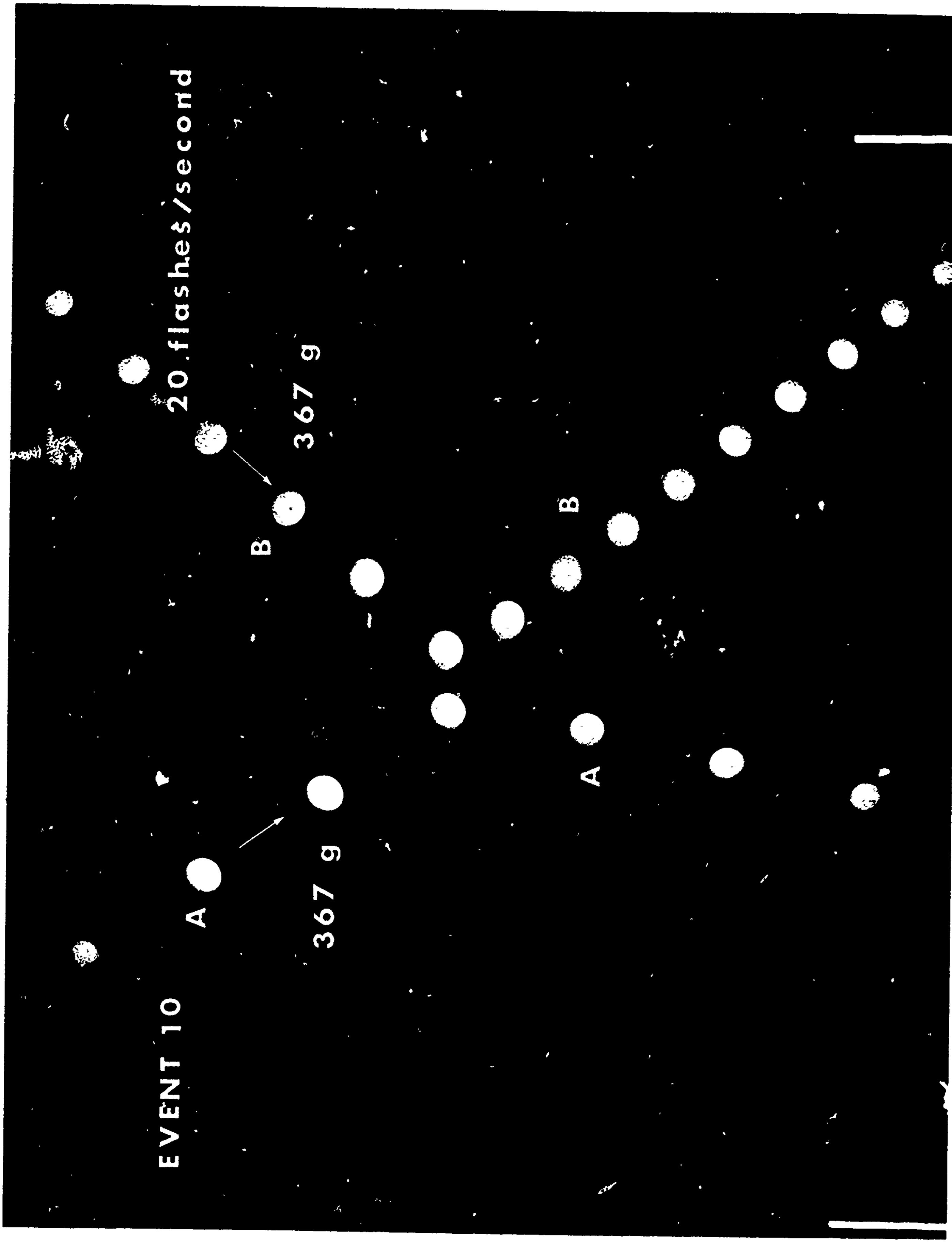
You are to use the same graphical methods as you used in event 13 to verify conservation of momentum. See the notes for those events for details about constructing vector diagrams. Event 14 is much more complex because you must add seven vectors, rather than two, to get the total momentum after the collision.

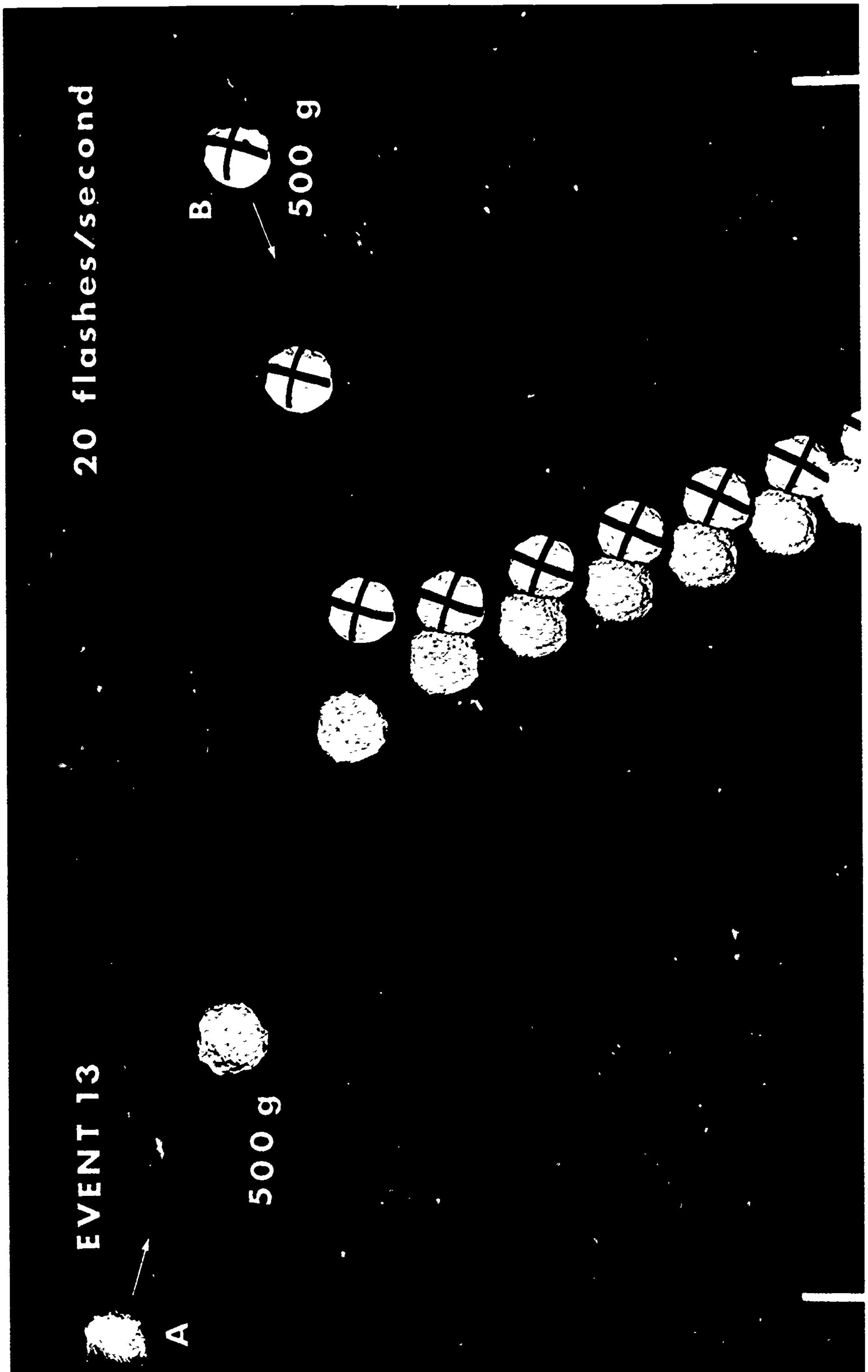
In event 14, one ball comes in and strikes a cluster of six balls of varying masses which were initially at rest. Two photographs are included: Print 1 shows the motion of each of the seven balls after the collision; Print 2 shows only the motion of ball A before the event.

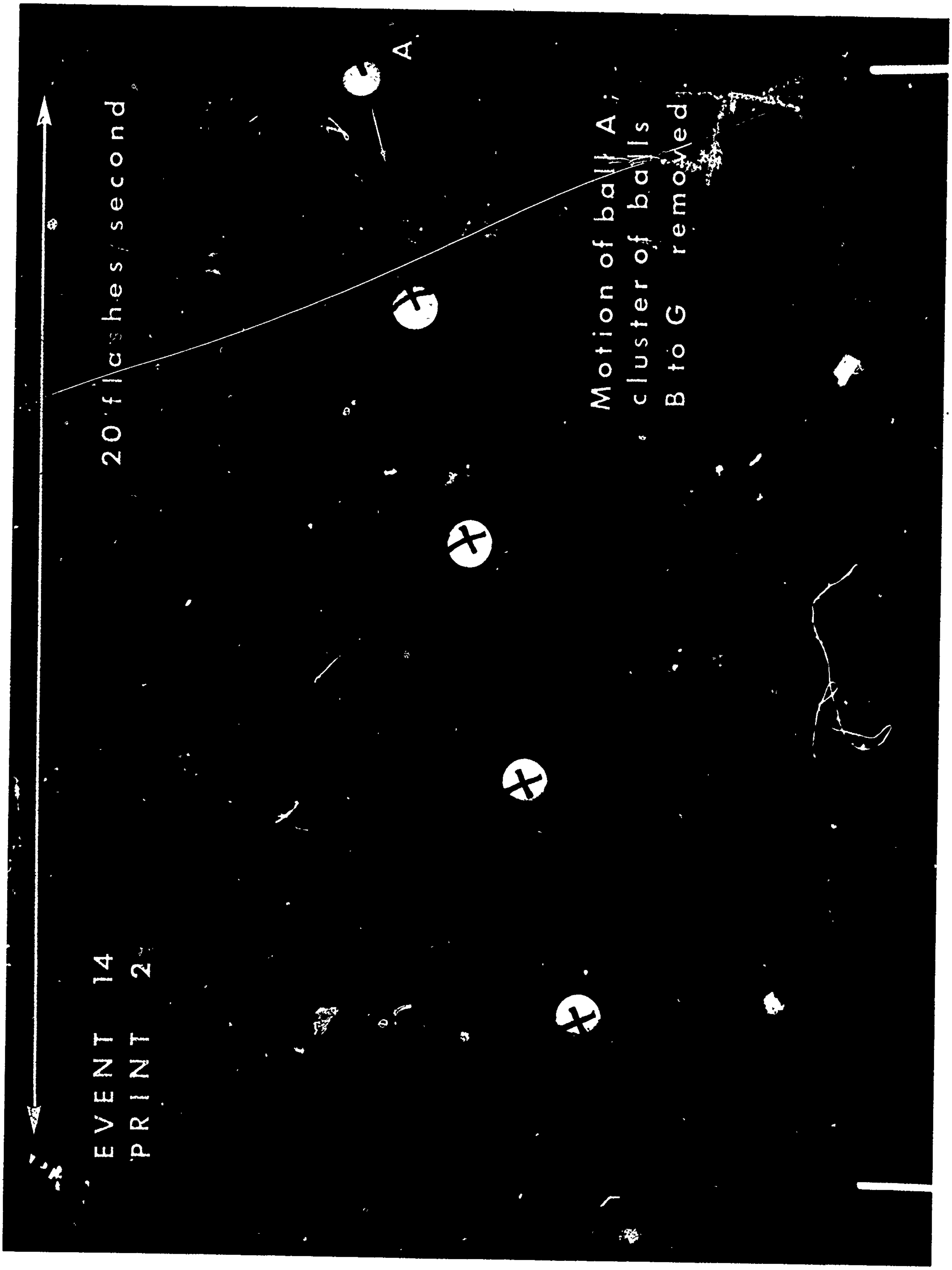
There are two different ways by which you can analyze this event. One is to determine the initial momentum of ball A from measurements taken on Print 2, and then compare it to the total final momentum of the system of seven balls from measurements taken on Print 1. The second method is to determine the total final momentum of the system of seven balls on Print 1, predict the momentum of ball A, and then take measurements on Print 2 to see whether ball A had the predicted momentum. Choose one method.

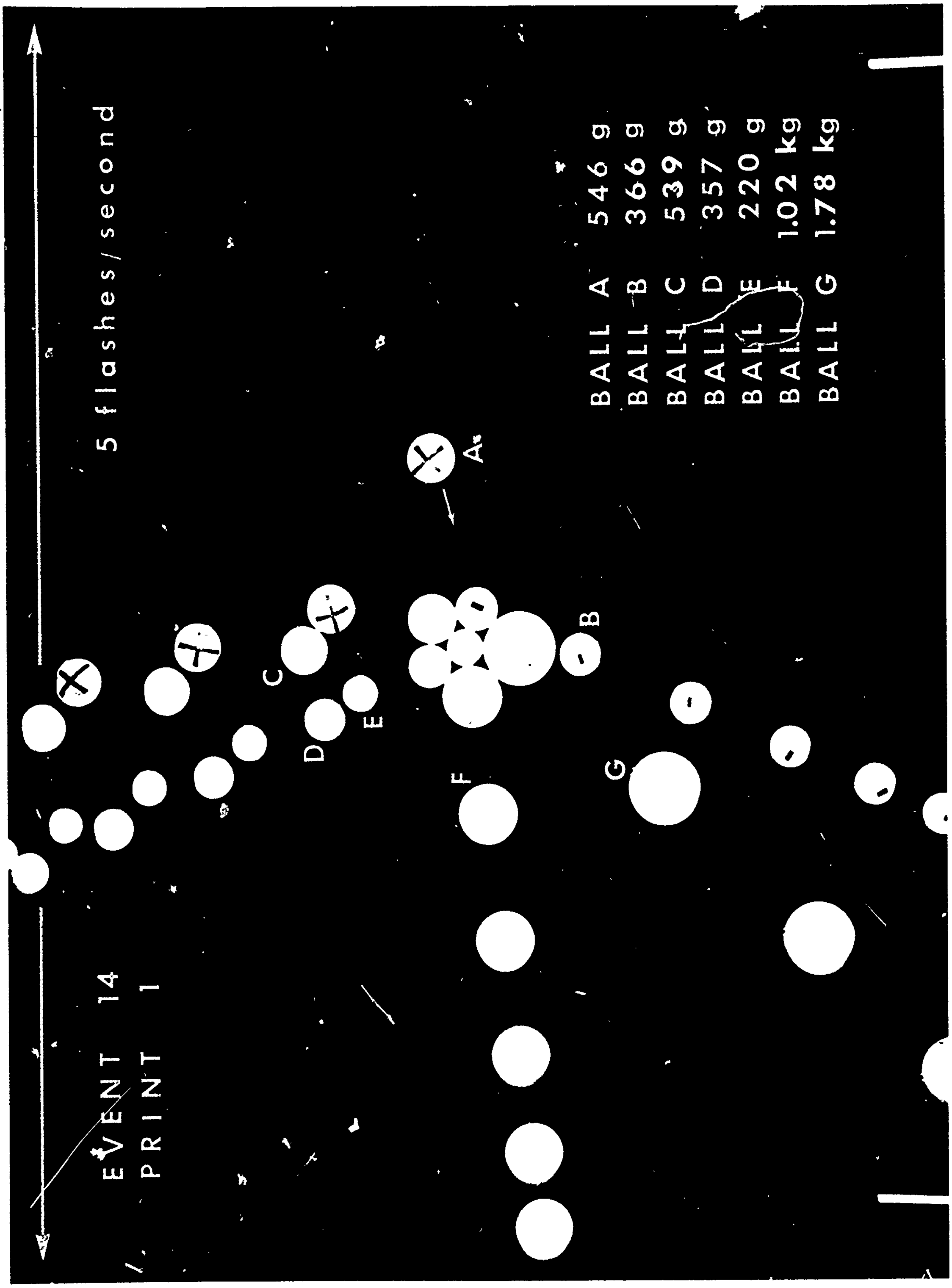
Procedure: For either method, you must first carefully mount Print 1 and Print 2 on your drawing paper so that the velocity of ball A in print 1 has the same direction as the velocity of ball A in Print 2. To help you do this there are long white arrows at the top of each print.

There are two other hazards which you must avoid. First, the time scales are different on the two prints. Print 1 was taken at a rate of 5 flashes/second, and Print 2 was taken at a rate of 20 flashes/second. Second, the distance scale may not be exactly the same for both prints. Remember that the distance from the center of the tip of one of the white bars to center of the tip of the other is 1 meter ± 2 mm in real space. Check this scale carefully on both prints to determine each of the conversion factors.


20 flashes/second
367 g
B
B
A
367 g
A
EVENT 10

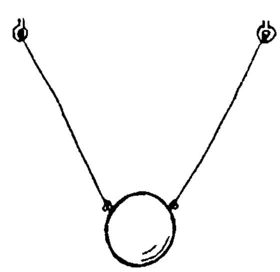

20 flashes/second
B
500 g
EVENT 13
500 g
A


EVENT 14
PRINT 2
20 flashes/second
A
Motion of ball A;
cluster of balls
B to G removed.


5 flashes/second
EVENT 14
PRINT 1
BALL A 546 g
BALL B 366 g
BALL C 539 g
BALL D 357 g
BALL E 220 g
BALL F 1.02 kg
BALL G 1.78 kg
A
B
C
D
E
F
G

Interesting Case of Elastic Impact

You have read in Sec. 9.6 how the elastic collision of two hard wood balls of the same size interested the members of the Royal Society back in 1666. There is an intriguing case of elastic impact of suspended balls, where one of the balls has three times the mass of the other and both balls are started from rest at equal distances on opposite sides of the center. Can you predict the result? If not, a good activity is to make two pendula with bobs of steel ball bearings, glass marbles or wooden balls, each pair to have the mass ratio of three to one, and see the answer for yourself. A "bifilar" suspension will help to keep the bobs swinging in the same plane.



Further suggestions for construction may be found in apparatus catalogs such as Cenco or Welch under the headings of momentum, collision, or impact. A complete story will be found in an article, "An Almost Forgotten Case of Elastic Impact," by Harvey B. Lemon, in the American Journal of Physics, vol. 3, p. 35 (1935).

Is Mass Conserved?

In Sec. 9.1 of your text you read about some of the difficulties in establishing the law of conservation of mass. There are several different experiments you can do to check this law.

Alka-Seltzer. You will need the following equipment: Alka-Seltzer tablets; 2-liter flask, or plastic one-gallon jug such as used for bleach, distilled water, or duplicating fluid; stopper for flask or jug; warm water; balance (sensitivity better than 0.1 g); spring scale (sensitivity less than 0.5 g).

Balance a tablet and 2-liter flask containing 200-300 ml of water on a sensitive balance. Drop the tablet in the flask. When the tablet disappears and no more bubbles appear, readjust the balance. Record the decrease in mass, which is the mass of the gas which escaped.

Repeat the procedure above, but include the rubber stopper in the initial balancing. Immediately after dropping in the tablet, place the stopper tightly in the mouth of the flask. (The pressure in a 2-liter flask goes up by no more than 20 per cent, so it is not necessary to tape or wire the stopper to the flask. Do NOT use smaller flasks in which proportionately higher pressure would be built up. Do you notice a change in mass? Remove the stopper after all reaction has ceased; what happens? Discuss the difference between the two procedures.

If you have more time, and tablets, repeat the above using the less sensitive spring scale. How do your conclusions differ?

Brightly Colored Precipitate. You will need: 20 g lead nitrate; 11 g potassium iodide; Erlenmeyer flask, 1000 cc with stopper; test tube, 25 × 150 mm; balance.

Place the lead nitrate in the Erlenmeyer flask, add 400 cc of water, and stir until dissolved. Place the potassium iodide in the test tube, add 30 cc of water, and shake until dissolved. Place the test tube, open end upward, carefully inside the flask and seal the flask with the stopper. Place the flask on the balance and bring to equilibrium. Tip the flask to mix the solutions and form the precipitate. Replace on balance. Does the total mass remain conserved? What does change in this experiment?

Burning Candle. Make a balance by suspending a ruler from its midpoint. Suspend a candle in a paper cup from one end, and add weights to the other end to balance the weight of the candle. Light the candle, and observe the system. Is matter conserved when the candle burns? What does change in this system?

Magnesium Flash Bulb. On the most sensitive balance you have available, measure the mass of an unflashed magnesium flash bulb. Clear the pans and repeat the measurement several times. The average difference among your measurements gives you an estimate of the precision of the measurement.

Flash the bulb by connecting it to a battery. Be careful to touch the bulb as little as possible, so as not to wear away any mass or leave any massive fingerprints. Measure the mass of the bulb several times, as before. If you cannot detect any change in mass within the range of precision previously established, you can get a feeling for how small a mass change you could have detected by seeing how large a piece of tissue paper you have to put on the balance to produce a detectable difference.

Exchange of Momentum Devices

The six situations described below are more complex cases for checking conservation of momentum, but you will gain a deeper understanding of the full generality of the conservation law and of the importance of your frame of reference if you try some of them.

a) Fasten a section of HO guage model railroad track to two ring stands as shown in Fig. 1. Set one truck of wheels from a car on the track and from it suspend an object with mass roughly equal to that of the truck. Hold the truck, pull the object to one side, and release both at the same instant. What happens? Predict what you think would happen if you released the truck an instant after releasing the object. Try it. Try increasing the suspended mass. Students in one class were able to get about three exchanges of momentum before motion ceased.

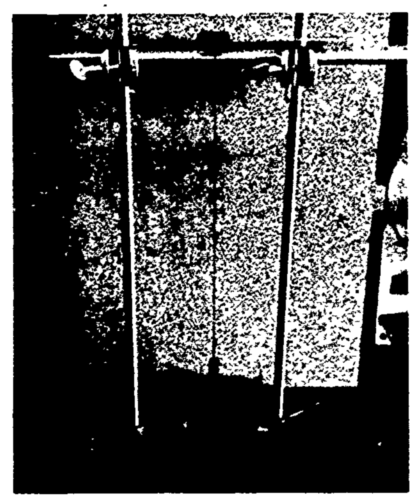


Fig. 1

b) Fig. 2 shows a similar situation, using the air track supported on ring supports. An object of 20 g mass was suspended by a 50 cm string from one of the small air track gliders. One student trial continued for 166 swings.

Fig. 2

c) Fasten two dynamics carts together with four hacksaw blades as shown in Fig. 3. Push the top one to the right, the bottom to the left, and release them. Try giving the bottom cart a push across the room at the same instant that you release them.

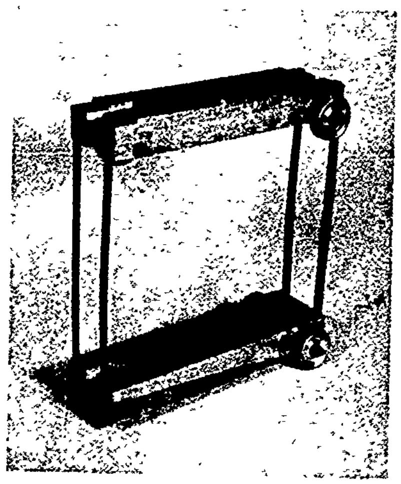


Fig. 3

What would happen when you released the two if there were 10 or 20 bearing balls or small wooden balls hung as pendula from the top cart? You might find this model useful to you in Chapter 11.

d) Suspend five pendula of different lengths from a taut wire or slightly flexible stick between two supports (see Fig. 4). Suspend a sixth pendulum with the same length as the medium pendulum. Pull aside one of the two pendula of equal length and release it. Observe what happens. This is an example of resonance, which is discussed later in the course.

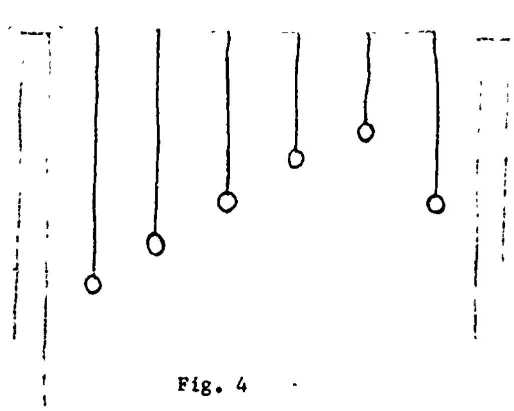


Fig. 4

e) Push two large rubber stoppers onto a short piece of glass tubing or wood (Fig. 5). Let the "dumbbell" roll down a wooden wedge so that the stoppers do not touch the table until it is almost to the bottom. When the dumbbell touches the table, it suddenly increases its linear momentum as it moves off along the table. There are principles of rotational momentum and energy involved here which we have not covered in our text, but even without extending the text we can deal with the "mysterious" increase in linear momentum when the stoppers touch the table. Using what you have learned about conservation of momentum, what do you think could account for this increase? (Hint: set the wedge on a piece of cardboard supported on plastic beads in a glass tray and try it.)

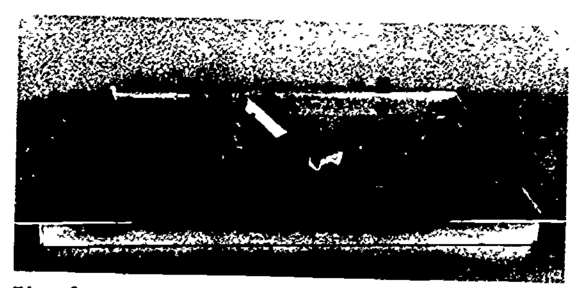


Fig. 5

Chapter 10 Energy

EXPERIMENT 24 Conservation of Mechanical Energy

In the previous experiment you recorded the results of a number of collisions involving carts and gliders having different initial velocities. You found that in each case momentum was conserved. You can now use the results of these collisions to learn about another extremely useful conservation law, the conservation of energy.

There is initially no reason to believe that the product of m and $\vec{v}$ should prove to be the only conserved quantity. From the data obtained from your photographs, look for other combinations of quantities which might be conserved. Find values for m/v, m^2v and mv^2 for each cart before and after each collision, to see if the sum of these quantities for both carts is conserved. Compare the results of the elastic collisions with the inelastic ones. Consider the "explosion" too.

Q1 Is there a quantity which is conserved for one type of collision but not for the other?

Again there are several alternative procedures of which you will do just one.

Procedure I — dynamics carts

To take a closer look at the details of an elastic collision, photograph two dynamics carts as you may have done in the previous experiment. Set the carts up as shown in the sketch:

The mass of each cart is 1 kg. Extra mass is added to make the total masses 2 kg and 4 kg. There is a light source on each cart. So that you can distinguish between the images formed by the two lights make sure that one of the bulbs is slightly higher than the other (you can do this by bending it up gently).

Place the 2 kg cart at the center of the table and push the other toward it from the left so that the two spring bumpers come together.

If you use the 12-slot disc on the stroboscope, you should get several images during the time that the springs are touching. You may have to try different initial speeds for the 4 kg cart to get this sort of photograph.

One of the twelve slots on the stroboscope disc is slightly more than half covered with tape. Images formed when the slot that is partly covered is in front of the lens will be fainter than the others. Use this to tell which image

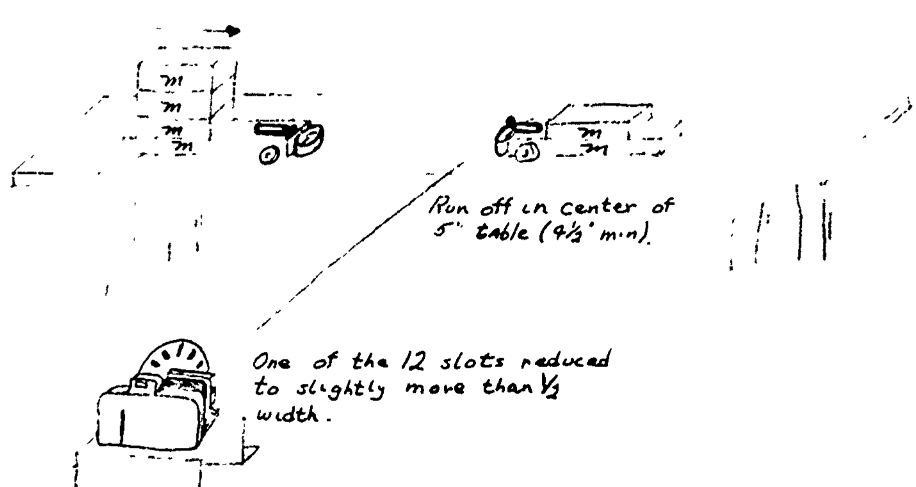


Fig. 1

of the right-hand cart was made at the same instant as a given image of the left-hand cart.

Compute and assemble in a table the values for the momentum ($m\vec{v}$) for each cart for each time interval while the springs were touching, plus at least three intervals before and after they touched. Remember that the lighter cart was initially at rest while the heavier one moved towards it. This means that the first few values of $m\vec{v}$ for the lighter cart will be zero.

On a sheet of graph paper, plot the momentum of each cart as a function of time, using the same coordinate axes for both. Make sure that you have paired off the values for the two carts correctly. Connect each set of values with a smooth curve. Now draw a third curve which shows the sum of the two values of $m\vec{v}$, the total momentum of the system, for each time interval.

Q2 Was the final momentum of the system the same as the initial momentum—was momentum conserved in the collision?

Q3 What happened to the momentum of the system while the springs were touching—was momentum conserved <u>during</u> the collision?

Now compute values for the scalar quantity mv^2 for each cart for each time interval, and add them to your table. On another pair of coordinate axes, plot graphs of mv^2 for each cart for each time interval. Plot a curve of the sum of the two mv^2 values for each time interval.

Q4 How does the final value of mv^2 for the system compare with the initial value?

Q5 Is mv^2 a conserved quantity?

Q6 How would the appearance of your graph change if you multiplied each quantity by $\frac{1}{2}$?

(The quantity $\frac{1}{2}mv^2$ is called the "kinetic energy" of the object of mass m and speed v.)

Q7 How does the total amount of kinetic energy of both carts after the collision compare with the sum of their kinetic energies before the collision?

Q8 Does the total amount of kinetic energy vary <u>during</u> the collision?

Q9 You probably found about as much energy afterwards as before. What became of it <u>during</u> the collision?

Procedure II — magnets

Many of the interactions that you can study in the laboratory involve actual physical contact between two objects that move in the same straight line. Experiments in which air track gliders and dynamics carts bang into each other are examples of such "collisions in one dimension."

In this experiment you will investigate a different sort of interaction: you will look for conserved quantities when the two bodies are free to move in two dimensions and the force between them is magnetic.

Put some Dylite spheres (tiny plastic beads) on a glass tray or other flat surface. A disc magnet will slide freely on this low friction surface. Level the surface carefully.

Put one puck at the center and push a second one towards it, slightly off center. You want the magnets to repel each other without actually touching. (You may have to turn one of them over.) Try varying the speed and direction of the moving magnet until you find conditions that make both magnets move off after the collision with about equal speeds.

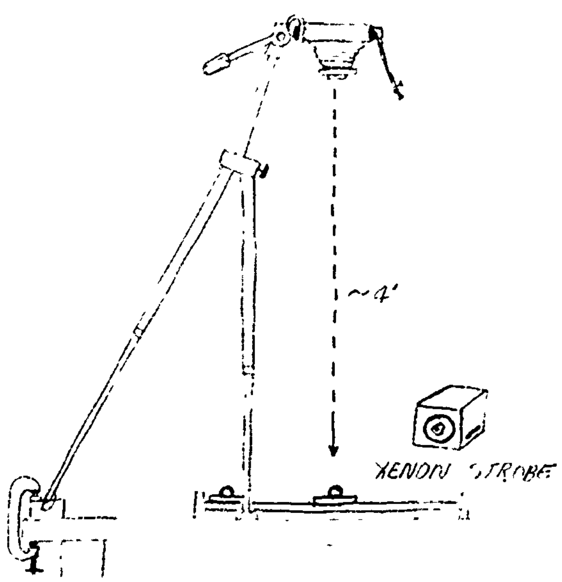


Fig. 2

To record the interaction you must set up a camera directly above the glass tray and a xenon stroboscope to one side as in Fig. 2.

Mount a steel ball or styrofoam hemisphere on the center of each disc with a small piece of clay. The ball will give a sharp reflection of the strobe light.

Take strobe photographs of several interactions. There must be several images before and after the interaction, but you can vary the initial speed and direction of the moving magnet, to get a variety of interactions.

From the photograph measure the "before" and "after" speeds of each disc.

Momentum, $m\vec{v}$, like velocity, is a vector quantity. To analyze your experiment to see if momentum is conserved you would have to consider the <u>direction</u> of motion of the pucks. But the quantity mv^2 is not a vector: there is no direction associated with it and so we need only consider its magnitude. Calculate the value of mv^2 for each disc both before and after the interaction.

Q10 Is mv^2 a conserved quantity? Is $\frac{1}{2}mv^2$ a conserved quantity?

If you find that there has been a decrease in the total kinetic energy of the system of interacting magnets you should consider the following: the surface is not perfectly frictionless and a single magnet disc pushed across it will slow down a bit. Make a plot of $\frac{1}{2}mv^2$ against time for a moving puck to get an estimate of the rate at which kinetic energy is lost in this way.

Q11 How much of the loss in $\frac{1}{2}mv^2$ that you observed in the interaction can be due to friction?

When the two discs are close together (but not touching) there is quite a strong force between them pushing them apart. If you put the two pucks down on the surface close together and release them they will fly apart: the kinetic energy of the system has increased.

If you have time to go on you should try to find out what happens to the quantity $\frac{1}{2}mv^2$ of the discs while they are close together during the interaction. To do this you will need to work at a fairly high strobe rate, and shoot the projectile magnet at fairly high speed—without letting the two magnets actually touch, of course. Close the camera shutter before the discs are out of the field of view, so that you can match images by counting backwards from the last images.

Now, working backwards from the last interval, measure v and calculate $\frac{1}{2}mv^2$ for each puck. Make a graph in which you plot $\frac{1}{2}mv^2$ for each puck against time. Draw smooth curves through the two plots.

Now draw a third curve which shows the sum of the two $\frac{1}{2}mv^2$ values for each time interval.

Q12 Is the quantity $\frac{1}{2}mv^2$ conserved <u>during</u> the interaction, i.e., while the repelling magnets approach very closely?

Try to explain your observations.

Procedure III — inclined airtracks

Suppose you give a push to a glider at the bottom of an inclined airtrack. As it moves up the slope it slows down, stops momentarily and then begins to come back down the track.

Q13 Is any quantity (such as mass, momentum, etc.) conserved in this system?

Clearly the bigger the push you give the glider (the greater its initial velocity $\vec{v}_i$), the higher up the track it will climb before stopping. From experience we know that there is some connection between v_i and d, the distance it moves along the track.

According to Sec. 10.4 of the text, when a stone is thrown upwards the kinetic energy that it has initially ($\frac{1}{2}mv_i^2$) is transformed into gravitational potential energy ($ma_g h$) as the stone moves up. In this experiment you will test to see whether the same relationship explains the behavior of the glider on the inclined airtrack.

Three people are needed to participate in this experiment. One gives the glider the initial push; another marks the highest point on the track that the glider reaches; while the third uses a stopwatch to time the motion from push to rest.

Raise one end of the track a few centimeters above the tabletop. The launcher should practice pushing until he can reproduce a push that will carry the glider nearly to the top end of the track.

Record the distance traveled and time taken for several trials.

These measurements will give you the glider's average velocity along the track

$$v_{av} = \frac{\Delta d}{\Delta t}.$$

In Unit 1 we found that the glider moves with uniform acceleration (down the track). Therefore, we can use the formula

$$v_{av} = \frac{v_i + v_f}{2}.$$

(See Sec. 2.7.)

Since the final velocity at the top of the track, v_f, is zero this simplifies to

$$v_{av} = \frac{v_i}{2}$$

$$\text{or } v_i = 2v_{av}.$$

Calculate v_i for each of your trials. Weigh the glider.

Q14 What is the initial kinetic energy, $KE = \frac{1}{2}mv_i^2$?

