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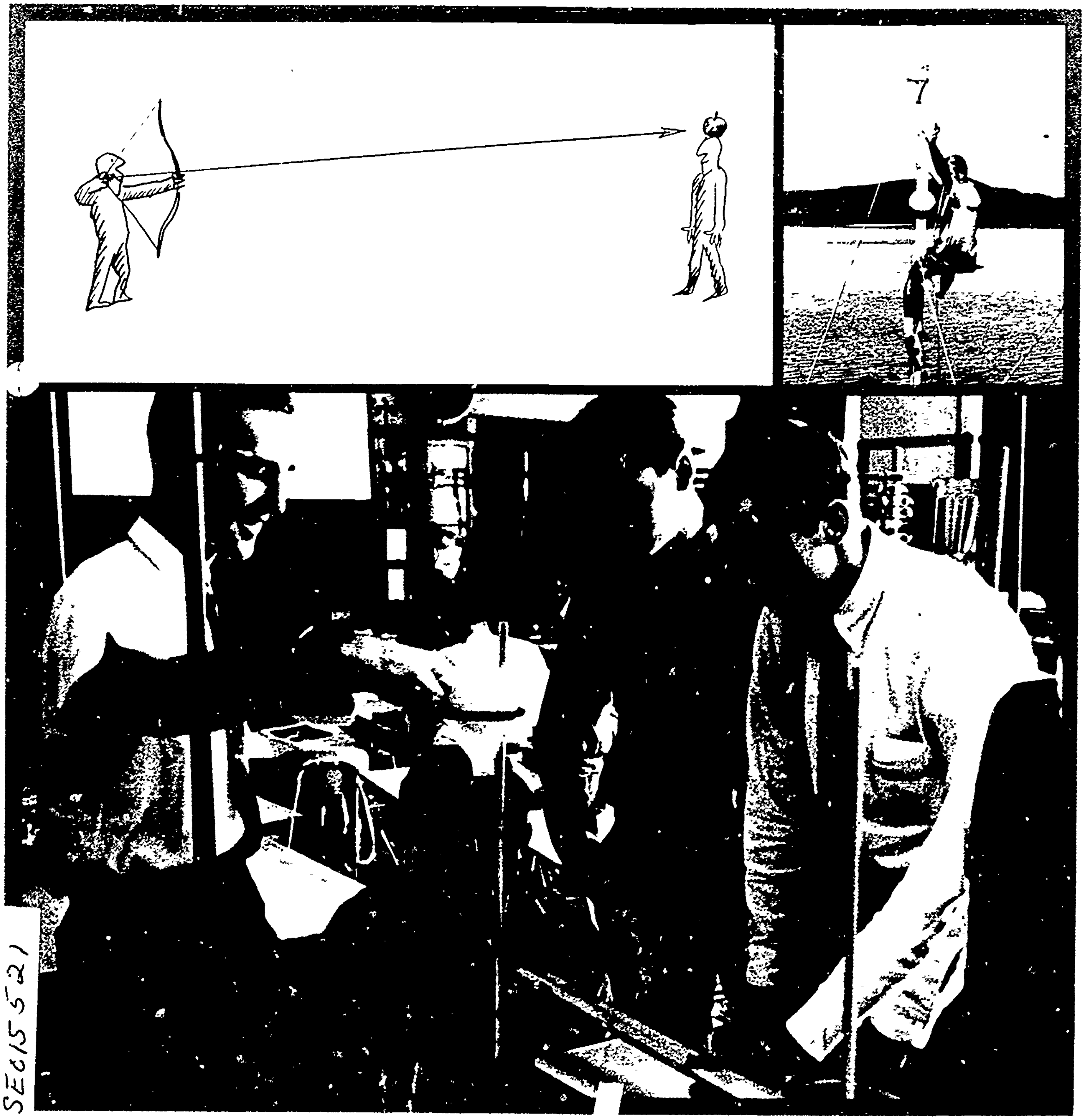
ABSTRACT

Thirteen experiments and 15 activities are presented in this unit handbook for student use. The experiment sections are concerned with naked-eye observation in astronomy, regularity and time, variations in data, uniform motion, gravitational acceleration, Galileo's experiments, Netson's laws, inertial and gravitational mass, trajectories, and circular motion. Suggestions for demonstrations, construction projects, and self-directed instructions are given in the activity sections to deal with aspects of stroboscopes, frictionless pucks, air resistance, time determination, falling weights, accelerometers, projectile motion, motion in a rotating reference frame, centripetal forces, and harmonograms. Methods of keeping records, using the Polaroid Camera, and physics readers are discussed in the introductory section. 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 in assignments, and the remaining are open to students' free selection. Illustrations and film loop notes for explanation purposes are included. Additional suggestions for activities, a guide for planet and eclipse observations, and the best time for viewing meteor showers are also provided as appendices. 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** 1

An Introduction to Physics

Concepts of Motion



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 1 Concepts of Motion

Authorized Interim Version 1968-69

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New York • Toronto

Introduction

Chapter 4 Understanding Motion

Experiments

Activities

Film Loop Notes

Appendix

This Student Handbook is different from laboratory manuals you may have worked with before.

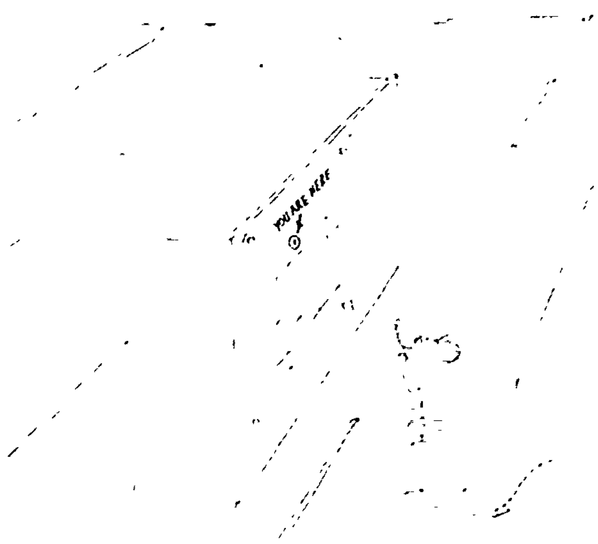
There are far more things described in this handbook than any one student can possibly do. Only a few of the experiments and activities will be assigned. You are encouraged to pick and choose from the rest any of the activities that appear interesting and valuable for you. A number of activities may 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.

In short, at the end of the year your handbook will be a personal collection, reflecting what you found of particular interest in your study of physics.

The first section of the handbook contains general instructions and tables—for example, the operation of the Polaroid camera in the laboratory. These you will probably need to read over only once and then refer to as the occasion arises.

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.

Keeping records of observations

There are many ways of keeping records of observations made in the laboratory or at home. Your teacher will suggest how to write up your records of observations. But regardless of the procedure followed, the key question for deciding what kind of record you need of your work is this: "Do I have a clear enough record so that I could pick up my lab notebook a few months from now and explain to myself or others what I did"?

A few general comments and the sample lab pages reproduced below will amplify this principle and your instructor's own directions. There are some ground rules which are followed in every laboratory—all over the world. Your records should be neatly written without being fussy. You should organize all numerical readings, if possible, in tabular form as in the example below. You should always identify the units (centimeters, kilograms, seconds, etc.) for each set of data you record. You should identify the equipment you are using, so that you can find it again later if you need to recheck your work.

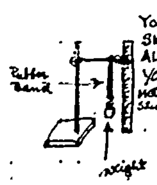
In general, it is better to record more rather than fewer data. Even details

EXPERIMENT 5

Tommy Foster. July 28, 1967

This experiment is to see how a rubber band streches under the influence of forces.

YOUR OWN QUICK SKETCH WILL ALWAYS HELP YOUR MEMORY



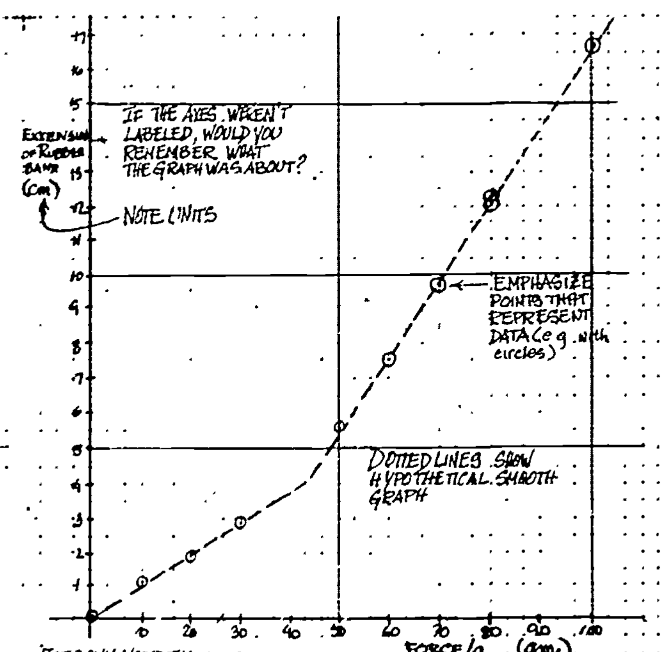
I put different masses on the end of the rubber band and recorded the position of the top of the the hook that holds the weight.

Room Temperature 26°C

Position of top of rubber band 30.3 cm

INCLUDE ANY DATA YOU THINK MAY BE RELEVANT

	mass (gm)	Force (nt)	Pos. of bottom (cm)	Extension (cm)	ALWAYS SHOW UNITS OF TABULATED QUANTITIES
(weights from set, no error)	0	0	44.0 ±.1	0	
	10	.098	45.1	1.1 ±.2	ESTIMATE THE ERROR OF EVERY QUANTITY YOU MEASURE.
	20	.196	45.8	1.8	
	30	.294	46.8	2.8	
	50	.490	49.6	5.6	second 20 gm weight is missing from set. INCLUDE COMMENTS ON YOUR DATA
	60	.588	51.5	7.5	
	70	.686	53.7	9.7	
	80	.784	56.1	12.1	KEEP DATA IN NEAT TABLES
	100	.980	60.6	16.6	
	80	.784	56.2	12.2	recheck



JOT DOWN YOUR THOUGHTS...
INCLUDE POSSIBLE QUESTIONS—ESPECIALLY ONES YOU CAN'T ANSWER.

There are obviously two different straight lines. It would have been nice to see what it was at 40 gm, since that's just where the two lines cross.

The slopes of the two lines are the force constant F = -kx. for the first line k = .105 nt/cm and for the second k = .0938 nt/cm.

Pages from a student's lab notebook. The table is used to record both observed quantities (mass, scale position) and calculated quantities (force, extension). The graph shows at a glance that the extension of the rubber band changes as the force is increased in a non-linear way (that is, a different rate 0 to 5 cm and above 5 cm).

that may seem to have little bearing on the experiment you are doing—such as the temperature and whether it fluctuated during the observations, the time when the data were taken—may turn out to be important information in analyzing the results.

If you have some reason to suspect that a particular datum may be less reliable than others—perhaps you had to make it very hurriedly, or a line on a photograph was very faint—make an explanatory note of the fact. But don't erase a reading. When you think an entry in your notes is in error, draw a single line through it—don't madly scratch it out. You may find it was significant after all.

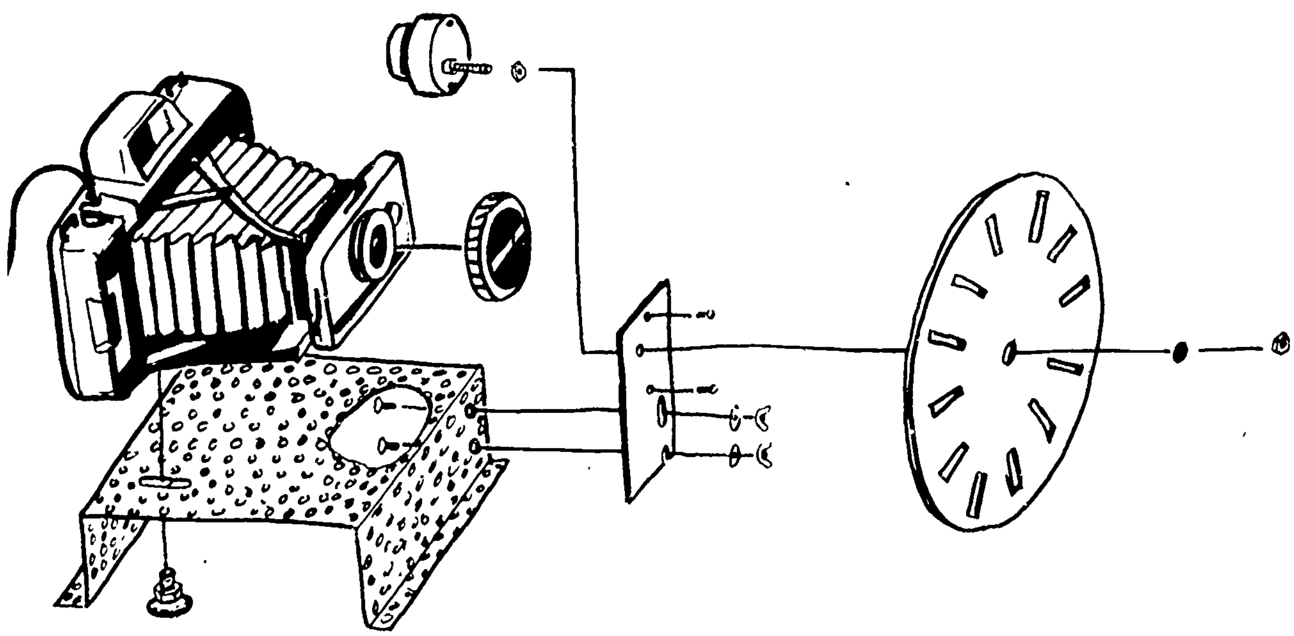
There is no "wrong" result in an experiment. If your observations and measurements were carefully made, then your result will be correct. Whatever happens in nature, including the laboratory, cannot be "wrong." It can be irrelevant, or mixed up with so many other events which you did not expect that your report is not useful. Therefore you must think carefully about the interpretation of your results.

Finally, the cardinal rule in a laboratory is to choose in favor of "getting your hands dirty" instead of "dry-labbing." Archytas, in 380 B.C., summed it up pretty well:

> In subjects of which one has no knowledge, one must obtain knowledge either by learning from someone else, or by discovering it for oneself. That which is learnt, therefore, comes from another and by outside help; that which is discovered comes by one's own efforts and independently. To discover without seeking is difficult and rare, but if one seeks, it is frequent and easy; if, however, one does not know how to seek, discovery is impossible.

Use of the Polaroid Camera

You will find the Polaroid camera a very useful device for recording your laboratory observations. Section 1.3 of your textbook shows how the camera is used to study moving objects. In the experiments and activities described in this book, there are many suggestions for photographing moving objects, both with an electronic stroboscope (rapidly flashing xenon light) and with a mechanical disc stroboscope (a slotted disc rotating in front of the camera lens).



Find out the model number of the camera which you will be using in the laboratory, and use the corresponding checklist below when you are ready to start your experiment.

Checklist of operations for Polaroid Camera, Experimental Model 002

1. Make sure that there is film in the camera. If no white tab shows in front of the door marked "4" you must put in new film.

2. Fasten camera to tripod or disc strobe base. If you are using the disc strobe technique, fix the clip-on slit in front of the lens.

3. Check film (speed) selector. Set to suggested position (75 for disc strobe or blinky; 3000 for xenon strobe).

4. If you are taking a "bulb" exposure, cover the electric eye.

5. Check distance from lens to plane of object to be photographed. Adjust focus if necessary. Work at the distance that gives an image just one-tenth the size of the object, if possible. This distance is about 120 cm.

6. Look through viewer to be sure that whatever part of the event you are interested in will be recorded. (At a distance of 120 cm the field of view is just under 100 cm long.)

7. Make sure the shutter is cocked (by depressing the number 3 button).

8. Run through the experiment a couple of times without taking a photograph, to accustom yourself to the timing needed to photograph the event.

9. Take the picture: keep the cable release depressed only as long as necessary to record the event itself. Don't keep the shutter open longer than necessary.

10. Pull the white tab all the way out of the camera. Don't block the door (marked "4" on the camera).

11. Pull the large yellow tab straight out—all the way out of the camera. Begin timing development.

12. Wait 10 to 15 seconds (for 3000-speed black-and-white film).

13. Ten to 15 seconds after removing film from the camera, strip the white print from the negative.

14. Take measurements immediately. (The magnifier may be helpful.)

15. After initial measurements have been taken, coat your picture with the preservative supplied with each pack of film. Let this dry thoroughly, label it on the back for identification and mount the picture in your (or a partner's) lab report.

16. The negative can be used, too. Wash it carefully with a wet sponge, and coat with preservative.

17. Recock the shutter so it will be set for next use.

18. Always be careful when moving around the camera that you do not inadvertently kick the tripod.

19. Always keep the electric eye covered when the camera is not in use. Otherwise the batteries inside the camera will run down quickly.

Checklist of operations for Polaroid Cameras, Models 95, 150, 160, 800

1. Make sure there is film in the camera. Note the number on the edge of the film. If it says "end," put in a new roll.

2. Fasten camera to tripod (or disc strobe base). If you are using the disc strobe technique, tape the auxiliary slit in front of the camera lens.

3. Check lens opening, set at suggested EV number.

4. Check distance from lens to the event you want to photograph. Teachers should determine the distance that gives a 10:1 reduction experimentally. (The distance is about 1.4 meters or 55 inches.)

5. Set the range to this distance, or if your camera has a range finder, set it appropriately.

6. Check through the viewer to assure that whatever part of the event you are interested in will be recorded. (At a distance of 1.4 meters the field of view is about 1.0 meter long.)

7. Check the knob on the front of the camera to see if it is in the correct postion. Position "I" will give you an instantaneous exposure; position "B" will give you a "bulb" exposure. Remember: <u>on bulb exposures the lens will remain open only as long as the plunger remains depressed</u>!

8. Run through the event a couple of times without taking a photograph, to accustom yourself to the timing necessary to photograph the event.

9. Take the picture: keep the cable release depressed only as long as necessary to record the event. Don't keep the shutter open longer than necessary.

10. Push the button or turn the red switch on the back of the camera.

11. Lift the cutter bar on the end of the camera back opposite the button or switch referred to in 10.

12. Grasp the exposed film end firmly and pull steadily until it locks in place.

13. Press the cutter bar back into place.

14. Tear off the film back you have just pulled from the camera. It is the negative of the picture just preceding the one you took.

15. Wait 10 seconds for 3000-speed film (or whatever time the instructions say for the film you are using).

16. Open the camera back and remove the picture, starting at the cutout.

17. Straighten the picture by drawing it smoothly, face up, over the edge of a table.

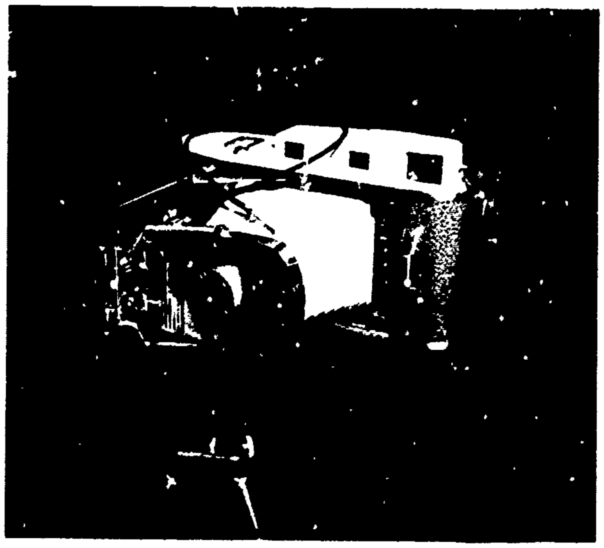
18. Take measurements immediately (the magnifier may be helpful).

19. After initial measurements have been taken, coat your picture with the preservative supplied with each roll of film. Let this dry thoroughly, label it on the back for identification and mount the picture in your (or a partner's) lab report.

20. When the next picture has been taken, you may retrieve your negative. Wash the negative carefully with a wet sponge and coat with preservative.

21. <u>If you are taking time exposures, do not forget to reset the camera to "B" before the next picture</u>.

22. In moving about the camera, always be careful that you do not inadvertently kick the tripod.

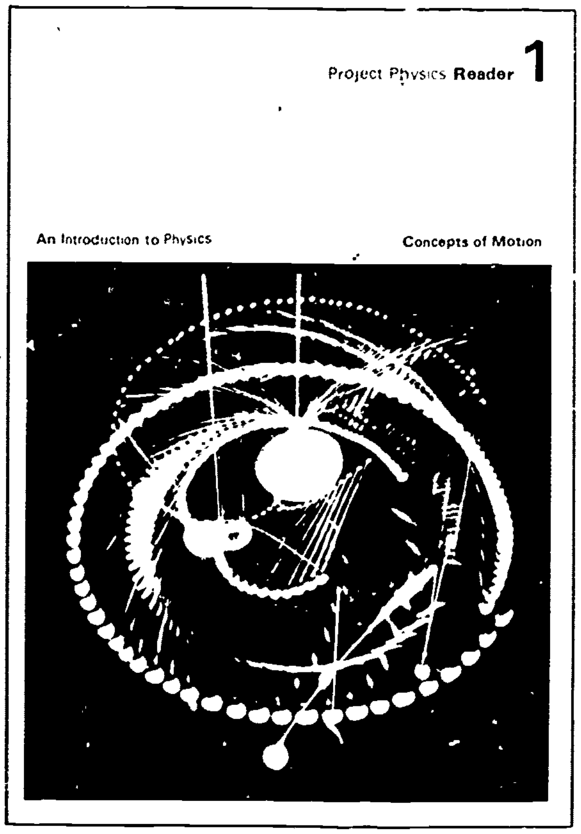


The Physics Readers

Your teacher probably will not assign most of the articles in the Physics Reader, but you are encouraged to look through it for articles of interest to you. We are sure you will enjoy the chapter from Fred Hoyle's science fiction novel, The Black Cloud. This chapter, "Close Reasoning," is fictional, but nevertheless reflects accurately the real excitement of scientists at work on a new and important problem.

Since the reader is intended for browsing, and since different people have very different interests, nobody can tell you which articles you will most enjoy. Those with interests in art or the humanities will probably like Gyorgy Kepes' article, "Representation of Movement." Students particularly interested in history and in the role science plays in historical development are particularly advised to read the Butterfield and Willey articles.

You may want to see alternative treatments of mechanics, and the reader provides several which either supplement or go beyond the Unit 1 text. Thus Sawyer gives a discussion of the concept of speed, following a logical path different from that used in the text. Clifford's approach is interesting because of its use of geometry rather than algebra in explaining the fundamental ideas. For those seeking a deeper understanding of mechanics, we particularly recommend the article from the Feynman Lectures on Physics.



EXPERIMENT [illegible] Naked Eye Astronomy

[illegible]

[illegible] In what direction does the sun set? [illegible] of observation from the [illegible] position. If you don't [illegible] view of the horizon, [illegible] disappears behind the [illegible] in the evening.

[illegible] At what time does the sun set, or [illegible] your artificial horizon?

[illegible] these observations about [illegible] a simple sketch show[illegible] on the horizon [illegible] the setting sun.

[illegible] observation a week later. [illegible] time of sunset [illegible] change in a month? [illegible] these observations for [illegible] months.

If you are up at sunrise, you can [illegible] time and position, too [illegible] the weather forecast the night [illegible] sure that the sky will be clear.

[illegible] does the length of the day, from [illegible], change during a week? A month?

Observations

Below there are more detailed suggestions for observations to be made on the sun, the moon, the stars and the planets. Choose at least one of these objects and later compare notes with classmates who concentrated on others.

<u>Choosing references</u>

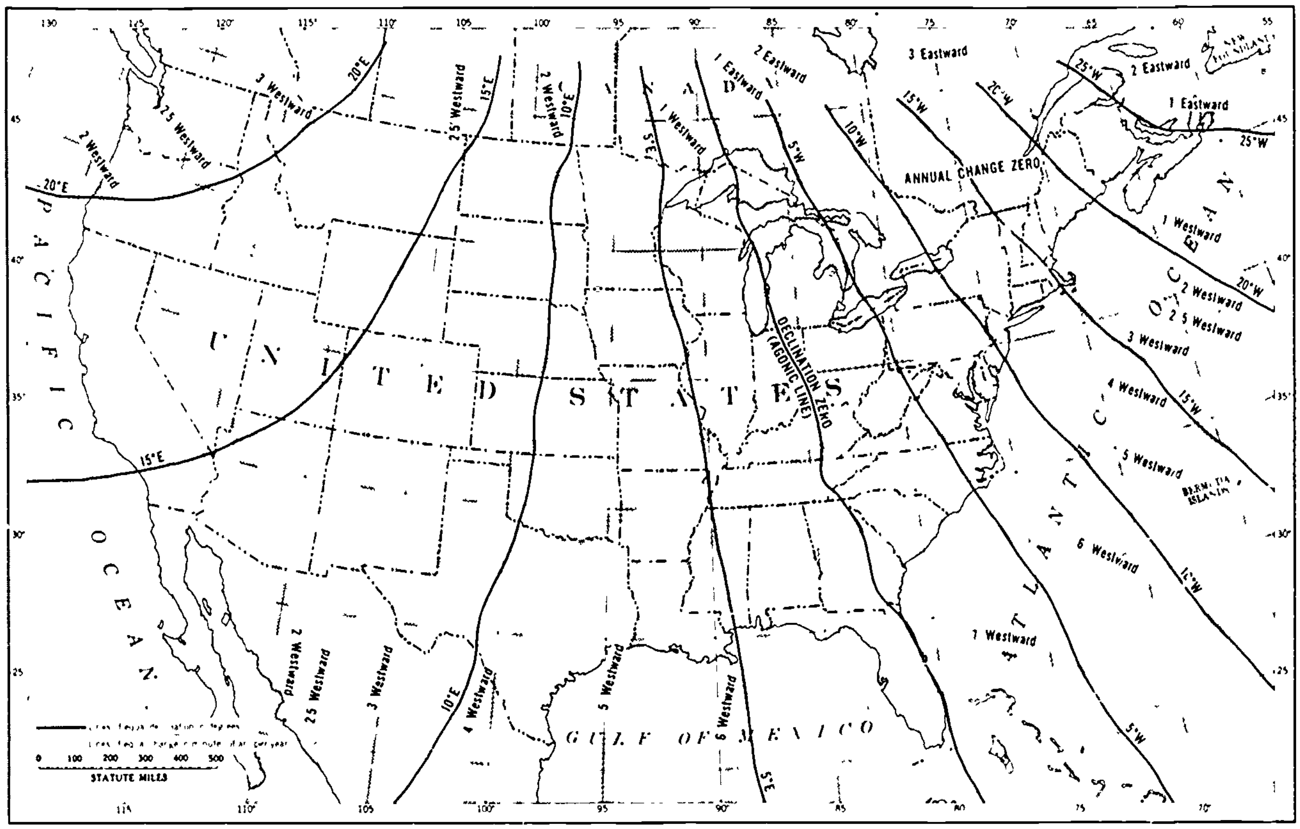
Before you can locate the positions of objects with respect to each other you must choose some fixed lines or planes to which all measurements may be referred. For example, establish a north-south line, and then with a protractor measure positions of all objects in the sky around the horizon with reference to this line. Such angles around the ·. izon are called azimuths and are mea d ·om the north point through east (90°) to south (180°) and west (270°) around to north (360°, or 0°).

A horizontal plane is the second reference. This plane can be used even when the true horizon is hidden by trees, buildings, hills or other obstructions. The angle between the line to a star and the horizontal plane is called the altitude.

Establishing a reference

The north-south line can be established in several different ways. A compass is used to establish magnetic north, which may not be the same as true north. The magnetic north pole toward which your compass points, is more than 1000 miles from the geographic north pole, so in most localities the compass does not point true north. The angle between magnetic north and true north is called the angle of magnetic declination. At some places the magnetic declination is zero and the compass points toward true north. On a map of the U.S.A. these points lie along a wiggly line which runs through western Michigan, Indiana, eastern Kentucky, Tennessee, across Alabama and along the eastern side of Florida. At places east of this line, the compass points west of true north; at places west of the line, the compass points east of true north. In the far northwestern or northeastern United States (e.g., Portland, Oregon or Portland, Maine) the difference between magnetic north and true north is nearly 20°. You can find the angle of declination for your area from the map (Fig. 1).

The North Star (Polaris) is also used to establish the north-south line. It is the one star in the sky that does not move much from hour to hour or with the seasons, and it is almost due north of an observer anywhere in the northern hemisphere.



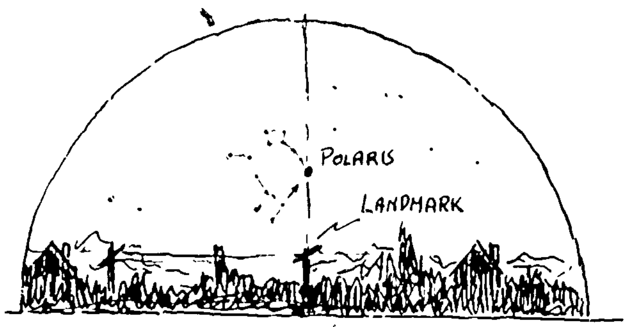
Distribution of magnetic declination for 1965 (derived from C&GS Chart 3077)

Fig. 1.

B.C. by John Hart

By permission of John Hart and Field Enterprises, Inc.

You may use a prominent constellation (star group) to locate Polaris. First, find the "Big Dipper" which on a September evening is low in the sky and a little west of north. The two stars forming the side of the dipper opposite the handle are known as the "pointers," because they point to the North Star. A line passing through them and extended upward passes very close to a bright star—the last star in the handle of the "Little Dipper." This bright star is the Pole Star, Polaris. On September 15 at 8:30 p.m. these constellations are arranged about as shown in the diagram:



Imagine a line from Polaris straight down to the horizon. The point where this line meets the horizon is due north of you.

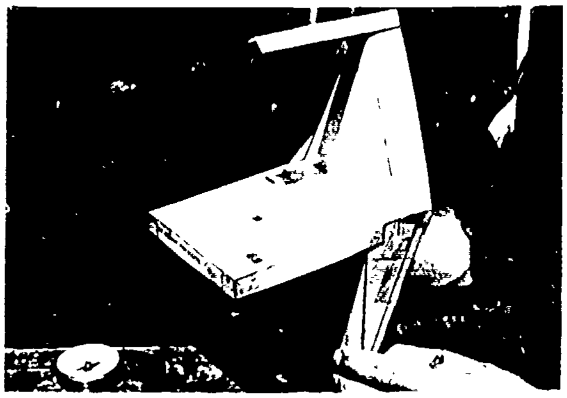
Now that you have established a north-south line, either with a compass or from the North Star, note its position with respect to fixed landmarks, so that you can use it day or night.

A. Sun

You can use the "shadow theodolite" to make observations of the altitude of the sun (height of sun above horizon) and its azimuth (angle between your north point and a line to the sun). Follow the assembly instructions packed with the shadow theodolite parts; work carefully—the accuracy of your instrument depends upon the precision with which you assemble it.

Set the theodolite so that the zero line on the horizontal table points north-south. When the plumb line passes through the hole without touching it, the table is horizontal. This will be easier to do if you support the instrument on the top of a post or wall.

Look for the shadow of the plumb line on the table. Read off its position in degrees: this the sun's direction east or west of the south point. To find the true azimuth add 180° to the reading. Example: a reading of -30° means that the sun is 30° east of south at the time of observation. Azimuth = -30° + 180° = 150°.



Now rotate the theodolite until the thread's shadow is on the zero line. Look for a bright rectangle on the vertical plate caused by sunlight passing through one of the windows in the top plate. Make sure the plate is still horizontal; read off the position of the bright area on the scale. This is the sun's altitude.

Some things to observe:

Record the date and time of all your observations.

Observations to be made during one day

(1) Sun's azimuth at various times during the day. Keep a record of azimuth and time of observation. Does the azimuth angle change steadily during the day, or is the sun's apparent motion more rapid at some times than at others? How fast does the sun move, in degrees per hour?

(2) When is the sun due south?

(3) How does the sun's angular altitude change during the day? When is it greatest?

Observations to be made over an extended period

Try to make these observations about once a week for a period of at least a month or two. Continue for longer if you can. Don't worry if you miss some observations because of poor weather.

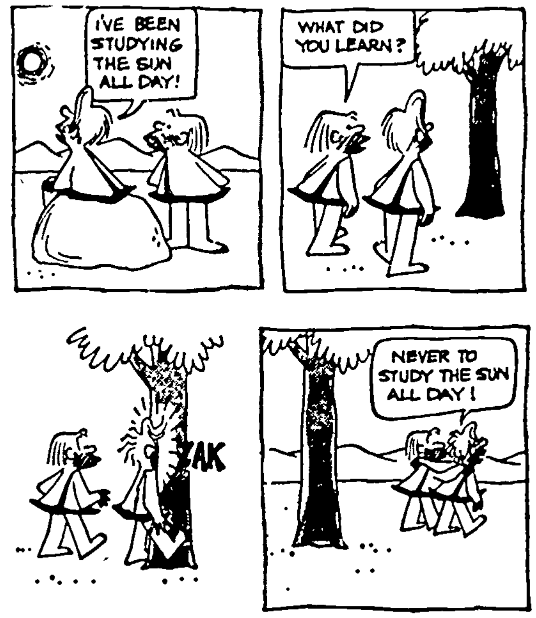
(1) Altitude of sun at noon—or some other convenient hour. On what date is the noon altitude of the sun a minimum? What is the altitude angle on that date?

(2) Try to use your theodolite to make similar observations of the moon (at full moon) too.

B. Moon

1. Observe and record the position and shape of the moon on successive evenings through as much of its cycle as possible.

B.C. by John Hart



By permission of John Hart and Field Enterprises, Inc.

If you miss a night, just record the existence of the gap in the data. Make sketches showing the relative positions of moon and sun. Show the moon's phase. If the sun is below the horizon when you can see the moon, you will have to estimate the sun's position.

2. Can you locate the position of the moon against the background of fixed stars and plot its position on a sky map? Sketch the phase of the moon on the Constellation Chart (SC-1) supplied by your teacher.

3. What is the full moon's maximum altitude? How does this compare with the sun's maximum altitude on the same day? How does it vary from month to month?

4. At full moon you may be able to use the shadow theodolite, described in section A, on sun observations, to determine the moon's altitude and azimuth Try it.

5. There will be an eclipse of the moon on October 6, 1968. Consult Table 1 of the Unit 1 Handbook Appendix for the dates of lunar eclipses in other years.

This multiple exposure picture of the moon was taken with a Polaroid Land Camera by Rick Pearce, a twelfth-grader in Wheat Ridge, Colorado. The time intervals between successive exposures were 15 min, 30 min, 30 min, and 30 min. Each exposure was for 30 sec using 2000-speed film.

C. Stars

1. On the first evening of observation locate some bright stars that will be easy to find on successive nights. Look for star groups that will be easy to relocate. Later you will identify some of these groups with constellations that are named on your star map (Fig. 2). Record how much the stars have changed their positions after an hour; after two hours.

2. Take a photograph (several minutes' exposure) of the night sky to show this motion. Try to work well away from bright street lights, and on a moonless night. Include in the picture some of the horizon for reference. Prop up your camera so it won't move during your time exposures. Use a <u>small</u> iris opening (large f-number) to reduce fogging of your film.

3. When viewed at the same time each night, are the positions of the star groups constant in the sky from month to month? Do any new constellations appear after one month? After 3 or 6 months?

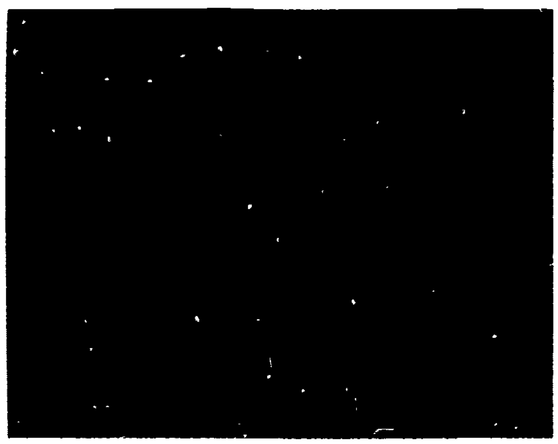
D. Planets and Meteors

See Table 1 of the Unit 1 Handbook Appendix for the positions of planets in this and other years.

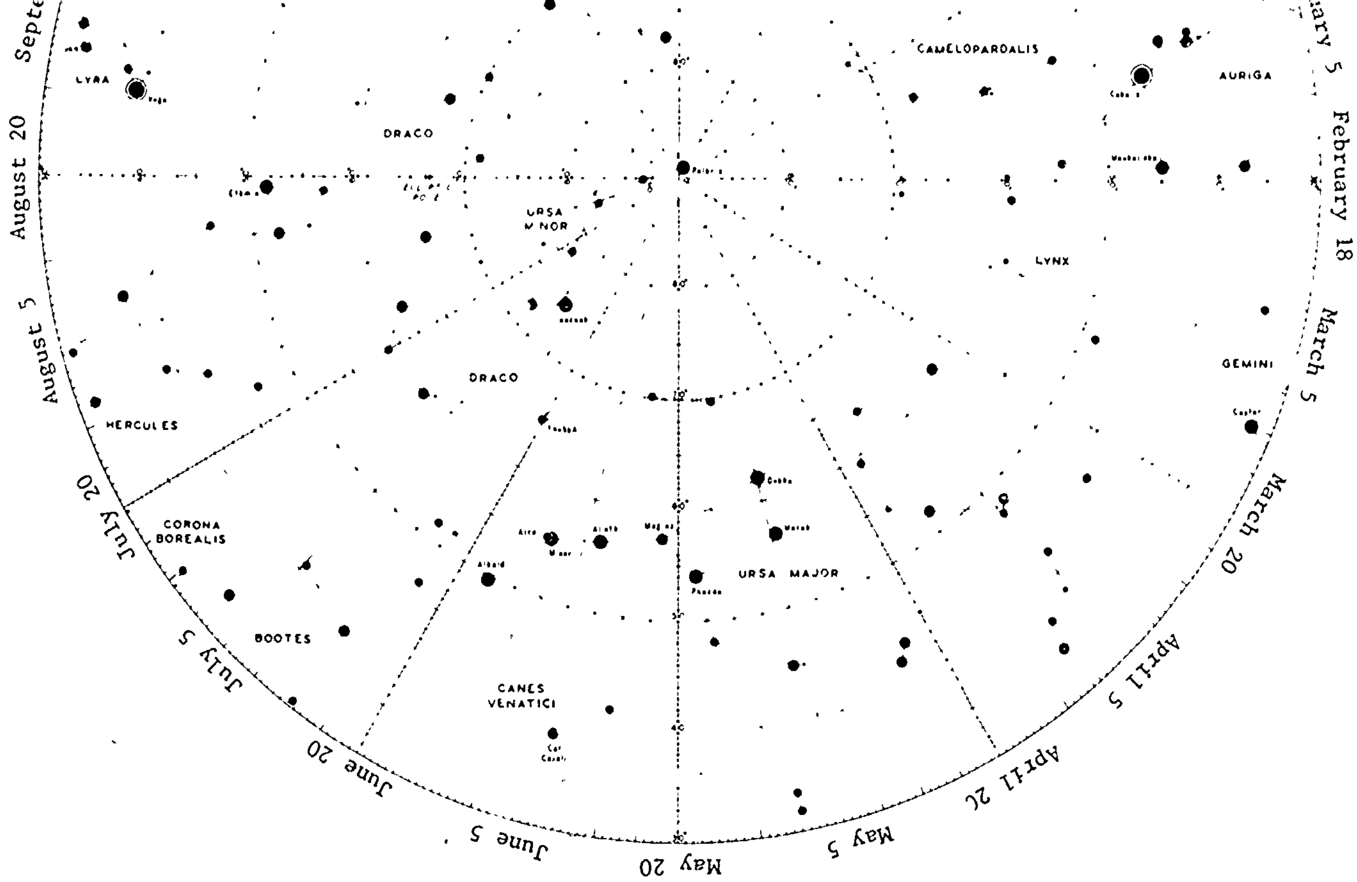
1. If you can identify a planet, check its position in the sky relative to the stars at two-week intervals. The planets are located within a rather narrow band, along which the moon and sun move. In what direction does the planet move against the star background?

2. Consult the Celestial Calendar and Handbook and the monthly magazine <u>Sky and Telescope</u> for more details on the positions of planets, when they are close to the moon, etc.

3. Look for meteor showers each year around November 5 and November 16, beginning around midnight. The dates of meteor showers in other months are given in Table 2 of the Unit 1 Handbook Appendix. Moonlight interferes with meteor observations whenever the moon is between first and third quarter.



A time exposure photograph of Ursa Major ("The Big Dipper") taken with Polaroid Land Camera on an autumn evening in Cambridge, Massachusetts.



This chart of the stars will help you locate some of the bright stars and the constellations. Rotate the chart until today's date is at the top. The stars will be in these positions at <u>8 P.M.</u> For each hour <u>earlier</u> than 8 P.M., rotate the chart 15° (1 sector) clockwise. For each hour <u>later</u> than 8 P.M., rotate the chart counterclockwise.

Making the measurements

The formula is derived for a pendulum with all the mass concentrated in the bob. Hence the best pendulum to use is one whose bob is a metal sphere hung up by a fine thread. In this case you can be sure that almost all the mass is in the bob. The pendulum's length, ℓ, is the distance from the suspension to the <u>center</u> of the bob.

Your suspension thread can have any convenient length. Measure ℓ as accurately as possible, in either feet or meters.

Set the pendulum swinging with <u>small</u> swings. The formula doesn't work with large swings, as you can test for yourself later.

Time at least 20 complete round trips, preferably more. By timing many trips instead of just one trip you make the errors in starting and stopping the clock a smaller fraction of the total time being measured. Why is this desirable?

Divide the total time by the number of swings to find the time of one swing, T.

Repeat your measurement at least once

If you think it was your measurement of length and you think you might be off by as much as 0.5 cm, change your value of ℓ by 0.5 cm and calculate once more the value of a_g. Has a_g changed enough to account for your error? (If a_g went up and your value of a_g was already too high, then you should have altered your measured ℓ in the opposite direction. Try again!)

If your possible error in measuring ℓ is not enough to explain your difference in a_g, try changing your <u>total</u> time by a few tenths of a second—a possible error in timing. Then you must recalculate T and thence a_g.

If neither of these attempts works (nor both taken together in the appropriate direction) then you almost certainly have made an error in arithmetic or in reading your measuring instruments. It is most unlikely that a_g in your school differs from the above values by more than one unit in the third digit.

Find your <u>percentage error</u> by dividing your error by the accepted value and multiplying by 100:

% error =

the strip chart recorder.

One lab partner marks each "tick" of the standard clock on one side of the strip chart recorder tape while the other lab partner marks each "tick" of some other phenomenon. After a long run has been taken, you can inspect the tape to see how the regularities of the two phenomena compare. Run for about 300 ticks of the standard. For each 50 ticks of the standard, find on the tape the number of ticks of the other phenomenon, estimating to 1/10 of a tick. Record your results in a table something like this:

STANDARD CLOCK	YOUR CLOCK
First 50 ticks	____ ticks
Second 50 ticks	____ ticks
Third 50 ticks	____ ticks
Fourth 50 ticks	____ ticks

The results for the different periods are almost certain to be different; but is the difference a real difference in regularity, or could it come from your recording or measuring being a little off? If you think that the difference is larger than you would expect from human error, then which of the two phenomena is <u>not</u> regular?