To calculate the increase in gravitational potential energy you must measure the vertical height h through which the glider moves for each push. You will probably find that you need to measure from the tabletop to the track at the initial and final points of the glider's motion (see Fig. 3).

Fig. 3

Q15 What is the potential energy increase, the quantity $ma_g h$, for each of your trials?

Compare the kinetic energy loss with the potential energy increase in each trial. Be sure that you use consistent units: m in kilograms, v in meters/second, a_g in meters/second^2, h in meters.

Q16 Are the kinetic energy loss and the potential energy increase equal; that is, does $\Delta(P.E.) = -\Delta(K.E.)$, to within your experimental uncertainty, or is there a significant difference?

Q17 Can you explain your result?

Q18 Suppose you released the glider from a point near the top end of the track—height h above the bottom end. What would you expect its velocity to be by the time it reached the bottom of the track?

Try it out to see if your prediction is confirmed. Measure the time it takes for the glider to reach the bottom of the track and use $v_f = 2v_{av}$ as before.

Now increase the slope of the track. Locate a point that is the same <u>vertical</u> distance above the bottom of the track as in the last experiment.

Q19 What do you predict will be the final velocity of the glider after traveling the shorter distance to the bottom of the track?

Q20 How will the final velocity change as the track is made steeper and steeper but the glider always released from the same height above the bottom of the track?

Do experiments at several different inclinations to test your predictions.

If you have worked along this far you should be able to say how well the equation

$$\tfrac{1}{2}mv^2 = ma_g h$$

applies to the motion of a glider on the airtrack. Here are two more things you can do if you have time to go on.

a) Take a strobe picture of the glider as it goes down the track after you release it from rest. From the photograph measure v (in meters/second) at several points along the track. Measure h (meters) at the same points. Compute $\tfrac{1}{2}mv^2$ and $ma_g h$. On a graph plot $\tfrac{1}{2}mv^2$ against position (distance along the track). On the same graph and with the same axes plot $ma_g h$ against position.

b) Now plot a third curve that represents the sum ($\tfrac{1}{2}mv^2 + ma_g h$) against position.

Q21 Is the total energy (kinetic energy + gravitational potential energy) constant? If not, can you explain why?

When the glider rebounds from the rubber band at the bottom of the track it is momentarily stationary—its kinetic energy is zero. And so is its gravitational potential energy. And yet the glider will rebound from the rubber band (regain its kinetic energy) and go quite a way up the track (gaining gravitational potential energy) before it stops.

Q22 Can you explain what happens at the rebound in terms of the conservation of mechanical energy?

The glider does not get quite so far up the track on the second rebound as it did on the first. There is evidently a steady loss of energy.

Q23 How could you measure how much energy is lost each time?

Procedure IV—film loops

Several film loops show experiments that you cannot actually perform in the laboratory. Since they are shown in slow motion you can make measurements directly from the pictures projected onto graph paper and analyze your data in the same way as your classmates using the other procedures.

Read the notes about the loop you will use before you begin to take measurements. you begin to take measurements.

EXPERIMENT 25 Measuring the Speed of a Bu"et

Sections 9.2 and 9.3 discuss collisions, define momentum, and give the general equation of the principle of conservation of momentum for two-body collisions, namely $m_A\vec{v}_A + m_B\vec{v}_B = m_A\vec{v}_A' + m_B\vec{v}_B'$. In this experiment you will use the principle of the conservation of momentum to determine the speed of a bullet.

The projectile is fired into a heavy block or box. The projectile is fired horizontally, parallel to the direction in which the block or box is free to move. Since all velocities before and after the collision are in the same direction, we may neglect the vector nature of the above equation and talk only of speeds. To avoid subscripts we shall denote the mass of the heavy target pendulum by M and the much smaller mass of the projectile by m. Before impact the pendulum is at rest. Therefore we have only the speed of the projectile, v, to consider. After impact both pendulum and embedded projectile move with a common speed v'. Thus the general equation becomes

$$mv = (M + m)v'$$

which we can rearrange to show that

$$v = v'(M + m)/m.$$

The masses can be readily measured. Therefore, if the comparatively slow speed v' can be found after impact, the high speed of the projectile before impact may be computed. There are at least two ways to find v'.

Method I — airtrack

The most direct way to measure v' is to mount the mass M on the airtrack and to time its motion after the impact. Mount a small (juice) can lightly packed with cotton on an airtrack glider. Make sure that the glider will still "float" freely with this extra load on it. Fire the bullet horizontally, parallel to the length of the airtrack. If M is large enough compared to m, the glider's velocity will be low enough so that you can use a stopwatch to time it over a meter. Repeat the measurement a few times until you get consistent results.

Q1 What is your value for the bullet's speed? Show how you obtained this answer.

Q2 Suppose the collision between bullet and can were not completely inelastic—i.e., the bullet bounced back a little after impact; how would this affect your result?

Q3 Can you describe a way to check your result, i.e., an independent way of measuring the speed of the bullet? If you can, go on and do the independent measurement and account for any differences between the two results.

Method II — ballistic pendulum

This is the original method which was invented in 1742 and is still used in ordnance laboratories to determine the speed of bullets. The heavy block or box is suspended as a freely swinging pendulum. The actual collision is completely inelastic, so kinetic energy is not conserved during the impact. But mechanical energy is conserved in the nearly frictionless swing of the pendulum after the impact: the increase in gravitational potential energy of the pendulum during its swing up is equal to its kinetic energy immediately after impact. So v' can be found from the mass and rise distance of the pendulum (plus projectile).

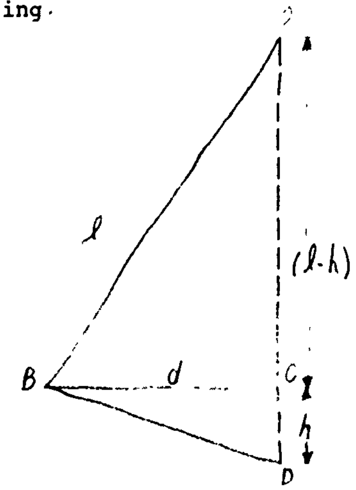
That is,

$$\tfrac{1}{2}(M + m)v'^2 = (M + m)a_g h$$

where a_g is the acceleration due to

gravity. The change of vertical height, h, is difficult to measure; but the horizontal displacement of the pendulum which may be 10 centimeters or more can be determined without difficulty. The relation between h and d follows from a little plane geometry.

The kind of pendulum will depend upon the nature and speed of projectile. If pellets from a toy gun are used, a cylindrical cardboard carton stuffed lightly with cotton and suspended by threads from a laboratory stand will do. If you use a good bow and arrow, a fairly stiff corrugated box stuffed with straw and hung from the ceiling will do. To prevent the target pendulum from twisting, it should be hung by parallel cords connecting four points on it to four points directly above them. This prevents the target from twisting.



In the figure, the center of the circle, O, represents the point from which the pendulum is hung. The length of the cords is ℓ.

In the triangle OBC

$$\ell^2 = d^2 + (\ell - h)^2$$

$$\ell^2 = d^2 + \ell^2 - 2\ell h + h^2$$

$$\therefore 2\ell h = d^2 + h^2$$

For small swings, h is small compared with ℓ and d so we may neglect h^2 in comparison with d^2, and write the close approximation,

$$2\ell h = d^2$$

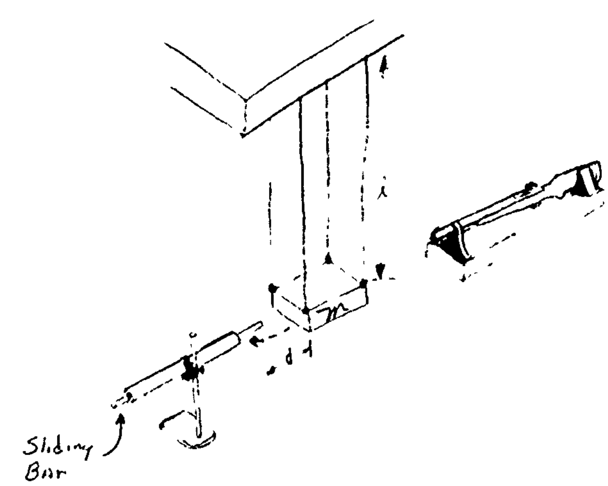
$$h = d^2/2\ell.$$

Returning to the energy equation, the masses cancel and replacing h with $\frac{d^2}{2\ell}$ we get

$$v = [(M + m)/m]d\sqrt{a_g/\ell}\ .$$

Usually the mass of the projectile, m, may be neglected in comparison with that of the pendulum, M, in the numerator of the above expression.

To measure d experimentally, a light rod (a pencil or a soda straw will do) is placed in a tube which is clamped to a stand. The rod extends out of the tube on the side toward the pendulum. As the pendulum swings it shoves the rod back into the tube so that the rod's final position marks the end of the



swing of the pendulum. Of course the pendulum must not hit the tube and there must be sufficient friction between rod and tube so that the rod comes to rest with the pendulum. The original rest position of the pendulum is readily found so that the displacement, d, may be measured.

Repeat the experiment a few times to get an idea of how precise your value for d is. Use the equation $h = \frac{d^2}{2\ell}$ to calculate h, the height to which the pendulum rises. From this calculate the potential energy gained by the pendulum. Then use the principle of the conservation of energy to calculate the initial speed of the pendulum plus bullet.

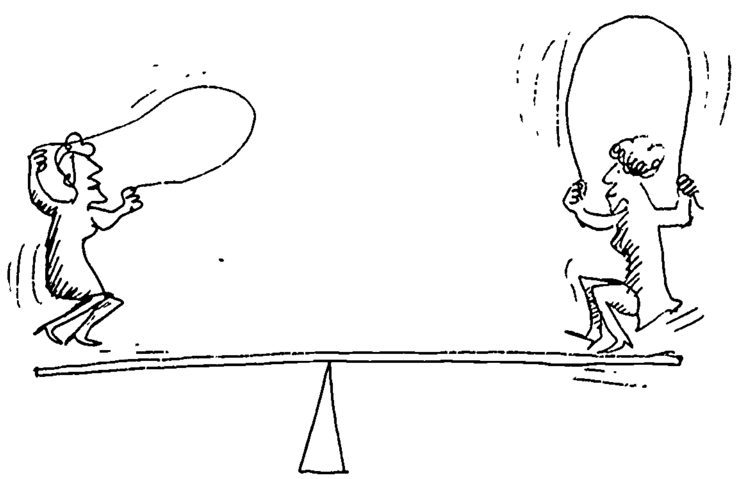
Finally use the conservation of momentum principle to calculate the bullet's speed.

Compare the kinetic energy before impact with that of the block after impact.

Q4 Why is there such a large difference?

Q5 Can you from your measurements determine the average force on the projectile as it is being fired from the gun?

Q6 Can you describe an independent method of checking your result for v? If you have time, go on to perform it, and explain any difference between the two values.



EXPERIMENT 26 Hotness, Thermometers, Temperature

It is easy to tell which of two similar bodies is the hotter—although one can also be misled. (Try putting your left hand in cold water and your right in hot and then transferring both to lukewarm water: it will feel hot to the left and cold to the right.) But if we want to measure how hot something is or to communicate a result to somebody else, we have to find some way of assigning a number to "hotness." This number is what we call temperature, and the instrument used to get this number is a thermometer.

It's not too difficult to think of standard units for measuring intervals of time and distance—the day and the foot are both natural units. But try to imagine yourself living in an era before the invention of thermometers and temperature scales, that is, before the time of Galileo. How would you describe, and if possible, give a number to, the "degree of hotness" of an object?

Q1 How many different properties (such as length, density) can you think of that vary with "hotness"?

Q2 Which of them could be measured quantitatively?

Any property (length, volume, density, pressure, resistance, etc.) which changes with hotness and which can be measured could be used as a measure of temperature; and any device which measures this property could be used as a thermometer.

In this experiment you will be using liquid-expansion and gas-expansion thermometers, and electrical resistance thermometers. Others are possible: thermocouples, optical pyrometers, gas pressure, etc. Each of these devices has its own particular merits which make it suitable, from a purely practical point of view, for some applications, and difficult or impossible to use in others. But of course it's most important that readings given by two different types of thermometers agree. In this experiment you will make your own thermometers, put temperature scales on them, and then compare them to see how well they do agree with each other.

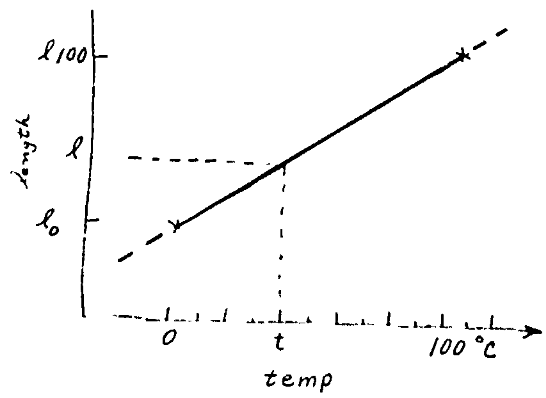
Fixed Points

As well as deciding what property (length, volume, etc.) of what substance (mercury, air, etc.) to use in a thermometer, we must decide on two fixed points. A fixed point uses a physical phenomenon which always occurs at the same degree of hotness. Two convenient ones to take are the melting point of ice and the boiling point of water. On the Celsius (centigrade) system they are assigned the values 0° C and 100° C respectively (at ordinary atmospheric pressure). Once the fixed points have been established intermediate temperatures can be measured.

Suppose you measure the length of a column of liquid at 0° C and again at 100° C. The length of the column now can be used to measure other temperatures. Suppose its length was ℓ_0 at 0° and had increased to ℓ_{100} at 100°. We define the temperature scale by saying that equal temperature changes cause equal changes in the length of the column. Frequently, if we divide the total increase in length $(\ell_{100} - \ell_0)$ into 100 equal parts, $\left(\frac{\ell_{100} - \ell_0}{100}\right)$, we can say that if the length of the column changes by one of these parts, then the temperature change is "one degree."

Q3 What is the temperature on this scale if the column's length is $\ell_0 + \frac{79}{100}(\ell_{100} - \ell_0)$?

The simplest way to find an intermediate temperature from a thermometer reading is to plot the two fixed points on a graph. Draw a straight line between them:



Now the temperature on this scale (t), corresponding to any intermediate length (ℓ), can be read off the graph.

Other properties and other substances can be used of course: the volume of different gases, the electrical resistance of different metals and so on, and the temperature defined in the same way. The thermometers will have to agree at the two fixed points, but do they agree at intermediate temperatures? That is the question that this lab experience will answer.

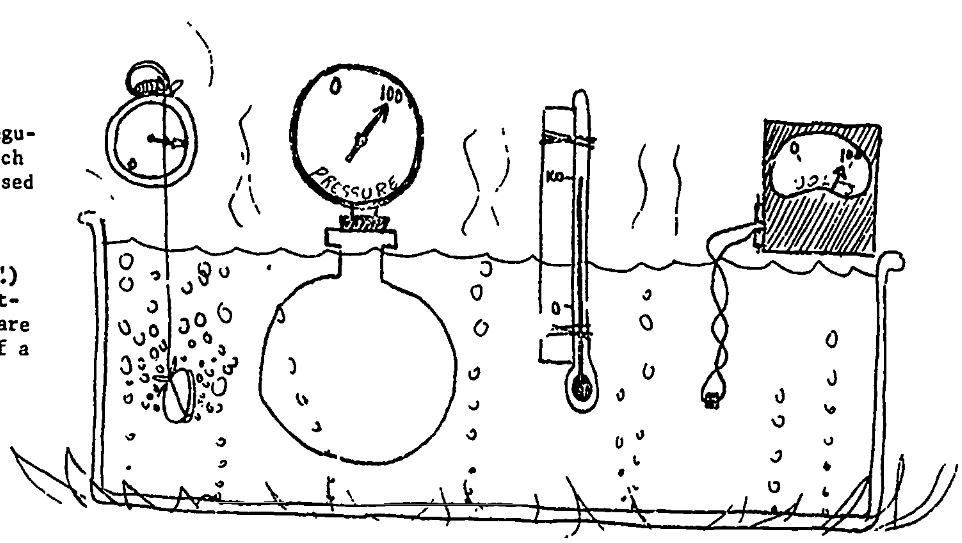
Experimental

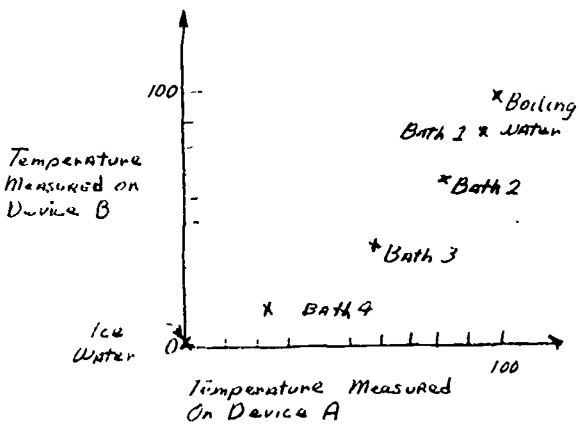
You will make or be given two "thermometers" to compare. Take readings of the appropriate quantity—length of liquid column, volume of gas, electrical resistance, thermocouple voltage, or whatever, when the devices are placed in an ice bath, and again when they are placed in a boiling water bath. Record these values. Define these two temperatures as 0° and 100° and draw the straight line graphs that define intermediate temperatures as described above.

Now put your two "devices" in a series of baths of water at intermediate temperatures, and again measure and record the length, volume, resistance,... each time. Put both devices in the bath at the same time in case it is cooling down. Use your graphs to read off the temperatures of the water baths as measured by the two devices.

Q4 Do the temperatures measured by the two devices agree, or is there consistently a difference between them? To help you answer this question draw another graph on which you plot the temperatures against each other; for example:

Any quantity that varies regularly with hotness, and which can be measured, could be used to establish a temperature scale. (Even the time it takes for an alka seltzer tablet to dissolve in water!) Two fixed points (e.g., melting ice and boiling water) are needed to define the size of a degree.





If the two devices do give the same readings at intermediate temperatures, then you could apparently use either as a thermometer. But if they do not you must clearly decide on only one of them as a standard thermometer. Give whatever reasons you can for choosing one rather than the other.

Discussion

Certainly it is true that we encounter mercury thermometers more often than, for example, thermistor thermometers. Is this simply because a mercury thermometer is more convenient to use for many applications, or is there some more fundamental reason? How should we decide whether to use expansion, or gas pressure, or electrical resistance, or perhaps some other property to define temperature scales?

If we compare many gas thermometers—constant volume as well as pressure, different gases, and different initial volumes and pressures—we find that they all behave quantitatively in very much the same way with changes in hotness. If a given hotness change causes a 10 per cent increase in the pressure of gas A, then the same change will cause a 10 per cent increase in gas B's pressure, too. Or if the volume of one gas sample decreases by 20 per cent when transferred to a particular cold bath, then a 20 per cent decrease in volume will also be observed in a sample of any other gas. This means that the temperatures read from different gas thermometers all agree. And the gas pressure thermometers agree with the gas volume thermometers. This sort of close similarity of behavior between different substances is not found as consistently in the expansion of liquids or solids, or in their other properties—electrical resistance, etc.—and so these thermometers do not agree.

This suggests two things. First, that there is quite a strong case for using the change in pressure (or volume) of a gas to <u>define</u> the temperature change; we could say that a 10 per cent pressure increase means a 10 per cent temperature increase; or a 20 per cent volume decrease means a 20 per cent temperature decrease. Second, the fact that in this set of experiments all gases do behave quantitatively in the same way suggests that there may be some underlying simplicity in the behavior of gases not found elsewhere, and that if one wants to learn more about the way things change with heat, or indeed about their nature in general, one would do well to start with gases.

EXPERIMENT 27 Calorimetry

Speedometers measure speed, voltmeters measure voltage, accelerometers measure acceleration. In this experiment you will use a device called a calorimeter. The name suggests that it measures a quantity connected with heat. The calorie is a unit of heat energy. Unfortunately, the amount of heat energy present in an object cannot be measured as directly as some of the other quantities mentioned above.

The text (Sec. 10.6, etc.) discusses the transformation of energy from one form to another—from mechanical energy to heat energy, from chemical energy to heat energy to mechanical energy, and so on. In this experiment you will investigate some of the properties of heat itself.

You will measure the heat absorbed or given off by a substance by observing the change in temperature of a standard substance. The calorimeter you will use is simply an insulated container in which measured quantities of materials can be mixed together without an appreciable amount of heat being gained from or lost to the outside. The first experiment described below will give you an idea of how good an isolated or "closed" system it is.

Preliminary

Prepare three calorimeters (plastic cups) to test their insulating ability. Fill one cup about half full of ice water. In the second cup put the same amount of ice water with one or two ice cubes floating in it. Put about half a cup of hot water in the third. Measure the temperature of the water in each cup, and record the temperatures and the time of observation in your notebook.

Repeat the observations at about five-minute intervals throughout the period and prepare a sheet of graph paper with coordinate axes so that you can plot temperature as a function of time.

A. Mixing hot and cold liquids

(While you are doing this experiment, continue to take readings of the temperature of the water in your three test cups.)

You are to make several assumptions about the nature of heat, and then use those assumptions to predict what will happen when you mix two samples which are initially at different temperatures. If your prediction is correct, then you can feel some confidence in your assumptions—at least, you can continue to use the assumptions until they lead to a prediction which turns out to be wrong.

First, assume that, in your calorimeter, heat behaves like a fluid which is conserved—that is, it can flow from one substance to another but the total quantity of heat H present in the calorimeter in any given experiment is constant. In symbols,

$$-\Delta H_1 = \Delta H_2$$

heat lost by warm object	heat gained by cold object

Next, assume that if two objects at different temperatures are brought together, heat will flow from the warmer to the cooler object until they reach the same temperature.

Finally, assume that the amount of heat fluid ΔH which must enter or leave an object to produce a given change in temperature is proportional to the mass of the object m, and to the change in temperature ΔT. In symbols,

$$\Delta H = cm\Delta T,$$

where c is a constant of proportionality.

You can use these assumptions to predict the final temperature of the mixture formed when you mix two quantities of water which are initially at different temperatures. You can test the assumptions by measuring the temperature of the mixture to see if the prediction is correct.

Measure and record the mass of two empty plastic cups. Then put about 1/3 cup of cold water in one and about the same amount of hot water in the other, and record the mass and temperature of each. Now mix the two together in one of the cups, stir gently with a thermometer and record the final temperature of the mixture.

Multiply the change in temperature of the cold water by its mass. (Don't forget to subtract the mass of the empty cup.)

Do the same for the hot water.

Q1 What is the product (mass x temperature change) for the cold water?

Q2 What is this product for the hot water?

Q3 Are your assumptions confirmed, or is the difference between the two products greater than can be accounted for by uncertainties in measurement?

(Don't forget that you should be taking readings of the temperature of your three test calorimeters about every five minutes.)

Try another mixture using different quantities of water, for example 1/4 cup of hot water and 1/2 cup of cold. Before you mix the two, try to predict the final temperature.

Q4 What do you predict the temperature of the mixture will be?

Q5 What final temperature do you actually observe?

Estimate the uncertainty of your thermometer readings and your mass measurements.

Q6 Is this uncertainty enough to account for the difference between your predicted and observed values?

Q7 Can you say that you have "proved" that your assumptions are valid for these calorimeter experiments?

The units in which we measure heat have been defined so that they are convenient for calorimeter experiments. The calorie is defined as the quantity of heat necessary to change the temperature of one gram of water by one Celsius degree. (This definition has to be refined somewhat for very precise work but is adequate for our purpose.) In the expression

$$\Delta H = cm\Delta T,$$

when m is measured in grams of water and Δt in Celsius degrees, ΔH will be the number of calories. Because we have defined the calorie this way, the proportionality constant c has the value $1 \frac{cal}{g\ C^\circ}$ when water is the only substance in the calorimeter.

Next you will do a similar experiment mixing materials other than water in the calorimeter to see if your assumptions can still be used. Two such experiments are described below. You may have time for only one of them in what remains of the period. Choose either B or C.

B. Specific heat capacity

(While you are doing this experiment continue to take readings of the temperature of the water in your three test cups.)

Measure the mass of a small metal sample. Put just enough cold water in a calorimeter (plastic cup) to cover the sample. Tie a thread to the metal sample and suspend it in a beaker of boiling water. Measure the temperature of the boiling water.

Record the mass and temperature of the water in the calorimeter.

When the sample has been immersed in the boiling water long enough to be heated uniformly (2 or 3 minutes), lift it out and hold it just above the surface for a few seconds to let the water drip off, then transfer it quickly to the calorimeter cup. Stir gently with a thermometer and record the temperature when the metal sample and water have come to equilibrium.

Q8 Is the product of mass and temperature change the same for the metal sample and for the water?

Q9 If not must you modify the assumptions about heat that you made earlier in the experiment (Sec. A, above)?

In the expression

$$\Delta H = cm\Delta T$$

the constant of proportionality may be different for different materials. For water the constant has the value $1\ \frac{\text{cal}}{\text{g C}^\circ}$. You can find a value of c for the metal you used as follows:

$$\Delta H_w = \Delta H_s$$

heat gained by water · heat lost by sample

$$c_w m_w \Delta t_w = c_s m_s \Delta t_s$$

$$c_s = \frac{c_w m_w \Delta t_w}{m_s \Delta t_s}$$

The constant c_s measured in $\frac{\text{cal}}{\text{g C}^\circ}$, is called the specific heat of the sample.

Q10 What is the value of c_s for the metal sample you used?

C. Latent heat

The cups you filled with hot and cold water at the beginning of the period should show a measurable change in temperature by this time. If you are to hold to your assumption of conservation of heat fluid, then it must be that some heat has gone from the hot water into the room and from the room to the cold water.

Q11 How much has the temperature of the cold water changed?

Q12 How much has the temperature of the water that had ice in it changed?

The heat that must have gone from the room to the water-ice mixture evidently did not change the temperature of the water as long as the ice was present. But the ice melted, so apparently the heat that leaked in was used to melt the ice. Evidently heat was needed to cause a "change of state" (in this case to melt ice) even if there was no change in temperature. The additional heat required to melt one gram of ice is called "latent heat of fusion." Latent means hidden, dormant. The units are cal/g—there is no temperature unit here because no temperature change is involved in latent heat.

Use your calorimeter to find the latent heat of fusion of ice. Start with about 1/2 cup of water which is a little above room temperature, and record its mass and temperature. Place a small piece of ice on paper toweling for a moment to dry off water on its surface, and then transfer it quickly to the calorimeter.

Stir gently with a thermometer until the ice is melted and the mixture reaches an equilibrium temperature. Record this temperature and the mass of the water plus melted ice.

Q13 What was the mass of the ice that you added?

The heat given up by the warm water is:

$$\Delta H_w = c_w m_w \Delta t_w .$$

The heat gained by the water formed by the melted ice is:

$$\Delta H_i = c_w m_i \Delta t_i .$$

The specific heat, c, is the same in both cases: it is the specific heat of water.

The heat given up by the warm water (a) melts the ice, and (b) heats up the water formed by the melted ice:

$$\Delta H_w = H_L + \Delta H_i .$$

So the heat needed to melt the ice is

$$\Delta H_L = \Delta H_w - \Delta H_i .$$

Q14 What is your value for the latent heat of fusion of ice?

When this experiment is done with ice that has been made from distilled water, and which has no inclusions of liquid water, the latent heat is found to be 80 calories per gram of ice. How does your result compare with the accepted value?

D. The law of cooling

If you have been measuring the temperature of the water in your three test cups you should have enough data by now to plot three curves of temperature against time.

Mark the temperature of the air in the room on your graph too.

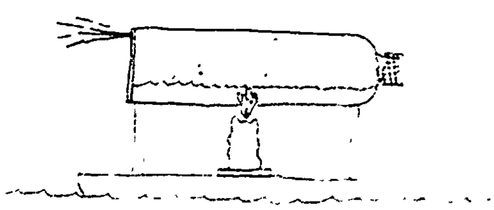
Q15 How does the rate at which the hot water cools depend on its temperature?

Q16 How does the rate at which the cold water heats up depend on its temperature?

Weigh the amount of water in the cups. From the rate of temperature change (degrees/minute) and the mass of water calculate the rate at which heat leaves or enters the cup, at various temperatures. Use this information to estimate the error in your earlier results for specific or latent heat.

Steam Powered Boat

You can make a steam-propelled boat that will demonstrate the principle of Heron's steam engine from a small tooth-powder or talcum-powder can, a piece of candle, a soap dish and some wire.



Punch a hole near one edge of the bottom of the can with a needle. Construct wire legs to support the can horizontally over the candle on the soap dish, rotating the can so that the needle hole is at the top. Half fill the can with water, replace the cover, and place this "boiler" over the lighted candle in the soap dish. If this boat is now placed in a large pan of water, it will be propelled across the pan.

Can you explain the operation of this boat in terms of the conservation of momentum?

Measuring a_g by Whirling an Object

By making a few assumptions you can get a fair value for the acceleration due to gravity by timing an object as you whirl it on the end of a string in a vertical circle of radius r.

You assume that the gain in kinetic energy of the object at the bottom of its swing over that at the top is equal to its loss of gravitational potential energy. That is, you don't wiggle your hand to feed energy into the system; energy is conserved. You also assume that the average speed of the object is the average of the speed at the top, v_1, and that at the bottom, v_2. This is not strictly true because the acceleration is not constant.

You must practice until you can whirl the object at such a rate that it just makes it to the top of the circle. You should feel no upward tension in the string at the top if the speed is just right. At this point the centripetal force equals the weight of the object, or

$$ma_g = \frac{mv_1^2}{r}.$$

We may cancel out m on the assumption that gravitational mass and inertial mass are the same. Substituting this value for a_g into the energy equation,

$$\frac{mv_2^2}{2} = \frac{mv_1^2}{2} + 2ma_g r = \frac{mv_1^2}{2} + 2mv_1^2,$$

so that

$$v_2^2 = v_1^2 + 4v_1^2 \text{ or } v_2 = \sqrt{5}v_1$$

and the average velocity,

$$\bar{v} = \frac{v_1 + v_2}{2} = \frac{v_1(1 + \sqrt{5})}{2} = 1.62\ v_1.$$

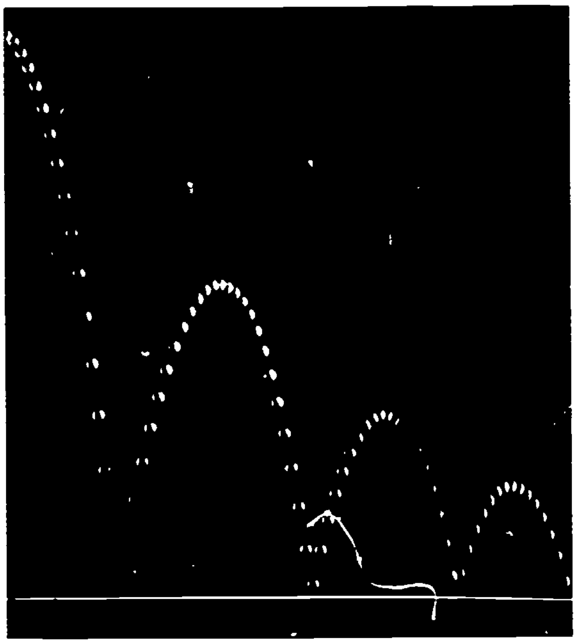
Because of our assumptions, this average velocity is the circumference of the circle divided by the period T from which $\bar{v} = \frac{2\pi r}{T} = 1.62\ v_1$,

and $a_g = \frac{v_1^2}{r} = \frac{4\pi^2 r^2}{T^2(1.62)^2 r} = \frac{15.1r}{T^2}$.

Be sure to use a strong string, about one meter long.

Bouncing-ball Determination of a_g

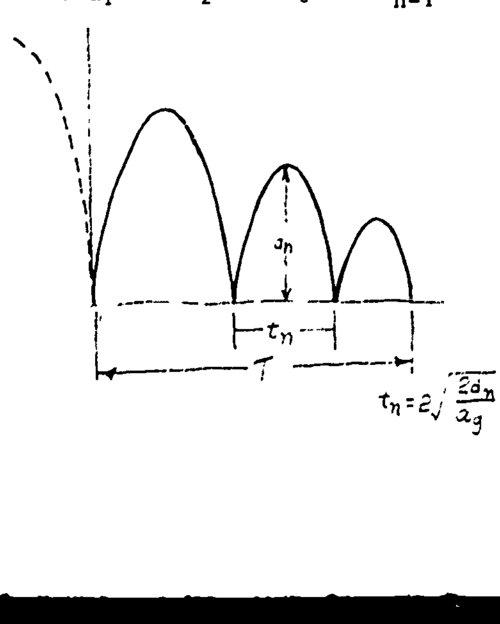
By timing the bounces of a ball, you can determine a_g. The total time required for a ball to make a certain number of successive bounces depends on four factors: 1) the height of its first bounce, 2) the coefficient of elasticity, which is explained below, 3) the number of bounces, and 4) a_g. You can measure the first three and thereby determine a_g.



The distance scale is determined by knowing that a golf ball was used. The time between flashes was 1/30 second.

Theory: Fig. 1 is a photograph of the height vs. the time elapsed for a ball making repeated bounces after falling from height d. Each time the ball bounces, a fraction of its total energy is lost so it does not return to the same height. The coefficient of elasticity, given by $e = \sqrt{\frac{d_1}{d_0}}$, is a measure of how elastic the bounce really is. (Newton defined this as the negative of the ratio of relative speed after impact to that before; hence the radical sign.) If the ball didn't bounce at all, e would be 0; if it bounced to the same initial height, e would be 1. If e remains constant for successive bounces (nearly true for a uniform ball),

$$e = \sqrt{\frac{d_2}{d_1}} = \sqrt{\frac{d_3}{d_2}} = \sqrt{\frac{d_4}{d_3}} = \sqrt{\frac{d_n}{d_{n-1}}} \quad (1)$$



In Unit 1 you learned that the time taken by a ball to fall a height d is $\sqrt{\frac{2d}{a_g}}$. It will take twice as long for a ball to rise to a height d and fall back to the ground. So the time, t_n, between the two bounces when the ball rises to the height d_n, is given by

$$t_n = 2\sqrt{\frac{2d_n}{a_g}}.$$

Thus, the total time from t_0 to t_n is:

$$T_n = 2\sqrt{\frac{2d_1}{a_g}} + 2\sqrt{\frac{2d_2}{a_g}} + 2\sqrt{\frac{2d_3}{a_g}} + \dots + 2\sqrt{\frac{2d_n}{a_g}}$$

$$\text{or } T_n = 2\sqrt{\frac{2}{a_g}}[\sqrt{d_1} + \sqrt{d_2} + \sqrt{d_3} + \cdots + \sqrt{d_n}].$$

Since we say in equation (1) that $\sqrt{d_n} = e\sqrt{d_{n-1}}$, then:

$$T_n = 2\sqrt{\frac{2d_1}{a_g}}[1 + e + e^2 + \cdots + e^{n-1}].$$

This is a geometric series. The sum of the first n terms is:

$$T_n = 2\sqrt{\frac{2d_1}{a_g}}\left[\frac{1-e^n}{1-e}\right].$$

Therefore,

$$a_g = \frac{8d_1}{(T_n)^2}\left[\frac{1-e^n}{1-e}\right]^2.$$

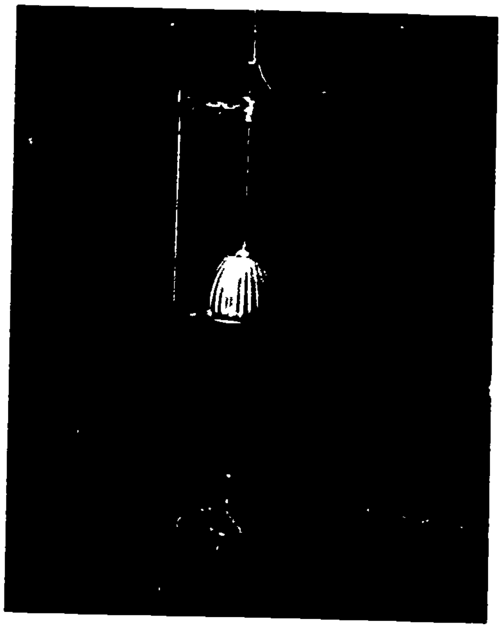
Procedure: Determine the coefficient of restitution by measuring the height to which the ball bounces after having been dropped from a known height, and applying the formula, $e = \sqrt{\frac{d_1}{d_0}}$. Check this for various heights to make sure that e for this ball and surface does not vary significantly.