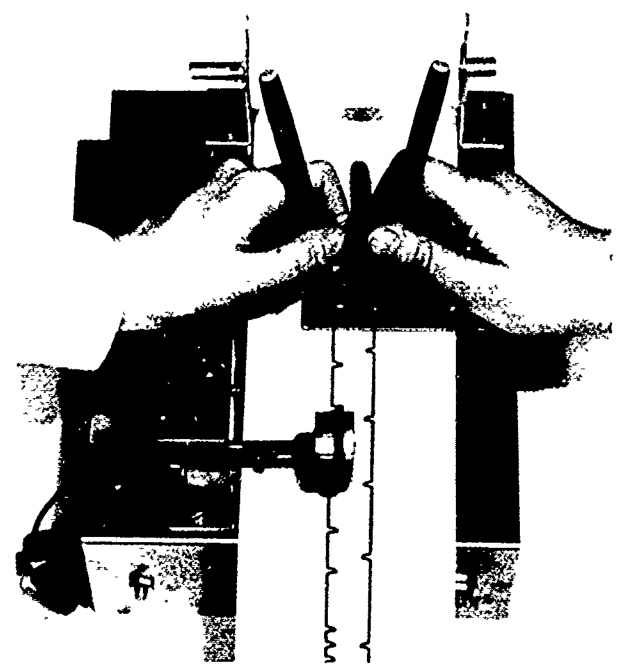
watch your clock. Tabulate your results something like this:

TELEPHONE TIME STATION

"7 p.m. exactly"
"7 a.m. exactly" } 12:00:00 hr
"7 p.m. exactly" } 12:00:00 hr

ELECTRIC WALL CLOCK

7: : ______
7: : ______ } ___:___:___
7: : ______ } ___:___:___



Experiments

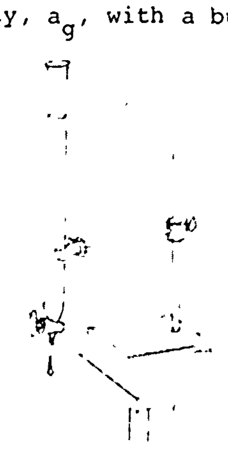
c) slow motion photography (film loop)

With a slow-motion movie camera you could photograph an object falling along the edge of a measuring stick. Then you could determine a_g by projecting the film at standard speed and measuring the distance the object fell in successive frames of the film.

This procedure has been followed in Project Physics Film Loops 1 and 2. Detailed directions are given for their use in separate film loop notes.

d) falling water drops

You can measure the acceleration due to gravity, a_g, with a burette and a pie plate.



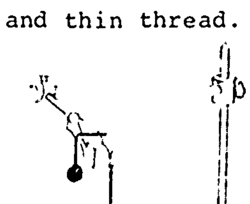
to hit the plate. The time that it takes a drop to fall to the floor is now equal to the time interval between one drop and the next. When you have adjusted the rate of drip in this way, find the time interval between drops, t. (To gain accuracy, you may want to count the number that fall in one minute, or if your watch has a second hand, by timing 100 drops.) You also need to measure the height from plate to tap, d.

You now know the time t it takes a drop to fall a distance d from rest. From this you can calculate a_g (since $d = \frac{1}{2} a_g t^2$ for objects falling from rest).

Can you adapt this method to something that can be done at home, e.g., in the kitchen sink?

e) falling ball and turntable

You can measure a_g with a record-player turntable, a ring stand and clamp, carbon paper, two balls and thin thread.



EXPERIMENT 3 Variations in Data

The success which physics has had in contributing to scientific knowledge is due in no small part to man's ability to measure. Yet every measurement is to some extent uncertain. The numbers resulting from measurements are not simply the same as the numbers used for counting. That is, <u>numbers read from measuring instruments are not exact</u> in the sense that <u>one</u> or <u>two</u> is exact when one counts objects. If the number of chairs or people in a room is counted at a certain time, an exact value is obtained; but if the width of this sheet of paper is measured, the value found is known only within a margin of uncertainty.

The uncertainty in measurement of length mentioned above is just one of the causes of variation in data. This experiment should point out how some of the variations in data arise.

Various stations have been set up around the room. At each station there is some measurement to be made. Each of you will write your results on the board in order to compare and discuss them. Some interesting patterns should emerge. To see these patterns it is important that your measurements are not influenced by anyone else's—therefore, you shouldn't talk about how you measured or what results you obtained until everyone is through.

Keep a record of your observations. This tabulation form is convenient:

Type of Measurement	Remarks	Measurement

EXPERIMENT 4 Uniform Motion

In this experiment, just as in Sec. 1.3, you will record the successive positions of a moving object. You do this in order to find its velocity at several points during its motion. Then you will try to decide if the velocity remained constant.

This decision may be harder than you expect, since your experimental measurements can never be exact; therefore there will always be ups and downs in your final results. Your problem will be to decide whether the ups and downs are due partly to real changes in velocity or due entirely to uncertainty in measurement.

If the velocity turns out to be constant, we have an example of uniform motion. Such motion is described in Sec. 1.3 in the text, which you should read carefully before doing this experiment.

Doing the experiment

The set-up is shown in Fig. 1. You will see that it takes two people. You can get similar results by yourself if you gather data by one of the other methods mentioned in the next section below.

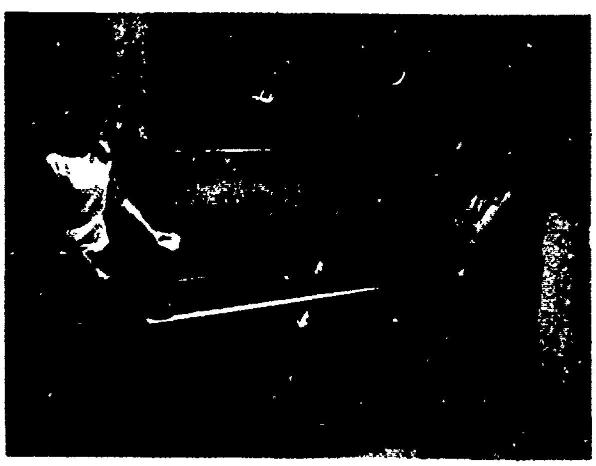


Fig. 1.

The set-up in Fig. 1 uses for the moving object a disc like the one illustrated in Sec. 1.3 of the text. It is made of metal or plastic instead of dry ice and it slides with almost no friction at all if the surface it slides on is smooth and free of grit or dust. Make sure the surface is quite level, too, so that the disc will not start to move once it is at rest.

Set up the Polaroid camera and the stroboscope equipment according to your teacher's instructions. Unlike the picture in the book, no ruler is necessary. Instead you will use a ruler of your own to measure the photograph.

Either your teacher or a few trials will give you an idea of the camera settings and of the speed at which to launch the disc, so that the images of your disc are clear and well-spaced in the photograph. One student operates the camera while his companion launches the disc. A "dry run" or two without taking a picture will probably be needed for practice before you get a good picture. A good picture is one in which there are at least five sharp and clear images of your disc far enough apart for easy measuring on the photograph.

Other ways of getting data

Instead of discs sliding on a table, you can photograph other objects, such as a glider on a level air track or a blinky (steadily flashing light) pushed by a toy tractor. Your teacher will explain their use. Excellent photographs can be made of either one.

If you do not use a camera at all or if you work alone, then you may measure a transparency or a movie film projected on the blackboard. Or you may simply work from a previously prepared photograph such as the one in Sec. 1.3.

Drawing Conclusions

Whatever method you have used, the next step is to measure the spaces between successive images of your moving object. For this, use a ruler with millimeter divisions and estimate the distances to the nearest tenth of a millimeter. List each measurement in a table like Table 1.

As your time unit, use the time needed for the moving object to go from one position to the next. Of course it is the same time interval in all cases. Therefore if the velocity is constant the distances of travel will all be the same, and the motion is uniform.

Q1 How will you recognize motion that is not uniform?

Q2 Why is it unnecessary to find the time interval in seconds?

Table 1

Distance traveled in each time interval	Time interval
0.48 cm	1st
0.48	2nd
0.48	3rd
0.48	4th
0.48	5th
0.48	6th

Here in Table 1 we have data that indicate uniform motion. Since the object traveled 0.48 cm during each time interval, the velocity is 0.48 cm per unit time.

It is more likely that your measurements go up and down as in Table 2.

Table 2

Distance traveled in each time interval	Time interval
0.48 cm	1st
0.46	2nd
0.49	3rd
0.50	4th
0.47	5th
0.48	6th

Q3 Is the velocity constant in this case?

Since the distances are not all the same you might well say, "No, it isn't."

Or perhaps you looked again and said, "The ups and downs are because it is difficult to measure to 0.01 cm with the ruler. The velocity really is constant as nearly as I can tell."

Which statement is right?

Look carefully at your ruler. Can you read your ruler accurately to the nearest 0.01 cm? If you are like most people you read it to the nearest 0.1 cm (the nearest whole millimeter) and estimated the next digit.

In the same way, whenever you read the scale of any measuring device you should read accurately to the nearest mark and then estimate the next digit in the measurement. This means that your value is the estimated reading plus or minus no more than half a scale division.

Suppose you assume that the motion really is uniform, and that the slight differences between distance measurements are due only to the uncertainty in reading the scale. What is then the best estimate of the constant distance the object traveled between flashes?

To find the "best" value of distance you must average the values. The average for Table 2 is 0.48 cm, but the 8 is doubtful.

If the motion recorded in Table 2 really is uniform, the distance traveled in each time interval is 0.48 cm plus or minus 0.05 cm, written as 0.48 $\pm$0.05 cm. The 0.05 is called the uncertainty of your measurement. It is commonly half a scale division for a single measurement.

Now we can return to our big question: is the velocity constant or not? Because the numbers go up and down you might suppose that the velocity is constantly changing. Notice though that the changes of data above and below our average value of 0.48 cm are always smaller than the uncertainty, 0.05 cm. Therefore, the ups and downs may all be due to your difficulty in reading the ruler to better than 0.05 cm—and the velocity may, in fact, be constant.

Our conclusion is that the velocity is constant to within the uncertainty of measurement, which is 0.05 cm per unit time. If the velocity goes up or down by less than this amount we simply cannot reliably detect it with our ruler.

If we measured more precisely

A more precise ruler might show that the velocity in our example was not constant. For example if we used a measuring microscope whose divisions are accurate to 0.001 cm to measure the same picture again more precisely, we might arrive at the data in Table 3.

Table 3

Distance traveled in each time interval	Time interval
0.4826 cm	1st
0.4593	2nd
0.4911	3rd
0.5032	4th
0.4684	5th
0.4779	6th

Q4 Is the velocity constant when we measure to such high precision as this?

The average of these numbers is 0.4804, and they are all presumably correct to half a division, which is 0.0005 cm. Thus our best value is 0.4804 ±0.0005 cm.

Drawing a graph

If you have read Sec. 1.5 in the text you have learned that your data can be graphed. If you have never drawn graphs before, your data provide an easy example to start with.

Just as in the text example on page 19, lay off time intervals along the horizontal axis. Your units are probably not seconds; they are "blinks" if you used a stroboscope, or simply "arbitrary units," which means here the equal time intervals between positions of the moving object.

Likewise the total distances traveled should be laid off on the vertical axis. The beginning of each scale is in the lower left-hand corner of the graph.

Choose the spacing of your scale divisions so that your data will, if possible, spread across the entire page.

The data of Table 2 are plotted here as an example (Fig. 2).

Q5 In what way does the graph of Table 2 show uniform motion? Does your graph show uniform motion too?

If the motion of your object is uniform, find the value of the uniform velocity from your graph. Describe how you found it.

Q6 What does a graph look like if the motion is not uniform?

If your motion is not uniform, review Sec. 1.7 of the text and then from your graph find the average speed of your object over the whole trip.

Q7 Is the average speed for the whole trip the same as the average speeds between successive measurements?

Additional Questions

Q8 Could you use the same methods to measure the speed of a bicycle? A car? A person running? (Assume they are moving uniformly.)

Q9 The speedometer scale on many cars is divided into units 5 mi/hr in size. You can estimate the reading to the nearest 1 mi/hr.

a) What is the uncertainty in a speed measurement?

b) Could you measure reliably velocity changes as small as 2 mi/hr? 1 mi/hr? 0.5 mi/hr? 0.3 mi/hr?

Q10 Sketch the shape of a distance-time graph of

a) an object that is slowly gaining speed.

b) a bullet during the second before and the second after it hits a brick wall.

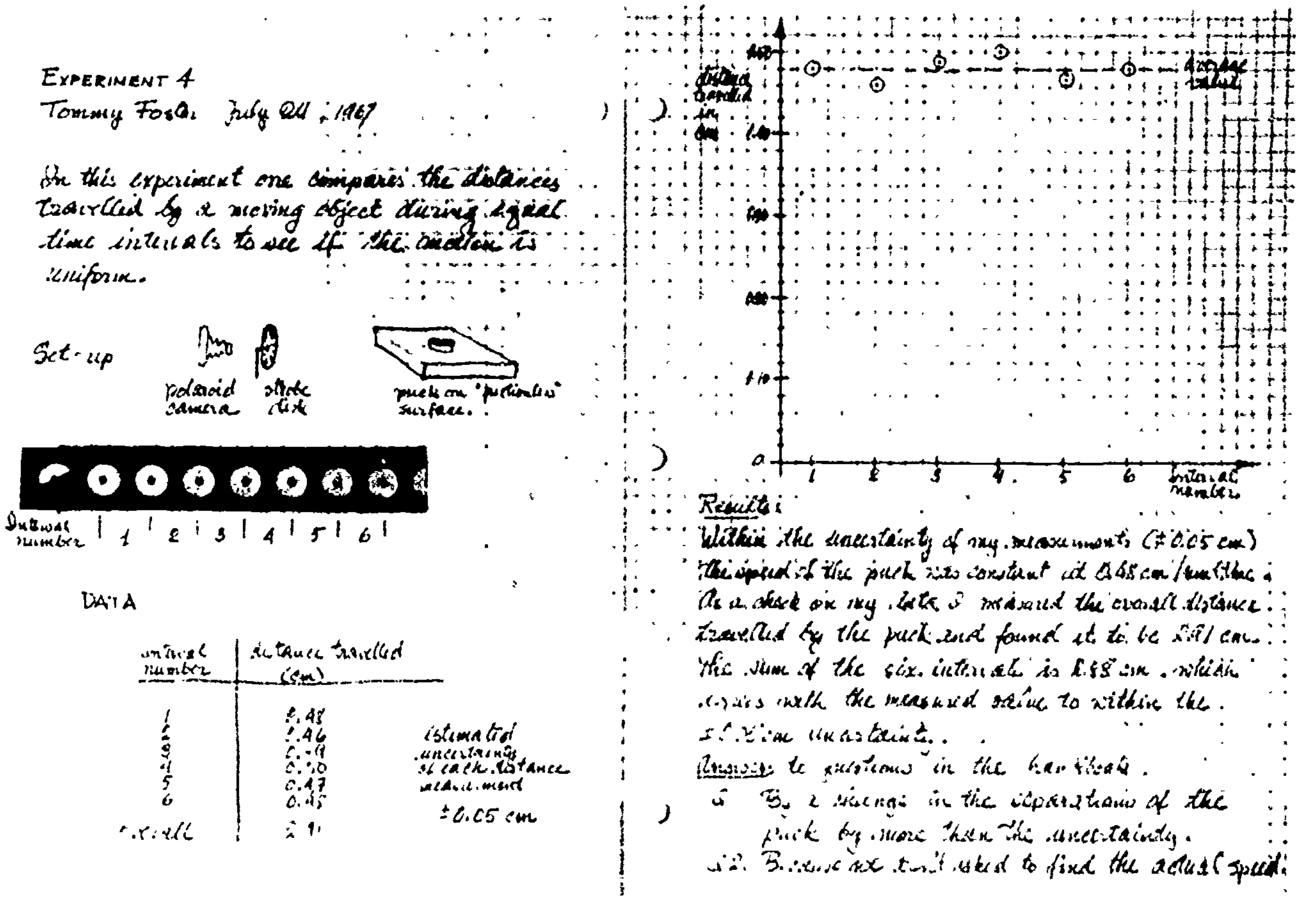


Fig. 2.

ACTIVITY 1 Electronic Stroboscope

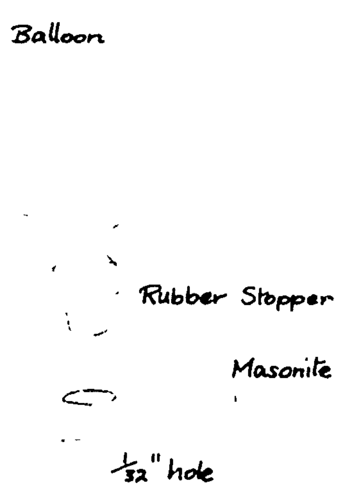
Examine some moving objects illuminated by an electronic stroboscope. Put a piece of tape or a chalkmark on a fan blade and watch the pattern as you turn the fan on and off. How can you tell when there is exactly one flash of light for each rotation of the fan blade?

Observe a stream of water from a faucet, objects tossed into the air and the underside of a sewing machine. If you can darken the room completely, try catching a thrown ball with only the light from the stroboscope.

ACTIVITY 2 Making Frictionless Pucks

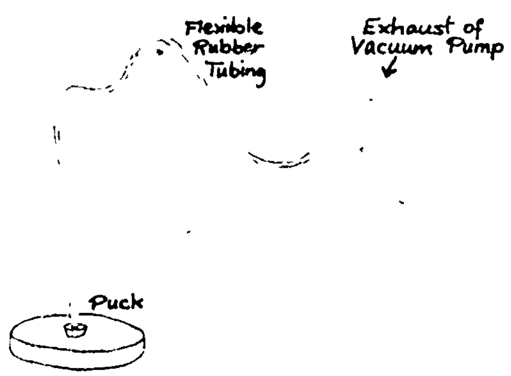
Method 1. Use a flat piece of dry ice on a very smooth surface, like glass or formica. When you push the piece of dry ice (frozen carbon dioxide) it moves in a frictionless manner because as the carbon dioxide sublimes it creates a layer of CO_2 gas between the solid and the glass.

Method 2. Make a balloon puck. First cut a 4-inch diameter disc of 1-inch thick masonite. Drill a 1/32" hole through the center of the disc. Drill a 1/2" diameter hole on the same center and on the top of the disc, so it will hold a rubber stopper. Drill a 1/16" hole through the center of a stopper.



Inflate a balloon, stretch it over the stopper and insert the stopper in the hole in the masonite disc. Place the disc on glass or formica.

Method 3. Make a disc as described in Method 2. Instead of using a balloon, attach a piece of flexible tubing from the exhaust of a vacuum pump. It helps to run the tubing to an overhead support so it does not interfere with the motion of the puck.



Method 4. Drill a 1/32" hole in the bottom of a smooth-bottomed cylindrical can, such as one for a typewriter ribbon. Break up dry ice (DON'T touch it with bare hands) and place the pieces inside the can. Seal the can with tape, and place the can on a very smooth surface.

Accelerated Motion

In Chapter 2 you have been reading about Galileo's interest in accelerated motion. Scientists are still interested in accelerated motion today. In the following experiments you learn to measure acceleration in a variety of ways, both old and new.

If you do either of the first two experiments you will try to find, as Galileo did, whether d/t^2 is a constant for motion down an inclined plane.

The remaining experiments are measurements of the value of the acceleration of gravity, a_g—the value that $2d/t^2$ would approach as an inclined plane is made more and more nearly vertical. Perhaps you would like to try one of them.

EXPERIMENT 5 A Seventeenth-Century Experiment

This experiment is similar to the one discussed in the Two New Sciences by Galileo. It will give you first-hand experience in working with tools similar to those of a seventeenth-century scientist. You will make quantitative measurements of the motion of a ball rolling down an incline, as described by Galileo. From these measurements you should arrive at a suitable definition of acceleration—the major purpose of the exercise. It is also possible to calculate the value of a_g (acceleration due to gravity), which you should try to do.

The reasoning behind the Experiment

You have read in Sec. 2.6 how Galileo discussed his belief that the speed of free-falling objects increases in proportion to the time of fall—that is, that they have uniform acceleration. But since free fall was much too rapid to measure, he assumed that the speed of a ball rolling down an incline increases in the same way as an object in free fall does, only more slowly. Its average speed could now be measured.

But to see if the accelerations of the ball were the same from point to point required a knowledge not of average speed but of instantaneous speed at each point, and even a ball rolling down a low incline still moved too fast to measure the speed at a point at all accurately. So he worked out the relationship $\frac{a}{2} = \frac{d}{t^2}$, an expression for acceleration in which speed has been replaced by the total time and total distance rolled by the ball. Both these quantities can be measured. Be sure to study Sec. 2.7 in which this derivation is described. If Galileo's original assumptions were true, this relationship would hold for both freely falling objects and rolling balls. Since total distance and total time are not difficult to measure, seventeenth-century scientists now had a secondary hypothesis they could test by experiment. And so have you. Section 2.8 of the text discusses much of this.

Apparatus

The apparatus which you will use is shown in Fig. 1. It is similar to that discussed by Galileo.

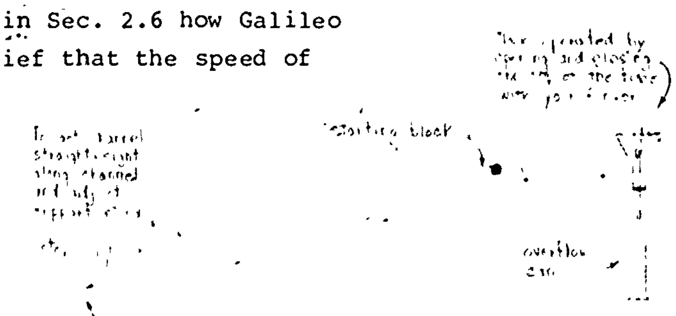


Fig. 1.

fore, with a ruler, and release it by quickly moving the ruler away from it down the plane. The end of the run is best marked by the sound of the ball hitting the stopping block.

A brief comment on recording data

You can find a good example of a way to record your data in Fig. 2. We should emphasize the need for neat, orderly work. Orderly work looks better and is more pleasing to you and everyone else. It may also save you from extra work and confusion. If you have an organized table of data, you can easily record and find your data. This will leave you free to think about your experiment or calculations rather than worry about which of two numbers on a scrap of paper is the one you want, or whether you made a certain measurement or not. A few minutes' preparation before you start work will often save you

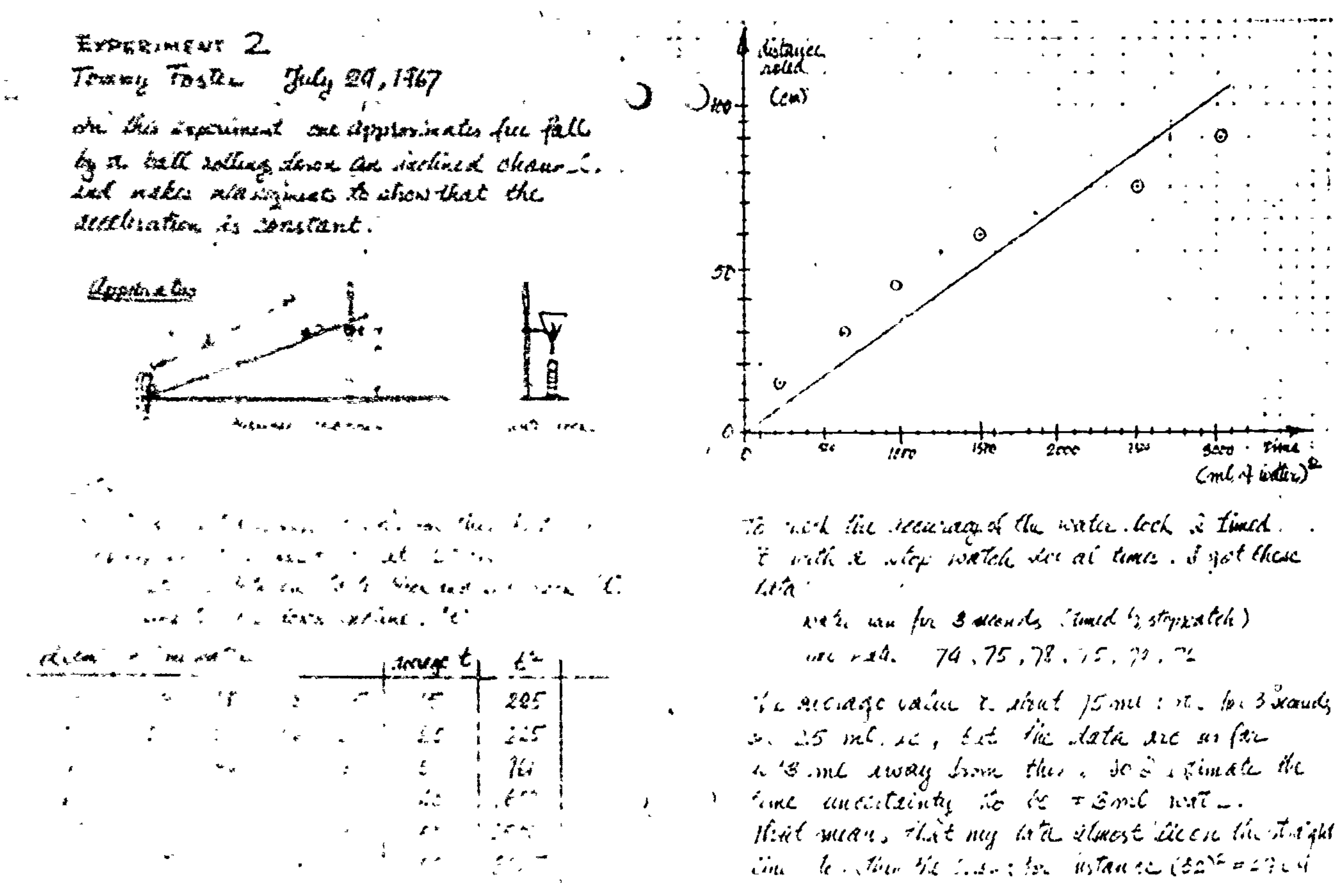


Fig. 2.

an hour or two of chasing around checking in books and with friends to see if you did things right.

Some operating suggestions

You should measure times of descent for several different distances, keeping the inclination of the plane constant and using the same ball. Repeat each descent four times, and average your results. Best results are found for very small angles of inclination (the high end of the channel raised less than about 30 cm). At greater inclinations the ball tends to slide as well as to roll. With these data you can check the constancy of d/t^2.

Then if you have time, go on to see if Galileo or Aristotle was right about the acceleration of objects of various sizes. Measure d/t^2 for several different sizes of balls, all rolling the same distance down a plane of the same inclination.

If you try to find the acceleration of an object in free fall, a_g, you should measure the time a ball takes to descend the full length of the plane at various carefully measured angles. Use angles up to the steepest for which you can measure the times of descent. From these data you can extrapolate to free fall (90°). You might want to use a stopwatch here instead of a water clock.

From data to calculations

Galileo's definition of uniform acceleration (text, page 49) was "equal increases in speed in equal times." Galileo expected that if an object actually moved in this way the total distance of travel should be directly proportional to the square of the total times of fall.

Q1 Why does this follow from his definition? (See Sec. 2.7 in the text if you cannot answer this.)

When you have collected enough data, plot a graph of the distances rolled (vertical axis) against the squared times for each inclination.

Q2 What must your graph look like if it is to support Galileo's hypothesis?

Q3 Does your graph support the hypothesis?

You have been using a water clock to time this experiment because that was the best timing device available in Galileo's time. How accurate is it? Check it against a stopwatch or, better yet, repeat several trials of your experiment using a stopwatch for timing.

Q4 How many seconds is one milliliter of time?

Extension

Review Sec. 2.7. There you learned that $a = 2d/t^2$.

Use this relation to calculate the actual acceleration of the ball in one of your runs.

If you have time you might also try to calculate a_g from your results. This is a real challenge. Your teacher may need to give you some help on this.

Additional Questions

Q5 Does the acceleration depend upon the size of the ball? In what way does your answer refute or support Aristotle's ideas on falling bodies?

Q6 Galileo claimed his results were accurate to 1/10 of a pulse beat. Do you believe his results were that good? Did you do that well?

Q7 Galileo argues that in free fall, an object tends to accelerate for as long as it falls. Does this mean that the speed of an object in free fall would keep increasing to infinity?

EXPERIMENT 6 A Twentieth-Century Version of Galileo's Experiment

In Sec. 2.9 of the text you read about some of the limitations of Galileo's experiment.

In the modern version with improved clocks and planes you can get more precise results, but remember that the idea behind the improved experiment is still Galileo's idea. More precise measurements do not always lead to more significant conclusions.

The apparatus and its use

For an inclined plane use the air track. For timing the air track glider use a stopwatch instead of the water clock.

Otherwise the procedure is the same as that used in the first version above. As you go to higher inclinations you should stop the glider by hand before it hits the stopping block and is damaged.

Instead of a stopwatch your teacher may have you use the Polaroid camera to make a strobe photo of the glider as it descends. A piece of white tape on the glider will show up well in the photograph. Or you can attach a small light source to the glider. You can use a magnifier with a scale attached to measure the glider's motion recorded on the photograph. Here the values of d will be millimeters on the photograph and t will be measured in an arbitrary unit, the "blink" of the stroboscope.

Plot your data as before on a graph of t^2 vs. d.

Compare your plotted lines with graphs of the preceding cruder seventeenth-century experiment, if they are available. Explain the differences between them.

Q1 Is d/t^2 constant for an air-track glider?

Q2 What is the significance of your answer to the above question?

As a further challenge you should, if time permits, predict the value of a_g, which the glider approaches as the air track becomes vertical. To do this, of course, you must express d and t in familiar units such as meters or feet, and seconds. The accepted value of a_g is 9.8 m/sec^2 or 32 ft/sec^2.

Q3 What is the percentage error in your measurement? That is, what percent is your error of the accepted value?

Percentage error =

$$\frac{\text{accepted value - measured value}}{\text{accepted value}} \times 100$$

so that if your value of a_g is 30 ft/sec^2

percentage error =

$$\frac{32 \text{ ft/sec}^2 - 30 \text{ ft/sec}^2}{32 \text{ ft/sec}^2} \times 100$$

$$= \frac{2}{32} \times 100 = 6\%.$$

Notice that you cannot carry this out to 6.25% because you only know the 2 in the fraction 2/32 to one digit. You cannot know the second digit in the answer (6%) until you know the digit following the 2. This would require a third digit in the measurements of 30 and 32.

Q4 What are some of the sources of your error?

EXPERIMENT 7 Measuring the Acceleration of Gravity

a) a_g by direct fall*

In this experiment you measure the acceleration of a falling weight when you drop it. Since the distance of fall is too small for air resistance to be important, and since other sources of friction are very small, the acceleration of the falling weight is very nearly a_g.

How to do the experiment

The falling object is an ordinary laboratory hooked weight of at least 200 gm. (Friction has too great an effect on the fall of lighter weights.) The weight is suspended from a few feet of ticker tape as shown above. Reinforce the tape by doubling a strip of masking tape over one end and punch a hole in the reinforcement one centimeter from the end. With careful handling you can support at least a kilogram weight.

When the suspended weight is allowed to fall, the tape dragged behind it is to have equal time intervals marked on it by a vibrating tuning fork.

The tuning fork must have a frequency between about 100 vibrations/sec and about 400 vibrations/sec. In order to mark the tape the fork must have a tiny felt cone (cut from a marking pen tip) glued to the side of one of its prongs close to the end. Such a small mass affects the fork frequency by much less than 1 vibration/sec. Saturate this felt tip with a drop or two of marking pen ink, set the fork in vibration and hold the tip very gently against the tape.

The falling tape is most conveniently guided in its fall by two thumbtacks in the edge of the table. The easiest procedure is to have an assistant hold the weighted tape straight up until you have touched the vibrating tip against it and said "go." After a few practice runs you will become expert enough to mark several feet of tape with a wavy line as the tape is accelerated past the stationary vibrating fork.

Analyzing your tapes

Mark with an A one of the first wave crests that is clearly formed near the beginning of the pattern. Count 10 intervals between wave crests, and mark the end of the tenth space with a B. Continue, marking every tenth wave with a letter throughout the length of the record, which must be at least 40 waves long.

At A the tape already had a velocity of v_0. From this point to B the tape moved in a time t a distance we shall call d_1. The distance d_1 is described by the equation of free fall:

$$d_1 = v_0 t + \frac{a_g t^2}{2} .$$

In covering the distance from A to C the tape took a time exactly twice as long, 2t, and fell a distance d_2 described (on

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

substituting 2t for t) by the equation:

$$d_2 = 2v_0t + \frac{4a_gt^2}{2}.$$

In the same way the distances AB, AE, etc., are described by the equations:

$$d_3 = 3v_0t + \frac{9a_gt^2}{2}$$

$$d_4 = 4v_0t + \frac{16a_gt^2}{2}$$

and so on.

All of these distances are measured from A, the arbitrary starting point. To find the distances fallen in each 10-wave interval we must subtract each equation from its successor, getting:

$$AB = v_0t + \frac{a_gt^2}{2}$$

$$BC = v_0t + \frac{3a_gt^2}{2}$$

$$CD = v_0t + \frac{5a_gt^2}{2}$$

$$DE = v_0t + \frac{7a_gt^2}{2}.$$

From these equations you can see that the weight falls farther during each time interval. Moreover, when we subtract each of these distances, AB, BC, CD,... from the subsequent distance we find that the increase in distance fallen is a constant. That is, each subtraction BC - AB = CD - BC = DE - CD = a_gt^2. This quantity is the increase in the distance fallen in each successive 10-wave interval and hence is an acceleration. Our formula agrees with our knowledge that a body falls with a constant acceleration.

From your measurements of AB, AC, AD, etc., tabulate AB, BC, CD, DE, etc., and in an adjoining column, the resulting values of a_gt^2. The values of a_gt^2 should all be equal (within the accuracy of your measurements). Why? Make all your measurements to as many significant figures as are possible with the equipment—neither more nor less.

Find the average of all your values of a_gt^2, the acceleration in centimeters/(10-wave interval)^2. We want to find the acceleration in cm/sec^2. If we call the frequency of the tuning fork n per second, then the length of the time interval t is 10/n seconds. Replacing t of 10 waves by 10/n seconds then gives us the acceleration, a_g, incm/sec^2.

The ideal value of a_g is close to 9.8 m/sec^2, but a force of friction of about 15 gms impeding a falling kilogram is sufficient to reduce the observed value to 965 cm/sec^2, an error of about 1.5%.

Q1 What errors would be introduced by using a tuning fork whose vibrations are slower than about 100 vibrations per second?

Q2 Higher than about 400 vibrations per second?

Q3 Is a_g the same everywhere (a) on the earth's surface? (b) in the solar system?

b) a_g from a pendulum

An easy way to find a_g is to time the back-and-forth oscillations of a pendulum. Of course the pendulum is not falling straight down, but the time it takes for a round-trip swing still depends on a_g. The time T it takes for a round-trip swing is

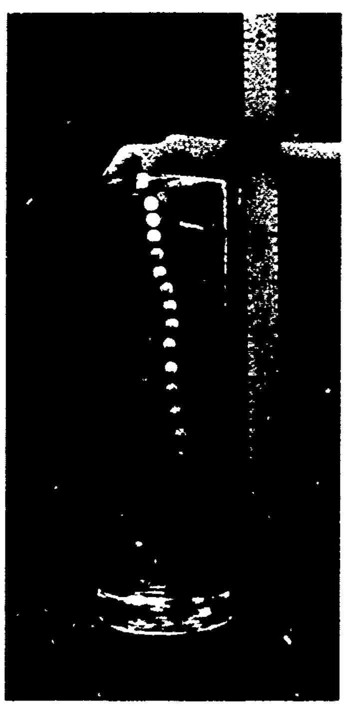
$$T = 2\pi\sqrt{\frac{\ell}{a_g}}.$$

In this formula ℓ is the length of the pendulum. If you measure ℓ with a ruler and T with a clock, you should be able to solve for a_g.

You may learn in a later physics course how to derive the formula. Scientists often use formulas they have not derived themselves, as long as they are confident of their validity.

ACTIVITY 3 When is Air Resistance Important?

By taking strobe photos of various objects falling side by side, you can determine when air resistance begins to play an important role. You can determine the terminal velocity for less dense objects such as a ping-pong or styrofoam ball by dropping them from greater and greater heights until the measured velocities do not change with further increases in height. (A ping-pong ball achieves terminal velocity within 2 m.) Similarly, ball bearings and marbles can be dropped in containers of liquid shampoo or cooking oil to determine factors affecting terminal velocity in a liquid.



A magnet is a handy aid for getting the ball bearing back to the top of the oil.

ACTIVITY 4 Measuring Your Reaction Time

Your knowledge of kinematics can help you calculate your reaction time. Have someone hold the top of a sheet of paper while you space your thumb and forefinger around the bottom edge of the paper. As soon as the other person releases the paper, you catch it. By measuring from the bottom of the sheet to the place where you caught it, you can compute your reaction time from the relation $d = \frac{1}{2}a_g t^2$, solving for t.

A challenge is to try this with a one-dollar bill, saying the other person can have it if he can catch it.

ACTIVITY 5 Falling Weights

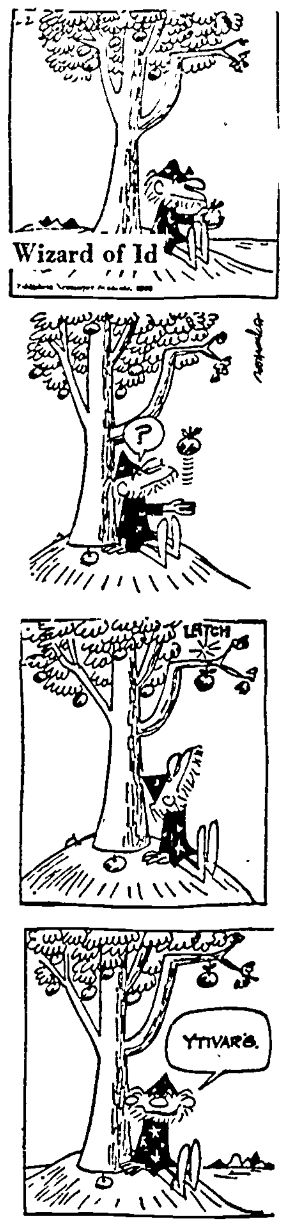
This demonstration shows that the time it takes a body to fall is proportional to the square root of the vertical distance ($d \propto t^2$). Suspend a string on which metal weights are attached at the following heights above the ground:

3", 1', 2'3", 4', 6'3", 9', 12'3", 16'.

Place a metal tray under the weights and then burn or cut the string at the point of suspension. The weights will strike the tray at equal intervals of time—about 1/8 second.

Compare this result with that obtained using a string on which the weights are suspended at equal distance intervals.

by Parker and Hart



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EXPERIMENT 8 Newton's Second Law

Newton's Second Law is one of the most important and useful laws of physics.

Review Sec. 3.7 to make sure you understand what it says.

This is not a law that you can prove before trying it, as you can prove that the path of a projectile will be a parabola. The law is simply a description, much as the conservation laws are that you will study in Unit 3.

This is not even a law that you can verify, in the sense that you can verify by experiment that a projectile's path really is a parabola. Newton's Second Law has to agree with experiments simply because the law is used to define the units of all Second Law experiments in such a way as to make them come out right.

So what can be the use of our doing an experiment?

Our experiment has two purposes.

First, just because the law is so important it is useful to get a feeling for the behavior of F, m and a. The first part of the experiment is devoted to doing this.

Second, the experiment is an excellent one in which to consider the effect of uncertainties of measurement. This is the purpose of the latter part of the experiment.

How the apparatus works

You are about to find the mass of a loaded cart on which you then exert a measurable force. If you accept Newton's Law as true then you can use it to predict the resulting acceleration of the loaded cart.

Arrange the apparatus as shown in Fig. 1. A spring scale is firmly taped to a dynamics cart. The cart, carrying a

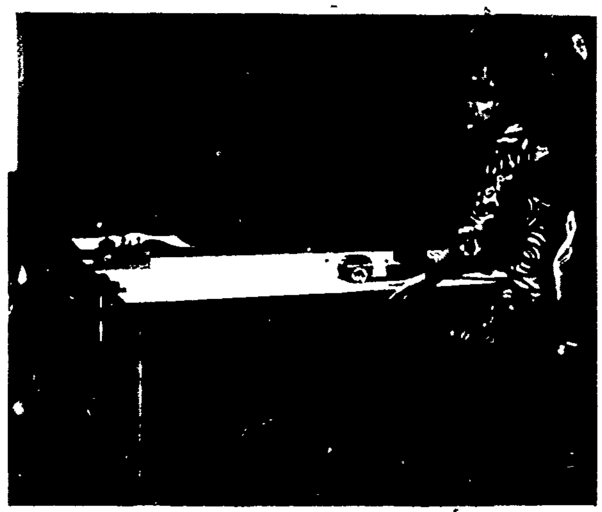


Fig. 1(a).

blinky, is pulled along by a cord attached to the hook of the spring scale. The scale therefore measures the force exerted on the cart.

The cord runs over a pulley at the edge of the lab table and from its end hangs a weight. The hanging weight can be changed so as to exert various tensions in the cord and hence various accelerating forces on the cart.

Measure the mass of the cart together with the blinky, the spring scale and any other weights you may want to include with it. This is the mass m being accelerated.

Now you are ready to go.

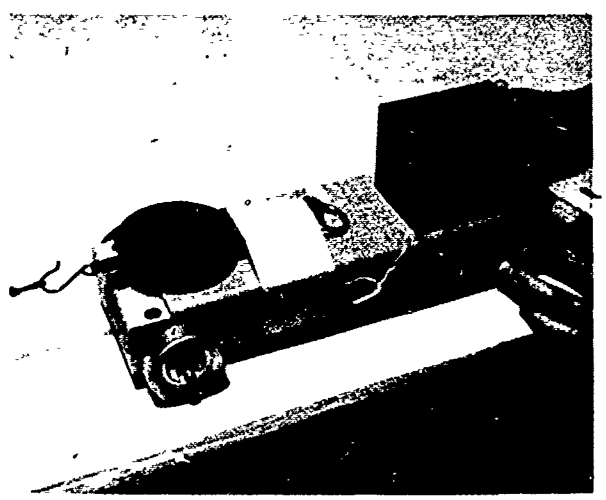


Fig. 1(b)

Begin the experiment by releasing the system and allowing to accelerate. Repeat the motion several times while watching the spring scale pointer. With a little practice you should be able to see that the pointer has a range of positions. The midpoint of this range is a fairly good measurement of the average force F_{av} (often written $\bar{F}$) producing the accelerations.

Record $\bar{F}$ in newtons.

Our faith in Newton's Law is such that we assume the acceleration is the same and is constant every time this particular $\bar{F}$ acts on the mass m.

Use Newton's Law to predict $\bar{a}$.

Then measure a to see if your prediction agrees with reality.

To measure the acceleration $\bar{a}$ take a Polaroid photograph of the flashing blinky (or a strobe picture of a light source) mounted on the cart. As an alternative you might use a liquid surface accelerometer, described in detail elsewhere in this book. Analyze the record just as in the experiments on uniform and accelerated motion in order to find a.

This time, however, you must know the distance traveled in meters and the time interval in seconds, not just in blinks. To find the time interval, count the number of blinks in a minute and divide the total by 60.

Q1 Does $\bar{F} = m\bar{a}$?

Q2 By what percent do your two values disagree?

Your teacher may ask you to observe the following effects without actually making numerical measurements.

1. Keeping the mass of the cart constant, observe how various forces affect the acceleration.
2. Keeping the force constant, observe how various masses of the cart affect the acceleration.

Q3 Do your observations support Newton's Second Law? Why do you think so?

Experimental errors

It is unlikely that your values of $\bar{F}$ and $m\bar{a}$ were equal.

This does not necessarily mean that you have done a poor job of taking data. There are at least two other possible reasons for the inequality.

a) You have not yet measured everything necessary in order to get an accurate value for each of your three quantities.