Then drop the ball from a known height, from which you can calculate d_1, start a timer as the ball hits the first time, and time as many bounces as possible.

The data for the height of each bounce will be useful to you again in Unit 6.

Heron's Engine

You can make a working model of Heron's engine from a metal toilet float and two empty metal tubes from ball point pens, as shown in Fig. 1.



Unscrew the metal rod from the float. Drill a hole into the float through the socket where the rod attaches, being careful not to damage the socket threads. This hole is used to fill the float with water.

Drill two holes exactly opposite each other along the central flange of the float. Make them just large enough to be a tight fit with the metal pen tubes.

Cut two sections of tube about 3" long and bend them in the middle to form a right angle. Be careful in bending them not to collapse the tubing. Several small bends are better than trying one large one. Solder these in place in the two holes in the float. NOTE: Turn them so that the rotation of the float will tend to TIGHTEN the float on the rod; otherwise the float may come loose while it is rotating.

Fill the float about one-fourth full and screw the rod in tightly. Suspend the rod and float from a fishing swivel or beaded chain such as used for light switches so that they can swivel freely. Place a bunsen burner under the float.

As the steam spurts out one way, the float must turn the other way since momentum must be conserved. A balloon behaves in a similar way when released to fly about a room.

Be careful not to get too close to the steam as it spurts out the tubes. You may find it helpful to pinch the ends of the tubes slightly.

CAUTION: Don't let the pressure in the float get too high. When the float starts turning, reduce the heat to a level just necessary to keep the float turning. You don't want a boiler explosion!

One Student = ? Horsepower

When you walk up a flight of stairs, the work you do goes into frictional heating and increasing gravitational potential energy. The $\Delta(PE)_{grav}$, in joules, is just the product of your weight in newtons and the height of the stairs in meters. (In foot-pounds, it is your weight in pounds time the height of the stairs in feet.)

Your useful power output is the rate at which you did the lifting work—that is, the total change in $(PE)_{grav}$ divided by the time it took to do the work.

Walk or run up a flight of stairs, and have someone time how long it takes. Determine the total vertical height that you lifted yourself by measuring one step, and multiplying by the number of steps.

Calculate your useful work output and your power, both in watts and in horsepower.

Energy Analysis of a Pendulum Swing

According to the law of conservation of energy, the loss in gravitational potential energy of a simple pendulum as it swings from the top of its swing to the bottom is completely transferred into kinetic energy at the bottom of the swing. You can check this with the following photographic method.

A one-meter simple pendulum (measured from the support to the center of the mass) and a 0.5 kg mass work well. Release the pendulum from a position where its vertical displacement is 10 cm.

To simplify the calculations, set up the camera for 10:1 scale reduction (see page 4 of the Unit 1 Student Handbook). Two different strobe approaches have proved successful: 1) tape an AC blinky to the mass, or 2) attach an AA cell and bulb to the pendulum and use a motor strobe in front of the camera lens. (Directions for building an AC Blinky are given on p. 110 of the Equipment Notes in the Unit 1 Teachers' Guide. Ask your instructor about them.) Make a time exposure for one swing of the pendulum. In either case you may find it necessary to use a two-string suspension to prevent the pendulum bob from spinning while swinging.

You can either measure directly from the print, or make pinholes at the center of each image on the photo and project the hole images onto another sheet of paper. Calculate the instantaneous speed, v, at the bottom of the swing by dividing the distance traveled between the images nearest the bottom of the swing by the time interval between the images. The kinetic energy at the bottom of the swing, $\frac{1}{2}mv^2$, should equal the change in potential energy from the top of the swing to the bottom. If h is the difference in vertical height between the bottom of the swing and the top, then $v = \sqrt{2a_g h}$.

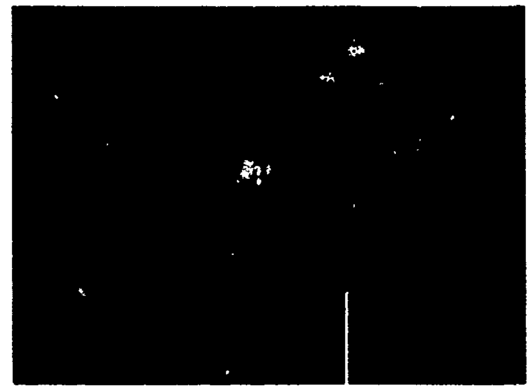


Fig. 1

If you plot both the kinetic and potential energy on the same graph (Fig. 2), and then plot the sum of KE + PE, you can check whether total energy is conserved during the entire swing.

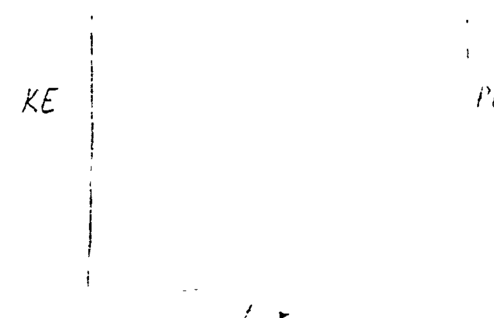
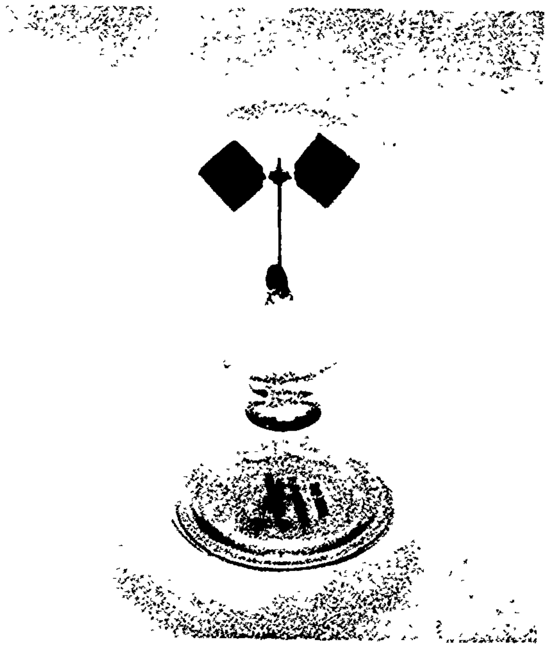


Fig. 2

Crooke's Radiometer

A toy which may be purchased for a dollar or so in novelty shops or at science museums is known as the Crooke's radiometer. It consists of a sort of paddlewheel with four vanes which, balanced on a needle point, is free to rotate readily. One side of each vane is blackened and the whole apparatus is contained within a partially exhausted spherical bulb. When placed on a window-sill exposed to sunlight, the wheel will whirl rapidly.

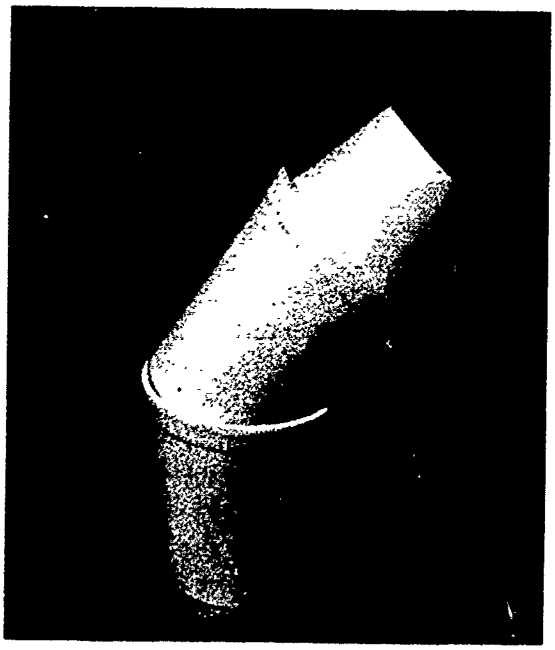


We find the explanation in our kinetic model of a gas. To work, the bulb must contain some residual gas. The gas molecules, if they are at a uniform temperature throughout the bulb, will strike both sides of a vane with the same momentum and no rotation will result. If, however, the vanes are exposed to radiation, be it light or heat, the blackened side will absorb more energy and become hotter. Now when molecules strike this side their temperature rises as does their velocity. Then when they leave the vane their momentum is greater than when they approached. The vane recoils and rotates in the direction observed. You may test this hypothesis by cooling the bulb. Instead of setting the radiometer between two electric light bulbs, set it between two cakes of ice. The paddlewheel rotates in the opposite direction.

There are many questions which arise regarding the radiometer. What is the critical residual pressure to make it work efficiently? Is this related in any way to the mean free path of the molecules and the size of spherical bulb? If the radiometer is actuated by a light bulb, when the bulb is removed the paddlewheel slows down and then stops; but if you observe carefully it will start to turn in the opposite direction for a bit. If you don't mind ruining one radiometer for normal use, carefully break the tip off the long glass tube used to seal the bulb. Then you can place the radiometer in a bell jar and use a vacuum pump to investigate what happens under various pressure conditions.

Ice Calorimetry

A simple apparatus made up of thermally insulating styrofoam cups can be used for doing some ice calorimetry experiments. Although the apparatus is simple, careful use will give you excellent results. To determine the heat transferred in processes in which heat energy is given off, you will be measuring either the volume of water or the mass of water from a melting sample of ice.



You will need either three cups the same size (8 oz or 6 oz), or two 8 oz and one 6 oz cup. Also have some extra cups ready. One large cup serves as the collector, A, (Fig. 1), the second as the ice container, I, and the smaller one (or one of the same size cut back to fit inside the ice container as shown) as the cover, K.

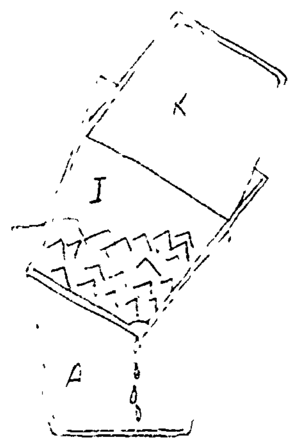


Fig. 1

Cut a hole about 1/4" in diameter in the bottom of cup I so that melted water can drain out into cup C. To keep the hole from becoming clogged by ice, place a bit of window screen in the bottom of I (Fig. 2).

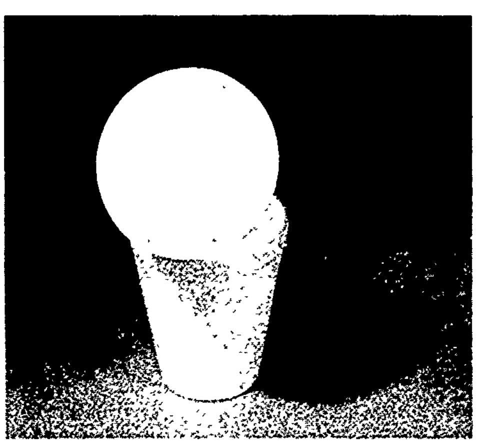


Fig. 2

In each experiment, ice is placed in cup I. This ice should be carefully prepared, free of bubbles, and dry, if you want to use the known value of the heat of fusion of ice, L_f. However, you can use ordinary crushed ice, and determine experimentally the effective heat of fusion of this non-ideal ice first before doing any of the experiments. (Why should these two values differ?)

In some experiments which require some time to complete (such as Exp. b), you should set up two identical sets of apparatus (same quantity of ice, etc.), except that one does not contain a source of heat, and so on. One will serve as a fair measure of the background effect. Measure the amount of water collected in it during the same time, and subtract it from the total amount of water collected in the experimental apparatus, thereby correcting for the amount of ice melted just by the heat in the room. An efficient method for measuring the amount of water is to place the arrangement on the pan of a balance and lift up cups I and K at regular intervals (about 10 min.) while you weigh A with its contents of melted ice water.

a) Heat of Fusion of Ice:

Fill a cup about 1/2 to 1/3 full with crushed ice. (Crushed ice has a larger amount of surface area, and so will melt more quickly, thereby minimizing errors due to heat from the room.) Bring a small measured amount of water (e.g. 20 cc) to a boil in a beaker or large test tube and pour it over the ice in the cup. Stir briefly with a poor heat conductor, such as a glass rod, until equilibrium has been reached. Pour the ice-water mixture through cup I. Collect and measure the amount of water (m_f) in C. If m_o is the original amount of hot water at 100°C with which you started, then $m_f - m_o$ is the amount of ice that was melted. Hence,

$$L_f\ (m_f - m_o) = m_o\ (100 - 0),$$

and

$$L_f = \frac{m_o}{m_f - m_o} \times 100$$

Note: this derivation is true only if there is still some ice in the cup afterwards. If you start with too little ice, the water will come out at a higher temperature.

For crushed ice which has been standing for some time, the value of L_f will vary between 70 and 75 calories per gram.

b) Heat Exchange and Transfer by Conduction and Radiation:

For several possible experiments you will need the following additional apparatus. Make a small hole in the bottom of cup K and thread two wires, soldered to a lightbulb, through the hole. A flashlight bulb which draws between 300 and 600 milliamperes is preferable; but even a GE #1130 6-volt automobile headlight bulb (which draws 2.4 amps) has been used with success.

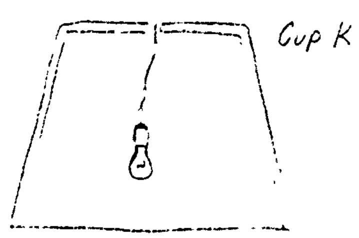


Fig. 3

In each experiment, you are to observe how different apparatus affects heat transfer into or out of the system.

(1) Place the bulb in the ice and turn it on for 5 minutes. Measure the ice melted.

(2) Repeat (1), but place the bulb above the ice for 5 minutes.

(3) and (4): Repeat (1) and (2), but cover the inside of cup K with aluminum foil.

(5) and (6): Repeat (3) and (4), but in addition cover the inside of cup I with aluminum foil.

(7) Prepare "heat absorbing" ice by freezing water to which you have added a small amount of dye, such as India ink. Repeat any or all of experiments (1) through (6) using this specially prepared ice.

Some questions to guide your observations: does any heat excape when the bulb is immersed in the ice? What arrangement keeps in as much heat as possible?

Predicting the Range of a Bow

The Teacher Guide contains instructions for predicting the range of a slingshot by calculating how much work you do on the slingshot while drawing it back (Demonstration 34 in Chapter 11). Ask your instructor for these if the demonstration wasn't done in class.

A more challenging problem is to estimate the range of an arrow by calculating the work done in drawing the bow. A bow behaves even less according to Hooke's law than a slingshot; the force vs. displacement graph is definitely not a straight line.

To calculate the work done, fasten the bow securely in a vise or some solid mounting. Attach a spring balance to the bow and record values of force (in newtons) as the bowstring is drawn back one centimeter at a time from its rest position (without having an arrow notched). Plot a force vs. displacement graph. Count squares to find the "area" (force units times displacement units) under the graph; this is the work done on the bow—equal to the elastic potential energy of the drawn bow.

Assume that all the elastic potential energy of the bow is converted into the kinetic energy of the arrow and predict the range of the arrow by the same method outlined in Demonstration 34.

Chapter 11 The Kinetic Theory of Gases

EXPERIMENT 28 Monte Carlo Experiment on Molecular Collisions

In Chapter 11 on kinetic theory you saw the discussion of a model for a gas consisting of a large number of very small particles in rapid random motion. In Sec. 11.4 you saw how Clausius modified this model by giving the particles a finite size. Clausius showed that the average distance a molecule travels between collisions, the so-called "mean free path," is given by

$$D = V/NA \qquad (1)$$

where V is the volume of the gas under consideration, N is the number of molecules in that volume, and A is the cross-section of an individual molecule. Other contributors to this modified model were Maxwell, who showed that the viscosity of the gas is proportional to the ratio of the momentum of the individual molecule to its cross-section, mv/A, and Loschmidt, who was able to estimate a value for N.

This experiment will show how from a comparatively small random sample of molecules one estimates properties of the gas as a whole. The technique is named the Monte Carlo method after that famous (or infamous) gambling casino in Monaco. (The essence of the method is randomness, illustrated by the numbers at which a roulette wheel stops.) The experiment consists of two parts. You are asked to complete only one.

Part A. Collision probability for a gas of marbles.

In this part you will try to determine the diameter of a "target marble" by rolling a "bombarding marble" into an array of target marbles placed at fixed random positions on a level sheet of graph paper. You count the number of hits and misses. To assure randomness to the motion of the bombarding marble, you start it at the top of an inclined board studded with nails spaced about an inch apart—a sort of pin-ball machine (Fig. 1). To get a fairly even yet random distribution of its motion, move successive releases of the bombarding marble one space at a time across the top of the inclined board.

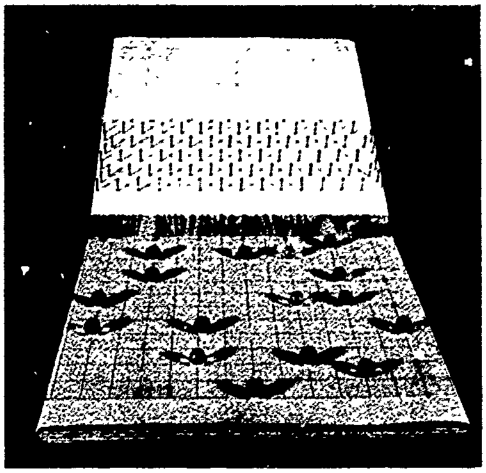


Fig. 1

It remains to place the target marbles at random. On your graph paper draw a network of crossed grid lines spaced at least two marble diameters apart. (If you are using marbles whose diameters are half an inch, these grid lines should be spaced 1.5 to 2 inches apart.) Number the grid lines as shown in Fig. 2.

One way of placing the marbles at random is to go to the table of 380 two-digit random numbers printed at the end of the experiment. Each student should start at a different place in the table (chosen at random) and then select the next eight numbers. Let these numbers locate positions on the grid. The first digit of each number gives the x coordinate, the second gives the y—or if you prefer, always the other way around. Place the target marbles in these positions. (For example, the eight locations indicated in Fig. 2 come from the top

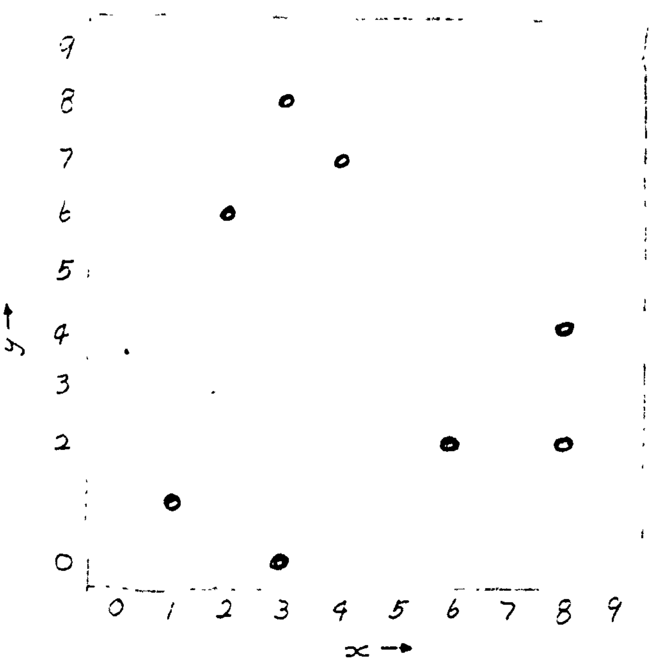


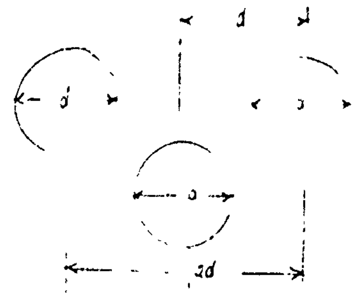
Fig. 2 The first eight numbers in the last column of the table of random numbers were used to place the marbles.

of the last column of the table. Check these locations if you are in any doubt about the procedure. (How could you have used a Roulette wheel instead of the random number table to distribute the marbles at random?)

With your array in place make about fifty trials with the bombarding marble, and compute the ratio, R, of hits to total trials. A hit is obvious. You should return the target marble to its original position if it is dislodged. Any time the bombarding marble goes completely through the array (whether it bounces off a side wall or not) without hitting a target marble, it is a miss. (Books may be placed along the sides of the graph paper and across the back to serve as containing walls.)

This ratio R of hits to total trials is an experimental result obtained by this method (which may be called the "Monte Carlo" method) on a random sample. Let us see how the ratio leads to the diameter of the target object. It will help us see how the same method works for determining size of molecules (but with 10^{20} or so molecules instead of 8 "marble molecules.")

If there were no target marbles, the bombarding marble would get a clear view of the full width, say D, of the back wall enclosing the array. There could be no hit. If, however, there were N target marbles, the 100 per cent clear view or window would be cut down. The bombarding marble would see unobstructed "daylight" through a width D reduced by Nd, where d is the diameter of a target marble.
(It is assumed that no target marble is hiding behind another and that target and bombarding marbles have the same size.) However, it is not sufficient for the bombarding marble to see some daylight head-on to avoid a hit. If its center passes within a distance of one radius on either side of a target marble there will be a glancing hit. This means that a target marble has a blocking effect over twice its diameter (its own diameter plus two radii).



Therefore the ratio of hits to total trials is 2Nd/D (total blocked width to total width). This leads to the expression for the diameter of the target marble,

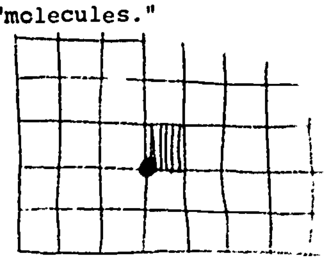
$$d = RD/2N.$$

To check the efficacy of the Monte Carlo method, compare the value for d obtained from the above formula with that obtained by direct measurement of the target marble. For example line them up against a book, measure the total length of all of them together, and divide by the number of marbles to find the diameter d of one.

Part B. Mean free path for collision squares.

In this part, in place of marble "molecules" you will play with blacked-in squares as target molecules. On a sheet of graph paper, say 50 units on a side (2500 squares), you will locate by the Monte Carlo method between 40 and 100 molecules. Each student should choose a different number of molecules.

Go to the table of random numbers provided. You will find it contains 190 pairs of numbers arranged in five columns. Let each pair be the coordinates of a point on your graph paper. (If a particular pair should contain a number greater than 49 you cannot use it. Ignore it and take the next pair.) Then black in the squares in which these points are the lower left hand corners. You now have a random array of square target "molecules."



(03, 02)

Let us see how a test particle traverses this array. It is bound to collide with some of the target molecules. There are certain rules to this game of collision. We list five.

a) The test particle can travel only along lines of the graph paper, up or down, left or right. The kick-off is from some point (chosen at random) on the left hand edge of the graph paper, and the test particle initially moves horizontally from this point until it collides with a square molecule or another edge of the graph paper.

b) If the test particle strikes the upper left hand corner of a target molecule it is diverted upward through a right angle. If it should strike a lower left hand corner it is diverted downward, again through ninety degrees (Fig. 3). This rule may be generalized for any corner collision as follows: the rebounding or reflected test particle turns at right angles but always avoids running along a side of a target molecule.

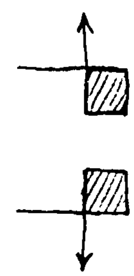
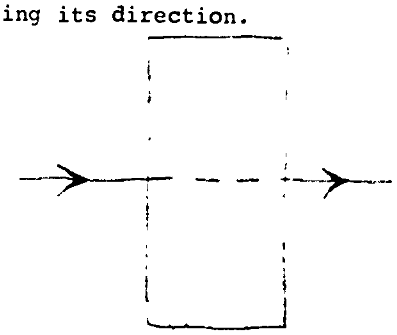


Fig. 3

c) When the path of the test particule meets an edge of the graph paper, it is not reflected directly back. (Such a reversal of path would make the particle retrace its previous paths.) Rather it moves two spaces to the right along the boundary before reversing its direction.

d) There is an exception to rule (c). Whenever the test particle strikes the boundary so near a corner that there isn't room for it to move two spaces to the right without meeting another edge of the graph paper, have it move two spaces to the left along the boundary.

e) It occasionally may happen that two target molecules occupy adjacent squares and that the test particle hits touching corners of the two target molecules at the same time. The rule is, it counts as a hit and the particle goes along the adjacent edges of the two target molecules straight through without changing its direction.



With these collision rules in mind you can trace the path of the test particle as it bounces about among the random array of target square molecules. Count the number of collisions with targets. Follow the path of the test particle until you get 51 hits. (Collisions with the boundary do not count.) Next record the 50 lengths of the paths of the particle between collisions. Distances to and from a boundary should be included, but <u>not</u> distances along a boundary (the two spaces introduced to avoid back-tracking). These 50 lengths are the free paths of the test particle. Total them and divide by 50 to obtain the mean free path, D, for your random two-dimensional array of square molecules.

You can check the efficacy of the Monte Carlo method by comparing your experimental mean free path with that obtained from a modification of formula (1) obtained for a three-dimensional array. Replace the volume, V, by the area of your graph paper, i.e. the total number of squares on it, and the cross-section A by twice the length of the side of a square molecule. N for you is the number of square molecules you used (somewhere between 40 and 100).

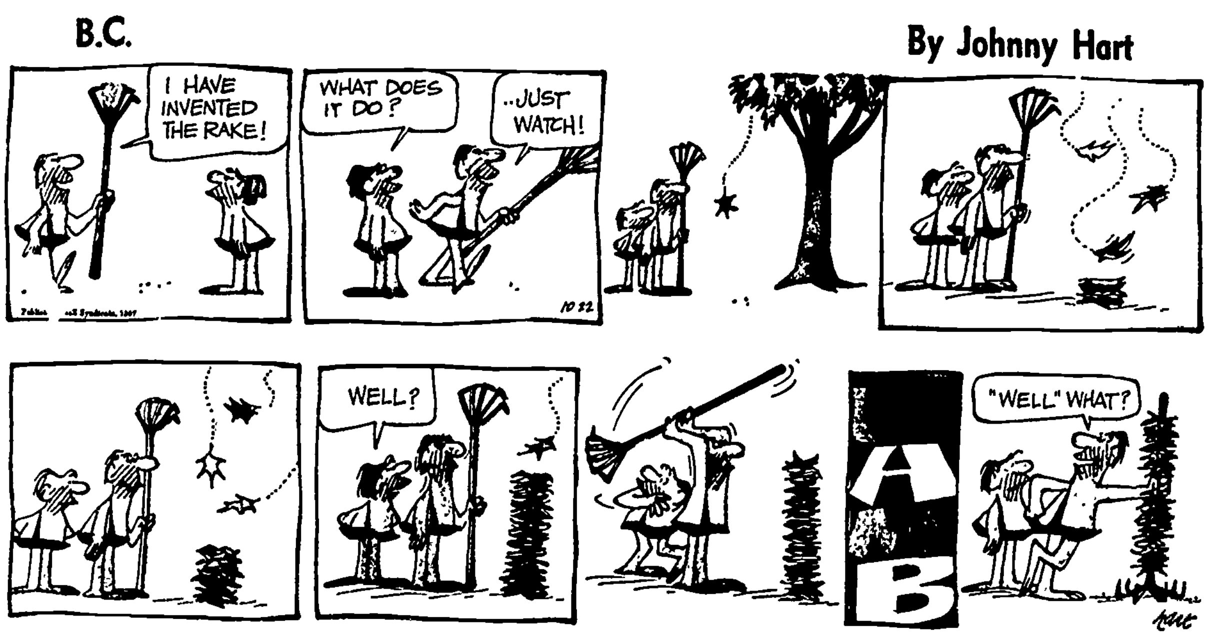


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Table of Random Numbers

25	19	24	10	92	93	01	98	30	62
23	02	50	00	41	77	04	18	14	82
55	85	44	37	46	52	75	85	88	26
68	45	90	57	61	03	99	43	61	47
69	31	50	74	53	06	39	68	13	38
37	31	44	04	92	06	60	97	59	11
66	42	32	74	24	20	26	01	95	30
33	65	75	73	74	75	10	96	39	84
76	32	76	18	74	67	97	91	73	19
43	33	00	17	12	70	91	98	33	17
28	31	54	95	36	44	78	01	39	59
97	19	69	99	96	96	78	65	13	09
82	80	64	82	70	06	10	09	78	80
03	68	41	46	07	78	60	99	62	85
65	16	66	96	76	21	76	89	66	48
24	65	19	69	55	17	06	89	61	00
02	72	46	29	64	67	09	81	52	16
79	16	61	28	70	22	97	68	00	12
04	75	19	24	61	64	28	62	52	48
40	64	78	12	51	70	61	61	88	22
06	27	06	19	36	16	23	61	51	63
62	40	42	02	37	71	88	80	55	83
00	98	93	43	57	55	06	74	98	00
50	64	21	63	95	54	97	60	12	64
38	54	37	14	84	62	51	59	12	81
46	86	03	13	04	44	23	49	35	72
90	72	58	11	28	28	96	37	96	34
66	21	58	57	59	35	47	53	85	33
87	05	64	07	85	18	42	95	83	33
46	90	78	63	98	94	02	84	82	34
11	88	14	93	94	13	73	21	42	07
11	05	64	57	35	91	49	12	02	73
33	94	07	34	35	22	34	16	38	93
24	89	03	87	59	20	81	64	58	35
15	19	48	18	94	87	04	12	93	55
05	64	19	18	34	69	63	44	42	17
57	49	52	25	20	56	74	29	62	37
77	82	80	97	60	64	31	52	54	36

EXPERIMENT 29 Behavior of Gases

Air is elastic or springy. You can feel this when you put your finger over the outlet of a bicycle pump and push down on the plunger. You can tell that there is some connection between the volume of the air in the pump and the force you exert, but the exact relationship is not obvious. There is also a connection between the volume of a sample of air (at constant pressure) and its temperature. Gases, like most solids and liquids, expand when they are heated. Seventeenth-century scientists were intrigued with the idea that these kinds of happenings in nature could often be described by simple numerical relationships.

Robert Boyle performed an experiment on the relation of volume to pressure shortly before 1660. In a book published that year, entitled New Experiments Physico-Mechanicall, Touching the Spring of the Air, he said that his purpose was not "to assign the adequate cause of the spring of the air, but only to manifest, that the air hath a spring, and to relate some of its effects."

The way in which he recorded his data tended to obscure the very simple relationship between pressure and volume which we now know as Boyle's Law. It was two centuries later that a theory was developed which accounted satisfactorily for the behavior of gases (the kinetic theory of gases).

The purpose of these experiments is not simply to show that Boyle's Law and Gay Lussac's Law (which relates temperature and volume) are "true." Rather, it is to show how data from such experiments can be analyzed and interpreted.

A. Pressure and volume at constant temperature

Boyle used a long glass tube in the form of a "J" to investigate the "spring of the air." The short arm of the J was sealed, and air was trapped in it by pouring mercury into the top of the long arm. Apparatus for using this method may be available in your school.

A simpler method requires only a small plastic syringe, calibrated in cc, and mounted so that you can push down the piston by piling weights on it. If you use this method, remember that the pressure on on the air in the syringe due to the weights on the piston (P_w) is equal to the force exerted by the weights divided by the area of the face of the piston. Remember that weight $F_g = ma_g$.

Q1 What is the weight (newtons) of a 0.1 kg mass?

Remove the piston from the syringe, measure the diameter (2R) of the piston, and compute its area ($A=\pi R^2$). Then insert the piston about half-way down the barrel of the syringe. The piston may tend to stick slightly. Give it a twist to free it and so help it come to its equilibrium position. Then record this position.

Add weights to the top of the piston and each time record the equilibrium position, after you have given the piston a twist to help overcome friction.

Record your data in a table with columns for volume, weight and pressure. Then remove the weights one by one to see if the volumes are the same with the piston coming up as they were going down.

If your apparatus can be turned over so that the weights pull out on the plunger, obtain more readings this way. Record these as negative forces. Of course, stop adding weights before the piston is pulled all the way out of the barrel. Again remove the weights and record the values on returning.

You will now have a set of numbers somewhat like the ones Boyle reported in his book. One way to look for a relationship between the pressure P_w and the volume V is to plot the data on graph paper, draw a smooth curve through the points, and try to guess what kind of mathematical expression would give that same curve when plotted.

Plot V (vertical axis) as a function of P_w (horizontal axis). Since volume decreases as P_w increases your curve may represent an inverse relationship. As a first guess at the mathematical description of this curve, try the simplest possibility, which would have the form

$$\left(\frac{1}{V}\right) = kP_w.$$

You can find out if this is the correct expression by plotting another curve with the reciprocal of the volume $\frac{1}{V}$ as a function of the pressure. If your guess was right, this curve will be a straight line. Add another column to your data table for values of $\frac{1}{V}$, and plot this against P_w to see if a straight line results.

Q1 Does the curve pass through the origin?

Q2 At what point does your curve cross the horizontal axis? (In other words, what is the value of P_w for which $\frac{1}{V}$ would be zero?) What is the value of V at this point? What is the physical significance of the value of P_w?

In Boyle's time it was not understood that air is really a mixture of several gases. Do you think you would find the same relationship between volume and pressure if you tried a variety of pure gases instead of air? If there are other gases available in your laboratory, flush out and refill your apparatus with one of them and try the experiment again.

Q3 Does the curve you plot have the same shape as the previous one?

Q4 Is the law that relates volume to pressure the same for all the gases you have tested?

B. Temperature and volume at constant pressure

Boyle suspected that the temperature of his air sample had some influence on its volume, but did not do a quantitative experiment to find the relationship between volume and temperature. It was not until about 1800, when there were better ways of measuring temperature, that this relationship was established.

You could use several kinds of equipment to investigate the way in which volume changes with temperature. One kind is a glass bulb with a J tube of mercury or the syringe described above. In both, the gas inside is at atmospheric temperature. Immerse the bulb, or syringe in a beaker of cold water and record the volume of gas and temperature of the water periodically as you slowly heat the water.

A simpler piece of equipment that will give just as good results can be made from a piece of glass capillary tubing, about 15 cm long. One end of the tube is closed off. A small pellet of mercury about half-way up the tube traps a fixed amount of air in the tube. Since the bore of the tube is constant, the volume of the gas sample is directly proportional to its length. Immerse the tube in a beaker of water and take readings of temperature and volume (length) as you heat the water up.

If you can, you should repeat the experiment using a gas other than air.

Whichever method you use, you should plot a graph of volume against temperature.

Q5 If the curve you plotted is a straight line, does this "prove" that the volume of a gas at constant pressure is proportional to its temperature?

Q6 Remember that the thermometer you used probably depended on the expansion of a liquid such as mercury or alcohol. Would your graph have been a straight line if a different type of thermometer had been used?

Your data from the above experiment should show that air expands when it is heated and contracts when it is cooled.

Q7 If you could continue to cool the air, would there be a lower limit to the volume it would occupy?

Draw a straight line as nearly as possible through the points on your V-T graph and extend it to the left until it shows the approximate temperature at which the volume would be zero. Of course you have no reason to assume that gases have this simple linear relationship between volume and temperature all the way down to zero volume. (In fact, air would change to a liquid long before it reached the temperature indicated on your graph for zero volume.) However, some gases do show this linear behavior over a wide temperature range, and the straight line always crosses the T-axis at the same point. This point represents the lowest temperature that has meaning for the behavior of gross matter—the "absolute zero" of temperature.

Q8 What value does your graph give for this temperature?