In particular, $\bar{F}$ means <u>net</u>, or resultant, force on the cart—not just the towing force that you measured. Friction force also acts on your cart opposing the accelerating force. You can measure it by reading the spring scale as you tow the cart by hand at <u>constant speed</u>. Do it several times and take an average, $\bar{F}_f$. Since friction, F_f, acts in a direction opposite to the towing force, F_T,

$$\bar{F}_{net} = \bar{F}_T - \bar{F}_{frict}.$$

If $\bar{F}_{frict}$ is too small to measure, then $\bar{F}_{net} = \bar{F}_T$, which is simply the towing force that you wrote as $\bar{F}$ in the beginning of the experiment.

b) Another reason for the inequality of $\bar{F}$ and $m\bar{a}$ may be that your value for each of these quantities is based on <u>measurements</u> and every measurement is uncertain to some extent.

You should estimate the uncertainty of each of your measurements.

Uncertainty in $\bar{F}$

For example, your uncertainty in the measurement of $\bar{F}$ is the average reading of your spring scale (converted to newtons if necessary) plus or minus the range of uncertainty you marked on your paper tape (also converted to newtons). Thus if your scale reading ranged from 1.0 to 1.4 N then the average is 1.2 N.

The range of uncertainty is 0.2 N. Thus the value of $\bar{F}$ is 1.2 ± 0.2 N.

What is your value of $\bar{F}$?

Uncertainty in m

Your uncertainty in m is half the smallest scale reading of the balance with which you measured it. Your mass consisted of a cart, a blinky and a spring scale (and possibly an additional weight). Record the mass of each of these in kilograms, in some way such as follows.

$m_{cart} = 0.90 \pm 0.05$ kg

$m_{blinky} = 0.30 \pm 0.05$ kg

$m_{scale} = 0.10 \pm 0.05$ kg.

The total mass being accelerated is the sum of these masses. The uncertainty in the total mass is the sum of the three uncertainties. Thus, in our example,

$m = 1.30 \pm 0.15$ kg.

Even when you subtract measured values the uncertainty is still the sum of the uncertainties.

What is your value of m?

Uncertainty in $\bar{a}$

Finally, consider the measurement of $\bar{a}$. You found this by measuring $\Delta d/\Delta t$ for each of the intervals between the points on your blinky photograph.

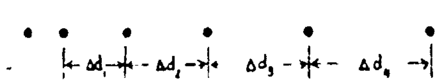


Fig. 2.

Suppose the points in Fig. 2 represent the record of blinky flashes. The distance between the points must be measured. Your table of data should be similar to Table 1.

The uncertainty in each value of $\Delta d/\Delta t$ is due primarily to the fact that the records of the blinky flashes are not true points. Suppose that the uncertainty in locating the distance between the centers

TABLE 1

AVERAGE SPEEDS

$\frac{\Delta d_1}{\Delta t} = 2.5 \frac{cm}{sec} \pm 0.1 \frac{cm}{sec}$	
	$\frac{\Delta v_1}{\Delta t} = 0.9 \frac{cm}{sec^2} \pm 0.2 \frac{cm}{sec^2}$
$\frac{\Delta d_2}{\Delta t} = 3.4 \frac{cm}{sec} \pm 0.1 \frac{cm}{sec}$	
	$\frac{\Delta v_2}{\Delta t} = 0.6 \frac{cm}{sec^2} \pm 0.2 \frac{cm}{sec^2}$
$\frac{\Delta d_3}{\Delta t} = 4.0 \frac{cm}{sec} \pm 0.1 \frac{cm}{sec}$	
	$\frac{\Delta v_3}{\Delta t} = 0.8 \frac{cm}{sec^2} \pm 0.2 \frac{cm}{sec^2}$
$\frac{\Delta d}{\Delta t} = 4.8 \frac{cm}{sec} \pm 0.1 \frac{cm}{sec}$	
	Average $0.8 \frac{cm}{sec^2} \pm 0.2 \frac{cm}{sec^2}$

of the dots is 0.01 cm as shown in the first column of Table 1. When we take the differences between successive values of the speeds, $\Delta d/\Delta t$, we get the accelerations, $\Delta v/\Delta t$, the speeds recorded in the second column. As we noted above, when a difference in two measurements is involved, we find the uncertainty of the difference (in this case, $\Delta v/\Delta t$) by adding the uncertainties of the two measurements. This results in a maximum uncertainty in acceleration of $\pm$ 0.2 cm/sec^2 as recorded in the table.

Comparing our results

We now have values of $\bar{F}$, m and $\bar{a}$ together with their uncertainties, and we should consider the uncertainty of $m\bar{a}$. When we have discovered the uncertainty of this product of two quantities, we shall then compare the value of $m\bar{a}$ with the value of $\bar{F}$ and draw our final conclusions.

When two quantities are multiplied the <u>percentage</u> uncertainty in the product is the sum of the <u>percentage</u> uncertainties in each of the factors. Thus, in our example,

$$m \times \bar{a} = 1.30 \text{ kg} \times 0.8 \frac{\text{cm}}{\text{sec}^2} = 1.04 \frac{\text{kg-m}}{\text{sec}^2}.$$

The percentage uncertainty in $\bar{a} = 0.8 \pm 0.2$ cm/sec^2 is 25% (since 0.2 is 25% of 0.8). The percentage uncertainty in m is 11.5%. Thus the percentage uncertainty in ma is 25% + 11% = 36% and we can write our product as

$$m\bar{a} = 1.04 \frac{\text{kg-m}}{\text{sec}^2} \pm 36\%$$

which is, to two significant figures,

$$m\bar{a} = 1.0 \pm 0.4 \frac{\text{kg-m}}{\text{sec}^2} \text{ (or newtons).}$$

In our example we found from direct measurement that $\bar{F}_{net} = 1.2 \pm 0.2$ N.

Are these the same quantity?

Although 1.0 does not equal 1.2, since the range of 1.0 ± 0.4 overlaps the range of 1.2 ± 0.2 we can say that "the two numbers agree within the range of uncertainty of measurement."

An example of lack of agreement would be 1.0 ± 0.2 and 1.4 ± 0.1. These cannot be the same quantity since there is no overlap.

In a similar way, work out your values of $\bar{F}_{net}$ and $m\bar{a}$.

Q4 Do they agree within the range of uncertainty of your measurement?

Q5 Is the relationship $F_{net} = ma$ an experimental fact? If not, what is it?

EXPERIMENT 9 Inertial and Gravitational Mass

Apparatus

Inertial balance, clamps, metal slug, wire, ring stand, cord, unknown mass, spring balance.

Procedure Notes

Weight is a measure of the gravitational force on an object. Mass is a measure of resistance of an object to changes in the state of motion, a measure of inertia.

The inertial balance is a simple device for measuring the inertial mass of different objects. The frequency of its horizontal vibration depends upon the inertial mass placed on the balance, since inertia is a resistance to any change of motion.

1. Measure the period of the balance alone by measuring the time for as many vibrations as you can conveniently count.

2. Select six identical objects of mass such as six C-clamps. Measure their period using first one, then two, then three, etc., of the clamps on the balance.

3. Measure the period of an unknown mass supplied by the instructor and record this result.

4. Calibrate the C-clamps by measuring their actual masses on a scale.

5. Discover whether or not gravity plays a part in the operation of the inertial balance. Load it with the iron slug. This can be done by inserting a wire through the center hole of the slug and letting the slug rest on the platform. Measure its period. Now lift the slug slightly so that it no longer rests upon the platform, support it from a ringstand and again measure the period.

Written Work

1. Plot the period, T, against the mass used in each case.

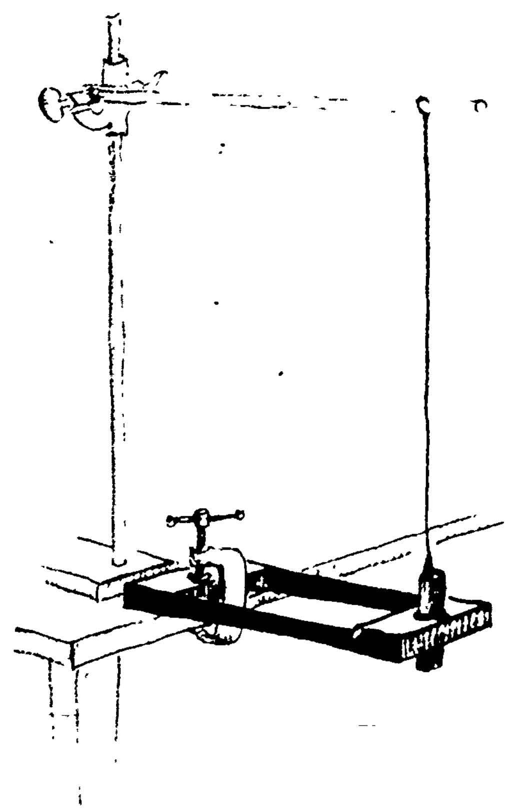
2. Arrange the data in orderly fashion.

3. Locate the value of the unknown mass on the prepared graph and compare with the actual measured value.

4. Compare the data obtained when the metal slug was supported by the platform and when it was free. Is inertia related to or dependent upon gravity?

5. Include a sketch of the apparatus.

6. Summarize briefly what you have learned from this exercise.

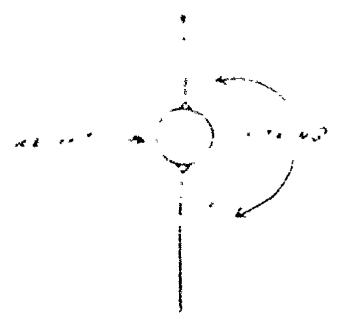


ACTIVITY 6 Newton's First Law

1. Place a fountain pen cap on a small piece of paper that protrudes beyond the edge of a table. Moisten a finger and [illegible] down hard on the paper. The paper will slide out leaving the cap still standing.

2. Stack several checkers. Put another checker on the table and snap it into the stack. Only the bottom checker in the stack will move.

3. One teacher suggests placing a glass beaker on top of a pile of three wooden blocks. Three quick back-and-forth swipes (NOT FOUR!) of a hammer leave the beaker sitting on the table.



4. Hang a weight by a string which just barely supports it, and tie another string below the weight. A slow steady pull of the string breaks it ABOVE the weight. A quick jerk breaks it BELOW the weight, because of the inertia of the weight.

ACTIVITY 7 Newton's Second Law

One way for you to get the feel of Newton's Second Law is actually to pull an object with a constant force. Load a cart with a mass. Attach one end of a long rubber band to the cart and stretch the other end around the end of a meter stick. Release the cart and move along with it so that the rubber band is maintained at a constant length—say 70 cm. The acceleration will be very apparent to the person applying the force. Vary the mass on the cart and the number of rubber bands, in parallel, to investigate the relationship between F, m and a.

ACTIVITY 8 Accelerometers

An accelerometer is a device that measures acceleration. Actually, everything that has mass is an accelerometer. Because you have mass, you were acting as an accelerometer the last time you lurched forward in the seat of your car as the brakes were applied. With a knowledge of Newton's laws and certain information about you, anybody could measure how far you leaned forward and how tense your muscles were to get a good idea of the magnitude and direction of the acceleration that you were undergoing. But it would be complicated.

Here are three accelerometers of a much simpler kind. With a little practice, you can learn to read accelerations

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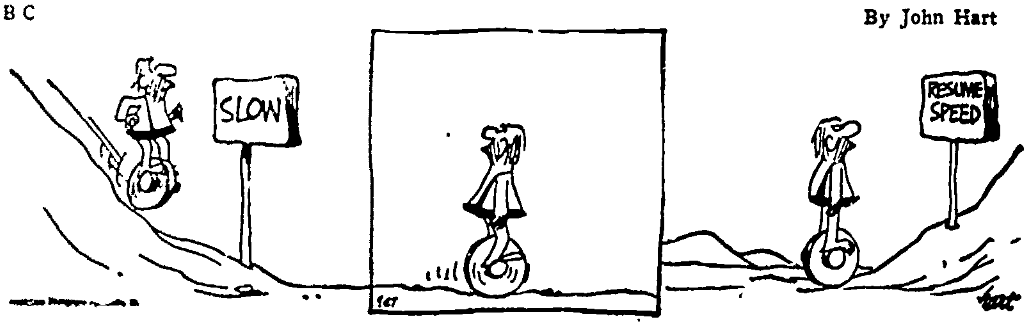


from them directly, without making any difficult measurements.

Liquid-surface accelerometer

This device is a hollow, flat plastic container partly filled with a colored liquid. When it is not being accelerated, the liquid surface is horizontal, as shown by the dotted line in Fig. 1. But when it is accelerated toward the left (as shown) with a uniform acceleration the surface becomes tilted, with the level

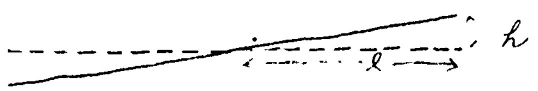


Fig. 1.

of the liquid rising a distance h above its normal position at one end of the accelerometer and falling the same distance at the other end. The more strongly the instrument is accelerated (that is, the larger a is), the more steeply the surface of the liquid is slanted. This means that the slope of the surface is a measure of the magnitude of the acceleration a.

The length of the accelerometer is 2ℓ. So the slope of the surface is

$$\text{slope} = \frac{\text{vertical distance}}{\text{horizontal distance}} = \frac{2h}{2\ell} = \frac{h}{\ell}.$$

Theory gives us a very simple relationship between this slope and the acceleration a:

$$\text{slope} = \frac{h}{\ell} = \frac{a}{a_g} \qquad (1)$$

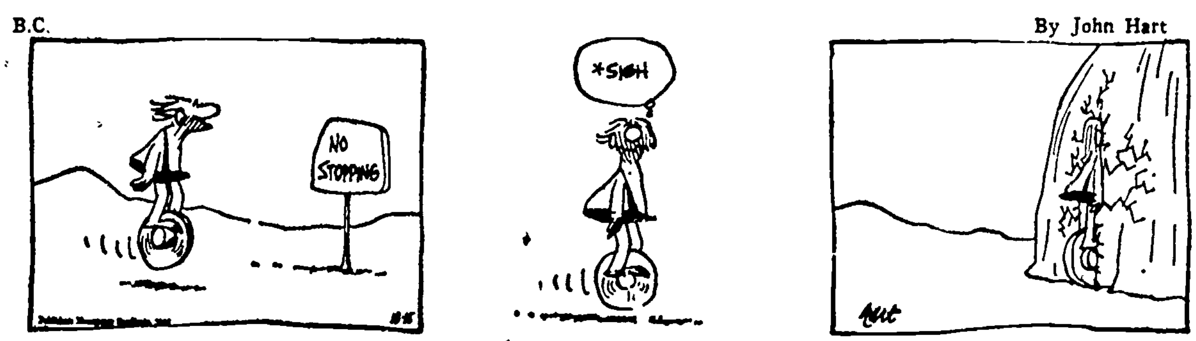
Notice what this equation tells us. It says that if the instrument is accelerating in the direction shown with just a_g (one common way to say this is that it has a "one-g acceleration"), the acceleration of gravity, then the slope of the surface is just 1; that is, $h = \ell$ and the surface makes a 45° angle with its normal, horizontal direction. If it is accelerating with half a g, then the slope will be $\frac{1}{2}$; that is, $h = \frac{1}{2}\ell$. In the same way, if $h = \frac{1}{4}\ell$, then $a = \frac{1}{4}a_g$, and so on with any size acceleration we care to measure.

To measure h, stick a piece of centimeter tape on the front surface of the accelerometer as shown in Fig. 2. Then stick a piece of white paper or tape to the back of the instrument, as shown; this makes it easier to read the level of the liquid.

Using the relation

$$a = \left(\frac{a_g}{\ell}\right)h \qquad (2)$$

which is the same as Eq. (1) above, you can convert your readings of directly



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into measurements of a. That is, since a_g is constant for any location, the proportionality factor $\frac{a_g}{\ell}$ is also a constant, once you have decided how long to make the length ℓ. You make this decision by choosing where to put the centimeter tape: the length ℓ is measured along the unaccelerated liquid surface from its center to the point at which it meets the measuring edge of the tape, as you see in Fig. 2. The accelerometer must be filled so that the unaccelerated surface crosses the scale just at the zero point.

With the scale attached, you can now read h in centimeters and convert it to values of a using Eq. (2). If your accelerometer is long enough (at least 20 cm), you can choose a particularly convenient value for ℓ so that the instrument will show accelerations directly in m/sec^2. Since a_g is very close to 9.8 m/sec^2 at the earth's surface, you can make the proportionality constant $\frac{a_g}{\ell}$ equal to one m/sec^2 per cm by simply choosing ℓ equal to 9.8 cm. That is, if you stick the centimeter tape just 9.8 cm from the center of the liquid surface, one cm on the scale is equivalent to an acceleration of one m/sec^2.

Calibration of the accelerometer

There is no reason to trust blindly the theory that we mentioned above; you can test it for yourself. Does the accelerometer really measure accelerations directly in m/sec^2? Stroboscopic methods give you an independent check on the correctness of the theoretical prediction.

Set the accelerometer on a dynamics cart and arrange strings, pulleys and masses as you did in Experiment 9 to give the cart a uniform acceleration on a long table top. Don't forget to put a block of wood at the end of the cart's path to stop it. Make sure that the accelerometer is fastened firmly enough so that it will not fly off the cart when it stops suddenly—we lose lots of accelerometers that way. Keep the string as long as possible, so that you use the entire length of the table.

Give the cart a wide range of accelerations by hanging different masses from the string. Use a stroboscope to record each motion. To measure the accelerations from your strobe records, plot t^2 against d, as you did in Experiment 5. (What relationship did Galileo discover between d/t^2 and the acceleration?) Or use the method of analysis you used in Experiment 8.

Compare your stroboscopic measurements with the readings on the accelerometer during each motion. It takes some cleverness to read the accelerometer accurately, particularly near the end of a high-acceleration run. One way is to station several students along the table and ask each to write down the reading as the cart goes by; use the average of these reports. If you are using a xenon strobe, of course, the readings on the accelerometer will be visible in the photograph; this is probably the most accurate method.

Plot the accelerometer readings against the stroboscopically-measured accelerations. This graph is called a "calibration curve." If the two methods agree perfectly, the graph will be a straight line through the origin at a 45° angle to each axis. If your curve turns out to have some other shape, you can use it to convert "accelerometer readings" to "accelerations"—if you are willing to assume that your strobe measurements are more accurate than the accelerometer. (If not, what can you do?)

Automobile accelerometer

You can measure the acceleration of your car with a liquid-surface accelerometer. It must be mounted, of course, so that the length ℓ is parallel to the car's motion.

Here is a modification of the previous design that you can build for yourself. Bend a small glass tube into a U shape, as shown in Fig. 3.

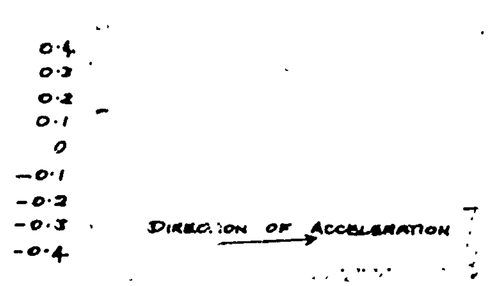

Fig. 3.

Calibration is easiest if you make the long horizontal section of the tube just 10 cm long, in which case each 5 mm on a vertical arm represents an acceleration of 1/10 g = (about) 1 m/sec^2, by the same reasoning as before. The two vertical arms should be at least three-fourths as long as the horizontal arm (to avoid splashing out the liquid during a panic stop). Attach a scale to one of the vertical arms, as shown. Pour colored water into the tube until the water level in the arm comes up to the zero-g mark (with the long arm held horizontally).

To mount your accelerometer in your car, fasten the tube with staples (carefully) to a piece of plywood or cardboard a little bigger than the U-tube. To reduce the hazard from broken glass, cover all but the scale (and the arm by it) with cloth or cardboard, leaving both ends open. Attach the board firmly to the door by the driver's seat, or to some more convenient place. (Careful, though: don't make it so convenient that you would get an eyeful of glass in case of an accident.)

Maximum positive acceleration in an XKE is around 0.3 g, although greater acceleration can be attained during braking.

Damped-pendulum accelerometer

One advantage of liquid-surface accelerometers is that it is easy to put a scale on them and read accelerations directly from the instrument. They have a drawback, though: they give only the component of acceleration that is parallel to their horizontal side. If you accelerate one at right angles to its axis, it doesn't register any acceleration at all. And if you don't know the direction of the acceleration, you have to use trial-and-error methods to find it with the accelerometers we have discussed so far.

A damped-pendulum accelerometer, on the other hand, indicates the direction of any horizontal acceleration; it also gives the magnitude, although less directly than the previous instruments do.

Hang a small metal pendulum bob by a short string fastened to the middle of the lid of a one-quart mason jar, as shown in Fig. 4. Fill the jar with water and screw the lid on tight.

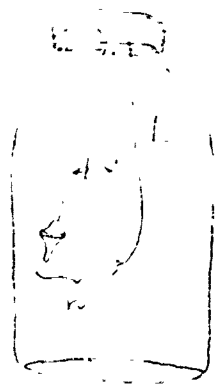

Fig. 4.

Q1 For any position of the pendulum, the angle b that you see depends on your position. What would you see, for example, if the bottle were accelerating straight toward you? Away from you? Along a table with you standing at the side? (Careful: this last question is trickier than it looks.)

Cork-in-bottle accelerometer

Here is a fascinating variation on the damped-pendulum accelerometer. To make it, simply replace the pendulum bob with a cork and turn the bottle upside down, as shown in Fig. 5. If you have punched a hole in the bottle lid to fasten the string, you can avoid leakage with sealing wax, paraffin or tape.

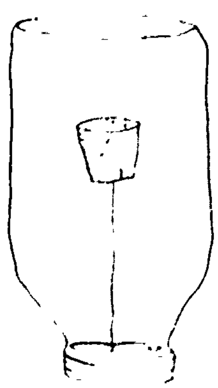

Fig. 5.

This accelerometer will do just the opposite from what you would expect: the cork will lean in the direction of the acceleration, not the other way, as the bob did. The explanation of this odd behavior is a little beyond the scope of the course: it is thoroughly explained in The Physics Teacher, vol. 2, no. 4, (April, 1964), p. 176.

Candle-flame accelerometer

Make another accelerometer by mounting a candle in the bottom of a glass jar. It will take some cleverness to arrange the candle so that it gets enough air to burn but is well shielded from drafts. This engineering problem is left for you to solve; it has been done before.

Q2 How does the candle flame react to an acceleration?

EXPERIMENT 10 Trajectories — I

When a ball rolls off a table top, we know it will eventually hit the floor and that before it does it will travel some distance horizontally. There are a number of paths it might follow in doing this.

In this experiment your problem is to find out just what path the ball does travel. You will probably then be able to find a mathematical description with which you can make useful and accurate predictions.

How to use the equipment

If you are setting up the equipment for the first time follow the manufacturer's instructions for assembling it.

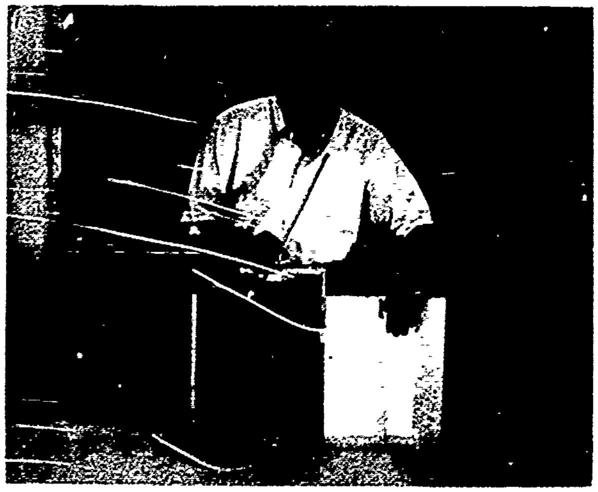

Fig. 1.

The apparatus (Fig. 1) consists of one or two ramps down which you can roll a steel ball. Adjust one of the ramps (perhaps with the help of a level) so that the ball leaves it horizontally. Set the vertical impact board on the plotting board so that a ball launched from the ramp will hit it.

Attach a piece of carbon paper to the side of the impact board facing the end of the ramp, with the carbon side facing the ramp. Then tape a piece of translucent onion skin paper over the carbon paper.

Tape a larger piece of paper, preferably squared graph paper, to the plotting board with its left-hand edge behind the end of the launching ramp.

Release the ball from various points on the ramp until you find one from which the ball falls close to the bottom right-hand corner of the plotting board. Mark the point of release on the ramp. Now when you put the impact board in its way, the ball hits it and leaves a mark, recording the point of impact between ball and board, that you can see through the onion skin paper. (Make sure that the impact board doesn't move when the ball hits it; steady it with your hand if necessary.) Transfer the point to the plotting board by making a mark on it just next to the point on the impact board.

Repeat this for other positions of the impact board to record more points on the ball's path. Move the board back equal distances every time and always release the ball from the same spot on the ramp. Continue until the ball does not hit the impact board any longer.

To release the ball do not hold it in your fingers—it is impossible to let go of it in the same way every time. Instead dam it up with a ruler held at a mark on the ramp and release the ball by lifting the ruler quickly.

Try releasing the ball several times (always from the same point) for the same setting of the impact board. Do all the impact points exactly coincide?

Now remove the impact board, release the ball once more and watch carefully to see that it moves along the points marked on the plotting board.

By observing the path the ball follows you have completed the first goal of the experiment.

The curve traced out by your plotted points is called the trajectory of the ball.

You may want to stop here, though you will find it useful to go further and explore some of the properties of your trajectory.

Analyzing your data

To help you analyze the trajectory, draw a horizontal line on the paper at the level of the lip of the launching ramp. Then remove the paper from the plotting board and draw a smooth continuous curve through the points.

If it is true that an object moves equal distances in equal times when no net force acts on it, then you can assume that the ball will move horizontally at constant speed.

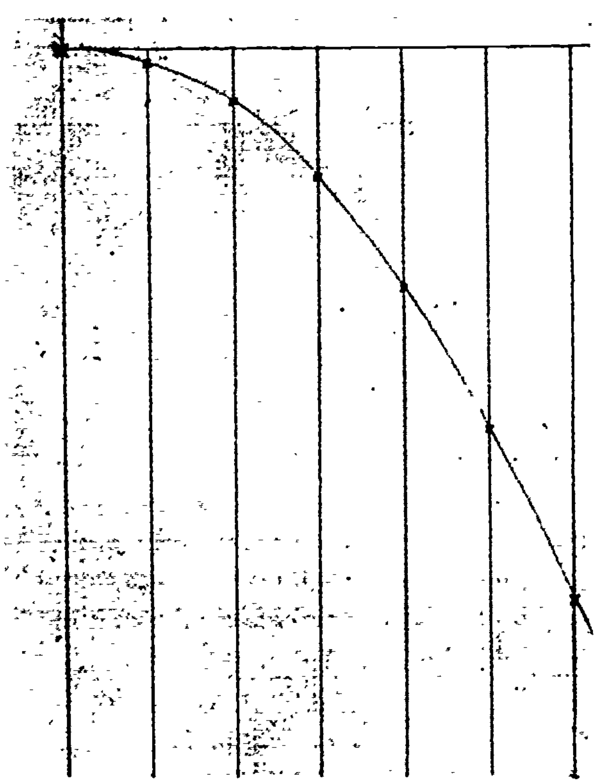

Fig. 2.

Draw vertical lines through the points on your graph (Fig. 2). Make the first line coincide with the lip of the launching ramp. Because of your plotting procedure these lines should be equally spaced. If the horizontal speed of the ball is uniform, these vertical lines are drawn through positions of the ball separated by equal time intervals. This means that the ball travels across the first measured space and reaches the second vertical line one unit of time after leaving the ramp; it reaches the third line after two time units, the fourth after three, and so on.

Now consider the vertical distances fallen in each time interval. Measure down from your horizontal line the vertical fall to each of your plotted points. Record your measurements in a column and alongside them in a parallel column record the corresponding horizontal distance measured from the first vertical line.

Q1 What would a graph look like on which you plot horizontal distance against time?

Earlier in your work with accelerated motion you learned how to recognize uniform acceleration (see Secs. 2.5-2.8 in the text and Experiment 5). Use the data you have just collected to decide whether the vertical motion of the ball was uniformly accelerated motion.

Q2 What do you find?

Q3 Do the horizontal and the vertical motions affect each other in any way?

Write the equation that describes the horizontal motion in terms of horizontal velocity, v_h, the horizontal distance, d_h, and the time of travel, t.

Q4 What is the equation that describes the vertical motion in terms of the distance fallen vertically, d_v, the vertical acceleration, a_g, and the time of travel, t?

Testing your model

A good test of such a model is to use it to make predictions which can be checked experimentally. Suppose you put the ramp near the edge of a table so that the ball would land on the floor. Could you predict for a given release point where it would land?

Here is one way you can do this; you may be able to think of others.

There will be some factors in the two equations for the ball's motion that you do not know (the times, the ball's initial horizontal speed). But you can combine the equations to get rid of these unknowns, and use just the vertical and horizontal distances that you measure on your plot. Then for the new vertical distance (height of the launch point above the floor) you can predict the horizontal distance that the ball will travel. Put down a sheet of paper at this point and mark your predicted spot. Before you test your prediction try to estimate how close to your mark you think the ball will actually land.

Extensions

There are many other things you can do with this apparatus. Here are some of them.

Q5 What do you expect would happen if you repeated the experiment with a glass marble of the same size instead of a steel ball? Try it!

Q6 What will happen if you next try to repeat the experiment starting the ball from a different point on the ramp?

Q7 What do you expect if you use a smaller or a larger ball starting always from the same reference point on the ramp?

Q8 Plot the trajectory that results when you use a ramp that launches the ball at an angle to the horizontal.

Q9 In what way is this curve similar to your first trajectory?

Q10 Find a_g from this experiment using a procedure similar to that described on page 5.

Q11 What other changes in the conditions of this experiment can you suggest? Consult your teacher before testing them.

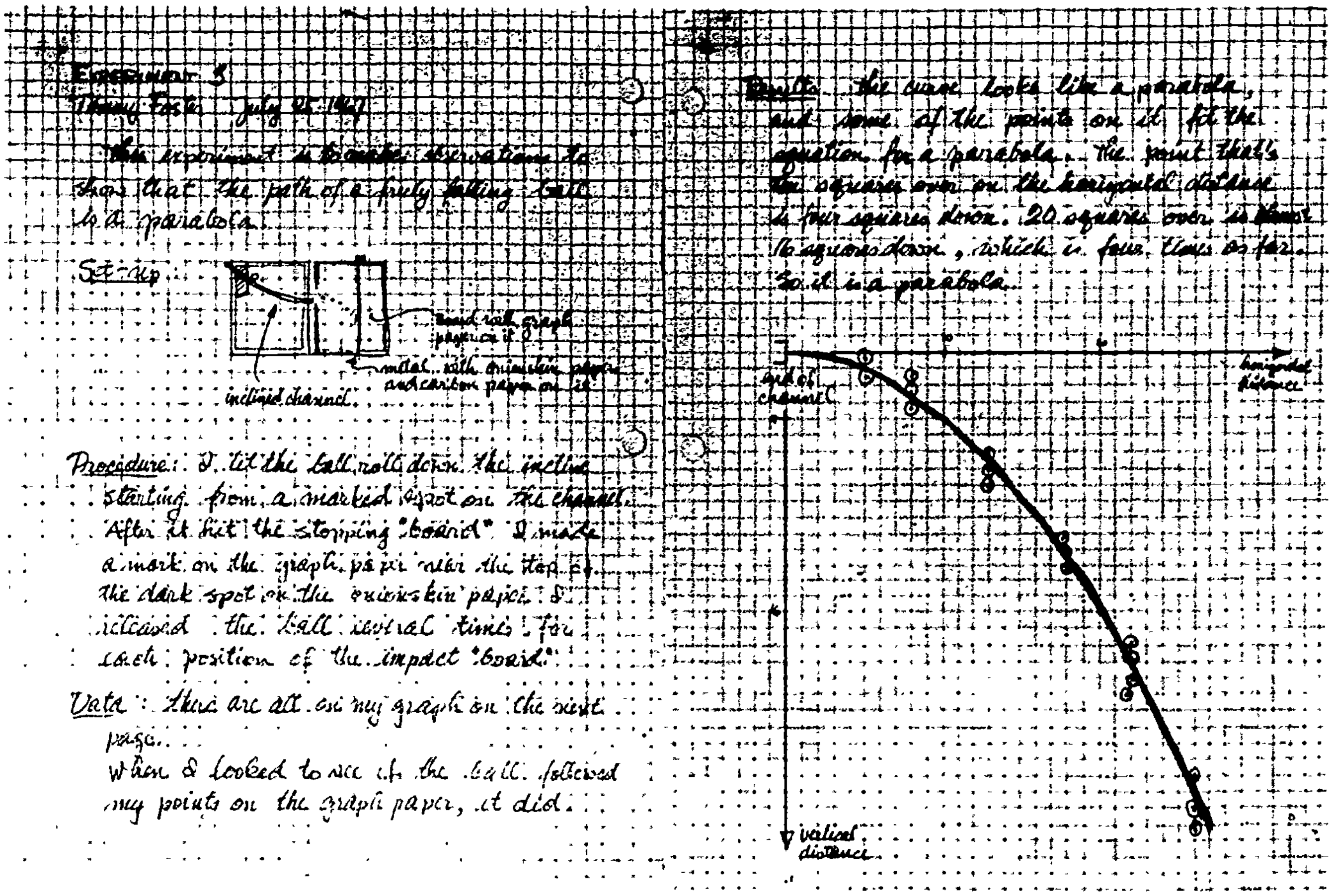

Fig. 3. Here is another example of a student laboratory report

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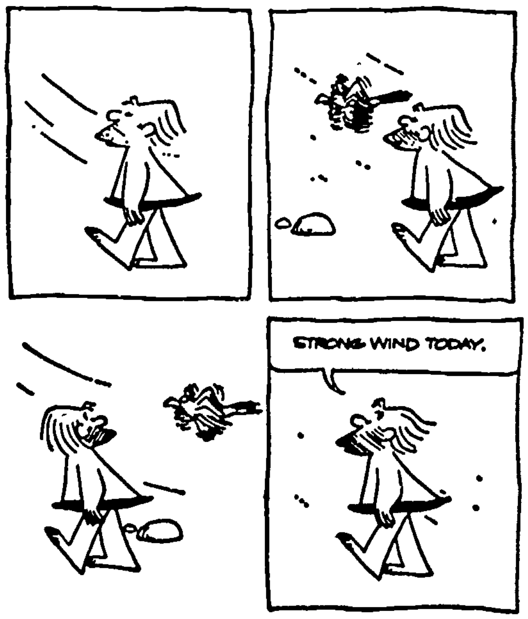

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EXPERIMENT 11 Trajectories — II

This experiment tests the equation for projectile motion by using it to predict the landing point of a ball launched horizontally from a table top. You will determine the speed, v_0, of the ball as it leaves the table and, knowing the height of the table above the floor and a_g, you will use the equation to predict where on the floor the ball will land.

The equation is based on certain assumptions. If it correctly predicts the landing point, then the assumptions are evidently valid.

The assumptions

If the ball continues to move horizontally with velocity v_0 (Assumption 1), the horizontal distance x at time t from launch will be given by the equation

$$x = v_0 t \qquad (1)$$

where v_0 is the horizontal velocity at launch.

Similarly, if the ball moves vertically with uniform acceleration (Assumption 2), the vertical distance fallen at time t will be given by this equation.

$$y = \tfrac{1}{2} a_g t^2 \qquad (2)$$

Solving equation (1) for t,

$$t = \frac{x}{v_0} . \qquad (3)$$

Substituting this into equation (2), we have

$$y = \tfrac{1}{2} a_g \left[\frac{x}{v_0}\right]^2 = \frac{a_g x^2}{2 v_0{}^2} . \qquad (4)$$

This is the equation to test, by using it to predict the value of x where the ball strikes the floor. Solving equation (4) for x, we have

$$x^2 = \frac{2 v_0{}^2 y}{a_g}$$

or,

$$x = \sqrt{\frac{2 v_0{}^2 y}{a_g}} = v_0 \sqrt{\frac{2y}{a_g}} .$$

From this last equation we can predict x if we know v_0, y and a_g.

The experiment

You can determine v_0 by measuring the time t that the ball takes to roll a distance ℓ along the table top (Fig. 1). Repeat the measurement a few times, always releasing the ball from the same place on the ramp, and take the average value of v_0.

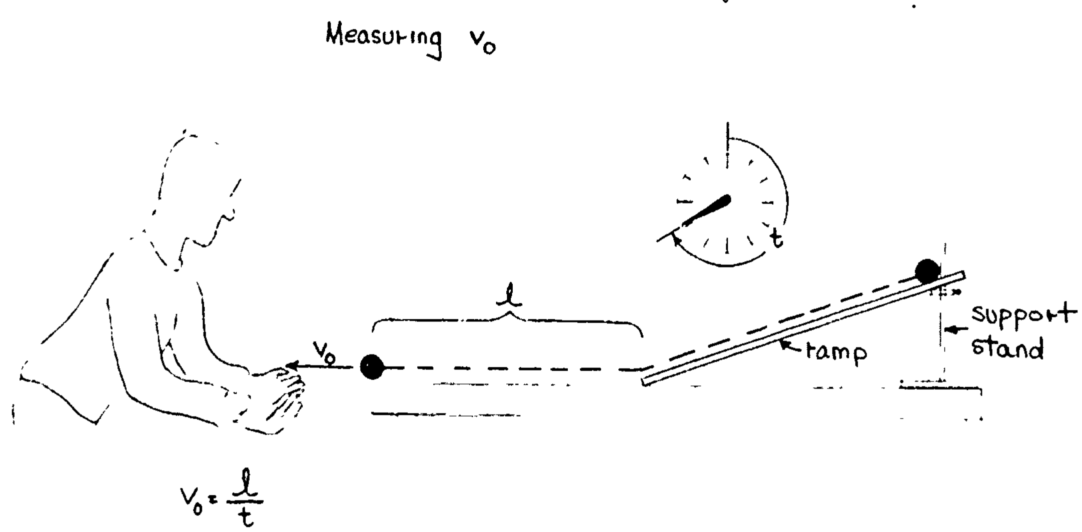

Fig. 1.

Measure y and calculate x. Place a target on the floor at your predicted landing spot. How confident are you of your prediction? Since it is based on measurement there is some uncertainty involved. Mark any area round the spot to indicate the uncertainty.

Now release the ball once more, and this time let it roll off the table and land on the floor (Fig. 2).

If the ball actually does fall within the range of values of x you have estimated, then you have verified the assumptions on which your calculation was based.

Q1 How could you determine the range of a ball launched horizontally by a sling shot if you knew the velocity?

Q2 Assume you can throw a baseball 100 meters on the earth's surface. How far could you throw that same ball on the surface of the moon, where the acceleration of gravity is one-sixth what it is at the surface of the earth?

Q3 Will the assumptions made in equations (1) and (2) hold for a ping-pong ball? If the table was 1,000 meters above the floor, could you still use equations (1) and (2)? Why or why not?

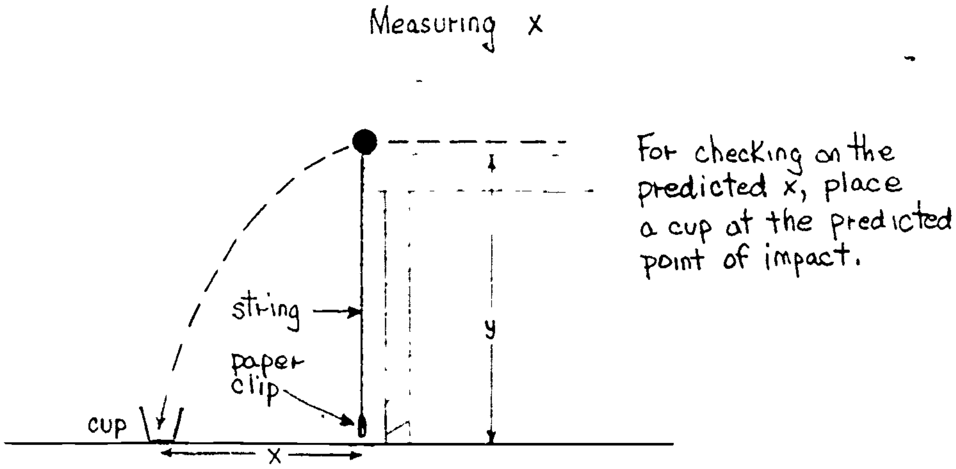

Fig. 2.

EXPERIMENT 12 Circular Motion—I

You may have had the experience of spinning around on an amusement park contraption known as the Whirling Platter. The riders seat themselves at various places on a large flat polished wooden turntable about 40 feet in diameter. The turntable gradually rotates faster and faster until everyone (except for the person in the center of the table) has slid off. The people at the edge are the first to go.

Q1 Why do the people fall off?

Study Sec. 4.6, where you learn that the centripetal force needed to hold a rider in a circular path is given by

$$F = mv^2/R.$$

Friction on a spinning table

On the rotating table the centripetal force is provided by friction. Friction is the centripetal force. On a frictionless table there could be no such centripetal force and everyone except a rider at the center would slide off right at the start.

Near the outer edge where the riders have the greatest velocity v the friction force F needed to hold them in a circular path is large. (The effect of R in the denominator also being large is more than cancelled out by the fact that v is squared in the numerator.)

Near the center where v is nearly zero very little friction force is needed.

Q2 Where should a rider sit on a frictionless table to avoid sliding off? Use the formula above to justify your answer.

Evidently, if you know the force needed to start a rider sliding across a motionless table top (the force of friction), you know the value of the centripetal force, mv^2/R, at which the rider would begin to slip when the table is rotating.

Fig. 1.

Studying centripetal force

Unfortunately you probably do not have a Whirling Platter in your classroom, but you do have a masonite disc which fits on a turntable. The object of this experiment is to predict the maximum radius at which a mass can be placed on the rotating turntable without sliding off.

If you do this under a variety of conditions, you will see for yourself how forces act in circular motion.

For these experiments it is more convenient to write the formula $F = mv^2/R$ in terms of the period T of the table instead of the value of v and R at some point on it. This is because it is easier to measure T and R than to measure v. We rewrite the formula as follows:

$$v = \frac{\text{distance travelled by a rider in one revolution}}{\text{time for one revolution}}$$

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

Substitute this into the expression for centripetal force

$$F = \frac{mv^2}{R} = \frac{m}{R} \times \frac{4\pi^2R^2}{T^2} = \frac{4\pi^2 mR}{T^2}$$

Then solve it for R.

$$R = \frac{FT^2}{4\pi^2 m}$$

You can measure all the quantities in this equation.

Your task is to predict the radius, R, at which a weight can be placed on the rotating table so that it will just barely remain and not slip.

Use a spring scale to measure the force, F, needed to make a mass, m, of 0.20 to 1.00 kg start to slide across the motionless disc (Fig. 1).

Then make a chalk mark on the table and time it for 100 revolutions to calculate T, the time for one revolution (or accept the given values of turntable frequency). Remember that T, the period, is 1/frequency.

Make your predictions of R for turntable frequencies of 33 rpm, 45 rpm and 78 rpm.

Then try it!

Q3 How great is the percentage difference between prediction and experiment in each case? Do you think this is reasonable agreement?

Q4 What effect would decreasing the mass have on the predicted value of R? Careful! Decreasing the mass has an effect on F also. Check your answer by doing an experiment.

Q5 What is the smallest radius you can turn a car in if you are moving 60 miles an hour and the friction force between tires and road is one third the weight of the car?

Q6 What happens to the period of an earth satellite as it falls into a lower orbit?