Questions for discussion

Both the pressure and the temperature of an air sample affect its volume. In these experiments you were asked to consider each of these factors separately.

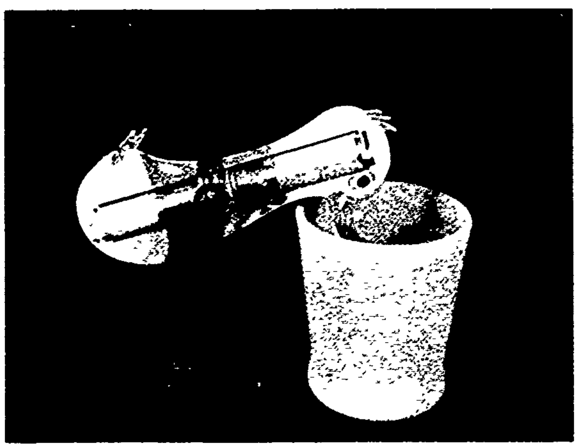
Q9 Were you justified in assuming that the temperature remained constant in the first experiment as you varied the pressure? How could you check this? How would your results be affected if in fact the temperature went up each time you added weight to the plunger?

Q10 In the second experiment the gas was at atmospheric pressure. Would you expect to find the same relationship between volume and temperature if you repeated the experiment with a different pressure acting on the sample?

Gases such as hydrogen, oxygen, nitrogen and carbon dioxide are very different in their chemical behavior. Yet they all show the same simple relationships between volume, pressure and temperature that you found in these experiments, over a fairly wide range of pressures and temperatures. This suggests that perhaps there is a simple physical model which will explain the behavior of all gases within these limits of temperature and pressure.

Drinking Duck

A toy called a Drinking Duck ($1.00, No. 60,264 in Catalogue 671, Edmund Scientific Co., Barrington, New Jersey 08007) demonstrates very well the conversion of heat energy into energy of gross motion by the processes of evaporation and condensation. The duck will continue to bob up and down as long as there is enough water in the cup to wet his beak.



Rather than ruin your spirit of adventure, we won't tell you how it works. First see if you can figure out a possible mechanism for yourself. If you can't, George Gamow's book, The Biography of Physics, has a very good explanation, as do some encyclopedias. Gamow also has an interesting calculation of how far the duck could raise water in order to feed himself. An interesting extension is to replace the water with rubbing alcohol. What do you think will happen?

Lest you think this device useful only as a toy, an article in the June 3, 1967 Saturday Review described a practical application being considered by the Rand Corporation. A group of engineers built a 7-foot long "bird" using Freon 11 as the working fluid. The object was to investigate possible usage of large size ducks for irrigation purposes in the Nile River valley.

Mechanical Equivalent of Heat

Joule's apparatus for measuring the heat generated by stirring a liquid is described in Sec. 11.1 of the text. By dropping a quantity of lead shot from a measured height and measuring the resulting change in temperature of the lead, you can get a value for the mechanical equivalent of heat.

Equipment

Cardboard tube	2 kg lead shot
Stoppers	Thermometer

Procedure

Close one end of the tube with a stopper, and put in about 1-2 kg of lead shot which has been cooled about 5°C below room temperature. Close the other end of the tube with a stopper which has been drilled and a thermometer inserted in it. Carefully roll the shot to the end of the tube and record its temperature. Quickly invert the tube, remove the thermometer, and plug the hole in the stopper. Now invert the tube so the lead falls the full length of the tube and repeat this one hundred times. Re-insert the thermometer and measure the temperature. Measure the average distance the shot falls, which is the length of the tube minus the thickness of the layer of shot in the tube.

Discussion

If the average distance the shot falls is h and it is inverted N times, the work done raising the shot with mass m is:

$$W = Nma_g h.$$

The heat ΔH needed to raise the temperature of the shot by an amount Δt is:

$$\Delta H = cm\Delta t$$

where c is the specific heat capacity of lead, $0.031 \frac{\text{cal}}{\text{gm C}^\circ}$.

The mechanical equivalent of heat is $\frac{W}{\Delta H}$. The accepted experimental value is 4,184 newton-meters per kilocalorie.

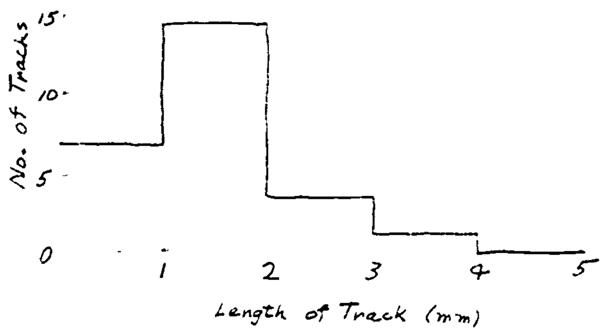


Fig. 2 Distribution obtained using Fig. 1

distribution of speeds for a given "temperature." How should the "temperature" of the bearing balls change if we shake the pan more violently before we take the picture? Try it and see. What happens to the shape of the distribution curve at higher "temperatures?"

Two other extensions are very much worth trying. If molecules of different mass are at the same temperature, the average velocities of the two types will be different. If you plot the speed distribution for each type of molecule separately, there should be two separate peaks on the curves. Fig. 3 shows a

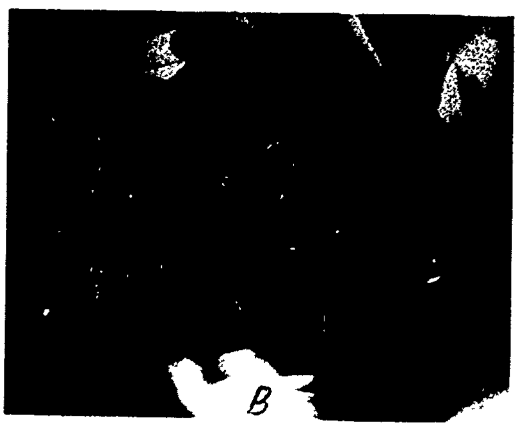


Fig. 3

photo obtained using 9 1/2" steel balls and 9 1/4" steel balls, and the two speed distributions are shown in Fig. 4.

The shape of the curves should become smoother if we increase the number of balls. Try using 30, 40, or 50.

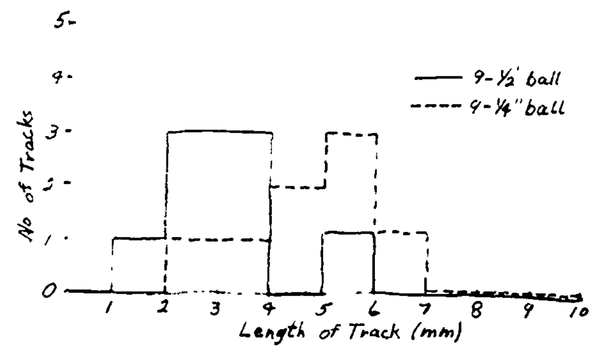


Fig. 4

Two cautions: the pan must be motionless at the instant the photo is taken or its motion will affect the distribution. (If you doubt this, try it!) Secondly, you may have to take several pictures before you get one that looks like the "right" distribution. What can you conclude about what you would have to do in order to make this a better model for what we observe using real gases?

Rockets

If setting off rockets can be legally arranged in your area, and their use is supervised, they can provide excellent projects for studying conversion from kinetic to potential energy, thrust, etc.

Demonstration 14, on page 96 of the Unit 1 Teacher Guide (ask your instructor for it) contains instructions for how to build two different types of small test stands for taking thrust data to use in predicting the maximum height, range, etc. Estes Industries, Box 227, Penrose, Colorado 81240, will send a very complete free catalogue and safety rules on request. Other good references are listed in the Teacher Guide article.

After steam: the 'Black Country' near Wolverhampton 1866

Problems of Scientific and Technological Growth

The era which you are studying in Unit 3 is rich in examples of man's disquiet and ambivalence in the face of the Industrial Revolution. Instead of pastoral waterwheel scenes, men lived in areas with pollution problems as bad or worse as those we face today, such as the scene above in Wolverhampton, England in 1866. As William Blake lamented in "Stanzas From Milton,"

And did the Countenance Divine
   Shine forth upon our clouded hills?
And was Jerusalem builded here
   Among these dark Satanic mills?

Ever since, we have profited from advances in technology. But we also still face problems: e.g., of pollution and of displacement of men by machines.

One of the major problems is that of a growing lack of communication between those working in science and those pursuing other areas of interest. When C. P. Snow in 1959 published a book on this particular aspect, entitled The Two Cultures and the Scientific Revolution, he initiated a wave of debate that is still rippling.

Collateral Reading for Physics Courses

Resource Letter ColR-1 (available free from AIP, 335 East 45th Street, New York, 10017, if you include a stamped return envelope) includes the following interesting readings:

Science and Ideas, by Arons and Bork; readings in the history, philosophy and sociology of science.

A Stress Analysis of a Strapless Evening Gown, by Baker; this volume gathers many well-known satires on science.

Science and Literature - A Reader, by Cadden and Brostowin, critical essays about the relation of science to literature, and excerpts from literature influenced by science.

The Two Cultures and the Scientific Revolution, Snow; the most famous of all the articles concerning the two cultures.

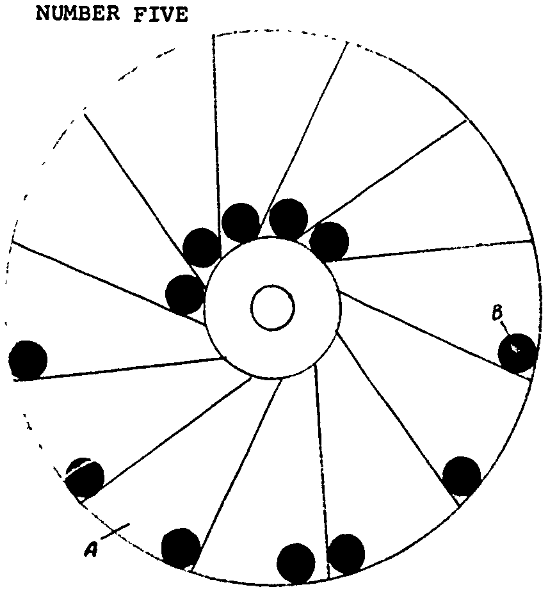
The Nature and Art of Motion, Kepes, Ed.; shows how motion can be exciting to the modern artist.

Perpetual Motion Machines?

You have heard of perpetual motion machines before—i.e., machines which, once started, will continue running and doing useful work forever. These proposed devices not only cannot be made to work, but also violate laws of thermodynamics; we now accept that it is in principle impossible to build one.

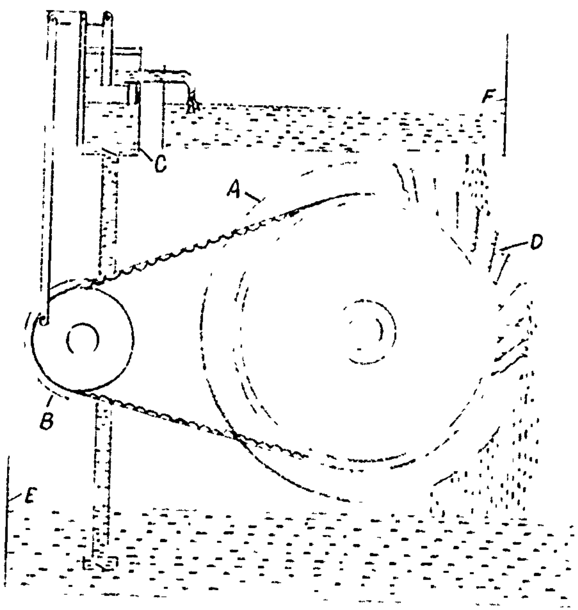
But the dream dies hard! Daily there are new proposals. Thus, S. Raymond Smedile, in Perpetual Motion and Modern Research for Cheap Power, maintains that this attitude of "it can't be done" negatively influences our search for new sources of cheap power. Sixteen examples of proposed machines are given in his book. Some are shown here, and more appear in the Unit 4 Handbook. Below are some other nominations; they may at least amuse you.

NUMBER FIVE



NUMBER 5 represents a wheel composed of twelve sections or chambers marked A. Each section or chamber contains a lead ball B which is free to roll in said chamber. The wheel turns and each ball by gravity seeks the lowest level in the contours of each chamber. The balls roll out to the periphery of the wheel in clockwise fashion and create a preponderance of weight on the right side of the wheel compared with those balls that roll toward the hub on the left side of the wheel. This causes the wheel to turn and is supposed to go on perpetually.

NUMBER SEVEN



Number 7 represents an overshot wheel marked A receives water from tank F. The water wheel is connected to pump B by means of an endless belt. The pump discharge flows into tank F and into the wheel. This operation is supposed to go on indefinitely.

Q1 If such machines would operate, would the conservation laws necessarily be wrong?

Q2 Is the reason that perpetual motion machines are not common due to "logical" or "practical" deficiencies?

Chapter 12 Waves

EXPERIMENT 30 Introduction to Waves

In this laboratory experiment you will study some properties of waves. You will make observations which will be useful in your study of sound and other kinds of energy in the next laboratory.

Waves in Spring

Many waves move too fast or are too small to watch easily. But in a long "soft" spring you can make big waves that move slowly. With a partner to help you, pull the "Slinky" out to a length of about 30 feet on a smooth floor. (Careful! Be sure not to let go of an end of the spring when it is stretched. The resulting snarl is almost impossible to untangle.)

Now with your free hand, grasp the stretched spring two or three feet from the end (Fig. 1).

Fig. 1

Pull the two or three feet of spring together toward the end and then release it, being careful not to let go of the fixed end with your other hand! Notice the single wave, called a pulse, that travels along the spring. In such a longitudinal pulse the spring coils move back and forth along the same direction as the wave travels. The wave carries energy and hence could be used to carry a message from one end of the spring to the other.

A longitudinal wave is hard to see. You will see it more easily if you tie pieces of string to several of the loops of the spring and watch their motion when the spring is pulsed.

A transverse wave is easier to see. To make one, practice a very quick back-and-forth motion of your hand at right angles to the stretched spring until you can produce a pulse that travels down only one side of the spring. This pulse is called "transverse" because the individual coils of wire move at right angles to (transverse to) the length of the spring.

Perform experiments to answer the following questions about transverse pulses.

Q1 Does the size, or amplitude, of the pulse change as it travels along the spring? If so, why does it change?

Q2 Does the pulse reflected from the far end return to you on the same side of the spring as the original pulse or on the opposite side?

Q3 Does a change in the tension of the spring have any effect on the speed of the waves? When you change the tension by stretching the spring you are, in effect, changing the medium through which the waves move.

Lay out a different kind of long spring or a length of rope along which you can send waves side by side to compare speeds.

Q4 What conclusions can you draw?

Adapted from Brinkerhoff and Taft, Modern Laboratory Experiments in Physics, by permission of Science Electronics, Inc.

Next observe what happens when waves go from one material into another—an effect called refraction. Attach to the far end of your "Slinky" the spring or rope in which you have just observed a different wave speed. The far end of the "Slinky" at the joint is now free to move back and forth, which it was unable to do before because your partner was holding it. A pulse will now be reflected back to you from the boundary (although it may take some close observation to distinguish it from the end reflection, especially if the boundary is close to the far end).

Q5 Have your partner send a pulse from the opposite end. What happens to it at the boundary?

Q6 Make a statement about the reflection of pulses from the boundary between two materials in which they have different speeds.

Have your partner detach the extra spring and once more grasp the far end of the "Slinky". Have him send out a pulse at the same instant you do, so that the two pulses meet. The interaction of the two pulses is called interference. As two pulses on the same side of the spring "collide," what do you observe about their amplitude? As the two pulses pass on opposite sides of the spring, can you observe a point on the spring that does not move at all?

Q7 From these two observations, what can you say about the displacement caused by the addition of two pulses at the same point?

You have now observed the reflection, refraction, and interference of single waves (pulses) traveling through different materials. These waves, however, moved only in one direction. We must next study these same wave properties spread out over a plane surface so that we can make a more realistic comparison with sound and other forms of traveling energy.

Waves in a Ripple Tank

Set up the ripple tank as shown in Figure 2 and fill it with water to a depth of 8 mm or more. The tank must be levelled so that it has equal depths at the four corners.

Fig. 2

Your pulses on springs were restricted to a straight line. To see what a single pulse looks like in a ripple tank, gently touch the water with your finger tip—or better, let a drop of water fall into it from a medicine dropper held only a few millimeters above the surface.

To prevent reflections from the walls of the tank it helps to put window screens or gauze in place along all four sides.

It is easier to study the waves if they are straight. To generate single straight waves, place along one edge of the tank a three-quarter-inch dowel or a section of broomstick handle, and roll it backward a fraction of an inch and then stop.

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To prevent reflections from the walls of the tank it helps to put window screens or gauze in place along all four sides.

It is easier to study the waves if they are straight. To generate single straight waves, place along one edge of the tank a three-quarter-inch dowel or a section of broomstick handle, and roll it backward a fraction of an inch and then stop.

Probe the space between the source and reflector, listening to the signal for changes in loudness. Record the positions of the nulls (positions of minimum loudness) or at least find the approximate distance between two consecutive nulls. These nulls are located ½ wavelength apart. Your ear is <u>most</u> sensitive to changes in intensity at very low intensity levels, so be sure to keep the volume low.

Q5 Measure the wavelength of sound at several different frequencies.

Track II — ultrasound

Your station is supplied with an audio oscillator amplifier, three ultrasonic transducers which transform electrical impulses into sound waves (or vice versa) just as a loudspeaker does, an oscilloscope (as in Fig. 7) or an amplifier and meter (Fig. 8), and several materials to be tested. One of the transducers, driven by the audio oscillator, is the source of the ultrasound. A second transducer is a detector.

Before you proceed, have the instructor check your setup and help you get a pattern on the oscilloscope screen or a reading on the meter.

The output of the transducer is highest at about 40,000 cycles per second, and the oscillator must be carefully "tuned" to that frequency. Place the detector a few centimeters directly in front of the source and set the oscillator switch to the "high" frequency position. Tune the oscillator carefully around 40,000 cycles/second for maximum deflection on the 'scope screen or the meter. If the signal output is too weak to detect beyond 25 cm, plug the detector into an amplifier and connect the output of the amplifier to the oscilloscope input.

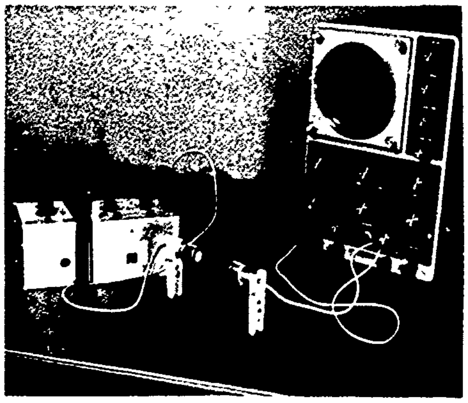


Fig. 7

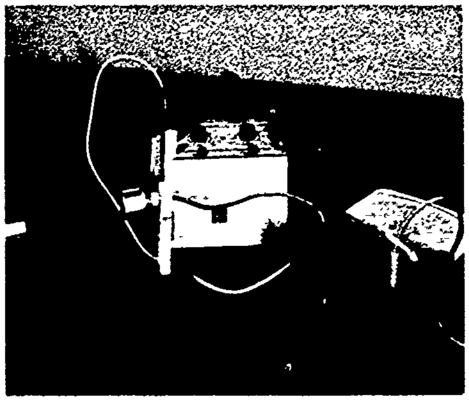


Fig. 8

Test the various samples at your station to see how they <u>transmit</u> the ultrasound. Your judgments are meant to be qualitative in terms of best, good, poor, etc. Hold the sample of the material being tested close to the detector and make a note of the effectiveness of each as a transmitter.

Test the same materials for their ability to <u>reflect</u> ultrasound. Be sure that the ultrasound is really being reflected and is not coming to your detector by some other path. You can check this by seeing how the intensity varies at the detector when you move the reflector. Some materials both transmit ultrasound and reflect it. Other materials may reflect, but not transmit.

Q6 Make a table of your observations.

You may find a material that neither reflects nor transmits well.

Q7 What happens to the energy of ultrasonic waves in such a material?

To observe diffraction around an obstacle, put a piece of wood or celotex about 3 cm wide, 8 or 10 cm in front of the source (see Fig. 9).

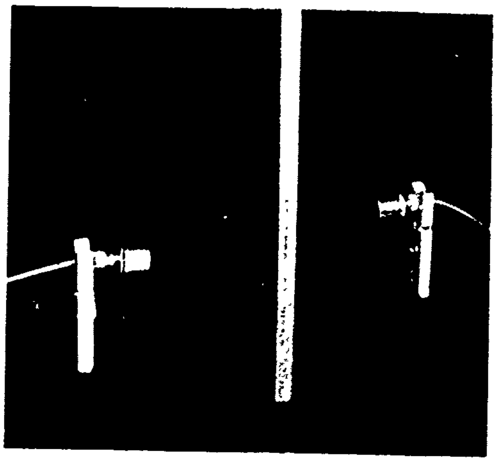


Fig. 9

Explore the region 5-10 cm behind the obstacle with the detector.

Q8 Do you find any signal in the "shadow" area? Do you find minimum or no signal (nodes) in the regions where you would expect a signal to be? Does there seem to be any pattern relating the areas of minimum and maximum si~nals?

Put a larger sheet of absorbing material 10 cm in front of the source so that the edge obstructs about one half of the source.

Q9 Again probe the "shadow" area and the area near the edge to see if a pattern of maxima and nodes seems to appear (see Fig. 10).

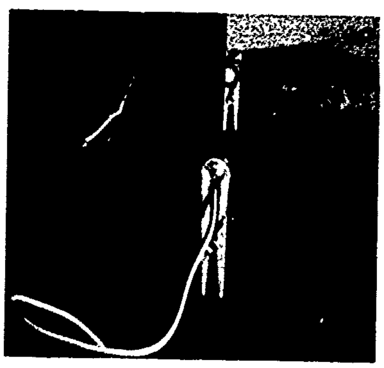


Fig. 10

Finally, investigate the standing waves set up between a source and a reflector, such as a hard tabletop or metal plate. Place the source about 10 to 15 cm from the reflector, and probe the space between source and reflector with the detector (see Fig. 11).

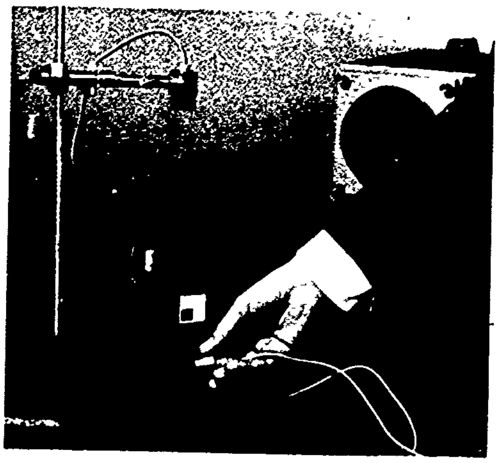


Fig. 11

Q10 Find the approximate distance between two consecutive maxima or two consecutive minima. This distance is one half the wavelength. Record the wavelength of the ultrasonic wave.

Track III — ripple tank

In Experiment 30 on waves you set up the ripple tank with two point sources arranged to show interference. Using the same arrangement in this experiment, you will learn how to compute th wavelength from measurements of the wave pattern.

You will then need to explain your method to your classmates working on the other two parts to the experiment. It is a method they can adapt in order to measure the lengths of their sound and ultrasonic waves.

The waves, as they leave the two point sources, are exactly in phase and of the same frequency. Fig. 12 illustrates a "frozen" or stopped view of these waves as they travel out from the two sources of ripples on the surface of water.

... elaborate ones were made. To make one, first you will need a column of water. You may find a large cylindrical graduate about the laboratory. The taller the better (Fig. 1). If not, you can improvise one out of a piece of glass tubing. Plug or fuse together the lower end and fit a one-holed stopper into the other with a rubber tube attached.

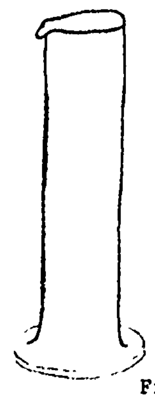


Fig. 1

Next construct the diver. You may limit yourself to pure essentials, namely a small pill bottle or vial which may be weighted with wire and partially filled with water so it just barely floats upside down at the top of the water column. If you are inclined, you can decorate the bottle so it looks like a real underwater swimmer. Or you can make yourself a little glass mannekin with holes in the bottom of his legs so that water is free to pass in or out (Fig. 2). The essential thing is that you have a body which just floats on account of the entrapped air.

Boyle's law, decreases the volume of entrapped air. Less of the water is displaced by the diver. The buoyant force, according to Archimedes' principle, falls off and the diver begins to sink.

If the original pressure is restored, the diver rises again. However, you will probably find that as you cautiously make him sink deeper and deeper down into the column of water he is more and more reluctant to return to the surface when the additional surface pressure is released. Indeed, you may find a depth at which he remains almost stationary. However, this apparent equilibrium when his weight just equals the buoyant force is unstable. A bit above this depth he will freely rise to the surface and a bit below this depth he will sink to the bottom of the water column from which he can be brought to the surface only by vigorous sucking on the tube.

If you are mathematically inclined, you can compute what this depth would be in terms of the atmospheric pressure at the surface, the volume of the entrapped air and the weight of the diver. If not so inclined, you can juggle with the volume of the entrapped air so that the point of unstable equilibrium comes about half way down the water column.

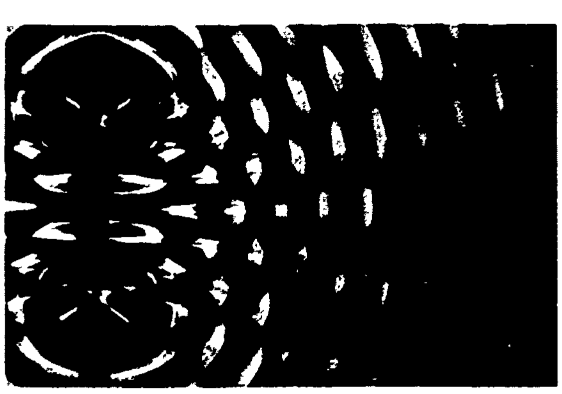


Fig. 12

As you study the pattern of ripples you will notice lines along which the waves cancel almost completely so that the amplitude of the disturbance is almost zero. These lines are called <u>nodal lines</u>. You have already seen nodes in your earlier experiment with standing waves in the ripple tank.

At a node the waves arriving from the two sources are half a wavelength out of step, or "out of phase." This means that for a point (such as B in Fig. 12) to be on a line of nodes it must be ½ or 1½ or 2½... wavelengths further from one source than the other.

In between the lines of nodes are regions of maximum disturbance. Points A and C in Fig. 12 are on lines down the center of such regions, called anti-

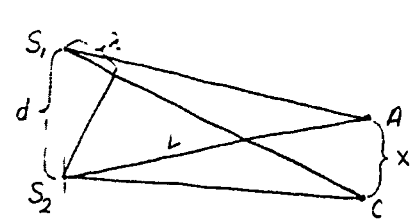


Fig. 13

are parts. Therefore, since corresponding pairs of sides of similar triangles are all in the same proportion,

$$\frac{\lambda}{d} = \frac{x}{L}$$

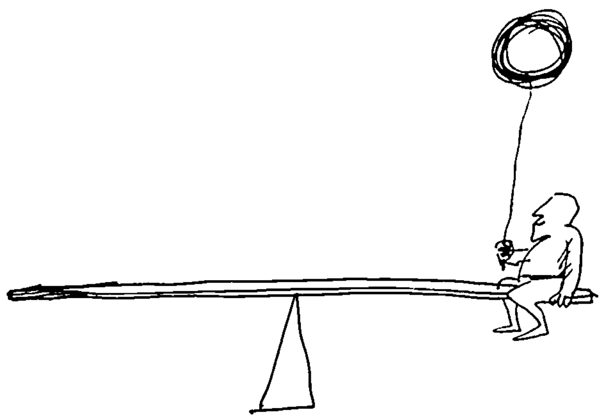
or

$$\lambda = \frac{xd}{L} .$$

Here d is the distance between the sources, x is the distance between two points on adjacent lines of nodes, both of them at the same distance L from the sources.

We have now a method for finding the wavelength, λ, from lengths that are easy to measure.

Q11 Measure x, d, and L in your ripple tank and compute λ. Then measure λ by one of the two independent methods de-like a diaphragm which increases the pressure within as they are pushed together. The bottle and diver are tightly sealed. In this case, add a rubber tube leading to a holeless stopper. Your classmates blowing as hard as they will cannot make the diver sink; but you secretely squeezing the bottle can make him perform at your command.



each ball. You may have to experiment a bit to get the light level adjusted so that as few collisions are shown in the photo as possible, and to perfect your shaking technique.

Fig. 1

After developing the photo, use the 10x magnifier to measure the length of the streak for each ball. Make a histogram plot of the number of balls having a given range of distances (between 1 and 2 mm on the photo, for example) vs. the range. The resulting plot shows the

It is possible to suppose initially that sound and ultrasound corsist of streams of particles traveling all the way from source to receiver.

Which of the various effects seen by students following tracks I and II are consistent with this particle idea? Which of their observations support the idea that sound is a wave phenomenon?

Does the evidence give conclusive support to either the wave model or the particle model?

Besides being inaudible, how does ultrasound differ from sound? What evidence supports this answer?

A further difference will become clear when the method of track III is adapted to sound and ultrasound. With the help of track III experimenters this method should now be tried out, as described in Part C.

Part C. Further Experiments

After a discussion of the wave properties of sound and ultrasound, track III experimenters should describe their method for finding wavelengths. Track I and track II experimenters should then return to the lab and try out this new method on their respective equipment. Members of track III can be observers and consult-

experiment. Move your ear or "stethoscope" along a line parallel to and about 50 cm from the line joining the sources. Can you detect distinct maxima and nodes? Move farther away from the sources, do you find any change in the nodes or their spacing?

Q12 What effect has a change in the source spacing upon the spacing of the nulls?

Q13 What happens to the null spacing if you change the frequency of the sound?

To make this experiment quantitative, carefully measure and record the distance d between centers of the two sources. Mount a meter stick parallel to the line joining the sources so that the nodes can be located and their positions noted from the stick (Fig. 14). Record the

Track II — ultrasound

Connect two transducers to the output of the oscillator amplifier and mount them about 5 cm apart. Set the oscillator switch to the "high" position. Connect a third probe (detector) to an oscilloscope or amplifier and meter as described in Part A of the experiment, and tune the oscillator for maximum signal from the detector when held near one of the sources (about 40,000 cycles/sec with the range switch on "high"). Move the detector probe along a line parallel to and about 25 cm in front of a line connecting the sources. Do you find distinct maxima and minima? Move closer to the sources; do you find any change in the nulls or their spacing?

Q5 What effect has a change in the source spacing on the spacing of the nulls?

To make this experiment quantitative, measure carefully and record the distance d between centers of the two sources. Mount a meter stick parallel to the line joining the sources, so that the nodes can be located and their positions noted from the stick (Fig. 15). Record the

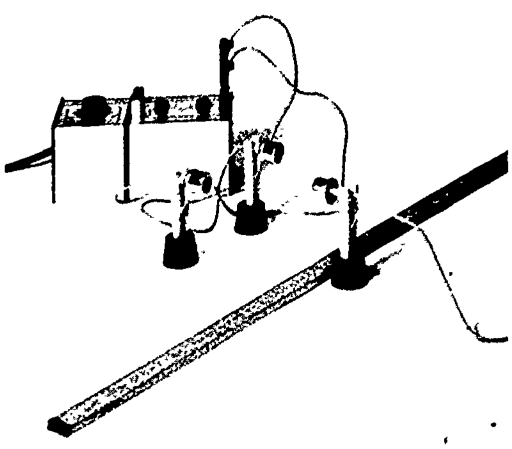


Fig. 15

distance L from the line of the sources to the meter stick. Do not change the frequency of the oscillator during this part of the experiment. Locate and record the position of the maxima and minima. Are the spacings all the same?

Q17 Find the average spacing, and use that average to find the wavelength λ. How does this length compare with wavelengths found by other groups in class?

The relationship between velocity v, wavelength λ, and frequency f, is $v = \lambda f$.

Q18 Use the frequency setting on the audio oscillator to calculate the wavelength.

"Least-time" or "Least-energy" Situations

Nature is lazy. She often behaves in such a way that as little work is done as possible. You can gain a great deal of understanding with some simple apparatus.

a) Hanging chain. Hang a three foot length of beaded chain (the type used on light sockets costs about 25 cents for 3 feet) from points as shown in Fig. 1.

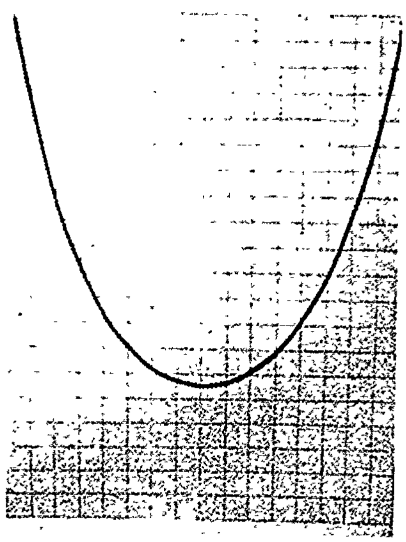


Fig. 1

It is interesting to note first what shape the chain assumes. At first glance it seems to be a parabola.

Check whether it is a parabola by finding the equation for the parabola which would go through the vertex and the two fixed points. Determine other points on the parabola by using the equation. Plot them and see whether they match the shape of the chain.

A more interesting question is why the chain assumes this particular shape, which is called a catenary curve. You will recall from Section 10.3 that the potential energy of a body of mass m is defined as ma_gh, where a_g is the acceleration due to gravity, and h the height of the body above the reference level we have chosen. Remember that it is only a "difference" in potential that is meaningful. A different reference level only adds a constant to each value associated with the original reference level. In theory, we could measure the mass of one bead on the chain, measure the height of each bead above the reference level, and then total up the potential energies for all the beads to get the total potential energy for the whole chain.

In practice that would be quite tedious, so we will use an approximation that will still allow us to get the point. (This would be an excellent computer problem if you have access to a computer terminal.) Draw vertical parallel lines about 1" apart on the paper behind the chain (or use graph paper). In each vertical section, make a mark beside the chain for the average height of the chain in that section (see Fig. 2).

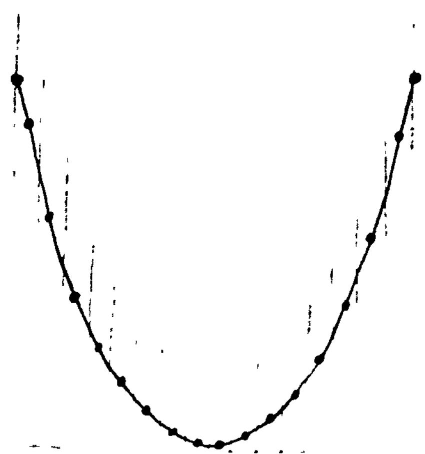


Fig. 2

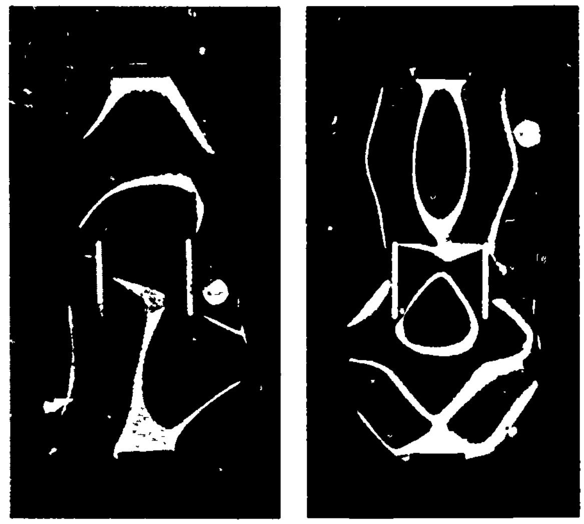
The total potential energy for that section of the chain will be approximately Ma_gh_{av}, where h_{av} is the average height which you marked, and M is the total mass in that section of chain. Notice that near the ends of the chain there

Turn on the tone and sprinkle salt or sand on the drumhead. If the frequency is near one of the standing wave resonant frequencies, the salt will collect along the nodes and be thrown off from the antinodes, outlining the pattern of the vibration. Tune the frequency for the clearest pattern, then photograph it and move on to the next frequency where you get a pattern.

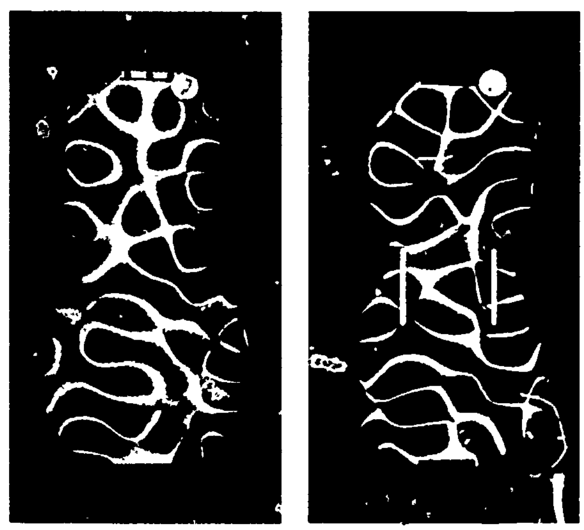
Move the speaker toward the edge of the drumhead to get antisymmetric modes of vibration. Experiment with the spacing between the speaker and the drumhead until you find the position that gives the clearest pattern; this position may be different for different frequencies.

If your patterns are distorted, the tension of the drumhead is probably not uniform. If you have used a balloon, you may not be able to remedy the distortion, since the curvature of the balloon makes the edges tighter than the center. By pulling gently on the rubber, though, you should be able to make the tension even all around the edge.

A similar procedure was used 150 years ago and is still used in analyzing the performance of violins as shown in the photos reprinted from Scientific American, "Physics and Music," July 1948. See also "The Physics of Violins," Scientific American, November 1962.



CHLADNI PLATES indicate the vibration of the body of a violin. These patterns were produced by covering a violin-shaped brass plate with sand and drawing a violin bow across its edge. When the bow caused the plate to vibrate, the sand concentrated along quiet nodes between the vibrating areas. Bowing the plate at various points, indicated by round white marker, produces different frequencies of vibration and different patterns. Low tones produce a pattern of a few large areas: high tones a pattern of many small areas. Violin bodies have a few such natural modes of vibration which tend to strengthen certain tones sounded by the strings. Poor violin bodies accentuate squeaky top notes. This sand-and-plate method of analysis was devised 150 years ago by the German acoustical physicist Ernst Chladni.



Moire Pat:erns

You are probably noticing a disturbing visual effect from the pattern below. Much of the present op art depends on similar effects, many of which are caused by Moiré patterns.

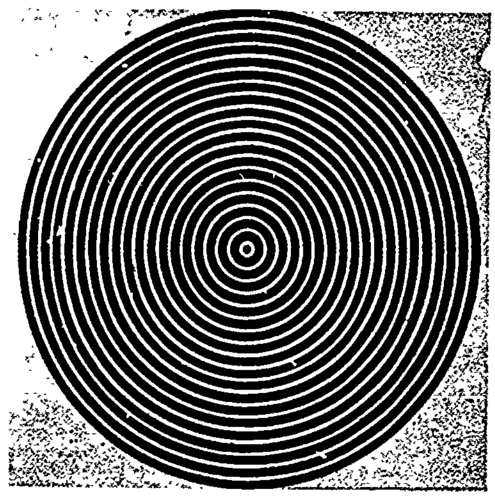


Fig. 1

If you make a photographic negative of Fig. 1, (not a Polaroid print) and place it on top of Fig. 1, you can use it to study the interference pattern produced by two point sources. The same thing is done on Overhead Transparency 28 which your teacher may have.

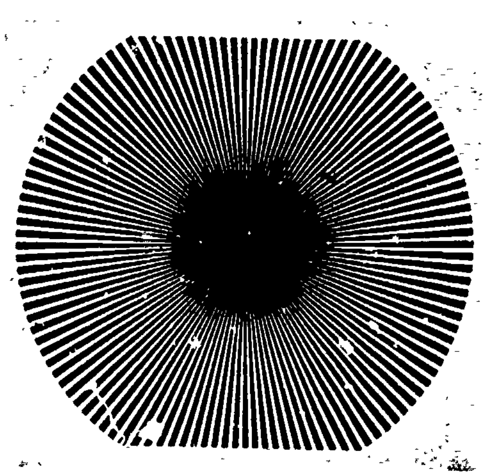


Fig. 2

If you make a photographic negative of Fig. 2 and place it over Fig. 2, you will get another set of patterns which will become meaningful in Unit 4.

Long before op art, there were an increasing number of scientific applications of Moiré patterns. Because of the great pattern changes caused by very small shifts in two regular patterns, they can be used to measure to one part in a billion, in some cases. Some specific examples: visualization of two- or multiple-source interference patterns; measurement of small angular shifts; measurement of diffusion rates of solids into liquids; representations of electric, magnetic, and gravitational fields. Some of the patterns created still cannot be expressed mathematically.

Scientific American, May 1963 has an excellent article, "Moiré Patterns," by Gerald Oster and Yasunori Nishijima. The Science of Moiré Patterns, a book by G. Oster, is available for $2.00 from Edmund Scientific Co., Barrington, N.J. 08007. Edmund also has various inexpensive sets of different patterns, which save much drawing time, and are much more precise than hand drawn patterns.

Mechanical Wave Machines

Several types of mechanical wave machines are described below. They can help a great deal in understanding the various properties of waves.

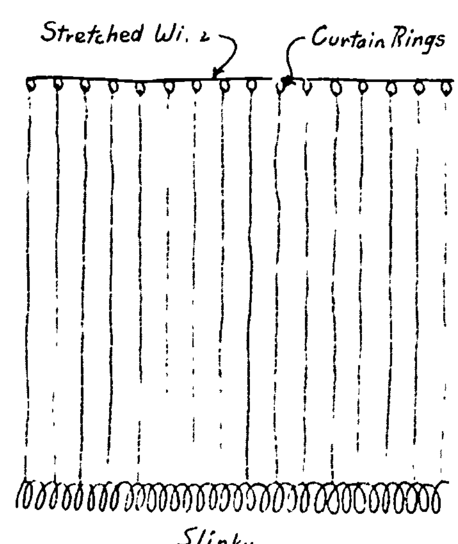


Fig. 1

drop of water.

Q8 Describe the shape of the reflected pulse.

To observe refraction, lay a sheet of glass in the center of the tank, supported if necessary so as to make a very shallow area. Try varying the angle at which the pulse strikes the boundary between deep and shallow. The waves change direction at the edge of this area because they change speed at the boundary of the shallow area.

Q9 Describe the way in which the waves change direction with changing speed.

To observe interference, arrange two point sources side by side a few centimeters apart. When tapped gently they should produce two pulses whose intersection corresponds to the intersection of the two pulses on the spring. You will see the action of interference better, however, if you vibrate the two point sources continuously with a motor and study the resulting pattern of waves.

Where are the points of destructive interference (cancellation)? Where are the points of constructive interference (reinforcement)?

diffraction pattern depend on the wavelength of the waves?

There are two ways of measuring the wavelength. You should try them both, if possible, and check one measurement against the other.

One way is to place a straight barrier across the center of the tank parallel to the advancing waves. When the distance of the barrier from the generator is properly adjusted, standing waves will be formed by the superposition of the advancing waves and the waves reflected from the barrier. In other words, the reflected waves are at some points reinforcing the original waves, while at other points, there is always cancellation. The points of cancellation are called nodes.

Q13 How does the distance from node to node compare with the length of the moving wave that produced the nodes?

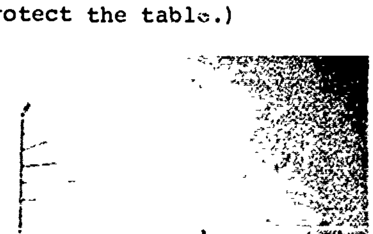
The second way to measure the wavelength is to remove the barrier and observe the moving waves with a hand-driven stroboscope. You can probably rotate the motor-driven stroboscope by hand at such a speed as to "stop" the wave motion. Measure the wavelength, λ, by counting

a) Slinky. A Slinky behaves much better when it is freed of friction with the floor or table. Hang a Slinky from strings at least three feet long tied to rings on a wire stretched from two solid supports. Tie strings to the Slinky at every fifth spiral for proper support (see Fig. 1).

Fasten one end of the Slinky securely and then stretch it out to about 20 or 30 feet. By holding onto a string about 10 feet long tied to the end of the Slinky, you can illustrate "open-ended" reflection of waves.

See Experiment 30, Springs and Ripple Tanks, in Chapter 12 of the Unit 3 Handbook for more details on demonstrating the different wave properties.

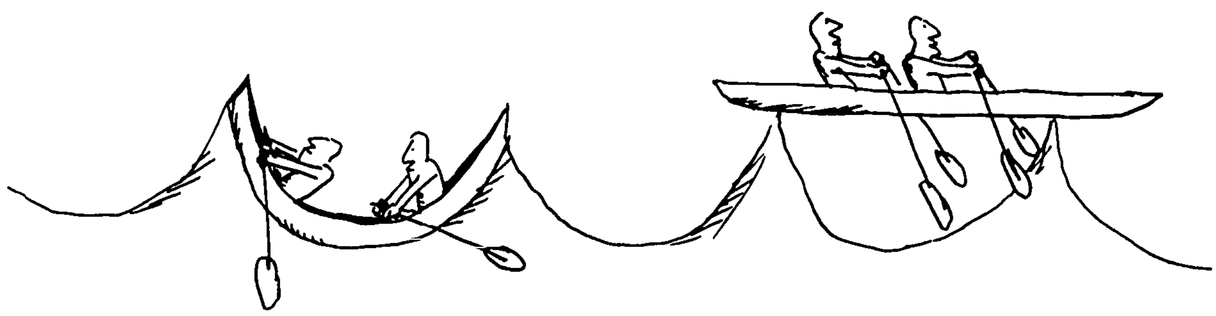
b) Rubber tubing and welding rod. clamp a piece of rubber tubing about 4 feet long to a table so it is under slight tension. Punch holes through the tubing every inch with a hammer and nail. (Put a block of wood under the tubing to protect the table.)



Cut enough one-foot lengths of welding rod for all the holes you punched. Unclamp the tubing, and insert one rod in each of the holes. Suspend the wave machine as shown in Fig. 2 to demonstrate transverse waves. Performance and visibility are improved by adding weights to the ends of the rods.

c) A paperback, "Similarities in Wave Behavior," written by Dr. John N. Shive of Bell Telephone Laboratories, has instructions for how to build a better torsional wave machine than described in (b) above. The book is available

value obtained by timing a single pulse across the known length of the tank. Do the two values of v agree?



Activities

Music and Speech Activities

a) Frequency Ranges: In the Unit 1 Equipment Notes in the Teacher Guide (ask your teacher to let you borrow them) you will find instructions on how to set up a microphone and oscilloscope so you can display the pressure variations of sound waves. Play different instruments and see how high C differs on them.

b) Some beautiful oscilloscope patterns result when you display the sound of the new computer-music records which use sound synthesizers instead of real instruments.

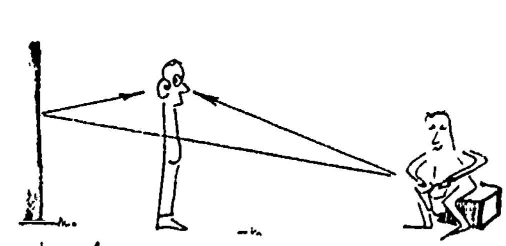
c) For interesting background, see the following articles in Scientific American: "Physics and Music," July 1948; "The Physics of Violins," November 1962; "The Physics of Wood Winds," October 1960; and "Computer Music," December 1959.

d) The Bell Telephone Company has two interesting educational items which may be available free through your local Bell Telephone office. A 33 1/3 LP record, "The Science of Sounds," has 10 bands demonstrating different ideas about sound. For instance, racing cars demonstrate the Doppler shift, and a soprano, a piano and

Measurement of the Speed of Sound

For this experiment you need to work out of doors in the vicinity of a large flat wall that produces a good echo. You also need some source of loud pulses of sound that come at regular intervals, about one a second or less. A friend beating on a drum or something with a higher pitch will do. He should be fairly far away from the wall, say a couple of hundred yards in front of it. The important thing is that the time between one pulse and the next doesn't vary. Therefore, a metronome would help.

Stand somewhere between the reflecting wall and the source of pulses. You hear both the direct sound and the sound reflected from the wall. As you move closer to the wall the interval between direct sound and echo decreases, and as you move away from the wall this time interval increases. The direct sound



Track I — sound

Your station is supplied with an audio oscillator amplifier, two small loudspeakers, and a group of materials to be tested. A loudspeaker is the source of audible sound waves, and your ear is the detector. First connect one of the loudspeakers to the output of the oscillator (switched to "low") and adjust the frequency to about 4000 cycles per second. Adjust the loudness so that the signal is just audible 1 m away from the speaker. Clamp the speaker as shown in Fig. 1. Keep the source as far away as possible from the floor, tabletop, and hard-surfaced walls, because reflected sound waves may interfere with your observations.

Fig. 1

good, poor, etc. Hold the sample of the material being tested close to the detector and make a note of the effectiveness of each as a transmitter.

Test the same materials for their ability to reflect sound. Be sure that the sound is really being reflected and is not coming to your detector by some other path. You can check how the intensity varies at the detector when you move the reflector and rotate it about a vertical axis (see Fig. 2). Some materials both transmit sound and reflect it. Other materials may reflect, but not transmit.

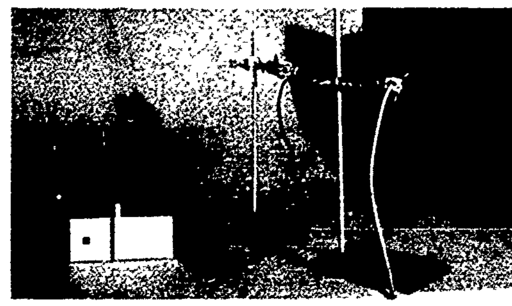


Fig. 2

Make a table of your observations.

Q1 You may find a material that neither reflects nor transmits well. What happens to the sound in such a material?

Refraction means the change of direction of waves as they pass from one ma-

If the distance from the source to the wall is great enough, the added time taken by the echo to reach you can amount to more than the time between drum beats. Then, you will be able to find a position at which you hear the echo of one pulse at the same time as you hear the direct sound of the next pulse. Then you know that the sound took a time equal to the interval between pulses to travel from you to the wall and back to you.

Measure this distance and calculate the time between pulses by measuring the time for a large number of pulses.

If you cannot get far enough away from the wall to get this synchronization, persuade the drummer to beat more rapidly.

If this is impossible you may be able to find a place where the time interval between pulse and echo is exactly equal to the time for the sound to go just from you to the wall. At this point you know that the time taken for the return trip from you to the wall and back is equal to half the time interval

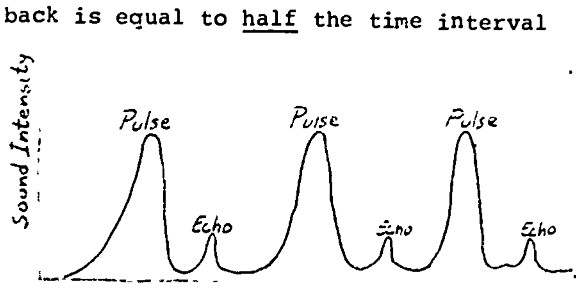


Fig. 2

between pulses. You will hear a pulse, then an echo, then the next pulse. You adjust your position so that these three sounds seem equally spaced in time.

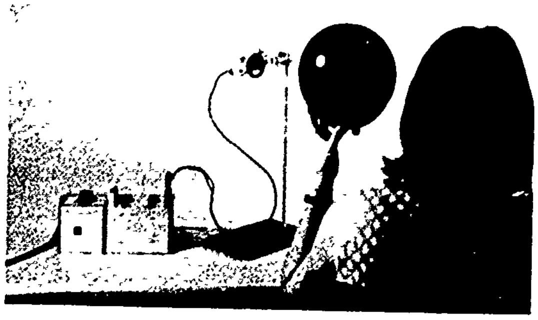


Fig. 3

where the sound seems loudest, and then remove the balloon.

Q2 Do you notice any difference in loudness when the balloon is in place?

To study diffraction around an obstacle, use a piece of thick plywood or celotex about 25 cm long, mounted vertically about 25 cm in front of the speaker (see Fig. 4). Slowly probe the area about 75 cm beyond the obstacle.

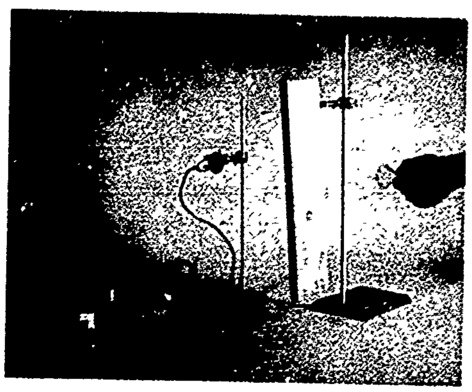


Fig. 4

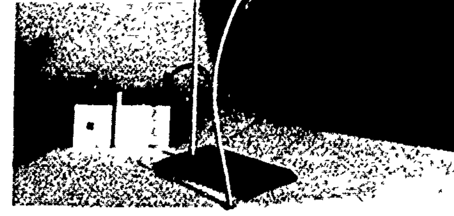


Fig. 5

Q4 Again explore the area inside the "shadow" zone and just outside it, and describe the "pattern" of sound that you observe.

Next investigate standing waves. In general, standing waves require that a good reflector be set up facing the source several wavelengths in front of it.

Set your loudspeaker about ½ meter above and facing toward a hard tabletop or floor or about that distance from a hard (smooth) plaster wall or other good sound reflector (see Fig. 6).

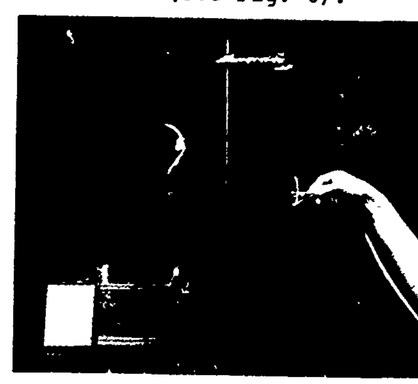
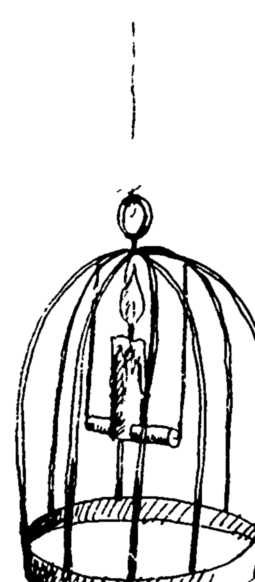


Fig. 6



The cartoons on this page (and others of the same style which are scattered through the Handbook) were drawn in response to some ideas in the Project Physics course by a cartoonist unfamiliar with physics. On being informed that the drawing below didn't represent conservation because the candle wasn't a closed system, he offered the solution at the upper right.

FILM LOOP 18 One-Dimensional Collisions
FILM LOOP 19 Further Example of One-Dimensional Collisions
FILM LOOP 20 Perfectly Inelastic One-Dimensional Collisions

These three loops are very helpful for studying both momentum in Chapter 9 and kinetic energy in Chapter 10. The instructions in Secs. I through VI of these notes are the same for all three loops. Section VII contains special notes about the individual loops. Read Secs. I through VI and that part of VII pertaining to the loop you are using before taking any data.

You will not be able to answer any of the questions referring to kinetic energy until you have studied Chapter 10. Save your data until then, so you will be able to finish your analysis without having to remeasure velocities, etc.

I. Materials You Will Need

In addition to the film loop, a projector, and these Notes, you will need: a large piece of paper; a transparent plastic ruler marked in millimeters; and a stopwatch, or other timing device, precise to one tenth of a second. (A pair of drafting triangles would be useful for drawing sets of parallel lines.)

II. How the Collisions Were Produced

Each ball was hung like a pendulum from two very long thin steel wires, (see Fig. 1.) This so-called "bifilar suspension" confines each ball's motion to a circular path in a vertical plane, and both balls move along the same circle. They collide at the bottom (point C). The radius of this circle is large compared to the field of view of the camera, so the curvature of path is barely noticeable in the film loop.

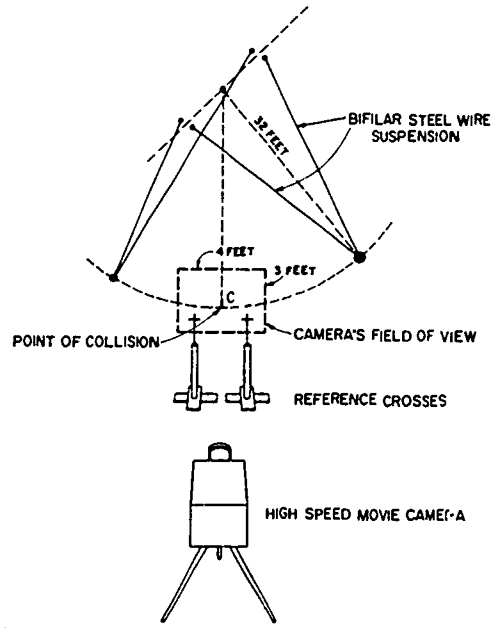


Figure 1. Schematic diagram of the apparatus used to produce the collisions. Not to scale. The pendula are very long.

The visible portions of the balls' motion can be taken to be horizontal straight lines although they are circular arcs. Strictly speaking, however, the balls gain speed whenever they approach point C where the collision occurs. And they lose speed as they move away from C. This should influence your decisions when taking measurements.

This set-up is shown below and in the opening scenes of Film Loop 18. The main parts of the loops are two "close-ups" of

the collisions taken at high speed. Your projector runs the film at much slower speed and shows the collisions in slow motion.

III. General Description

Two examples of collisions are given in each of the film loops. The figures in Sec. VII provide a qualitative summary of the conditions. Each example can be studied in quantitative detail by taking measurements upon the projected image.

When you are ready to take measurements, tape the sheet of paper to the wall and position the projector so that the frame at least fills the paper. The projector should not be moved throughout the experiment; however, if you trace on the paper the "crosses" appearing in the film, you can realign the projector if it is accidentally moved.

By marking off distances on the sheet of paper, and by timing the balls as they move through these distances, you can calculate the speeds of the balls before and after the collision. The balls' masses are given (see figures in Sec. VII). You can, therefore, calculate the total momentum (a vector!) of the pair of balls before and after collision.

IV. About the Measurements

You should find the balls' speeds just before and just after collision. This can be done by marking down a pair of vertical lines and timing the passage of the ball's image across the paper. There are two things to decide here. Where should the pair of lines be? How far apart should they be?

The ruler you use for measurements of distance permits you to estimate the tenth of a millimeter. You should estimate it, but this digit is doubtful. To obtain 3-digit precision with certainty, distances should be 10 cm or more! In some cases, however, a ball's speed may be so small that it doesn't move 10 cm. Displacement measurement will be less precise in these cases.

Which of the following procedures should be adopted when measuring distances with the ruler?

1. Place the "zero" end of the ruler against one line and estimate the position of the other line.

2. Place one of the thick centimeter rulings, somewhere in the middle, against one line and estimate the position of the other line.

3. Do as in (2), but place one of the thin millimeter rulings against the first line.

4. Repeat your measurement and ask your partner to take it at least twice, too. Then, use an average and find the average deviation. Should you also average repeated measurements when timing the balls?

V. About the Calculations and Results

Section III gives you clues as to the quantities which you have to calculate. The following additional points and questions will assist you in this work.

1. By measuring each distance several times, estimate the uncertainty of your distance values. After calculating the associated speed, also calculate the per cent deviation in it.

2. Assume that the given masses of the balls are exact (without error). Then the percentage uncertainty in the individual momenta is the same as for the speeds. Calculate the actual deviations of these individual momentum vectors.

3. When calculating the net momentum of the pair of balls before collision, and after, keep in mind that momentum is a

vector. In the first example of the film, the individual momenta before collision are in opposite directions. The same is true after collision.

Do not attempt Questions 4, 5, 6 or 7 if you haven't studied Chapter 10.

4. What is the difference between the total momentum before and after collision?

5. Is the difference between these total momenta—if any—accounted for by the uncertainties in measurements?

6. After calculating the kinetic energies, find the deviations in these.

7. Calculate the percentage of kinetic energy conserved in the collision. Explain the loss in kinetic energy, if any is found. The steel balls are "case-hardened." (Discuss this with your instructor.)

VI. If You Studied Both Examples In One Loop

The loss in kinetic energy may not be the same in the two examples. If this is true, then which is larger: (a) the difference between the losses, or (b) the range of possible values based on the errors obtained from average deviations? If (a) is larger, how can you explain it?

VII. Additional Notes for Each Loop

a) Loop 18 One-Dimensional Collisions

(The two examples in this film loop are also shown as Events 1 and 2 in "Stroboscopic Photographs of One-Dimensional Collisions" earlier in this chapter of the Handbook.)

In this loop a pair of steel balls is shown in two different head-on collisions occurring along one line. (Hence the name "one-dimensional.")

Ball B is initially at rest in the first example; ball A is initially at rest in the second example. Figures 2 and 3 provide a qualitative summary of the conditions.

FIRST EXAMPLE IN THE LOOP-FILM
"ONE-DIMENSIONAL COLLISIONS"

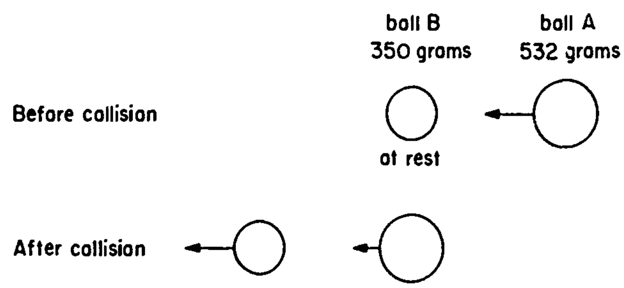


Fig. 2

SECOND EXAMPLE IN THE LOOP-FILM
"ONE-DIMENSIONAL COLLISIONS"

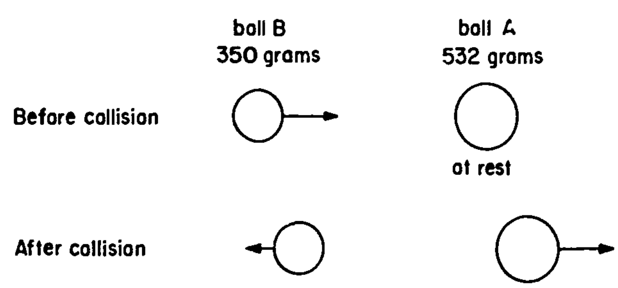


Fig. 3

b) Loop 19 Further Examples of One-Dimensional Collisions

(The two examples in this film loop are also shown as Events 3 and 4 in "Stroboscopic Photographs of One-Dimensional Collisions" earlier in this chapter of the Handbook.)

NOTE: The first example in this film is most instructive when studied jointly with the second. If you study only one example, then it should be the second example shown in the loop.

In this film a pair of steel balls is shown in two different head-on collisions occurring along one line.

Figures 4 and 5 provide a qualitative summary of the conditions. In the first example, the balls come at each other from opposite directions. In the second example, they move in the same direction, but ball A catches up to ball B.

FIRST EXAMPLE IN THE LOOP-FILM "FURTHER EXAMPLES OF ONE-DIMENSIONAL COLLISIONS"

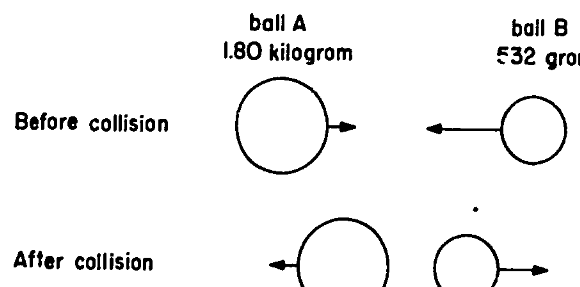


Fig. 4

SECOND EXAMPLE IN THE LOOP-FILM "FURTHER EXAMPLES OF ONE-DIMENSIONAL COLLISIONS"

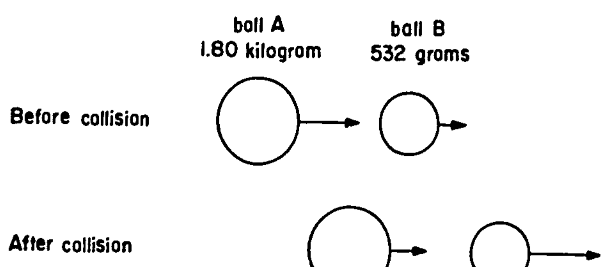


Fig. 5

c) Film Loop 20 Perfectly Inelastic One-Dimensional Collisions

(The two examples in this film loop are also shown as Events 5 and 6 in "Stroboscopic Photographs of One-Dimensional Collisions" earlier in this chapter of the Handbook.)

In this film a pair of plasticene balls is shown in two different head-on collisions occurring along one line. They stick together after colliding and move off together (hence the term, "perfectly inelastic").

Figures 6 and 7 provide a qualitative summary of the conditions. Ball A is initially at rest in the first example. In the second example, the balls come at each other from opposite directions.

FIRST EXAMPLE IN THE LOOP-FILM "PERFECTLY INELASTIC ONE-DIMENSIONAL COLLISIONS"

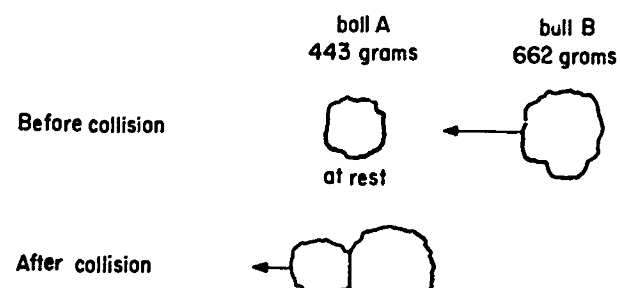


Fig. 6

SECOND EXAMPLE IN THE LOOP-FILM "PERFECTLY INELASTIC ONE-DIMENSIONAL COLLISIONS"

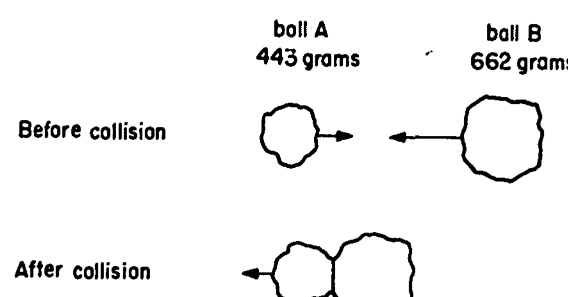


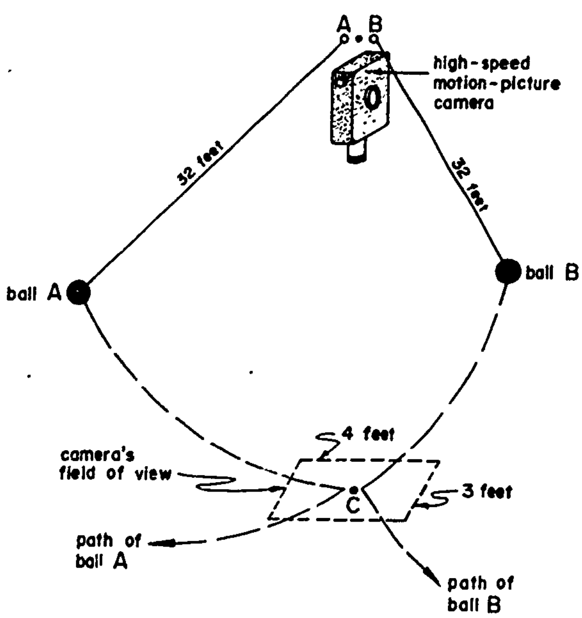
Fig. 7

FILM LOOP 21 Two-Dimensional Collisions
FILM LOOP 22 Further Examples of Two-Dimensional Collisions
FILM LOOP 23 Perfectly Inelastic Two-Dimensional Collisions

Sections I, II, and III of these notes apply to all three of the loops. Section IV contains a Table of Masses for the individual loops. Read Secs. I through III and that part of IV pertaining to the loop you are using before taking any data.

I. Description

As Fig. 1 shows, we suspended two hard steel balls from very long thin wires.



(This schematic diagram is not to scale)

Fig. 1

The balls were then displaced sideways and held until they were released simultaneously by electrical relay devices. They moved toward C along circular arcs of large radius. Point C lies directly below the suspension points A, B of the long wires.

Because the balls were hung from wires of equal length, the two balls took exactly the same time to reach C. (The time of swing of a pendulum for moderate arcs at a given location depends only on the length of the support.) A collision then took place at C, changing the balls' speeds and directions of motion.

In loops 21 and 22 the balls move away from point C along different circular arcs. In loop 23, the deformation brought about in the shape of the balls is not restored, and the balls stick together. They move off along a different circular arc with common speed, as if they were one particle whose mass is the sum of the masses of balls A and B.

A high-speed camera was mounted on a tower 25 feet above point C. The camera faced downward and took a motion picture of the collision, with a field of view of roughly 3 by 4 feet. The paths of the balls are very nearly horizontal over so small a distance.

The camera took pictures at a very high rate. Your projector, however, shows these pictures at a far slower rate than they were shot, and so shows the event in slow-motion.

Your film loop contains slow-motion footage for two such collision events. You may study one or both of these. Your task is to determine the direction and the magnitude of each ball's velocity before and after collision. This will involve taking distance and time measurements from the projected image, as described in Sec. II of these notes.

The calculated velocities, together with the given masses, allow you to determine whether the total momentum and the total kinetic energy of the pair of balls were conserved in collision. One of these quantities will always be conserved. Which one? The losses in the other—if any can be found—will permit you to draw conclusions about the elastic properties of the steel balls.

You will have to draw vector diagrams to determine the total momentum before and a .er collision. See Sec. III of these notes.

II. The Measurements

You will need the following materials:

1. A large sheet of paper (17" × 22' or bigger). Tape it to the wall; position the projector such that the film image covers the sheet. When you are ready to take data, do not move the projector until you are finished.

2. A pair of large draftsmen's triangles and a plastic transparent ruler marked in millimeters. The triangles permit you to draw long straight lines, and to displace such lines, keeping them parallel, on the paper.

3. A stopwatch or other timing device, precise to 1/10 second.

Run the slow-motion sequence of interest to you through the projector as often as is necessary to place dots on the paper, positioning the balls' centers as they slowly move across the picture. The more such dots, the better.

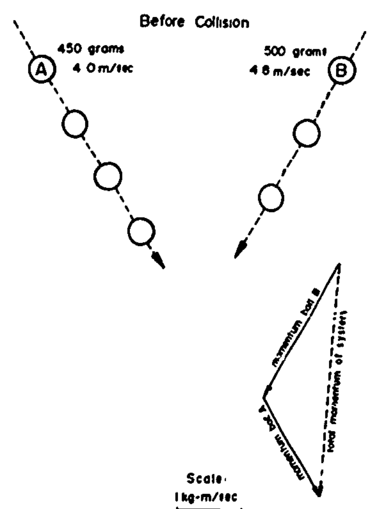
You will soon see that the image shakes a bit. This is due to the nature of high-speed motion picture photography. No camera has yet been made which, at 2000 to 3000 frames/sec, feeds the film through the mechanism with perfect smoothness. Thus the precision of your measurements is limited by the apparatus used to record the collision. But this is not just a characteristic of the camera. It is a characteristic of all measuring apparatus, even if it is not always so noticeable.