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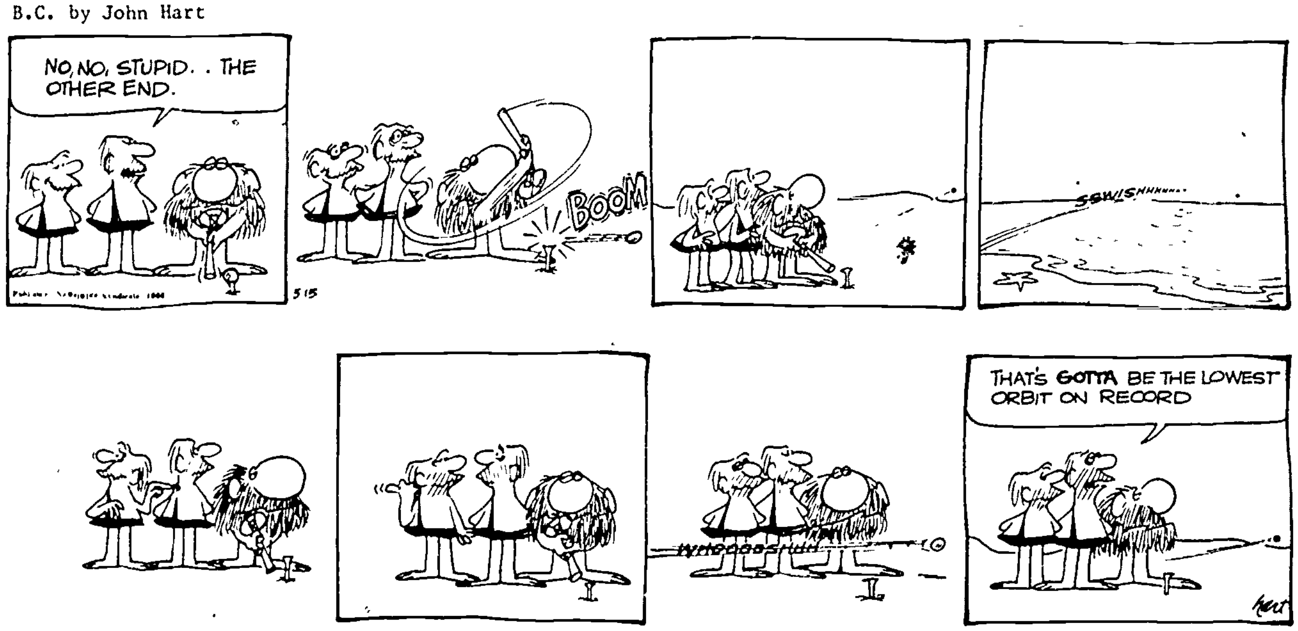
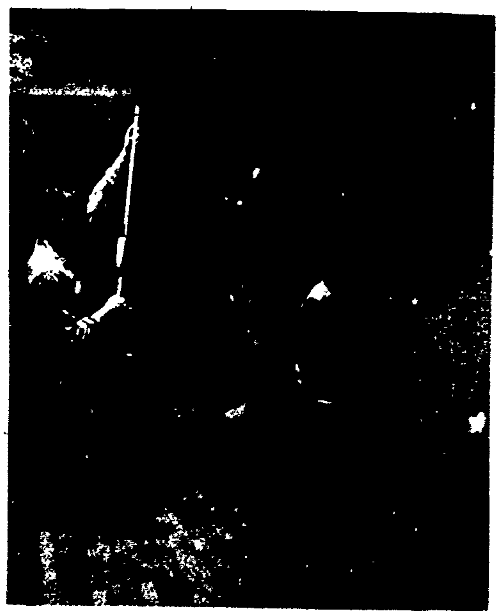


EXPERIMENT 13 Circular Motion — II

An earth satellite and a weight swung around your head on the end of a string are controlled by the same laws of motion. Both are accelerating toward the center of their orbit due to the action of an unbalanced force.

In the following experiment you discover for yourself how this centripetal force depends on the mass of the satellite and on its speed and distance from the center.



How the apparatus works

Your "satellite" is one or more rubber stoppers. When you hold the apparatus (Fig. 1) in both hands and swing the stopper around your head you can measure the centripetal force on it with a spring scale at the base of the stick. The scale should read in newtons or else its readings should be converted. Remember 1 N = the weight of 102 gms weight or 1 kg weight = 9.8 N.

You can change the length of the string so as to vary the radius, R, of the circular orbit, and you can tie on more stoppers to vary the satellite mass, m.

The best way to time the period, T, is to swing the apparatus in time with some periodic sound such as the tick of a metronome or have an assistant count out loud using a watch. You keep the rate constant by adjusting the swinging until you see the stopper cross the same point in the room at every tick.

Hold the stick vertically and have as little motion at the top as possible, since this would change the radius. Since the stretch of the spring scale also alters the radius it is helpful to move the scale up or down slightly to compensate for this.

Doing the experiment

The object of the experiment is to find out how the force read on the spring scale varies with m, with v and with R.

You should only change <u>one</u> of these three quantities at a time so that the effect of each one can be investigated independently of the others. It's easiest to either double or triple m, v and R (or halve them, etc. if you started with large values).

Two or three different values should be enough in each case. Make a table and record your numbers in it clearly.

Q1 How do changes in m affect F if R is kept constant? Write a formula that states this relationship.

Q2 How do changes in v affect F if m is kept constant? Write a formula to express this too.

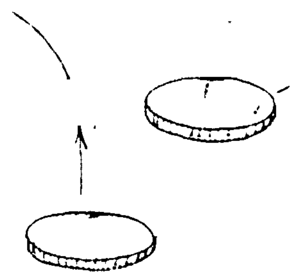
Q3 Measure the effect of R and express it in a formula.

Q4 Can you put m, v and R all together in a single formula for centripetal force, F?

<u>After</u> you have committed yourself, check your formula by studying text Sec. 4.6.

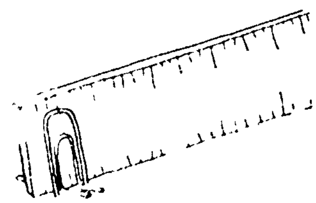
ACTIVITY 9 Projectile Motion Demonstrations

Here are three ways you can demonstrate projectile motion like that shown in [illegible] of your text.

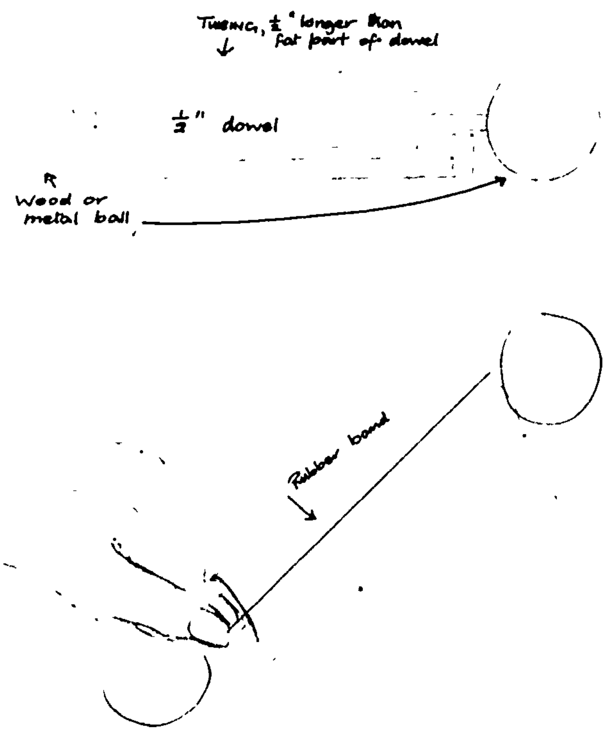


Method 1. Place one coin near the edge of a table. Place an identical coin on the table and snap it with your finger so that it flies off the table, just touching the first coin enough that it falls almost straight down from the edge of the table. The fact that you hear only a single ring as both coins hit shows that both coins took the same time to fall to the floor from the table. Incidentally, do the coins HAVE to be identical? Try different ones.

Method 2. Fasten two bent paper clips to a ruler, one on each side, and cut off the end of each clip. Clamp or hold the ruler in a horizontal position, for example, against the edge of a table. Place a small steel ball (about 3/8" diameter) in each holder. Give the ruler a sharp horizontal tap. One ball will fly off with a horizontal velocity, while the other will fall straight down (if you practice).



Method 3. If you want a more mechanical or instantaneous release mechanism, you can build the device at the right. There are commercial versions available, also. Cut a piece of 1/2" wooden dowel about 4" long. Cut or whittle both ends so one has a [illegible] diameter projection about 3/8" long, and the other 3/4" long. Cut a piece of metal or wood tubing 1/2" longer than the fat part of the dowel. Then take two wooden or metal balls, about 1" in diameter, and drill one hole halfway through each, so they will fit loosely on the ends of the wooden dowels. You will need to put a wooden stop over one end of the tube to stop the dowel so it does not fly out of the tube. Place a rubber band over the end of the dowel and the



stop end of the tube. Place the two balls on the ends of the dowel. Pull the dowel back and release. The dowel pulls out of one ball, letting it fall straight down. At the same instant the other ball flys off with a horizontal velocity.

ACTIVITY 10 Speed of a Stream of Water

Use the principles of projectile motion to calculate the speed of a stream of water issuing from a horizontal nozzle. Measure the vertical distance, d_y, from the nozzle to the ground and the horizontal distance, d_x, from the nozzle to the point where the water hits the ground. The initial horizontal speed can then be computed from the equation:

$$d_y = \frac{1}{2} a_g t^2$$

$$d_x = v_x t$$

$$d_y = \frac{1}{2} a_g \frac{d_x^2}{v_x^2}$$

$$v_x^2 = \frac{1}{2} a_g \frac{d_x^2}{d_y}$$

$$v_x = \frac{a_g}{2d_y} .$$

ACTIVITY 11 Photographing Projectile Motion

Method I Waterdrop Parabola

Using a Xenon strobe, doorbell timer, and water from a faucet, you can photograph a waterdrop parabola. The superposition principle and independence of vertical and horizontal motions are clearly evident.

Remove the wooden block from the timer. Place a piece of wood and the hose through which the water runs under the striker. (A doorbell without the bell could also be used. See Fig. 1.) To get more striking power, run the vibrator with a Variac connected to the 110 volt ac, gradually increasing the Variac from zero just to the place where the striker vibrates against the tubing at 60 cycles/sec. Adjust the water flow through the hose and glass dropper. By viewing the drops with the Xenon strobe set at 60 cycles/sec, a parabola of fixed individual drops is seen. Best Polaroid photos are made by lighting the parabola from the side (light in the plane of the parabola). With front lighting, the parabola can be projected onto paper for more precise measurement. Some heating of the coil does result, so the striker should not be run continuously for long periods of time.

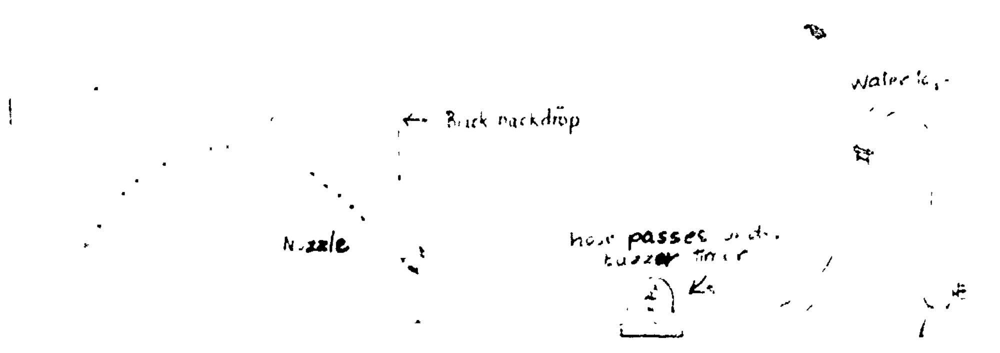


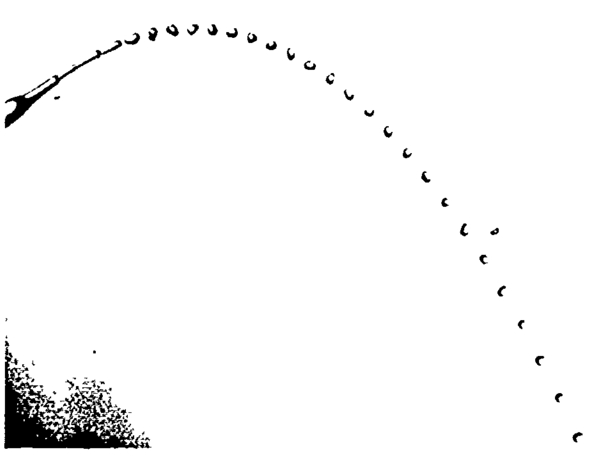
Fig 1.

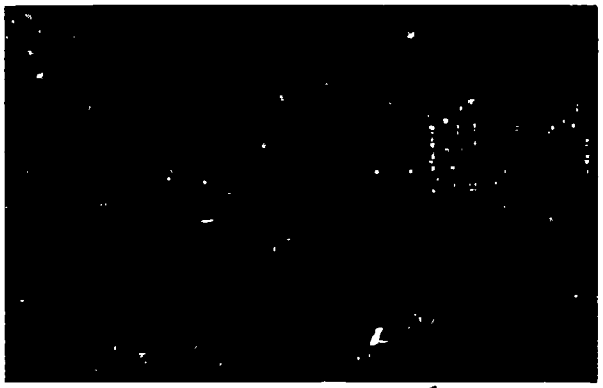
Method II

Fire a projectile straight up in the air from a cart which is rolling across the floor with nearly uniform velocity. You can use a commercial device called a ballistic cart or make one yourself. A spring-loaded piston fires a ball bearing when you pull a string attached to a locking pin. Use the electronic strobe to photograph the path of the ball bearing.

Method III

If you are fortunate enough to have a camera at hand when your community has a fireworks display, try a time exposure of the display. If you use a tripod and cable release, you may be able to get several bursts on the same film.



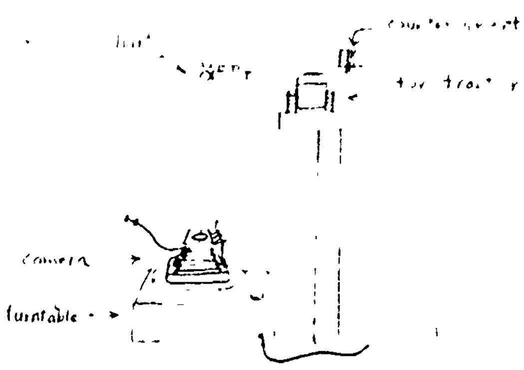


Motion in a Rotating Reference Frame

Here are two ways you can show how a moving object would appear in a rotating reference frame.

Method I

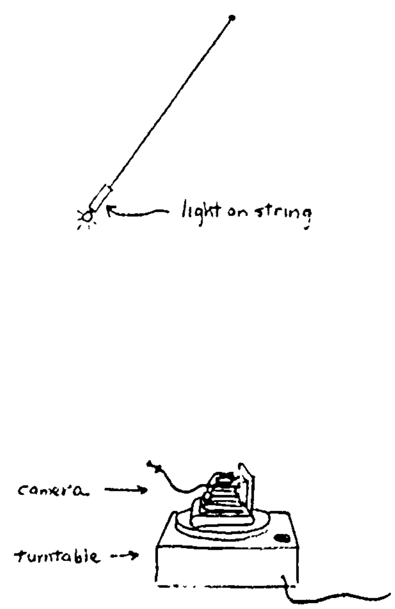
Place a Polaroid camera on the turntable on the floor and let a tractor run along the edge of a table, with a flashlight bulb on a pencil taped to the tractor so that it sticks out over the edge of the table.



Method II

How would an elliptical path appear if you were to view it from a rotating reference system? You can find out by placing a Polaroid camera on a turntable on the floor, with the camera aimed upwards. Hang a flashlight bulb and AA cell as a pendulum. Make the pendulum long enough that the light is about 4 feet from the camera lens.

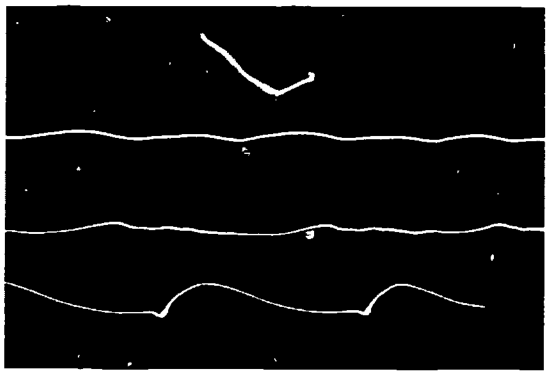
With the lights out, give the pendulum a swing so that it swings in an elliptical path. Hold the shutter open while the turntable makes one revolution. You can get an indication of how fast the pendulum appears to be moving at different locations by using a motor strobe in front of the camera.

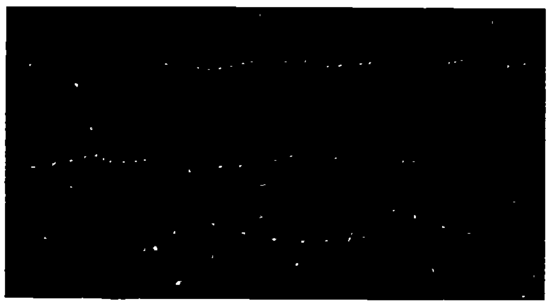


ACTIVITY 13 Photographic Analysis of Walking

Tape a penlight bulb and battery to your hip, knee and ankle and walk in front of a camera in a darkened room. Try first a simple time exposure, then try again with the motor strobe in front of the lens. What information can you get from the second picture which is lacking in the first?

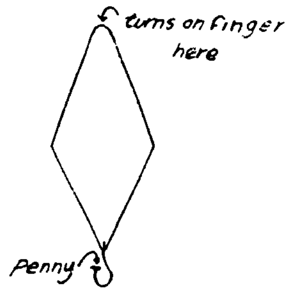
For examples of this kind of study, see "The Antiquity of Walking" in Scientific American, April 1967.





ACTIVITY 14 Penny and Coat Hanger

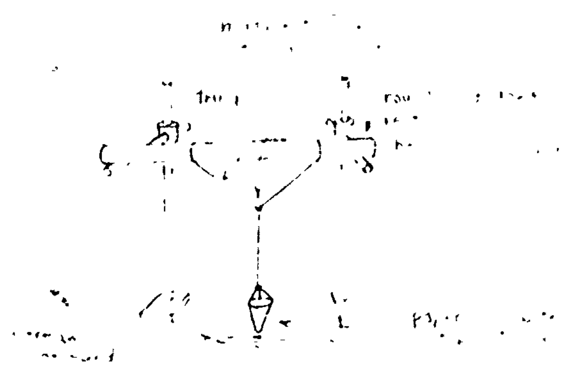
1. Bend a coat hanger into the shape shown in the diagram. Bend the end of the hook somewhat so that it points to where the finger supports the hanger. File the end of the hook flat. Balance a penny on the hook. Move your finger back and forth so that the hanger (and balanced penny) starts swinging like a pendulum. Much practice will enable you



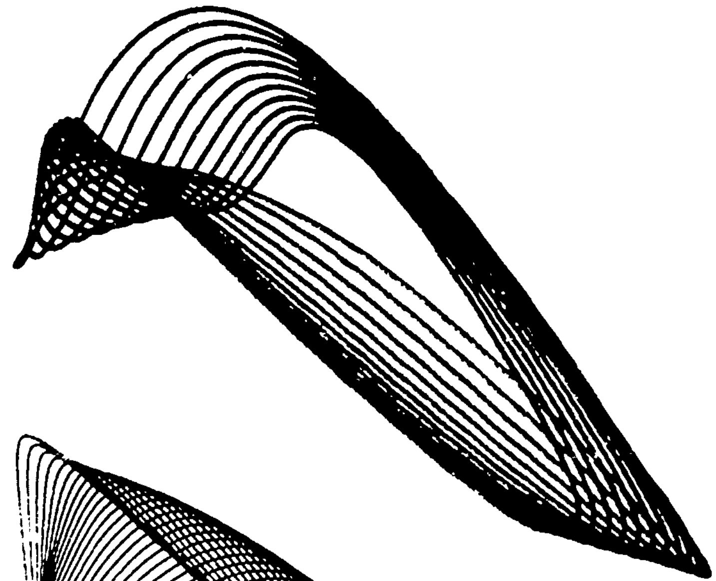
to swing the hanger in a vertical circle, or around your head, still keeping the penny on the hook. The centripetal force of the hanger keeps the penny from flying off on the straight line path it would like to follow. Some people have done this demonstration with a pile of five pennies at once.

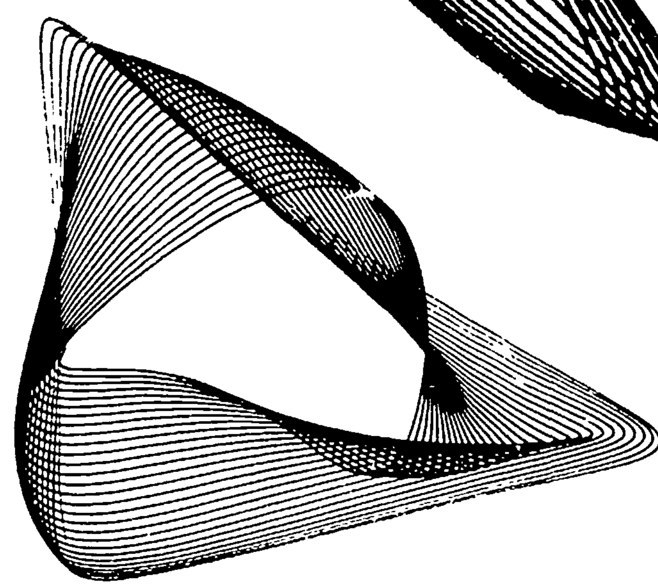
ACTIVITY 15 Harmonograms

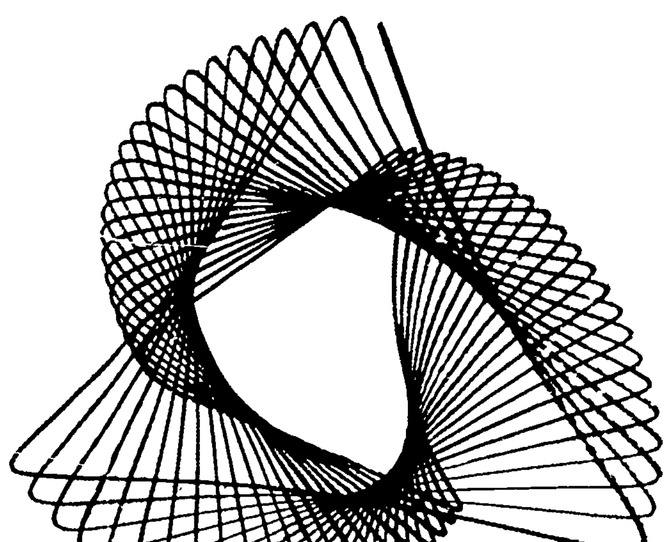
You can make fascinating patterns like the ones shown on this page by constructing a device called a harmonograph. Several ways this can be done are described in Scientific American, May, 1965. One of the simple methods is shown in the drawing below and described in the article. It is called a sand pendulum. You can assemble one quickly in the laboratory with standard ring stands and clamps. You can substitute granulated sugar or salt for sand if necessary.