The dots you have entered for ball positions before collision will not lie on a straight line, even though you are sure the balls' paths were straight. You must decide upon the best straight line, and draw it, one for each ball (unless one ball was at rest initially). You may decide that there is, in fact, a range of possible directions! Repeat the dotting procedure for the motion occurring after collision. Now you have estimates for the directions of the velocities.

To find their magnitudes, mark a pair of timing lines perpendicular to each straight line and measure the time interval the balls take to cover the distance between the lines. Measure the distance between the lines and calculate the speeds. All measurements should be repeated several times, so that an average value, as well as an estimate of uncertainty, will result for each speed.

III. Analysis

Look at Fig. 2. It shows two balls moving along straight lines, both lying in the plane of the paper. Each ball has a definite momentum (a vector quantity). Its magnitude is the product



The masses in Fig. 2 are not the same as the masses shown in the film loop. Your diagrams should be at least twice as large.

Fig. 2

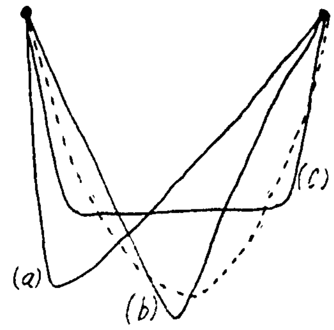


Fig. 3

Calculate the total potential energy for each shape. You will find that the catenary curve has the minimum total potential energy.

The following example may help you plot the parabola. The vertex in Fig. 1 is at (0, 0) and the two fixed points are at (-8, 14.5) and (8, 14.5). All parabolas symmetric to the y axis have the

resulting surface is not at all what you would expect, as shown for the wire cube in Fig. 4. An excellent source of sug-

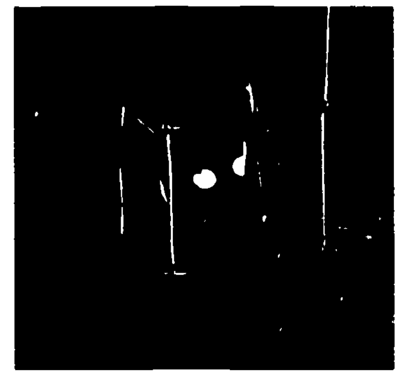


Fig. 4 (You will find soap films to be a difficult photographic challenge.)

gested experiments with soap bubbles, and recipes for good solutions, is the paperback Soap Bubbles and the Forces That Mould Them, by C. V. Boys, Double-Day Anchor Books. Also see "The Strange

B. C. **By Johnny Hart**

of the ball's mass and speed. Its direction is the same as the direction of the ball's velocity, which is the same as the ball's direction of motion.

Let us call the pair of balls a "system." The system also has a definite momentum, which we can call the "total momentum." The total momentum of the system is the vector sum of the momenta of the individual balls in the system, at a particular time.

To find the vector sum, draw lines parallel to the individual balls' directions of motion somewhere on the paper where they will intersect. The length of each ball's momentum vector (i.e., the magnitude of its momentum, or the product of its mass and speed) can be measured off by first deciding on a suitable scale (Fig. 2), which must be the same for both balls. The two individual momentum vectors must now be added. As shown in Fig. 2 the two vectors are added graphically by drawing the tail of one vector at the head of the other. The broken line is the sum: the total momentum.

Now suppose these balls collide and go off in different directions as they do in loops 21 and 22. This is shown in Fig. 3.

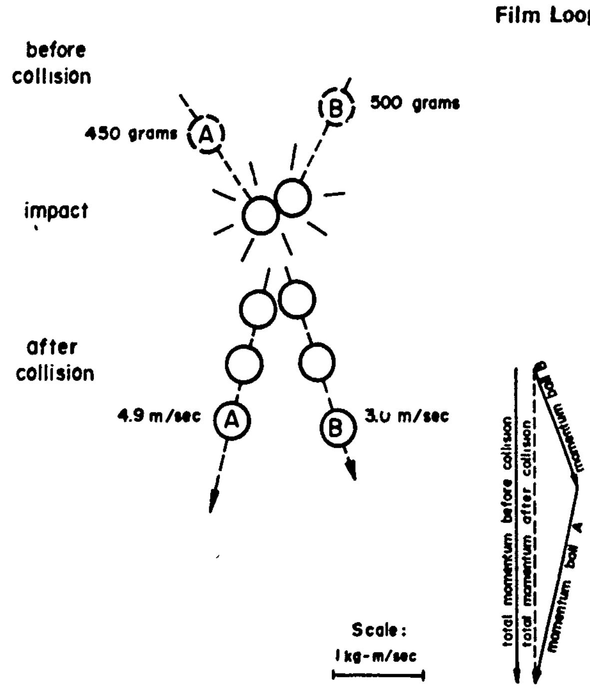
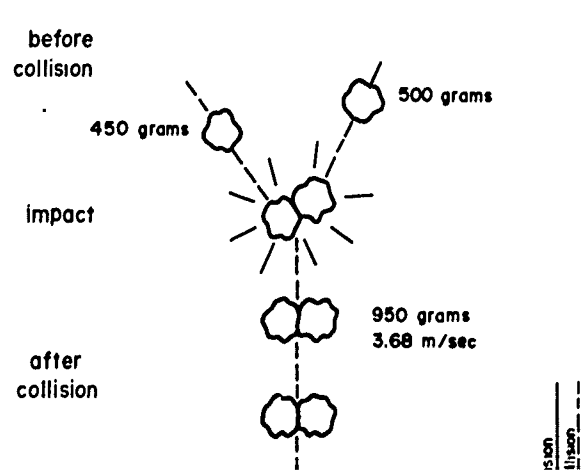


Fig. 3



vertical point as shown in Fig. 5, and

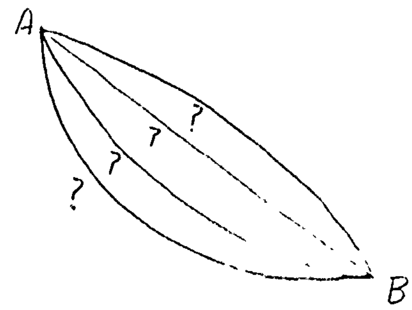


Fig. 5

we want to build a track between the two points so that a ball will roll from A to B in the least possible time. Should the track be straight or in the shape of a circle, parabola, cycloid, catenary or some other shape? (See page 53 of the Unit 1 Student Handbook for information on how to draw a cycloid.) Another interesting property of a cycloid, not to be confused with the challenge above, is that no matter where on a cycloidal track you release a ball, it will take the same amount of time to reach the bottom of the track. You may want to build a cycloidal track to check this. Don't make the track so steep that the ballslips, instead of rolling through.

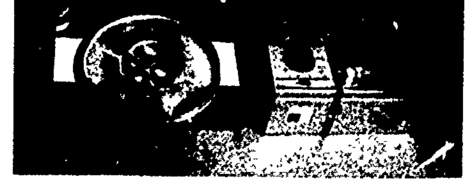


Fig. 1

Fig. 1 shows the apparatus in action, producing one pattern of standing waves. The drumhead in the figure is an ordinary 7" embroidery hoop with the large end of a balloon stretched over it. If you make your drumhead in this way, use as large and strong a balloon as possible, and cut its neck off with scissors. A flat piece of sheet rubber gives better results, since it is much easier to maintain an even tension over the entire drumhead if the rubber is not curved to begin with. Try other sizes and shapes of hoops, as well as other drumhead materials.

A 4" 45-ohm speaker, lying under the drum and facing upward toward it, drives the vibrations. Connect the speaker to the output of the amplifier.

In making the comparison, keep in mind that you will have, as a result of your measurements, a range of possible directions and magnitudes for the total momentum before collision, as well as after collision.

Do your results support the principle of momentum conservation?

If you are studying Chapter 10, calculate total <u>kinetic energy</u> before and after collision Considering the uncertainties in your data, can you conclude that kinetic energy is conserved?

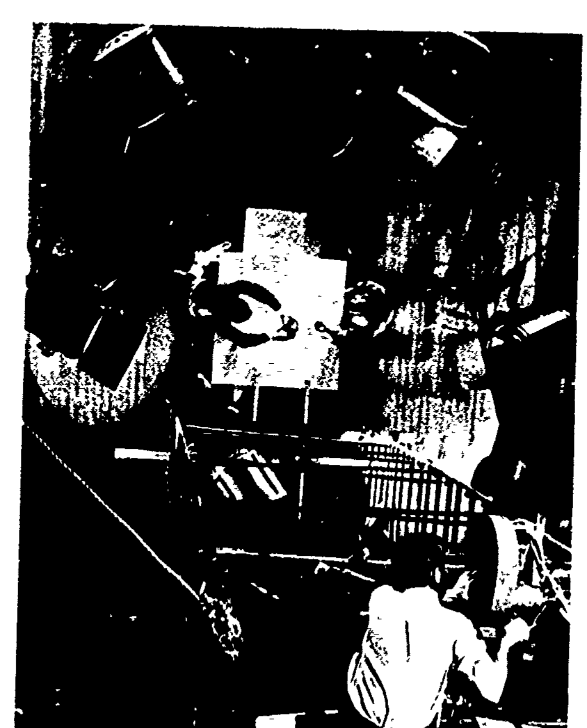
IV. Table Of Given Masses For Each Loop

(masses given in grams)

	Ball A	Ball B
Loop 21	539	361
Loop 22	367	367
Loop 23	500	500

FILM LOOP 24 Scattering of a Cluster of Objects
FILM LOOP 25 Explosion of a Cluster of Objects

(Scattering of a Cluster is also shown as Event 14 in "Stroboscopic Photographs of Two-Dimensional Collisions" earlier in this chapter of the Handbook.)



II. Description

In film loop 24 a case-hardened steel ball is shown entering from the right and striking a cluster of six balls at rest. A schematic diagram of conditions before collision is provided in Fig. 1(a).

Film loop 25 shows five balls, initially at rest, surrounding a small cylinder containing gun powder. The charge is exploded, and, among other things, the five balls can be seen headed in different directions. The initial array of the balls is shown in Fig. 1(b), along with their masses.

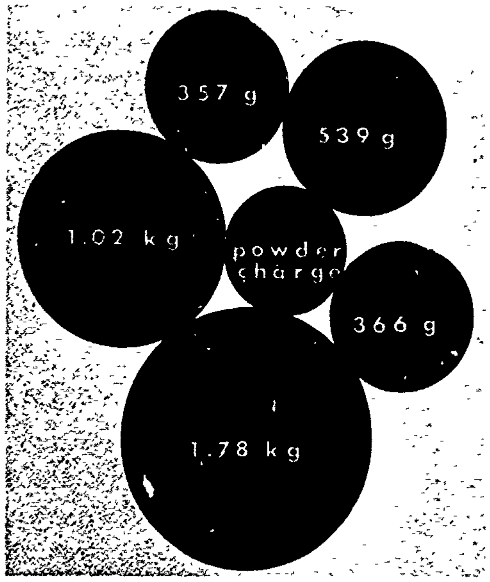


Fig. 1(b)

In each film there is a slow-motion sequence. It is your task to determine the ball velocities (direction as well as magnitude) by actual measurements. The following discussion describes recommended procedure.

For a list of the materials you will need, see p. 9-45 in the film loop notes for loops 21, 22 and 23.

For a description of analysis similar to that you are to use in loops 24 and 25, see p. 9-45 of the notes for loops 21, 22 and 23.

III. Film Loop 25 Explosion of a Cluster

What is the total momentum (both magnitude and direction) of the set of five balls after the explosion? Can you explain the discrepancy? (Hint: view the loop again and note the general direction of the blast.)

FILM LOOP 28 Recoil

In this film you can use the law of conservation of energy to calculate the recoil velocity of a gun.

A preliminary scene shows the recoil of a cannon which is fired during a ceremony at the fort on St. Helene Island, near Montreal. Then we go into a laboratory. The small brass cannon, suspended by long, thin wires, has a mass of 350 g, and the bullet has a mass of 3.50 g. When the fuse is ignited, a few seconds of burning (in slow motion) are needed before the powder charge is ignited. (Notice the change in smoke density just before the bullet emerges.)

Measurements. Project the film on a piece of paper and mark off a horizontal distance scale in centimeters. Time the motion of the bullet as it moves over a fairly large fraction of its observable motion. Thus obtain the bullet's velocity in apparent centimeters per second. Since we are interested only in relative values, it is not necessary to convert this velocity into actual cm/sec.

Use the law of conservation of momentum and the known mass ratio to predict the value of the gun's recoil velocity.

Test your prediction by running the film again and timing the gun's motion to find its recoil velocity experimentally. How well do the predicted and observed values agree? Can you explain any discrepancy?

NOTE ON CONSERVATION OF MOMENTUM

In the examples concerning conservation of momentum which we examined in Chapter 9 we assumed that the system was isolated: i.e., that the net force acting on it was zero. However, significant frictional forces occur in almost every practical example of motion and interaction. Usually the earth is involved directly (a slide in baseball) or indirectly (a bird landing in a tree). To show conservation of momentum, we ought to expand this system to include the earth, but because of the tremendous mass of the earth small changes in its momentum are undetectable.

The Little Prince on Asteroid B-612, reprinted from The Little Prince, Antoine de Saint-Exupéry, (New York, Harcourt, Brace, and World, 1943).

Suppose for example, that we apply this to a system consisting of one man and the earth, and suppose that the man begins to walk eastward. What happens to the earth? Why don't we notice it? What would happen if the man started walking on a tiny planet like that in The Little Prince?

As a thought-problem, suppose that every person on the earth could be persuaded to face the east and take one step at the same instant. How much would this change the length of one day?

What if the 2 billion people on earth all stood together in Texas and together jumped one meter into the air. How could the earth move?

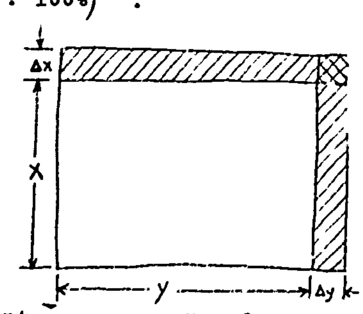
NOTE ON UNCERTAINTY IN CALCULATIONS

Show that if you measure a value X with a small uncertainty of $\pm\ \Delta x$, and measure a value Y with a small uncertainty $\pm\ \Delta y$, then the product XY has an uncertainty

$$\left(\frac{\Delta x}{X} + \frac{\Delta y}{Y}\right)\ XY.$$

Another way of stating this is that if the percentage uncertainty in X is $\frac{\Delta x}{X} \cdot 100\%$, and the percentage uncertainty in Y is $\frac{\Delta y}{Y} \cdot 100\%$, then the percentage uncertainty in XY is $\left(\frac{\Delta x}{X} \cdot 100\%\right) + \left(\frac{\Delta y}{Y} \cdot 100\%\right)$.

Fig. 1



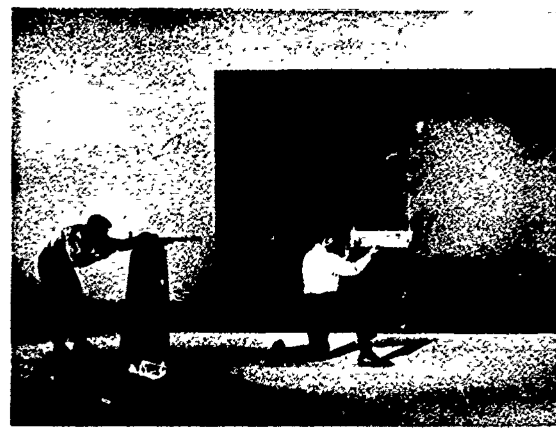
Hint: suppose X and Y represent the width and length of a rectangle, for which you wish to find the area (Fig. 1). The area you would measure is not exactly XY, but $(X + \Delta x)(Y + \Delta y)$. Multiply this out, and make the approximation that $\Delta x \Delta y$ is quite small compared to the other terms.

FILM LOOP 4 A Matter of Relative Motion

In this film loop, mechanical experiments are performed in which two simple carts of equal mass collide. Because of the steel spring bumpers of the carts, the collisions are almost perfectly elastic. In the film three sequences, labeled "Event A," "Event B," and "Event C" are photographed. In each event there is a collision between two carts on a ramp. The camera is on a cart which runs on a second ramp parallel to the one on which the colliding carts move. The camera is our frame of reference; this frame of reference may or may not be in motion. As photographed, the three events appear to be quite different. Describe these events, in words, as they appear to you (and to the camera).

By applying the laws of conservation of momentum and conservation of energy, we can show that all these collisions, just as they appear, are possible events. By applying the addition of velocity principle, we can show that the three events could actually be identical, but viewed from differently moving frames of reference. The question of which cart is "really" in motion is resolved by sequences at the end of the film, in which an experimenter stands near the ramp to provide a reference object. But is this "fixed" frame of reference any more fundamental than one of the moving frames of reference? Fixed relative to what?

FILM LOOP 26 Finding the Speed of a Rifle Bullet — Method I
FILM LOOP 27 Finding the Speed of a Rifle Bullet — Method II



I. Materials You Will Need

In addition to the film loop in the plastic cartridge, the projector, and these Notes, you will need: (1) a large piece of paper and some masking tape; (2) a plastic transparent ruler marked in millimeters; (3) a timer or stopwatch; (4) a pair of draftsmen's triangles to draw parallel lines.

If your instructor has one of the projector models with the "still-picture button," it may be of advantage to you here. It allows you to stop the film while the projector light is shining through (if the mechanism is in good working order). This, in turn, makes it possible to "stop motions" and measure positions on the screen at leisure.

The large paper sheet, taped to the wall, is to be your projection screen. When you are ready to take data, you can copy "positions" off the projected image. You can draw parallel "timing bars" on the paper. You can measure distances on it with your ruler, etc.

One precaution: once you have begun taking data, do not move the projector until you are certain you have finished taking data.

Place the projector such that the projected image "fills" the paper sheet.

II. Special Notes for Film Loop 26

a) About "Slow-Motion" Films

In this film there appears one extreme slow-motion sequence. You will be making time and distance measurements in this sequence.

The sequence was filmed with a high-speed camera. The rate at which this camera took "pictures" was carefully measured throughout the sequence. Its average value was <u>2,850 frames/second</u>.

Your projector projects this film at a far slower rate. This explains the "slow-motion" effect.

In the problem assigned to you—and discussed further below—<u>you will have to find the rate at which the projector delivers "pictures" to the screen</u>.

This you can do by timing the exact duration of the film loop with a timer or stopwatch. Between the end of the moving picture and its beginning, as the loop runs through the projector, there is a section of black "frames." One of these frames has a white circle in it. This frame "flashes" on the screen as it passes in front of the projection lens. The instant you see it again the film loop has run full course.

<u>There is a total number of 3,849 frames in this loop</u>.

With the help of this measurement, and with the data listed in this section, you can find "real time" from values of "projected time" in the slow-motion sequence.

In the present problem you have to convert to "real times."

In this film a rifle bullet of given mass (13.9 g) is shot into a massive wooden log (8.44 kg). The bullet's speed before impact is not known. The bullet enters the log and stays there. The log is initially at rest. The log (and bullet) move after impact.

Look at the film once or twice. You will notice that the height H of the log is also given (H = 15.0 cm). See also Fig. 1.

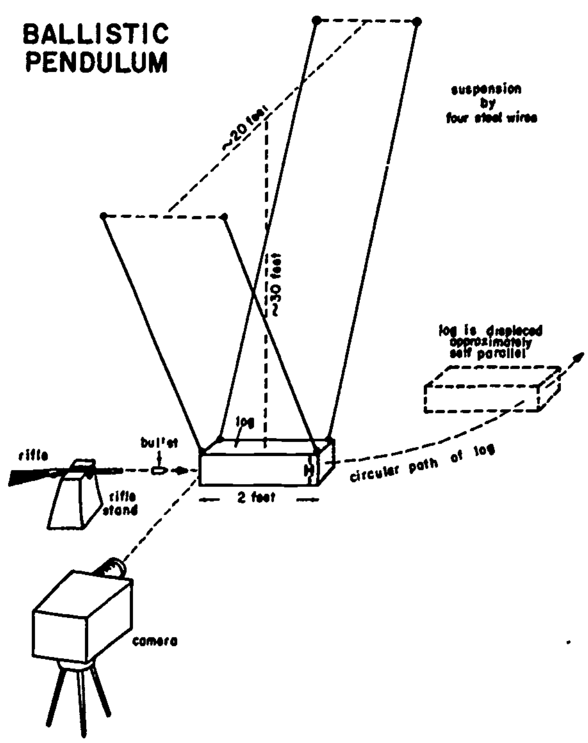


Fig. 1 (This schematic diagram is not to scale.)

It is possible in the slow-motion sequence) to determine the speed at which the log moves across the screen just after the bullet strikes. Distances between points in the image can be measured. But these are not the "real" distances!

However, knowledge of the actual height H of the log permits you to convert measured distances on the screen to "real" distances in the film studio by "scaling." Figure it out yourself!

To find the log's speed in the image on the screen, you must time its motion between two reference bars or points on the screen which you choose yourself. To find the log's "real" speed in the studio, you must not only "scale" distances. You must also convert to "real time." See Sec. II above.

b) Your Problem

What was the speed of the rifle bullet before impact? Here are some hints and suggestions which will assist you in finding an answer to this question.

The quantities you need in order to calculate this speed are either given to you, or can be found by measurement.

The given quantities are summarized in Table I.

TABLE I

Data Supplied to You

Type of rifle	"303"
Mass of bullet	13.9 g
Mass of wooden log	8.44 kg
Height H of wooden log	15.0 cm
Camera speed in the slow-motion scene intended for measurement	2850 frames/sec
Number of frames in entire film loop	3849 frames

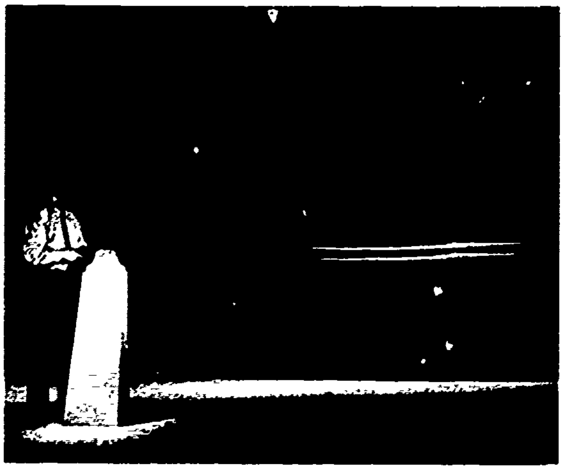
All the speed measurements are made in the extreme slow-motion scene. You also need to measure the total time necessary for the film loop to run through once.

Once you know the "real" speed of the log (plus bullet) after impact, you can calculate the bullet's speed before the collision.

By the way, it is interesting to calculate the kinetic energy given to the bullet by the rifle. You will find it to be large.

Now calculate, also, the kinetic energy of the log (plus bullet) after impact. Compare the two energies. Explain the difference.

III. Special Notes for Film Loop 27



a) Your Problem

In this film there appears one extreme slow-motion sequence intended for taking measurements. You will be measuring distances on the projected image.

Look at the film once or twice.

A rifle bullet of given mass (7.12 g) is shot into a massive wooden log (4.05 kg). The in-coming speed of the bullet is unknown. Your problem is to determine this speed.

The log is initially at rest, but it moves after impact. The bullet becomes embedded in the log and moves with it. See Fig. 1.

1. Suppose you knew the speed with which the log (plus bullet) leaves the scene of the impact. You should be able to answer the following question. Can you calculate the speed of the bullet before it strikes?

Write down an expression for the speed of the bullet before impact. Check your answer with your colleagues or your teacher.

2. In this film you are NOT expected to measure the speed of the log (plus bullet) after impact. Rather, you are to measure the vertical height of rise of the log as it departs from the scene of the impact on its circular path. The highest point reached by the log is the point at which the log reverses its motion and starts to swing back downward. This is visible in the film, and, in particular, it should not be hard to identify this point in the slow-motion sequence.

The kinetic energy of the log (plus bullet) just after impact will, during this swing, decrease toward zero. It will be exactly zero at the point of reversal because the speed is zero there.

The energy it began with is now the potential energy, i.e., the work of raising the weight of the log (plus bullet) through the (above-mentioned) vertical height of rise.

The two underlined amounts of energy are equal. Hence you can write down a relation between initial log speed and height of rise. Do it! Check your answer with your colleagues, or your teacher.

3. Somewhere in the film you are given H, the vertical dimension of the log, to be H = 9.0 cm.

In the slow-motion sequence, you can now mark off the distance on the paper which is equivalent to the real vertical dimension H = 9.0 cm of the log. The distance you have thus marked off becomes your scale for conversion of other distances, as measured on the paper, to "real" distances.

Now you are ready to run through the slow-motion sequence, and mark off the starting (lowest) and stopping (highest) positions of the log in its swing up the circular path. Calculate the "real" height of rise.

4. Calculate the speed with which the log (plus bullet) leaves its initial position.

What was the speed of the rifle bullet before it struck? Calculate its value in ft/sec too.

Calculate the kinetic energy of the rifle bullet before it strikes. You will find it to be large.

Calculate the kinetic energy of the log (plus bullet) after impact, and compare with that of the bullet before. Explain the difference.

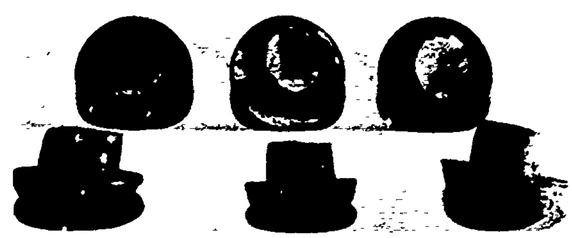
TABLE II

Summary of Data Given in Loop 27

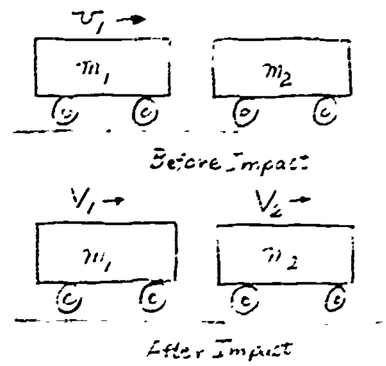
Mass of bullet	7.12 g
Mass of wooden log	4.05 kg
Height H of wooden log	9.0 cm

(Notes for Film Loop 28 will be provided when the loop becomes available.)

FILM LOOP 29 Colliding F ight Cars



What are they?



This film is designed to show a collision in a real-life situation. It was made during a test of freight-car coupling strength in which engineers deliberately caused collisions violent enough, in some trials, to break the couplings. The first part of the film shows how the "hammer car" picks up speed by coasting down a ramp. The force of the collision is monitored by equipment in a mobile laboratory in a truck near the point of impact. The momentary impulsive force between the cars is about 1,000,000 pounds. One of the collisions is shown in slow motion to allow you to measure speeds before and after impact. In this way you can test the law of conservation of momentum during this large-scale collision.

In a perfectly inelastic collision, the cars would stick together after impact. The collision we study is <u>partially</u> elastic, and after collision the cars separate to some extent (with a small relative relocity). In Fig. 1, the final velocities are related in such a way that V_1 is less than V_2, and the relative velocity of separation V_2-V_1 is less than the relative velocity of approach v_1.

Measurements. The masses of the cars are:

hammer car: m_1 = 95,000 kg (210,000 lb)
target car: m_2 = 120,000 kg (264,000 lb)

To measure the velocities, project the film on a piece of ruled paper and use a drag strip or stopwatch to measure the apparent time for one edge of the car to move through a given number of squares. To obtain all the necessary velocities, you will have to run the film several times. Express velocities as "squares/sec." Since we are interested only in relative values, it is not necessary to use real time or to convert velocities into actual meters per second.

Simple timing will give v_1 and V_2. For example, you might have v_1 = (10 squares)/(7.33 sec) = 1.36 squares/sec. However, the film was made on a cold winter day and friction was appreciable for the motion of the hammer car after collision. One way to allow for friction is to make a graph, assume a uniform (negative) acceleration, and extrapolate to t = 0, the instant after impact. An example will make this clear: Suppose the hammer car coasts 3 squares in 5 seconds after collision, and it coasts 6 squares in 12 seconds after collision. (If there had been no friction, we would have expected it to coast 6 squares in only 10 seconds. The <u>average</u> velocity during the first 5 seconds was V_1 = (3 squares)/(5 sec) = 0.60 squares/sec. In uniformly accelerated motion, the average velocity during any interval equals the instantaneous velocity at the mid-time of that interval, so we conclude that the car's velocity was $V_1 = 0.60$ squares/sec at $t = 2.5$ sec. Similarly, for the interval 0-12 seconds, the velocity was $V_1 = 0.50$ squares/sec at $t = 6.0$ sec. Now plot a graph as in Fig. 2 to find the value of V_1 at $t = 0$ sec. In this example, the graph shows that $V_1 = 0.67$ squares/sec at $t = 0$;

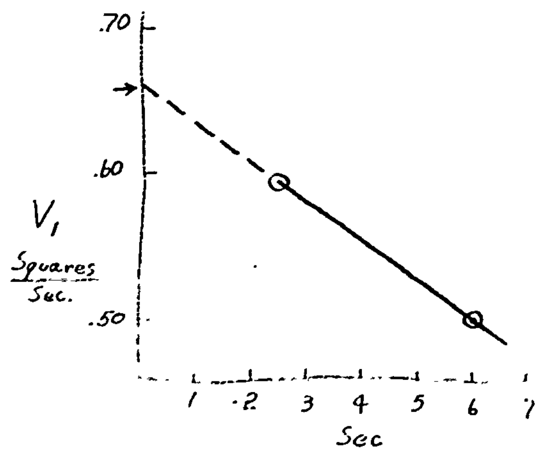


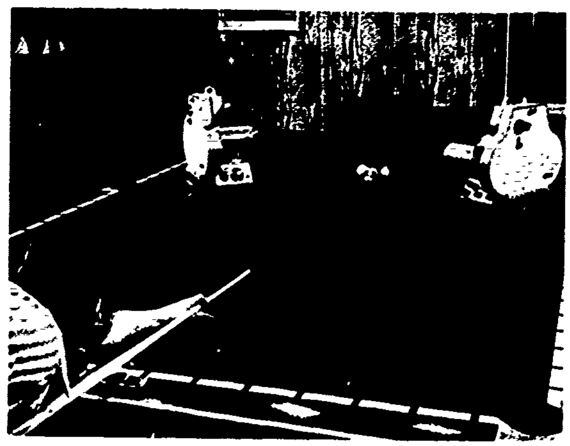
Fig. 2 Extrapolation to allow for friction in finding V_1.

this is the value of V_1 just after the collision.

You now have all the masses and velocities. Compare the total momentum of the system before collision with the total momentum after collision.

Energy Loss. Since this is not a perfectly elastic collision, <u>kinetic</u> energy is not conserved. This doesn't violate the law of conservation of energy, because some of the hammer car's original kinetic energy is transformed into work done to compress (and perhaps break) the couplings. To study this effect, use the masses and velocities which you have already found. This time calculate the kinetic energy of the system before and after collision. What fraction of the hammer car's original kinetic energy has been "lost?" What became of this energy?

(The "mushrooms" shown in the introductory photograph are actually three of fourteen rivets which were sheared when the cars collided with 1,500,000 pounds impact on the last test. The stem of the rivets is one inch in diameter.)



The two cameras shown on the table took side views of the collision, which are not shown in this film loop.

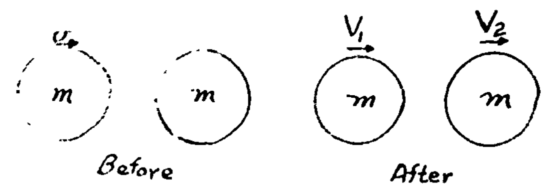
FILM LOOP 30 Dynamics of a Billiard Ball

This is a film in which we see a familiar action in extreme slow motion. You can make measurements to test the law of conservation of momentum.

The slow-motion scenes were shot at 3000 frames/sec, giving a slow motion factor of 166.7 if projected at 18 frames/sec. This factor is given only for orientation purposes. If you make measurements to test conservation of momentum, you may use the time scale of the projected images. Also you may express linear velocities in any convenient unit such as those on graph paper.

Suggested measurements:

1. Measure the linear velocity v of the cue ball before impact, and the velocity V_2 of the target ball as it slides along the table just after impact. Consider whether the linear motion V_1 of the cue ball after impact is large enough to worry about. The balls have the same mass (m), hence conservation of linear momentum predicts that $v = V_1 + V_2$. Test this prediction.



2. In the close-up you can see more clearly that the cue ball spins on its axis for a while before gaining enough forward speed to roll without slipping. Simultaneously, the target ball skids along the cloth of the table for some distance before starting to roll without slipping. You can sometimes see a similar phenomenon at the bowling alley: a ball may slide some 20 feet before it "digs in" and starts to roll without slipping. Complete analysis of the motions shown in the film is fairly complex. How closely do your results indicate that momentum is conserved? What motions did you neglect in your analysis?

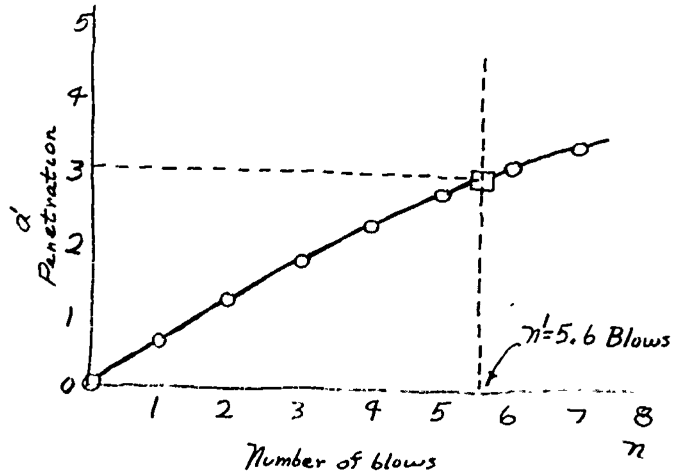
FILM LOOP 31 A Method of Measuring Energy — Nails Driven Into Wood

A body is said to have energy if it is capable of doing work. How can energy be measured? Since work W is found by multiplying the acting force F by the displacement d parallel to the force, we can measure work (and hence energy) in relative units by measuring displacement. In symbols, $W = Fd$, and if F is constant, we can say that W is proportional to d, but this will be a simple proportion only if the force is constant. In this film we test the validity of this way of measuring energy. Nails are driven into wood by repeated identical blows; each blow transfers the same energy, and does the same amount of work.

The initial scenes show a construction site where a pile driver does work as the falling weight strikes the pile over and over again. Then we move into a laboratory. The same weight, always falling from the same height, strikes a nail ten times. We can reasonably assume that during each blow the weight loses the same amount of energy; hence it does the same amount of work on the nail. But is the resisting force of the wood always the same?

Measurements. For convenience, number the blows by integers $n = 1$, $n = 2$, ... $n = 10$. Project the film on a screen. Measure the height of the nail head above the wood at the start, and after each blow. From this you can find the downward displacement d of the nail for each value of n. (At the start, before any blows, $d = 0$ and $n = 0$.) To test our method of measuring energy, make a graph of d, plotted vertically, versus n, plotted horizontally. Study the graph; is it a straight line? If the graph <u>is</u> straight or nearly so, then in other films we can use the depth of penetration of a nail as a direct measure of the energy of the object striking it.

For more precise work, you can use the results of this experiment as a <u>calibration</u> of the wood. Suppose the graph is curved as shown in Fig. 1. Then any observed penetration (in cm as measured on the screen) can be converted to an equivalent number of blows n', proportional to the energy transferred to the nail. Thus in Fig. 1, a penetration of 3 cm signifies 5.6 units of energy.

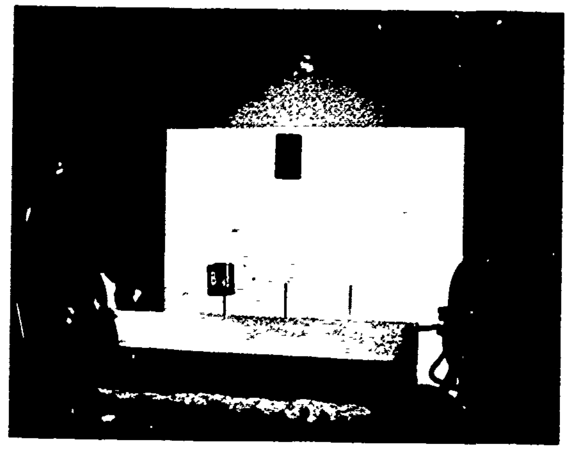


FILM LOOP 32 Gravitational Potential Energy

The gravitational potential energy (PE) of an object depends on two things: its weight (the force of gravity on it) and the height h to which it has been raised. Is this dependence a simple proportion, such as (PE) = ma_gh? Or is some more complex relationship needed to describe gravitational potential energy? From this film you can take data to test the formula for gravitational potential energy.

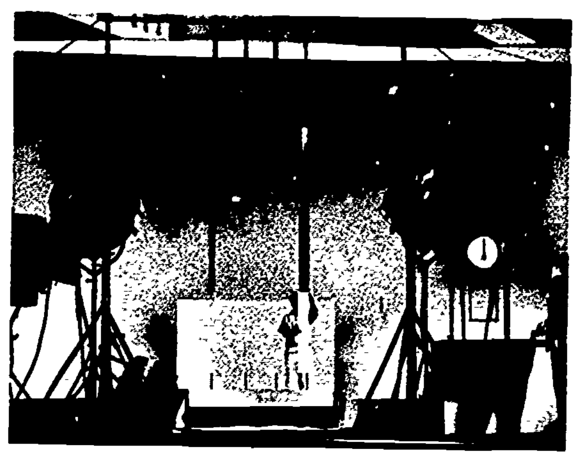
Measurements

1. Dependence upon weight. Objects of different weight are lifted through the same height. To measure the potential energy of each raised weight, we allow it to fall and drive a nail into wood. In Loop 31 we saw that the distance that the nail penetrates into the wood is a fairly good measure of the work done on the nail; hence it is a measure of the weight's original potential energy. Project the film on a piece of paper and use a ruler to measure the positions of the nail heads before and after impact of the falling weights. In this way find the penetration depth d. Make a graph of penetration d (proportional to energy) versus weight ma_g. Is this a straight line within experimental error?



2. Dependence on height. Equal weights are raised to different heights and allowed to fall. Make a graph of penetration d (proportional to energy) versus height h. Is this a straight line within experimental error?

If you have plotted a calibration curve for nail penetration (see Loop 31), you can improve the accuracy of this

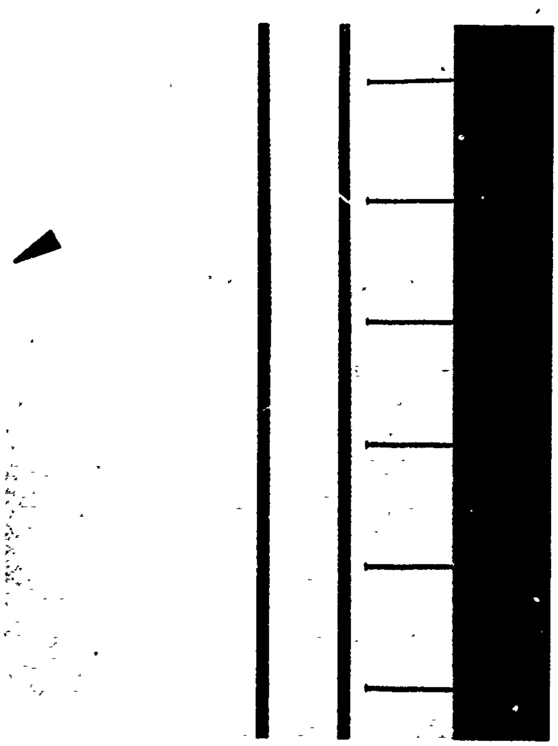


experiment. Convert each penetration depth to an equivalent number of blows (n') and use n' instead of d as a measure of energy.

FILM LOOP 33 Kinetic Energy

In this loop we test the way in which kinetic energy (KE) depends on speed (v). The formula is $(KE) = \frac{1}{2}mv^2$, so we must measure both (KE) and v, and keep the mass m constant. As shown in Loop 31, penetration of a nail driven into wood is a good measure of the work done on the nail, and hence is a measure of the energy lost by whatever object strikes the nail. The film offers a choice of two ways of measuring the speed of the moving object.

The preliminary scenes show that in fact the moving object receives its speed as a result of falling from some height. However, we are not concerned at all with this detail; only the speed just before it strikes the nail is important. To help you concentrate on the speed itself, the scenes intended for measurement were photographed with the camera on its side so that the moving mass appears to move horizontally toward the nail.



1. Measurement of speed. One way to measure the speeds is to use a drag strip or stop watch to time the motion of the leading edge of the moving mass as it moves from one reference mark to the other mark. A more direct way is to use the "clock" shown in the picture—a disk that rotates at 3000 revolutions per minute. Project the film on a sheet of paper and mark the position of the rotating pointer at the times when the mass crosses the two reference marks. The elapsed time can be taken to be proportional to the angle through which the pointer turns (measured with a protractor). Finally the speeds are proportional to the reciprocals of the times. Since we are testing the form of a law of physics, it is not necessary to convert these speeds into meters per second—any convenient unit can be used, such as 1/(cm on drag strip), or 1/(degrees of rotation of pointer). Measure the speed for each of the five trials.

2. Measurement of kinetic energy. The kinetic energy of the moving object is transformed into the work required to drive the nail into the wood. In Loop 31 we found that this work is nearly proportional to the distance of penetration d. Therefore we can use d as a measure of the kinetic energy. Measure the penetration of the nails for each of the five trials.

3. How does (KE) depend on v? The formula derived in the text using Newton's laws indicates that (KE) is proportional to v^2, the square of the speed, not to v. Test this by making two graphs. In one graph, plot (KE) (actually, d)

vertically and plot v^2 horizonaally. For comparison, plot another graph of (KE) versus v. What do you conclude from these two graphs?

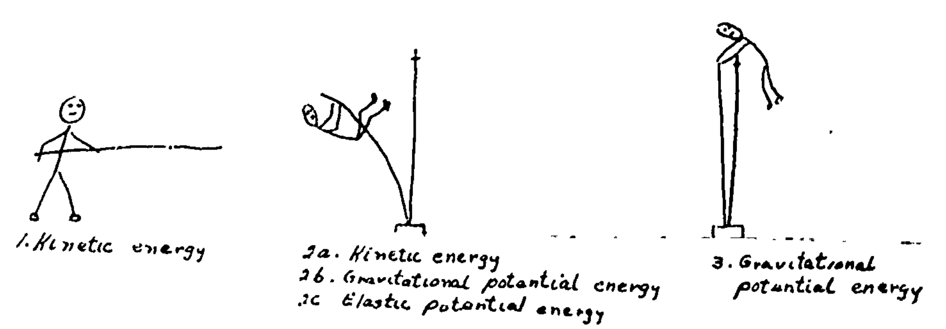
FILM LOOP 34 Conservation of Energy I — Pole Vault

This is a quantitative loop designed to help you study conservation of energy. A pole vaulter's jump is shown in slow motion. You can measure the total energy of the system (jumper and pole) at three times (Fig. 1): (1) just before he starts to rise; (2) part way up, when the pole has a distorted shape; and (3) when the jumper is at his highest point as he clears the bar. Notice how the total energy is converted from one form to another during the action. Since it takes work to bend the pole, the pole has elastic potential energy in position (2). This elastic energy comes from some of the initial kinetic energy which the vaulter has as he runs horizontally before inserting the pole into the socket. Later, the elastic potential energy of the bent pole is transformed into some of the jumper's gravitational potential energy when he is (momentarily) motionless at the top of the jump.

Measurements. According to the principle of conservation of energy, the total energy of the system is constant, although it is divided up differently at different times as indicated in Fig. 1.

Data: jumper's mass: m = 68 kg
jumper's weight:
mg = 68 x 9.8 = 670 newtons (150 lb)
jumper's height: 1.84 m (6 ft)
jumper's center of gravity: 1.02 m above the soles of his feet
height of cross bar above floor: 3.50 m (11.5 ft)
camera speed: 250 frames per sec

Position 1. The energy is entirely kinetic energy, given by (KE) = $\frac{1}{2}mv^2$. To help you measure the runner's speed, successive frames are shown while the runner moves past two markers separated



by 1 meter. Each "freeze-frame" represents a time interval of 1/250 sec. Count the number of frames required for the runner to move 1 meter; in this way find his average speed over this meter in m/sec. Then you can find the initial kinetic energy. If m is in kg and v is in m/sec, E will be in joules.

Position 3. Gravitational po energy is the work done to raise the jumper's center of gravity. From the given data, estimate the vertical rise of the center of gravity as the jumper moves from position (1) to position (3). (His center of gravity clears the bar by about a foot, or 0.3 m.) Multiply this height of rise by the jumper's weight to get potential energy. If weight is in newtons and height is in meters, the potential energy will be in joules. A small additional source of energy is in the jumper's muscles: judge for yourself how far he lifts his body by using his arm muscles as he nears the highest point. This is a small correction, so a relatively crude estimate will suffice. Perhaps he pulls with a force equal to his own weight through a vertical distance of 2/3 of a meter.

Testing the law of conservation of energy. How does the initial kinetic energy, plus the muscular energy expended in the pull-up, compare with the final gravitational potential energy? (An agreement to within about 10 per cent is about as good as you can expect from a measurement of this type.)

Optional—Bending of the pole. You may also wish to check the total energy at the intermediate position (2). Three types of energy are involved at position (2), designated as (2a), (2b), and (2c).

2a. Kinetic energy: Use the intermittent stop-frame action to obtain the speed of the jumper at position (2). (Use the seat of his pants as a reference.) Measure the speed along the direction of motion; make marks on a piece of paper at the start and the end of a known number of frames (the freeze-frames are 1/250 sec apart). The distance traveled during this time can be found from a proportion, using the 1-meter markers as standards.

2b. Gravitational potential energy: Estimate the height of rise of the jumper's center of gravity as he moves from position (1) to position (2); from this calculate his increase in gravitational potential energy.

2c. Elastic potential energy: The work done in deforming the pole is stored in the pole as elastic potential energy. In the final scene of the film, a chain windlass is used to bring the pole to a shape very similar to that which it assumes momentarily during the jump. When the chain is shortened by a certain amount (d), work is done on the pole. This work is given by

work=(average force)x(displacement),

or $W = (F_{av})(d)$.

During the cranking sequence shown, the force varied from an initial value F_1 to a final value F_2. Read these forces as shown by the spring balance, and calculate the average force as $F_{av} = \frac{1}{2}(F_1+F_2)$. Convert this average force to newtons. The displacement d can be estimated from the number of times the crank handle is pulled. To calibrate this, a close-up allows you to calculate how far the chain moves during a single stroke of the handle. Use F_{av} and d to calculate the work done (in joules) to crank the pole into its distorted shape.

You now have three amounts of energy,

(2a), (2b), and (2c) which can be added together to give the total energy at position (2). How does this compare with the original kinetic energy, in position (1)?

As a general reference, see "Mechanics of the Pole Vaule," 16th ed., by Dr. R.V. Ganslen; John Swift & Co., St. Louis, Mo. (1965); $2.00.

FILM LOOP 35 Conservation of Energy II—Aircraft Takeoff

This is a quantitative loop designed to help you study conservation of energy. During a takeoff maneuver, the pilot of a light aircraft (Cessna 150 A) brings it up to constant speed in level flight, just a few inches above the surface of the runway. Then, keeping the throttle fixed, he rotates the flaps so that the plane begins to rise. Finally, still with the same throttle setting, he levels off at an altitude of several hundred feet. At this altitude, the aircraft's speed is less than at ground level. You can make a test of the principle of conservation of energy because one disturbing factor—air resistance—has been canceled out, since the power supplied by the aircraft motor remained constant throughout the action. This power was evidently just enough to compensate for air resistance while the plane was flying horizontally at ground level. (We know this because the plane's initial speed was constant, indicating that the net force on it was zero.) To a good approximation, air resistance remained the same after lift-off, so the motor's power (held constant by the pilot) still balanced air resistance.

When the plane rose, its gravitational potential energy increased; this can only have come at the expense of the initial kinetic energy of the plane. (Remember

that the thrust from the motor is just enough to balance the air resistance.) Finally, at the upper level, the plane's kinetic energy is still less, but its potential energy is still greater. According to the principle of conservation of energy, the total energy (KE + PE) remained constant.

Data: length of plane: 7.5 m (23 ft)
mass of plane: 550 kg
weight of plane:
$550 \text{ kg} \times 9.8 \text{ m/sec}^2$
$= 5400$ newtons (1200 lb)
camera speed: 45 frames/sec

Project the film on a piece of paper and carefully mark off the length of the plane. This calibrates all distances; 1 centimeter on the screen corresponds to a known number of meters in actuality. To help you measure the plane's speed, its motion is shown in intermittent motion, every third frame princed, one frame at a time. In this way you can measure how far the plane travels in a known time of 15 or 20 "freeze frames." (Each frame corresponds to 3/45 sec, i.e. to 1/15 sec.) Measure the speeds at levels 1, 2, and 3. Express the speeds in meters per second. Measure the height above ground level when the plane is at levels 2 and 3. (Express these in meters.) Now you have all the data needed for calculating kinetic energy ($\frac{1}{2}mv^2$) and gravitational potential energy (ma_gh) at each of the three levels. Make a table showing (for each level) KE, PE, and E_{total}. Do your results substantiate the law of conservation of energy, within experimental error? How well do you think the pilot could maintain constant engine power?

Steve Acker, of Wheat Ridge High School, Wheat Ridge, Colorado, seems a bit skeptical about elastic potential energy. (Photo by Linda Cronquist)

FILM LOOP 38 Superposition of Waves

This loop is designed to help you understand how wave-forms can be combined. The basic wave-forms are <u>sinusoidal</u>, i.e., their graphs are like sine curves. In general, a sinusoidal wave need not pass through the origin; all the waves in Fig. 1 are called sinusoidal because their shapes are the same. A cosine wave is sinusoidal!

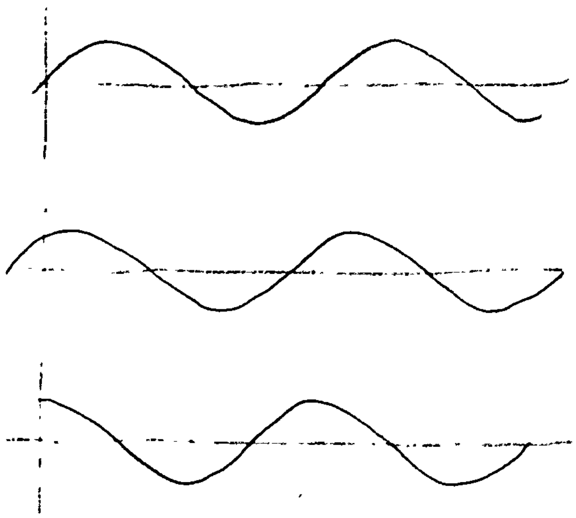


Fig. 1 Sinusoidal waves

The waves shown in the loop are generated electronically and are displayed on the face of a cathode ray oscilloscope. The operator can adjust the magnitudes and phases of several component waves to form a resultant wave. This algebraic addition is called superposition of waves.

Several superpositions are set up by the operator. If two waves of equal wavelength and amplitude are in phase, they add up to a king-sized wave of double amplitude; if they are combined when out of phase, their resultant is zero. If waves of different wavelength are combined, their superposition is not sinusoidal and the resultant wave-form is complex in shape. Your teacher can help you interpret these and other superpositions seen in the film.

Each of the photographs below shows three traces on the face of an oscilloscope. In each figure the bottom trace is the sum of the top two traces.

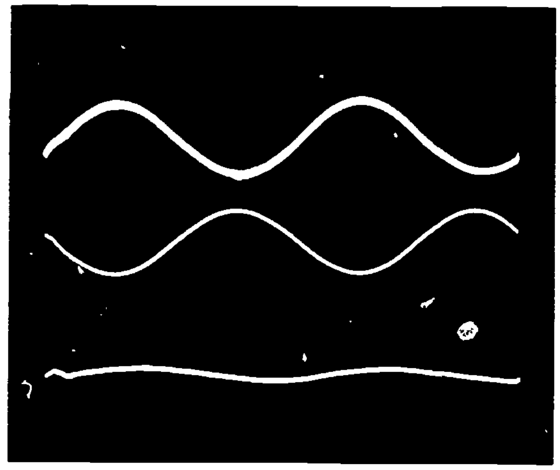


Fig. 1

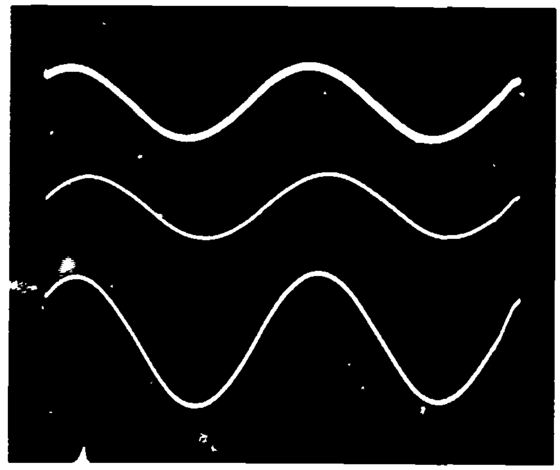


Fig. 2

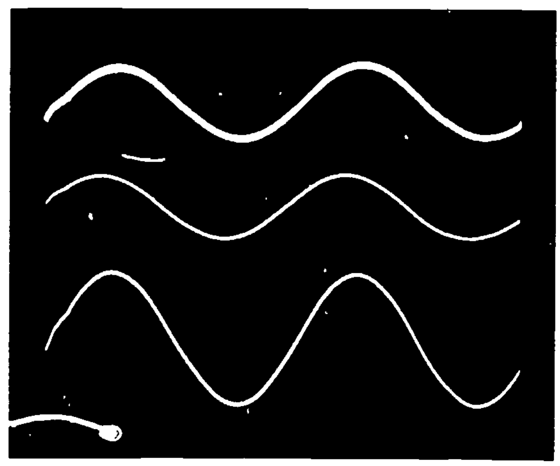


Fig. 3

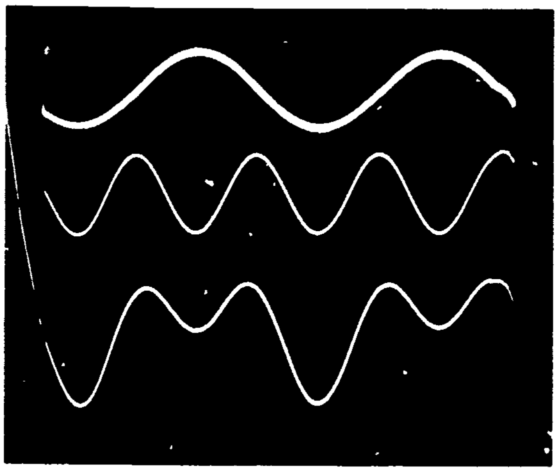


Fig. 4

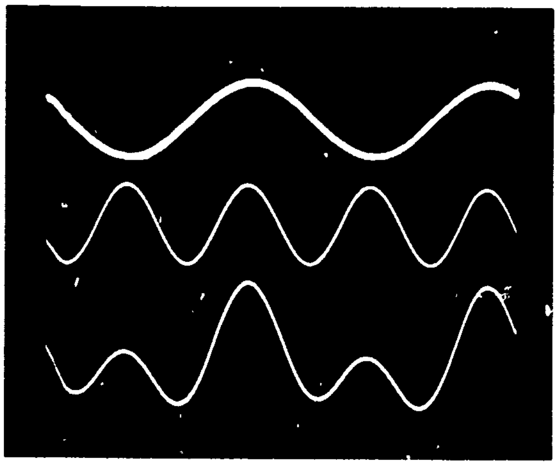


Fig. 5

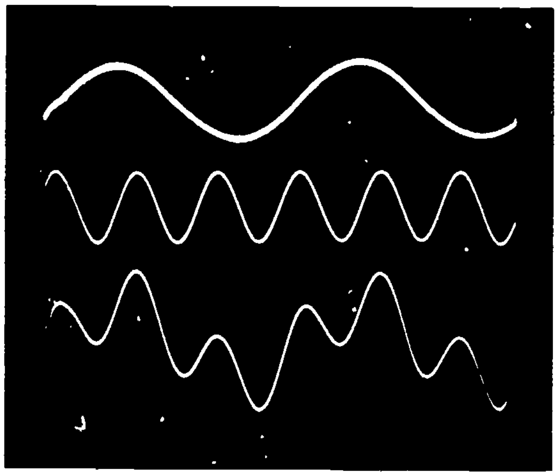


Fig. 6

FILM LOOP 39 Standing Waves on a String

Fig. 1

When the force of tension in a vibrating string is adjusted, a standing wave can be set up, but this occurs only when the tension has one of a set of "right" values. This is because the tension determines the speed of a pulse which might travel to the fixed end of a string and back again; if the tension (hence speed) is just what is required, the pulse will make a round trip in exactly the same time that the source makes one vibration. Because of this synchronism or resonance, a build-up occurs when the wave speed v is properly adjusted.

In the film, one end of a string is attached to a tuning fork of frequency 72 vibrations per second, and the tension is adjusted by sliding back and forth a wooden cylinder to which the other end of the string is attached. The cylinder is clamped at various points to give rise to different modes of vibration.

For example, in the third mode, the string vibrates in 3 segments with 2 nodes (points of no motion) between the nodes at each end. The nodes are half a wavelength apart, and in between the nodes are points of maximum vibration called antinodes. The frequency f is related to the wavelength λ by the equation $v = f\lambda$. We tune the strings of an instrument like a violin or guitar

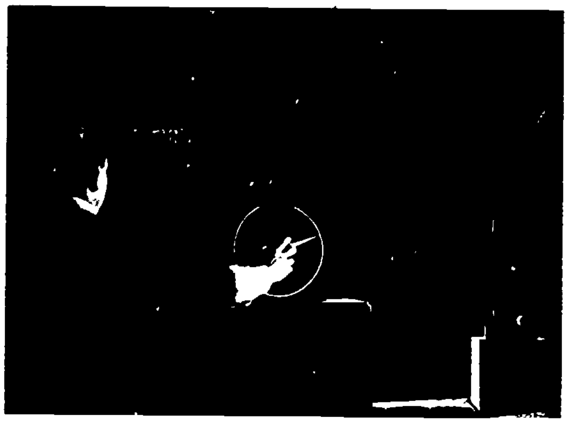


Fig. 2

by changing the tension on a string of fixed length. If the frequency of vibration of a string is fixed we can lower the pitch by increasing the tension (thus increasing the wave speed v) to obtain a longer λ. The film shows how, when the frequency remains constant, the wavelength changes as the tension is adjusted.

A high-speed snapshot of the string at any time would show its instantaneous shape. Points on the string move up and down, except at the nodes. The eye sees a blurred or "time exposure" superposition of string shapes. In the film, this blurred effect is reproduced by shooting at a slow rate; each frame is exposed for about 1/15 sec. Some of the modes of vibration are also photographed by a stroboscopic method. For example, if the string vibrates at 72 vib/sec and frames are exposed at the rate of 70 times per sec, then the string seems to go through its complete cycle of vibration at the difference frequency, i.e., 2 times per sec. In this way, a "slow motion" effect is obtained.

Standing waves are set up in air in a large diameter glass tube; the tube is closed at one end by an adjustable

FILM LOOP 40 Standing Waves in a Gas

piston, while a loudspeaker at the other end is a source of sound energy. The speaker is energized by a variable-frequency oscillator and a public address amplifier. About 20 watts of audio power gives notice to everyone in a large building that filming is in progress!

The film shows how a standing wave is formed when the frequency of the oscillator is adjusted to one of several discrete values. Resonance is indicated in each mode of vibration by a set of nodes and antinodes. There must be a node at the fixed end (where air molecules cannot move) and there must be an antinode at the speaker (where air is being set into motion). Between the fixed end and the speaker there may be additional nodes and antinodes.

How can we make visible the presence or absence of a stationary acoustic wave in a gas? In one method, very light and fluffy cork dust is laid down in a uniform thin line along the length of the tube. When a resonance is obtained, the dust is set into violent agitation by the movement of air molecules at the antinodes; the dust remains stationary at the nodes, where air molecules are not moving. In the first part of the film, dust is used to show standing wave patterns for the frequencies shown in Table 1 (read to the nearest 10 vib/sec).

Table 1.

mode	f (vib/sec)	number of half wavelengths
1	230	1.5
2	370	2.5
3	530	3.5
4	670	4.5
12	1900	12.5

The third mode of vibration is shown in Fig. 1; from node to node is $\frac{1}{2}\lambda$, and in

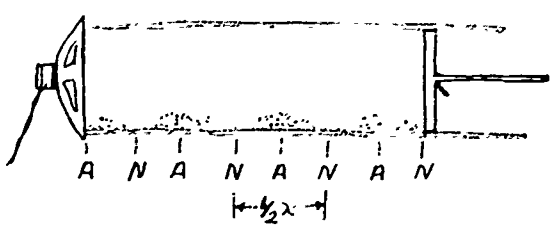


Fig. 1

this mode the length of the pipe is $3\lambda + \frac{1}{2}\lambda$ (the extra $\frac{1}{2}\lambda$ is the distance from the speaker antinode to the first node). In general, there are $(n+\frac{1}{2})$ half-wavelengths in the fixed length L, so $\lambda \propto 1/(n+\frac{1}{2})$. Since $f \propto 1/\lambda$, this means that $f \propto (n+\frac{1}{2})$. Divide each experimentally obtained frequency in Table 1 by $(n+\frac{1}{2})$ to find whether the result is reasonably constant.

Notice that in all modes the dust remains motionless near the stationary piston, which is a node.

In the second part of the film nodes are made visible by an entirely different method. A long thin wire running the length of the tube (near the top) is heated electrically to a dull red glow. When a standing wave is set up, the wire is cooled at the antinodes where air molecules in vigorous motion carry heat away from the wire. The bright regions correspond to nodes, where there are no air currents. The oscillator frequency is adjusted to give several standing wave patterns, in modes 1, 2, 3, 4, 8, and 15, with successively smaller wavelengths.

(Notes for Film Loop 42, Vibrations of a Rubber Hose, are found on page 12-31 with the notes for Loops 44 and 45.)

FILM LOOP 43 Vibrations of a Wire

This film shows standing wave patterns for a thin but stiff wire. The wave speed is determined by the wire's cross section and by the elastic constants of the metal. No external tension is used.

1. Straight wire. First we see how a vertical force can be applied at one point of the horizontal wire. The wire passes between the poles of a strong permanent magnet; when a switch is closed a steady current from a battery is set up in one direction through the wire. The interaction of this current and the magnetic field gives rise to a downward force on the wire. When the direction of the current is reversed, the force on the wire is upward. Repeated rapid reversal of the current direction can make the wire move up and down in a vibratory fashion.

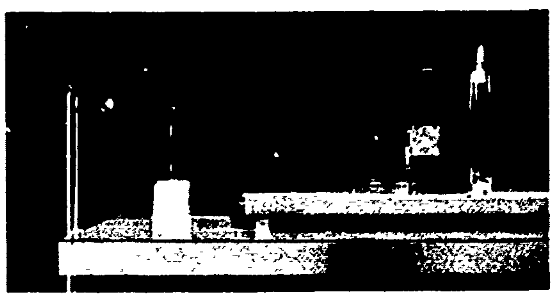


Fig. 1

The battery is replaced by a source of alternating current whose frequency can be varied. When the frequency is adjusted to match one of the natural or resonant frequencies of the wire, a standing wave builds up. Several modes are shown, each excited by a current of a different frequency. The "boundary conditions" for the wire's motion require that in any mode the fixed end of the wire is a node and the free end of the wire is an antinode. (A horizontal plastic rod is used to support the wire; this support is always placed at a node so that it will not disturb the natural vibration of the wire.) The wire is photographed in two ways: in a blurred "time exposure," as the eye sees it, and in "slow motion," simulated through stroboscopic photography (see notes for Loop 39).

Study the location of the nodes and antinodes in one of the higher modes of vibration. They are not equally spaced along the wire, as they were for the vibrating string (Loop 39). This is because the wire is stiff, while the string is perfectly flexible.

2. Circular wire. The wire is bent into a horizontal loop, supported at one point. The boundary conditions now require a node at this point; there can be additional nodes, equally spaced

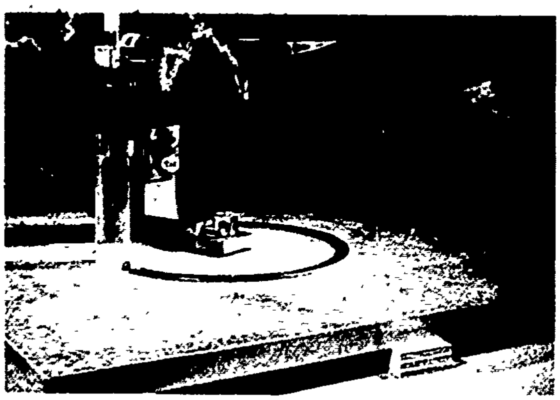


Fig. 2

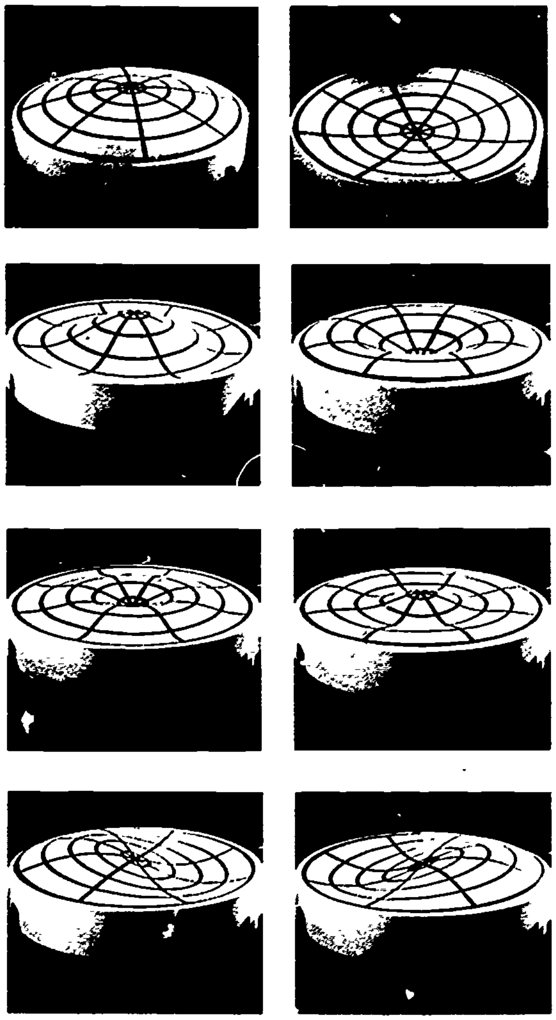
around the ring. Several modes are shown, both in "time exposure" and in "slow motion." To some extent the vibrating circular wire is a helpful model for the wave behavior of an electron orbit in an atom such as hydrogen; the discrete modes correspond to discrete "wave functions" for the atom.

FILM LOOP 42 Vibrations of a Rubber Hose
FILM LOOP 44 Vibrations of a Drum
FILM LOOP 45 Vibrations of a Metal Plate

In these film loops you will see three vibrating systems—a piece of rubber hose, a circular drum head and a square aluminum plate. The vibrations are known as standing waves. To see their wave nature and to review the technical terms used, refer to Chapter 12, particularly the sections on wave propagation, periodic waves and standing waves. Transparency 27, "Standing Waves," shows how this type of vibration is produced.

In Loop 42, a rubber hose is set into vibration by a variable-speed motor. The top of the hose is clamped, and so is a node. The motion of the eccentric arm which shakes the lower end is so slight that this end, too, may be considered a node. As the motor is gradually speeded up, the amplitude of the vibrations of the hose increases until a single well-defined oscillating loop is formed between the nodes. It is a half wavelength long. If the speed of the motor is doubled, two loops are formed. This oscillation frequency is known as the second harmonic. The hose is now one wavelength long. By further speeding up the motor a series of resonant frequencies will be reached. With care you may be able to count as many as 11 loops.

In Loop 44, a stretched rubber membrane is driven by a variable-frequency 30-watt loudspeaker. The rim of the



drum is a nodal circle. Stroboscopic pictures enable you to see the rapid vibrations in slow motion. Watch for the fundamental harmonic, when the membrane rises and falls as a whole. At a higher frequency a second circular node shows up between center and rim. Watch also for an antisymmetric mode where there is a mode along a diameter with a hill on one side and a valley on the other. Other symmetric and anti-symmetric vibration modes are shown. See if you can identify the nodal lines and circles. There is no simple relation of resonant frequencies for this two-dimensional system.

In Loop 45, the square metal plate is set into vibration by a loudspeaker. The plate is clamped at the center to make a permanent node there. The amplitudes of the vibrations are too small to be shown effectively in stroboscopic pictures. However. at resonant frequencies, sand sprinkled on the plate collects in patterns along nodal lines. (The patterns of sand are known as Chladni Figures.) As for the circular rubber membrane in Loop 44, there is no simple relation between the harmonic frequencies.

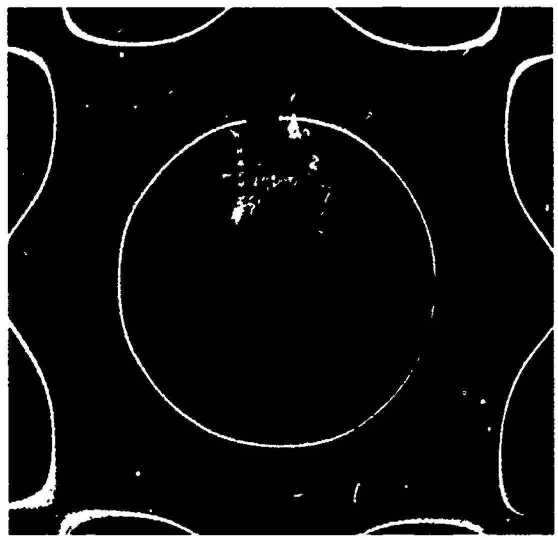


Fig. 1

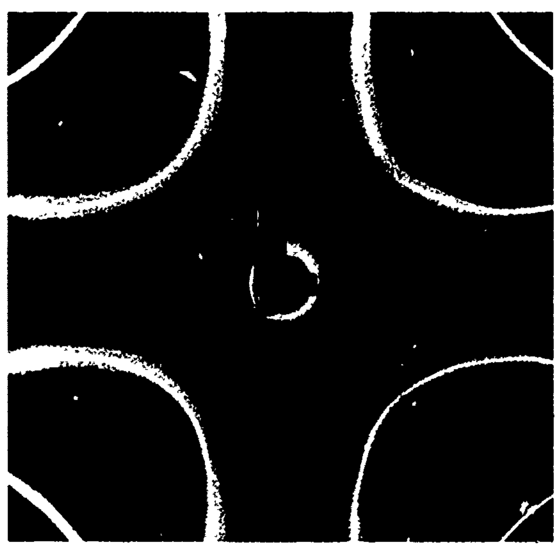


Fig. 2

Appendix

Additional Suggestions for Activities

Maxwell's Demon

With nothing more than a few pieces of plumbing, a source of compressed air, and some skill in working with metals, you can build a remarkably simple device for attaining moderately low temperatures. It separates high-energy molecules from those of low energy, and is called a Hilsch Vortex Tube.

For instructions, see "The Hilsch Vortex Tube" in The Amateur Scientist by C. L. Stong, Simon and Schuster, New York, 1960. An article, "Maxwell's Demon," is in Scientific American, November 1967.

What Shape Is That Odor?

The sense of smell, until recently, was one of the least understood. In 1963 several researchers established that odor depends on molecules of different shapes activating receptors of various shapes inside our noses, somewhat as a key fits into a lock. They identified seven primary smells, which can be combined in various ways to yield all other smells. They tested their theory by predicting the smell of a chemical on the basis of its structure and then verifying it with professional "sniffers." To get a whiff of their findings, see "The Stereochemical Theory of Odor," Scientific American, February 1964.

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Resource Letter ColR-1 on Collateral Reading for Physics Courses

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This is one of a series of Resource Letters on different topics, intended to guide college physicists to some of the literature and other teaching aids that may help them improve course content in specified fields of physics. No Resource Letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments and suggestions concerning the content and arrangement of the letters as well as suggestions for future topics will be welcomed. Please send such communications to Professor Joel E. Gordon, Chairman, Resource Letter Committee, Department of Physics, Amherst College, Amherst, Massachusetts.

Additional copies: Available from American Institute of Physics, 335 East 45 Street, New York, New York 10017. When ordering, request Resource Letter ColR-1, and enclose a stamped return envelope.

I. INTRODUCTION

THIS resource letter lists materials outside of physics suitable for use with physics classes as reading assignments, perhaps combined with class discussion. Most are for beginning courses, both for science majors and for nonscience majors.

One could easily construct a list 10 times as long; hence a large element of personal predilection is involved, and a reading list compiled by others might well include very different items. We should like to present the references listed here as suggestions and not as prescriptions. Each listing opens the door to a variety of other items that an individual teacher may find more to his own liking. Many of the given references have been used by us, as well as by many other teachers, in classroom situations.

There is some overlap between this resource letter and a few earlier ones which also consider similar material, particularly those dealing with the history of science and the relation of science to other aspects of our culture. We list other useful resource letters below.

Because almost all the selections are intended for beginning courses, the notation of levels E, I, and A, and the use of the asterisk, followed in other resource letters, are not employed.

Another arbitrary boundary condition on the present list is that it does not concern itself with original scientific papers. Many such sources are referred to in other resource letters or anthologies mentioned. The present list is restricted to articles which are not the raw material of science itself. In most cases specific articles rather than full books are listed, since we wish to confine ourselves to relatively short selections that lend themselves to assignment as collateral reading.

II. RELEVANT RESOURCE LETTERS

1. **"Philosophical Foundations of Classical Mechanics" (PhM-1).** MARY HESSE. Am. J. Phys. **32**, 905 (1964).
2. **"Science and Literature" (SL-1).** MARJORIE NICOLSON. Am. J. Phys. **33**, 175 (1965).
3. **"Evolution of Energy Concepts from Galileo to Helmholtz" (EEC-1).** T. M. BROWN. Am. J. Phys. **33**, 759 (1965).

A resource letter on History of Physics is currently being prepared by H. Woolf of The Johns Hopkins University, and, when published, it will also form a useful item in this sequence.

III. COLLECTIONS OF COLLATERAL READING AND BIBLIOGRAPHIES

4. **Science and Ideas.** ARNOLD B. ARONS AND A. M. BORK. (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1964.) Readings in the history, philosophy, and sociology of science: excerpts from such authors as Butterfield, Gillispie, Feynman, Bridgman, Einstein, Jammer, Conant, Merton, Frank, and others.

Reprinted from American Journal of Physics, Vol. 35, No. 2, February, 1967.

5. **A Stress Analysis of a Strapless Evening Gown.** ROBERT A. BAKER. (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963). Occasionally a point can best be made by the use of humor. This volume gathers many well-known satires on science.
6. **The Sociology of Science.** B. BARBER AND W. HIRSCH, EDS. (The Free Press of Glencoe, New York, 1962.) Articles by Parsons, Merton, Kubie, Kuhn, Price, Barber, Nagel, and others.
7. **Science and Language.** ALFRED M. BORK. (D. C. Heath Co., Boston, Mass., 1966.) This collection, not restricted to physics, is meant for freshman English classes; however, some of the articles should be useful with physics classes.
8. **Science and Literature—a Reader.** JOHN J. CADDEN AND PATRICK R. BROSTOWIN. (D. C. Heath Co., Boston, Mass., 1964.) The beginning contains critical essays about the relations of science to literature; the last part has excerpts from literature influenced by science. There is a brief bibliography.
9. **The Scientific Endeavor.** CENTENNIAL CELEBRATION OF THE NATIONAL ACADEMY OF SCIENCES. (The Rockefeller Institute, New York, 1963.) The last section, "The Scientific Endeavor" is particularly relevant. E. P. Wigner's article "Symmetry and Conservation Laws" is for beg[illegible] classes.
10. **Science and Society.** THOMAS D. CLARESON. (Harper and Brothers, New York, 1961.) Intended for freshman composition classes.
11. **The Validation of Scientific Theories.** PHILIPP FRANK, ED. (Collier Books, New York, 1961), Paperback A5101. Articles by Frank, Margenau, Lindsay, Bridgman, Skinner, Reshevsky, Guerlac, Koyré, Boring, and others.
12. **The Voices of Time: A Cooperative Survey of Man's Views of Time as Expressed by the Sciences and by the Humanities.** J. J. FRASER, ED. (George Braziller, New York, 1966.)
13. **Scientists as Writers.** J. HARRISON. (MIT Press, Cambridge, Mass., 1965.) Includes a useful bibliography.
14. **Studies in Explanation: A Collection of 27 Explanations from Physics, Biology, Psychology, Sociology, and History.** RUSSELL KAHL, ED. (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963).
15. **The New Scientist: Essays on the Methods and Values of Modern Science.** P. C. OBLER AND H. A. ESTRIN, EDS. (Doubleday-Anchor, Garden City, New York, 1962), Paperback A319.
16. **The New Treasury of Science.** HARLOW SHAPLEY, SAMUEL RAPPORT, AND HELEN WRIGHT, EDS. (Harper and Row, New York, 1965.) Contains selections different from those in their earlier book. The first two sections concern science in general and physics in particular.
17. **Readings in the Physical Sciences.** HARLOW SHAPLEY, SAMUEL RAPPORT, AND HELEN WRIGHT. (Appleton-Century-Crofts, New York, 1948.) Particularly relevant sections are Part I, "Science and the Scientific Method," and Part V, "Physics."
18. **Science and Society.** A. VAROULIS AND A. W COLVER (Holden-Day Inc., San Francisco, Calif., 1966. Essays useful for physical science classes.
19. **Exploring the Universe.** LOUISE B. YOUNG, ED. (McGraw-Hill Book Co., Inc., New York, 1963.)
20. **The Mystery of Matter.** LOUISE B. YOUNG, ED (McGraw-Hill Book Co., Inc., New York, 1964.) Both this and the above are published by the American Foundation for Continuing Education. Some material is suitable for beginning classes in physics; the bibliographies are useful.
21. **"Books on Science for the Nonscience Student."** COMPILED BY KENNETH FORD. In *The Proceedings of the Boulder Conference on Physics for the Nonscience Major.* M. Correll, Ed. (Commission on College Physics, Ann Arbor, Mich., 1965), p. 237.

IV. THE TWO-CULTURES CONTROVERSY

22. **"Literature and Science."** MATTHEW ARNOLD. In *Discourses in America* (Lecture 2) (1883–1884). This article, stimulated by a comment of T. H. Huxley concerning the lack of teaching of science, is an early discussion of the two cultures, the humanistic and the scientific.
23. **"Liberal Education in a Scientific Age."** BENTLEY GLASS. Long version in *Science and Liberal Education.* (Louisiana State University Press, Louisiana, n.d.), pp. 54–86; short version in Bull. Atomic Sci. 14, 346–353 (1958). An eminent biologist argues the importance of science in the modern curriculum, showing how it can be infused into almost every area of the curriculum, suggesting that science should be taught in the humanities.
24. **"Split Personality in the Universities."** E. ASHBY. In *Technology and the Academics.* (The MacMillan Co., Ltd., London, 1959). Ashby sees technology as the bridge between the sciences and the humanities.
25. **The Two Cultures and the Scientific Revolution.** C. P. SNOW. (Cambridge University Press, Cambridge, England, 1959). The most famous of all the articles concerning the two cultures. It contains three lectures; perhaps the first is the most useful. A later edition, published in 1963, contains a reply of Snow to his critics, an interesting restatement and expansion of his original position.
26. **"Modern Science and the Intellectual Tradition."** GERALD HOLTON. Science 131, 1187–1193 (1960). Also in *Science and Ideas* [4] and *The New Scientist* [15] and in several other collections. This is perhaps the most careful study arguing that there *is* a problem involving the interaction of scientists and humanists. The focus is on intellectual issues rather than the sociological ones which tend to cloud Snow's analysis. The middle section discussing false views of science in our society is particularly interesting.
27. **"Faintly Macabre's Story."** NORTON JUSTER. In *The Phantom Tollbooth.* (Epstein and Carroll, New York, 1961), pp. 71–77. Although this allegorical description of two cities, one where numbers are considered the

most important and the other where letters are most important, was done without knowledge of Snow, it is concerned with a similar problem. Particularly useful because of its allegorical humor. Short excerpt in *Science and Ideas* [4].

28. **Two Cultures? The Significance of C. P. Snow.** F. R. LEAVIS. (Chatto and Windus, London, 1962.) A violent attack on Snow both as a writer and as an individual, and on the thesis of the two cultures. This talk was not intended for publication, but it was published because of the notoriety it received.
29. **"A Comment on the Leavis-Snow Controversy."** LIONEL TRILLING. In Commentary (June 1962). Also in L. TRILLING, *Beyond Culture* (Viking Press, New York, 1965). A more moderate rebuttal of the Snow position.
30. **"The Battle of the Books."** MARJORIE HOPE NICOLSON. Brown University Papers, No. XLI, address before the graduate convocation, Brown University, 11 July 1964. Although this article starts with the interactions of science and literature, its thrust at the end is toward the two-cultures problem. "We are not antagonists. We supplement and complement one another." And again, "Perhaps what we really need to do is to laugh together."
31. **Science and the Shabby Curate of Poetry.** MARTIN GREEN. (W. W. Norton, New York, 1965.) A defense of Snow, particularly against the attacks of Leavis and Trilling, by a former student of Leavis. The writer felt it necessary to go back and study more science. There are interesting comments concerning popularization.

V. SCIENCE AND ART

32. **"The Relation to Literature."** H. J. MULLER. In *Science and Criticism.* (Yale University Press, New Haven, Conn., 1934), pp. 256–268. This passage, in a book with other interesting material for beginning science classes, concerns the interactions of science and the arts. Although examples are from literature, the discussion has wide general applicability.
33. **"The Representation of Motion."** GYORGY KEPES. In *Language of Vision.* (Paul Theobalz, Chicago, Ill., 1947), pp. 170–185. The theme is one that Kepes was to expand in the Vision+Values Series, the artist's reaction to the problem of motion.
34. **"Modern Art and the Humanities."** G. H. FORSYTH. In *Man and Learning in Modern Society,* papers and addresses delivered at the inaguration of Charles E. Odegaard as President of the University of Washington, 6 and 7 November 1958 (University of Washington Press, Seattle, Wash., 1959), pp. 141–155. The author's purpose is to stress "the importance of mutual respect in close understanding between the modern humanists and the modern scientist and to suggest that the visual arts provide a most effective channel between the two." His main concern is with the concept of space in contemporary art and science.
35. **"Initial Manifesto of Futurism, 1909."** J. C. TAYLOR. In *Futurism.* (Museum of Modern Art, New York, 1961), pp. 124–125. This might be interesting to read with physics classes to show the excitement that the prosaic topic of motion can generate in contemporary artists. It is a wild document.
36. **"The Cubist Perspective–The New World of Relationships: Camera and Cinema."** WYLIE SYPHER. In *Rococo to Cubism in Art and Literature.* (Random House, Vintage Books, New York, 1963), Chap. 1, Pt. 4. Although primarily concerned with cubism, this article refers to related developments in literature, philosophy, and science, particularly relativity. One persistent interest is the change in the concept of reality and another is the manipulation of time in both cinema and cubist views of perspective.
37. **"The Vision of Our Age."** J. BRONOWSKI. In *Insight—Ideas of Modern Science.* (Harper and Row, New York, 1964), Chap. 15. This is an attempt to place science in contemporary culture. Bronowski discussed the situation with four individuals: an artist, Eduardo Paoluzzi; an architect, Eero Saarinen; a physicist, Abdus Salam; and a novelist, Lawrence Durrell.
38. **The Nature and Art of Motion.** GYORGY KEPES, ED. (George Braziller, New York, 1965.) This is in the Vision+Values Series. Like all of Kepes's works, it is beautifully done and illustrated with material from both the arts and the sciences. It is listed, as a whole, because of the material from the artists—particularly Stanley William Hayter, George Rickey, and Katherine Kuh—showing how motion can be exciting to the modern artist.
39. **The Feynman Lectures on Physics.** R. P. FEYNMAN, R. B. LEIGHTON, AND M. SANDS. (Addison-Wesley Publ. Co., Reading, Mass., 1965), Vol. II, pp. 20-9 to 20-11. Feynman asks, in the middle of the second year of his course, "How do I imagine the electric and magnetic field?" This leads to a discussion of scientific imagination and to comments on beauty in scientific thought and experience.
40. **"Art in Science."** Albany Institute of History and Art, September 1965. The artistic value of scientific photographs has been noted by contemporary artists and contemporary scientists. Several exhibitions, with different organization, have been based on this theme, usually stressing the similarity between scientific photographs and contemporary abstract art. This is a catalog of one such recent exhibition.
41. **"Physical Science and the Temper of the Age."** ERWIN SCHRÖDINGER. In *Science and the Human Temperament.* Translated by J. Murphy and W. H. Johnston. (W. W. Norton, New York, n.d.), Chap. 5, pp. 106–132. Schrödinger begins, "I shall discuss the question of how far the picture of the physical universe as presented to us by modern science has been outlined under the influence of certain contemporary trends which are not peculiar to science at all."
42. **"The Esthetic Experience of the Machine."** LEWIS MUMFORD. In *Technics and Civilization.* (George

Routledge and Sons, London, 1947), pp. 335–344. Mumford is concerned with the relation between modern art and modern science. He ends with an interesting discussion on the film, viewing it as a Twentieth Century art form with close affinity to modern physics.

43. **"The Identity of Methods"** S. GIEDION. In *Space, Time and Architecture.* (Harvard University Press, Cambridge, Mass., 1963), 4th ed., pp. 11–17. Giedion argues that science and art are essentially interrelated.
44. **"The New Space-Conception: Space–Time."** S. GIEDION. In *Space, Time and Architecture.* (Harvard University Press, Cambridge, Mass., 1963), 4th ed., pp. 426–446. This could be read together with the previously mentioned selection of this book; it concerns the possible interaction between relativity and modern art.
45. **"The Impact of Recent Scientific Trends on Art."** ARMAND SIEGEL. In *Boston Studies in the Philosophy of Science.* M. W. Wartofsky, Ed. (R. Reidel Publ. Co., Dordrecht, The Netherlands, 1963), pp. 168–173. A physicist is unhappy with the effect of science on art.

VI. PHILOSOPHY OF SCIENCE

46. **"System-Connectedness, Completeness, and Logical Order."** M. R. COHEN. In *Reason and Nature—An Essay on the Meaning of the Scientific Method.* (Harcourt, Brace and Co., New York, 1931), pp. 106–114. A lucid account of the importance of a logical system in theory, discussing the nature of such a system and why it is useful for scientific purposes.
47. **"Newtonian Physics and Aviation Cadets."** ANATOLE RAPOPORT. In *Language, Meaning and Maturity.* S. I. Hayakawa, Ed. (Harper and Brothers, New York, n.d.). The main point is that the language often used in teaching classical mechanics can cause difficulties for the student because of its anthropomorphic overtones. An easy article on the problems associated with language.
48. **"Merits of the Quantitative Method."** RUDOLF CARNAP. In *Philosophical Foundations of Physics.* (Basic Books, Inc., New York, 1966), Chap. II, pp. 105–114. A leading philosopher of science illustrates, using historical examples such as Goethe's work on colors, the usefulness of quantitative methods over qualitative procedures.
49. **"The Unreasonable Effectiveness of Mathematics in the Natural Sciences."** E. P. WIGNER. Commun. Pure Appl. Math. **13**, 1–14 (1960). This is a personal discussion characterized by the title. While Wigner's views are not representative, they stem from a carefully thought-out position. Wigner calls the accuracy of mathematical laws in physics the "empirical law of epistemology." Toward the end of the article, he discusses the uniqueness of physical theory and whether independently developed physical theories are necessarily consistent with each other.
50. **"The Experimental Method."** RUDOLF CARNAP. In *Philosophical Foundations of Physics.* M. Gardner, Ed. (Basic Books, Inc., New York, 1966), Chap. 4, pp. 40–47. This short and lucidly written chapter explains the difference between experimentation and observation and tries to show why experimentation has been such a powerful tool.
51. **"Suggestions from Physics."** P. W. BRIDGMAN. In *The Intelligent Individual and Society.* (Macmillan Co., New York, 1938), pp. 10–47. A chapter on operationalism from one of Bridgman's lesser known books. Also reprinted in *Science and Ideas* [4].
52. **"Geometry: An Example of a Science."** PHILIPP FRANK. In *Philosophy of Science.* (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1957), pp. 48–89. A comprehensive introduction to positivistic philosophy of science, based on the example of geometry. Also reprinted in *Science and Ideas* [4].
53. **"Physics and Reality."** ALBERT EINSTEIN. In *Out of My Later Years.* (Philosophical Library, New York, 1950), pp. 59–65. A beautiful, very brief discussion of the nature of scientific knowledge.
54. **"Geometry and Experience."** ALBERT EINSTEIN. In *Ideas and Opinions.* (Crown Publishers, Inc., New York, 1954.) Considerations of reality and uncertainty in the experimental sciences, with geometry as an example: "···as far as the propositions of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality."
55. **"The Value of Science."** R. P. FEYNMAN. In *Frontiers in Science—A Survey.* E. Hutchins, Ed. (Basic Books, Inc., New York, 1958), pp. 260–267. This short article develops the theme that science is an open thing and that the admission that "we do not know" is a vital concomitant.
56. **"Malicious Philosophies of Science."** ERNEST NAGEL. In *Sovereign Reason and Other Studies in the Philosophy of Science.* (Free Press of Glencoe, New York, 1954), pp. 17–35. Also, in Barber and Hirsch [6]. Considers some common criticisms of science and attempts to show that they are without basis.
57. **"The Positivistic and the Metaphysical Conception of Physics."** PHILIPP FRANK. In *Between Physics and Philosophy.* (Harvard University Press, Cambridge, Mass., 1941), Chap. 5, pp. 127–138. A statement and defense of a moderate positivistic position, contrasted with a more metaphysical view held by Planck.
58. **"Philosophical Misinterpretations of the Quantum Theory."** PHILIPP FRANK. In *Between Physics and Philosophy.* (Harvard University Press, Cambridge, Mass., 1941), Chap. 7, pp. 151–171. This classic article warns against rushing to draw philosophical conclusions from a scientific theory. Frank shows lucidly how dangerous and foolish such an effort can be; quantum mechanics has been particularly fruitful for generating associated nonsense.
59. **"The Meaning of Reduction in the Natural Sciences."** ERNEST NAGEL. In *Science and Civilization.* Robert C. Stauffer, Ed. (University of Wisconsin Press, Madison, Wisc., 1949), pp. 99–135. Discusses the meanings attached to the idea that one scientific

theory has been "reduced" to another. Most of the examples are from physics.

60. "The Model in Physics." H. J. GROENWALD. In *The Concept and the Role of the Model in Mathematics and Natural and Social Sciences—Proceedings of the Colloquium sponsored by the Division of Philosophy of Sciences of the Internation Union of History and Philosophy of Sciences organized at Utrecht, January, 1960*. Hans Freudenthal Ed. (D. Reidel Publishing Co., Dordrecht, The Netherlands, 1961), pp. 98–103. This is a brief and readable account by a contemporary physicist of the ways the concept of the model is used in physics. If nothing else, it indicates that there is no standard use of the term in physics.
61. **Quest, the Evolution of A Scientist.** LEOPOLD INFELD. (Doubleday Doran and Co., Inc., New York, 1941.) The material toward the end of Infeld's book is an extremely personal statement about the nature and struggles of science.
62. **"The Reasonableness of Science."** W. H. DAVIS. Sci. Monthly 15, 193–214 (1922). Reprinted in abridged form in *Readings in the Physical Sciences* [17]. This easy-to-read article starts with a pleasant fable to illustrate the interaction between observation, invention, and deduction in the development of scientific theory.
63. **"Conditions of Scientific Discovery."** I. B. COHEN. In *Science, Servant of Man.* (Little, Brown and Co., Boston, Mass., 1948), pp. 16–35. Cohen studies two exampies of scientific developments: the discovery of penicillin and the invention of the battery.

VII. SOCIOLOGY OF SCIENCE

64. **"Resistance by Scientists to Scientific Discovery."** BERNARD BARBER. Science **134**, 596–602 (1961). Also in Barber and Hirsch [6]. A compendium of examples of resistance to scientific discovery and an attempt to sort out factors leading to this resistance.
65. **"The College Student's Image of the Scientist."** D. C. BEARDSLEY AND DONALD C. O'DOWD. In Barber and Hirsch [6]. A continuation of the Mead and Metraux study [69] to the college level, with similar results.
66. **"Reflections on Horror Movies."** ROBERT BRUSTEIN. Partisan Rev. 25, 288–296 (1958). Supplements and reinforces the studies of high school and college students' attitudes. The unconscious attitudes revealed in horror films are analyzed, particularly the association of theoretical science with evil.
67. **"Structural Change: Functional Differentiation."** WARREN O. HAGSTROM. In *The Scientific Community.* (Basic Books, Inc., New York, 1965), Chap. 5, pp. 244–253. In spite of sociological terminology such as that in the title, this is an interesting brief resume of the roles of the theorist and the experimentalist in physics. The emphasis is on the relative status value. This topic is often mentioned, but there seem to be few reading assignments usable with beginning classes.
68. **"The Image of the Scientist in Science Fiction: A Content Analysis."** WALTER HIRSCH. Am. J. Sociol. 63, 506–512 (1958). Also in Barber and Hirsch [6]. In this too-brief paper, science fiction becomes a source of sociological information on attitudes about the scientist. Hirsch divides the period from 1926 to 1950 into six subperiods and arbitrarily selects 50 works from each; the main emphasis is on the trends during successive periods.
69. **"Image of the Scientist Among High School Students."** MARGARET MEAD AND RHODA METRAUX. Science, 384–390 (1957). Also in Barber and Hirsch [6]. A statistical study of the views that high-school students have about scientists. Every teacher of science should be aware of the discouraging conclusions of the study.
70. **"Priorities in Scientific Discovery: A Chapter in the Sociology of Science."** ROBERT K. MERTON. Am. Sociol. Rev. 22, 635–659 (1957). Also in Barber and Hirsch [6]. One of a series of continuing studies by Merton concerning this problem. He argues that multiple discoveries are more common than we have previously suspected and may be the rule in scientific work. In this paper he is interested in the violent quarrels over multiple discoveries, using the institutional norms of science as a basis.
71. **"Science in the Social Order."** ROBERT K. MERTON. In *Social Theory and Social Structure.* R. K. Merton Ed. (Free Press of Glencoe, New York, 1962), rev. ed., Chap. 15, pp. 537–561. Also in Barber and Hirsch [6]. Merton starts with science in Nazi Germany and then notes other ways in which science interacts with society. The internal goals of science create problems for it in the general society. It might be interesting to combine this article in a reading assignment with Gerald Holton's "Modern Science and the Intellectual Tradition [26]."
72. **"Singletons and Multiples in Scientific Discovery: A Chapter in the Sociology of Science."** ROBERT K. MERTON. Proc. Am. Phil. Soc. **105**, 470–486 (1961). The first section concerns Francis Bacon's views; it can be omitted. Merton's theme is that multiple discoveries are more common than might be expected in science and are often hidden.
73. **"Water Witching as Magical Divination."** E. Z. VOGT AND R. HYMAN. In *Water Witching U. S. A.* (University of Chicago Press, Chicago, Ill., 1959.) The authors point out that a nonscientific activity survives in contemporary society and study the sociological implications.
74. There is a selected bibliography on sociology of science in Barber and Hirsch [6], covering the period from 1952 to 1961. There is an earlier bibliography [in *Science and the Social Order.* BERNARD BARBER. (Free Press, New York, 1952. Also Collier Books, Paperback B382X, New York, 1962)] for the work up to that time. A third bibliography is in *Sociology of Science: A Trend Report and Bibliography of Current Sociology.* BERNARD BARBER. (UNESCO, New York, 1956).

VIII. HISTORY OF SCIENCE

75. "Natural Science in the Fourteenth Century." E. J. DIJKSTERHUIS. In *The Mechanization of the World Picture.* (Oxford University Press, Oxford, England, 1961), pp. 164–219. This is a long chapter in an important book. It might be advisable to use only a part of it. The conventional view that nothing happened in science before Copernicus is far from correct.

76. "Medieval Mechanics in Retrospect." M. CLAGETT. In *The Science of Mechanics in the Middle Ages.* (University of Wisconsin Press, Madison, Wisc., 1959), pp. 673–682. A brief summary of an important but neglected area of the history of physics, written by a master.

77 "The Conservatism of Copernicus." H. BUTTERFIELD. *The Origins of Modern Science.* (The Macmillan Co., New York, 1957. Also Collier Books, Paperback AS259V). Copernicus is closer to Greek astronomy than he is often pictured; he uses most of Ptolemy's mathematical devices.

78. "Johannes Kepler's Universe: Its Physics and Metaphysics." G. HOLTON. Am. J. Phys. 24, 340–351 (1956). Kepler's astronomy and the problem of reality.

79. "The Galilean Revolution in Physics." A. RUPERT HALL. In *From Galileo to Newton.* (Harper and Row, New York, 1963), pp. 36–77. An account of Galileo's contributions by a well-known historian of science.

80. "Newton with His Prism and Silent Face." C. C. GILLISPIE. In *The Edge of Objectivity.* (Princeton University Press, Princeton, N. J., 1960.) Of all the brief biographies, this is one of the most readable and one of the better for tracing the development of Newton's ideas. The author perhaps overemphasizes the difficulty of reading the *Principia.*

81. "The Newtonian World Machine." J. H. RANDALL, JR. In *Making of the Modern Mind.* (Houghton Mifflin Co., Boston, Mass., 1940), pp. 253–279. Randall surveys the overwhelming influence of Newtonian physics in many nonscientific areas. Bibliography. Also in *Science and Ideas* [4].

82. "The Significance of the Newtonian Synthesis." A. KOYRÉ. In *Newtonian Studies.* (Harvard University Press, Cambridge, Mass., 1965), pp. 3–24. An important statement by a leading historian of ideas. It is not easy to read.

83. "How the Scientific Revolution of the Seventeenth Century Affected Other Branches of Thought." BASIL WILLEY. In *A Short History of Science. Origins and Results of the Scientific Revolution.* (Doubleday-Anchor Books, New York, 1951), pp. 61–68. Main emphasis is on literature, because of Willey's background. Quite easy to read.

84. "The Development of Modern Science." ERNEST NAGEL. In *Chapters in Western Civilization.* Selected and edited by the Contemporary Civilization Staff of Columbia College. (Columbia University Press, New York, 1954), 2nd ed., Vol. 1, Chap. 8, pp. 282–324. This is perhaps one of the most readable accounts of the rise of modern science, considering the interaction of science with other phases of our society and emphasizing the history of ideas.

85. The Discovery of Neptune. M. GROSSER. (Harvard University Press, Cambridge, Mass., 1962.) This entire book can be covered in a series of reading assignments. It gives a very interesting view of scientific development. The ending will surprise many scientists. Useful when coupled with *The Black Cloud* [103].

86. "James Clerk Maxwell." J. R. NEWMAN. In *Science and Sensibility.* (Simon and Schuster, New York, 1961), Vol 1, pp. 139–193. This biography of Maxwell, like all the available ones, is based on the Campbell–Garnett *Life* (a new biography is currently under preparation). It also tries to review Maxwell's developing thought.

87. "Physics Just before Einstein." A. M. BORK. Science 152, 597–603 (1966). Primarily concerned with the history of electromagnetic theory after Maxwell.

88. "The Solvay Meetings and the Development of Quantum Physics." N. BOHR. In *Atomic Physics and Human Knowledge.* (John Wiley & Sons, Inc., New York, 1963), pp. 79–100. The Solvay Meetings were very important in the evolution of quantum physics; Bohr's account is useful as a historical introduction.

89. "The Fundamental Idea of Wave Mechanics." E. SCHRÖDINGER. *Nobel Lectures—Physics 1922–1941.* (Elsevier Publishing Co., Amsterdam, 1965), pp. 304–316. The historical development of wave mechanics, a history which is often mistold.

90. "The Function of Dogma in Scientific Research." T. S. KUHN. In *Scientific Change.* A. C. Crombie, Ed. (William Heinemann, London, 1963). Kuhn argues that scientific development has two very different stages, normal science and revolutions. This thesis is developed in more detail in *The Structure of Scientific Revolutions* (University of Chicago Press, Chicago, Ill., 1962).

IX. SCIENCE AND GOVERNMENT

91. The most useful reference on the detailed interaction between science and government in the United States is the "News and Comments" section of Science. Several reporters follow carefully the hearings of Congressional committees and the work of executive branches of the government, giving a day-by-day account of this interaction. This is a must for anyone interested in the area.

92. "Behind the Decision to Use the Atomic Bomb: Chicago, 1944–45." ALICE KIMBALL SMITH. Bull. Atomic Sci. 14, 280–312 (1958). A long and detailed account of how one group of atomic scientists, those at the metallurgical laboratory at the University of Chicago, reacted as time for using the atomic bomb appeared to be coming closer and closer. It is done with considerable care.

93. "Responsibilities of Scientists in the Atomic Age." EUGENE RABINOWITZ. Bull. Atomic Sci. 15, 2–7

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(1959.) Starts with the conflicting loyalties of the scientist to his nation and to society. It discusses the attitudes that various scientists have had toward the question of arms development and ends with the Pugwash program.

94. "The Scientific Establishment." DON K. PRICE. Proc. Am. Phil. Soc. 106, 235–245 (1962). Argues that we have hardly come to grips with the fact that science "has become the major Establishment in the American political system" (see item 101).
95. "Federal Expenditures and the Quality of Education." HAROLD ORLANS. Science 142, 1625–1629 (1963). The effect of federal support on education.
96. "Science Goes to Washington." MEG GREENFIELD. The Reporter 29, 20–26 (1963). Scientists work in many different areas of the federal government. Often a scientist will have several different attachments, making it unclear when he is acting as a scientist and when he is not. Some revealing examples are mentioned.
97. "Central Scientific Organization in the United States Government." A. HUNTER DUPREE. Minerva 1, 453–469 (Summer 1963). A historical account of the interactions between the American government and scientific organizations, going back to the earliest period in American history.
98. "Technology and Society." JEROME B. WEISNER. In *Science as a Cultural Force.* Introduction by Harry Woolf, Ed. (The Johns Hopkins Press, Baltimore, Md., 1964), Chap. 3, pp. 35–53. Weisner's theme is the extreme importance of technology in contemporary society and the implications this has for the government.
99. "Scientists and Politics: The Rise of an Apolitical Elite." R. C. WOOD. In *Scientists and National Policy-Making.* R. Gilpin and C. Wright, Eds. (Columbia University Press, New York, 1964), pp. 41–72. Wood reviews and comments on the attitudes commonly expressed on the interaction of scientists and politics. Many of the other articles in the volume could also be used in readings on this topic.
100. "The Nationalization of U. S. Science." S. KLAW. Fortune 70, 158 (1964). Primarily concerned with the financial support of science and technology by the national government.
101. "The Established Dissenters." DON K. PRICE. In *The Scientific Estate.* (Harvard University Press, Cambridge, Mass., 1965.)
102. "Where the Brains Are." R. E. LAPP. Fortune 73, 154 (1966). Scientists as a financial asset for their state; the geographical distribution of scientists and the distribution of federal funds.

X. MISCELLANEOUS

103. The Black Cloud. FRED HOYLE. (Harper and Bros., New York, 1957.) The portrait of scientific work in this science fiction book is very good, particularly in the early material. The entire book makes an exciting reading assignment.
104. "Style in Science." JOHN RADER PLATT. In *The Excitement of Science.* (Houghton-Mifflin Co., Boston, Mass., 1962.) Originally in Harper's Magazine (October 1956). Points out that the personality of the individual scientist is of importance in determining what kind of science he produces, emphasizing the human elements in scientific developments.
105. "Passion and Controversy in Science." MICHAEL POLANYI. Bull. Atomic Sci. (April 1957). Polanyi's purpose is to counteract the idea that scientists are not passionately involved in what they do. He gives historical examples of emotional involvement.
106. "The Importance of Science." LEWIS MUMFORD. In *Technics and Civilization.* (George Routledge and Sons, London, 1947), pp. 215–221. The dependence of modern engineering on the results of science.
107. "Scientific Concepts and Cultural Change." HARVEY BROOKS. Daedalus, pp. 66–83 (Winter, 1965.) Also in *Science and Culture.* G. Holton, Ed. (Houghton Mifflin Co., Boston, Mass., 1965), pp. 70–87. Suggests how "a number of important themes from the physical and biological sciences have found their way into our general culture, or have the potential for doing so." The themes are relativity, indeterminancy, feedback, and noise. Near the beginning there is some discussion of the ways science and culture interact.
108. "Society and the Intelligent Physicist." P. W. BRIDGMAN. Am. Phys. Teacher 7, 109 (1939). Talking just before the beginning of World War II, Bridgman asks how the contemporary intelligent physicist should behave in the light of national and international social problems.
109. "The Real Responsibilities of the Scientist." J. BRONOWSKI. Bull. Atomic Sci. 12, 10–20 (1956). Discusses the responsibility of the scientist to the society in which he lives. The principal conclusion is, "The sense of intellectual heresy is the life-blood of our civilization."
110. "Visionaries and the Era of Fulfillment." RENÉ DUBOS. In *The Dreams of Reason—Science and Utopias.* (Columbia University Press, New York, 1961), Chap. 3, pp. 40–62. Science increasingly has had enormous practical value and consequence in everyday life, making many of the dreams of past utopias practical realities; but this creates new social responsibilities for the scientist.
111. "Science and the Deallegorization of Motion." GERALD HOLTON. In *The Nature and Art of Motion.* Gyorgy Kepes, Ed. (George Braziller, New York, 1965). Also in Scientia 57, 1–10 (1963). Motion is a rich concept, with ramifications far beyond that in the sciences themselves. This beautiful paper is concerned with the "process of separation from the generalized meaning of motion during the rise of modern scientific conceptions···." This might be useful in connection with an elementary treatment of mechanics, since it stresses what is usually left out in the latter.
112. "The Ethical Basis of Science." BENTLEY GLASS. *Science and Ethical Values.* (University of North

Carolina Press, Chapel Hill, N. C., 1965), pp. 69–101. Glass holds that science and ethics are intimately interwoven. This long article gives a point of view too often missing from an elementary physics course.

113. "Quo Vadis." P. W. BRIDGMAN. In *Science and the Modern Mind.* G. Holton, Ed. (Beacon Press, Boston, Mass., 1958), pp. 83–91. Bridgman asks what consequences one would expect if one used the method of intellect more in the future society than we have already done. Also in *Science and Ideas* [4].

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