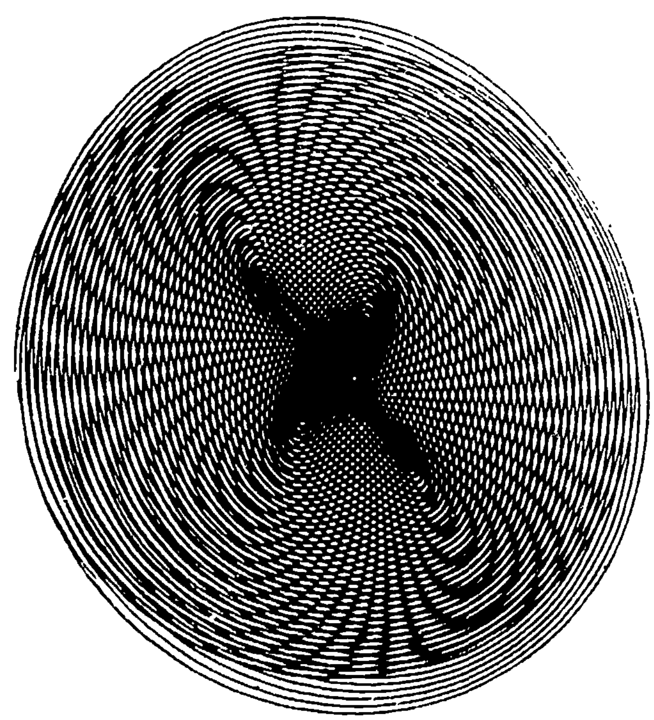


Simple sand harmonograph









Film Loop 1 Acceleration Due To Gravity — Method I

A bowling ball in free fall was filmed in slow motion. The film was exposed at 3900 frames/sec, and is projected at about 18 frames/sec. The slow-motion factor is therefore 3900/18, or about 217. Your projector may not run at exactly 18 frames/sec, so for best results you should calibrate it by timing the length of the entire loop, which contains 3273 frames between punch marks. To find the acceleration of the falling body we need the instantaneous speed at two times; then we can use the definition

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time interval}}.$$

We cannot measure instantaneous speed directly, but we can get around this by measuring the average speed during an interval. Suppose the speed increases steadily, as it does for a freely falling body. During the first half of any interval the speed is less than average, and during the second half of the interval the speed is greater than average. Therefore, for uniformly accelerated motion the average speed $\bar{v}$ equals the instantaneous speed at the midtime of the interval. We use this fact to find the values of instantaneous speed at the midtimes of each of two intervals. Then we can calculate the acceleration from

$$a = \frac{\bar{v}_2 - \bar{v}_1}{t_2 - t_1}$$

where $\bar{v}_1$ and $\bar{v}_2$ are the average speeds during the first and second intervals, and t_1 and t_2 are the midtimes of these intervals.

Two intervals 0.50 meter in length are indicated in the film. The ball falls 1 meter before the start of the first marked interval, so it has some initial speed as it crosses the first line. Use an ordinary watch (with a sweep second hand) to time the ball's

motion and record the times (by the watch) of crossing each of the four lines. From these times you can find the time (in apparent seconds) between the midtimes of the two intervals, and the times for the ball to move through each ½-meter interval. Repeat the measurements at least once, and find the average times. Now you can use the slow-motion factor to convert these times to real seconds, and then calculate the two values of $\bar{v}$. Finally, calculate the acceleration.

The film was made at Montréal, Canada. The value of the acceleration due to gravity there is, to 3 significant figures, 9.81 m/sec^2. When rounded off to ±1%, this becomes 9.8 m/sec^2. Try to decide from the internal consistency of your data (the repeatability of your time measurements) how precisely you should write your result.

Film Loop 2 Acceleration Due To Gravity — Method II

A bowling ball in free fall was filmed in slow motion. The film was exposed at 3415 frames/sec, and is projected at about 18 frames/sec. For best results, you should calibrate your projector by timing the length of the entire film, which contains 3695 frames between punch marks.

If the ball starts from rest and acquires a speed v after falling through a distance d, the average speed is $\bar{v} = \frac{0 + v}{2} = \frac{1}{2}v$, and the time to fall this distance is given by $t = \frac{d}{\bar{v}} = \frac{d}{\frac{1}{2}v} = \frac{2d}{v}$. The acceleration is given by

$$\text{acceleration} = \frac{\text{change of speed}}{\text{time interval}}$$

from which

$$a = \frac{v}{2d/v} \text{ or } a = v^2/2d.$$

Thus to measure the acceleration we need to know the instantaneous speed v of the falling body at a known distance d below the starting point. All we can measure, of course, is an average speed over some small interval. In the film, small intervals of 20 cm are centered on positions 1 m, 2 m, 3 m and 4 m below the starting point. We make the approximation that the average speed is the instantaneous speed at the midpoint of the interval. Actually, the average speed is the instantaneous speed at the mid*time*, not the mid*point*; but the error is negligible in our work because we are using such a short interval.

Determine the four average speeds by timing the ball's motion across the 20-cm intervals. Repeat each measurement several times to average out errors of measurement. Convert your measured times into real times, using the slow-motion factor. Compute the speeds, in m/sec, and then compute the value of $v^2/2d$ for each value of d.

To analyze your results, make a table of calculated values of a, listing them in the order of increasing values of d. Is there any evidence for a systematic trend in the values? State the result of your experiment by giving an average value of the acceleration and an estimate of the possible error. The error estimate is a matter of judgment, and should be based on the consistency of your four measured values of the acceleration.

Film Loop 3: Vector Addition I — Velocity of a Boat

The head-to-tail method of adding vectors is illustrated in Fig. 1. Since velocity is a vector quantity (it has both magnitude and direction) we can study vector addition by using velocity vectors.

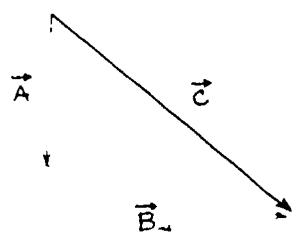


Fig. 1. $\vec{A} + \vec{B} = \vec{C}$

An easy way of keeping track of the order in which vectors are to be added is by using subscripts:

$\vec{v}_{BE}$ velocity of boat relative to earth

$\vec{v}_{BW}$ velocity of boat relative to water

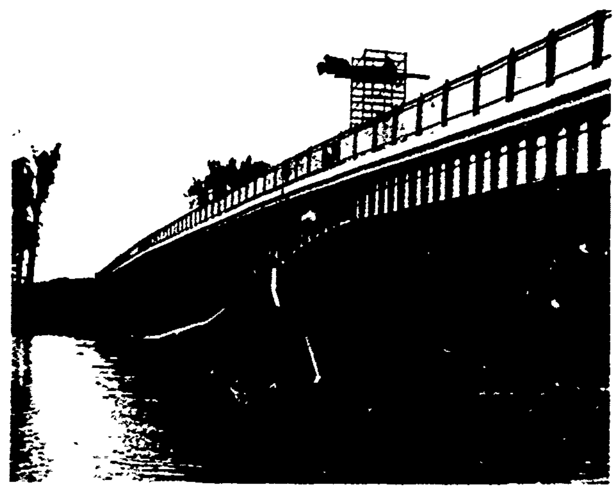
$\vec{v}_{WE}$ velocity of water relative to earth.

Then

$$\vec{v}_{BE} = \vec{v}_{BW} + \vec{v}_{WE}.$$

In the film a motorboat is photographed from a bridge above a river. The operator tried to keep a steady speed relative to the water by keeping the throttle at a fixed setting. The boat heads upstream, then downstream, then directly across stream, and finally it heads at an angle somewhat upstream so as to move straight across. For each heading of the boat, a vector diagram can be drawn by laying off the velocities to scale, using a ruler and a protractor.

First project the film on a piece of graph paper and mark out lines along which the boat's image moves. Then measure speeds by timing the motion of the boat as it moves some predetermined number of squares. Repeat each measurement three



times, and use the average times to calculate the speeds. Express all speeds in the same unit, such as "squares per second," or "square per cm" where cm refers to measured separations between marks on the moving paper of a dragstrip. There is no need to convert the speeds to meters per second. Why is it a good idea to use a fairly large distance between the timing marks on the graph paper? A suggested procedure is to record data for each of the five scenes, and draw the vector diagrams after taking all the data.

1. Two blocks of wood are dropped overboard. Time the blocks; find the speed of the river. This is $\vec{v}_{WE}$, to be used in the vector additions to follow.

2. The boat heads upstream. Measure $\vec{v}_{BE}$, then find $\vec{v}_{BW}$ using a vector diagram (Fig. 2).

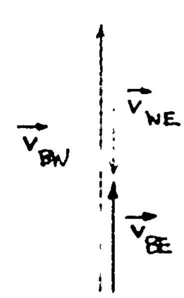


Fig. 2. $\vec{v}_{BE} = \vec{v}_{BW} + \vec{v}_{WE}$

3. The boat heads downstream. Measure $\vec{v}_{BE}$, then find $\vec{v}_{BW}$ using a vector diagram (Fig. 3).

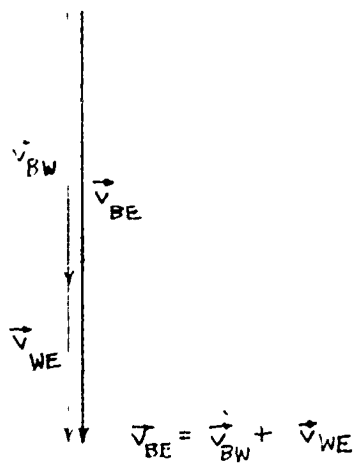


Fig. 3.

4. The boat heads across stream and drifts downward. Measure the speed of the boat and the direction of its path; these give you the magnitude and direction necessary to specify the vector $\vec{v}_{BE}$. Also measure the <u>direction</u> of $\vec{v}_{BW}$—this is the heading of the boat, the direction in which it points. A good way to record data is to refer everything to a set of axes with the 0° - 180° axis passing through the round markers anchored in the river. In Fig. 4 the numbers are deliberately falsified; record your own measurements in a similar diagram.

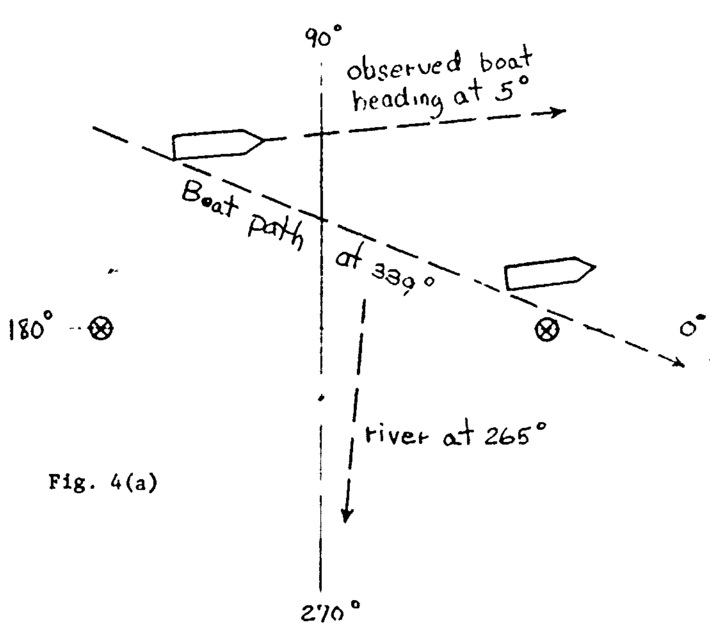


Fig. 4(a)

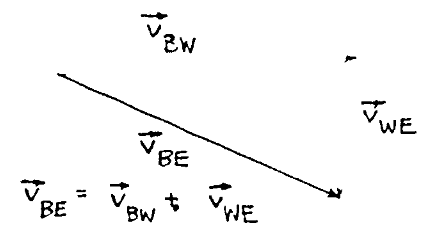


Fig. 4(b)

5. The boat heads upstream at an angle, but moves across stream. Typical data might be similar to those in Fig. 5.

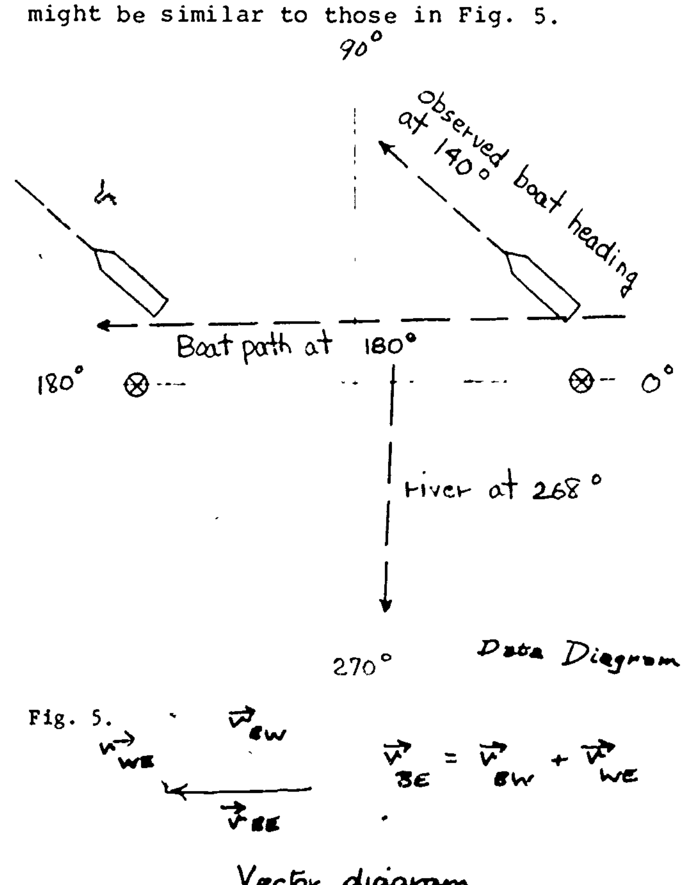


Fig. 5.

Checking your work

a) In parts 2, 3, 4 and 5 you have found four values of the magnitude of $\vec{v}_{BW}$. How well do these agree with each other? Can you suggest reasons for any discrepancies?

b) In part 4, you have found (by graphical construction) a direction for $\vec{v}_{BW}$, the calculated heading of the boat. How well does this angle agree with the observed boat heading?

c) In part 5, you have found a direction for $\vec{v}_{BW}$. How well does this angle agree with the observed boat heading?

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. In the film, three sequences labeled Event A, Event B and Event C are photographed by a camera on a cart which is 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). The question arises: could these three events really be similar events, viewed from different frames of reference?

Although to the observer Events A, B and C are visibly different, in each the carts interact similarly, and so could be the same event received from different reference frames. They are, in fact, closely similar events photographed from different 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 5. Galilean Relativity I — Ball Dropped from Mast Of Ship

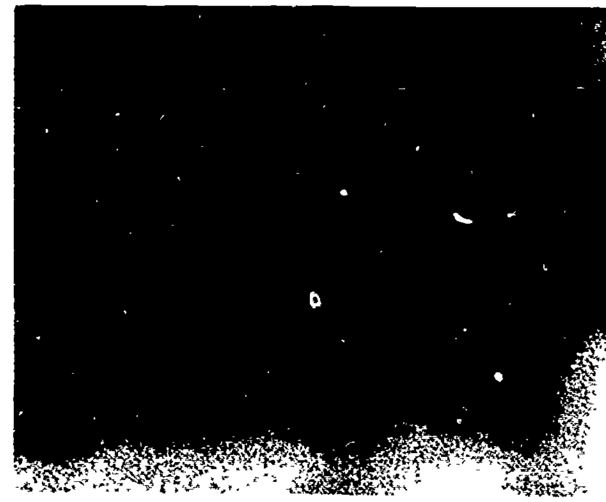
This film is a realization of an experiment described by Sagredo in Galileo's Two New Sciences:

> If it be true that the impetus with which the ship moves remains indelibly impressed in the stone after it is let fall from the mast; and if it be further true that this motion brings no impediment or retardment to the motion directly downwards natural to the stone, then there ought to ensue an effect of a very wondrous nature. Suppose a ship stands still, and the time of the falling of a stone from the mast's round top to the deck is two beats of the pulse. Then afterwards have the ship under sail and let the same stone depart from the same place. According to what has been premised, it shall take up the time of two pulses in its fall, in which time the ship will have gone, say, twenty yards. The true motion of the stone then will be a transverse line [i.e., a curved line in the vertical plane], considerably longer than the first straight and perpendicular line, the height of the mast, and yet nevertheless the stone will have passed it in the same time. Increase the ship's velocity as much as you will, the falling stone shall describe its transverse lines still longer and longer and yet shall pass them all in those selfsame two pulses.

Because the stone "remembers" its initial horizontal velocity which is the ship's motion, it will strike the deck of the ship at the base of the mast.

In the film, a ball is dropped three times. Event 1: As in Galileo's discussion, the ball continues to move forward with the boat's velocity, and it falls vertically relative to the mast. Event 2: The ball is tipped off a stationary support as the boat goes by; now it has no forward velocity and it falls vertically relative to the ground. Event 3: In the final trial, a student moving with the boat picks up the ball and holds it a few seconds before releasing it. Galilean relativity is illustrated by these three events. The ship and earth are the two frames of reference which are in relative motion. The same laws for the description of projectile motion are valid in either system. Thus each of the three events can be described as viewed in either of two frames of reference; but only one set of laws for projectile motion is needed for all six descriptions. For example, Event 1 in the boat frame is described thus: "A ball, initially at rest, is released. It accelerates downward at 9.8 m/sec^2 and strikes a point directly beneath the starting point." Event 1 in the earth frame is described differently: "A ball is projected horizontally toward the left; its path is a parabola and it strikes a point below and to the left of the starting point."

To test your understanding of Galilean relativity, you should also describe, in words, the following: Event 2 in boat frame; Event 2 in earth frame; Event 3 in boat frame; Event 3 in earth frame.



Film Loop 6: Galilean Relativity II — Object Dropped From Aircraft

A Cessna 150 aircraft 23 ft long is moving almost horizontally at about 100 ft/sec at an altitude of about 200 ft. A lighted flare is dropped from the cockpit of the aircraft; the action is filmed from the ground in slow motion. Quantitative measurements can be made at any of the "freeze frames" when the motion on the screen is stopped for a few seconds. Scene 1 shows part of the flare's motion; Scene 2, shot from a greater distance, shows the flare dropping into a lake.

Consider the motion relative to two frames of reference. In the earth frame, the motion is that of a projectile whose original velocity is the plane's velocity. The motion is a parabola in this frame of reference. Relative to the plane, the motion is that of a freely falling body which starts from rest. In this frame of reference (the plane frame) the motion is vertically downward. Scene 3 shows this vertical motion viewed head-on.

The plane is flying at uniform speed in a straight line, but its path is not necessarily a horizontal line. The flare retains the plane's original velocity both in magnitude and direction, and in addition it falls freely under the action of gravity. We might expect the displacement below the plane to be given by $d = \frac{1}{2} at^2$, but there is a slight problem. We cannot be sure that the first freeze frame occurs at the very instant the flare is dropped overboard. However, there is a way of getting around this difficulty. Suppose a time B has elapsed between the release of the flare and the first freeze frame. This time must be added to each of the freeze frame times, and so we would have

$$d = \tfrac{1}{2} a(t + B)^2. \qquad (1)$$

To see if the flare follows an equation such as this, take the square root of each side:

$$\sqrt{d} = (\text{constant})(t + B). \qquad (2)$$

Now if we plot $\sqrt{d}$ against t, we expect a straight line. Moreover, if B = 0, this straight line will also pass through the origin.

Suggested Measurements

a) Path relative to ground. Project Scene 1 on a piece of paper. At each freeze frame, mark the position of the flare and that of the aircraft cockpit. Measure the displacement d (in arbitrary units) of the flare below the plane. The times can be considered to be integers, t = 0, 1, 2,.... designating the various freeze frames. Plot a graph of $\sqrt{d}$ versus t. Discuss your result: does the graph deviate from a straight line? What would be the effect of air resistance on the motion, and how would this show up in your graph? Does the graph pass through the origin?

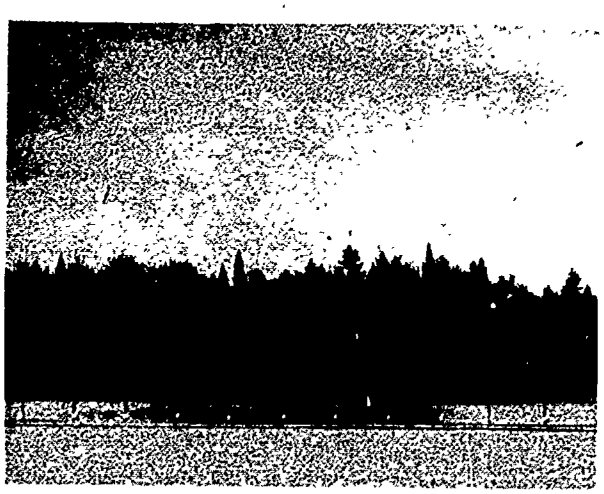
b) Analyze Scene 2 in the same way. Does this graph pass through the origin? Are the effects of air resistance noticeable in the horizontal motion? Does air resistance seem to affect the vertical motion appreciably?

c) Superposition of motions. Use another piece of graph paper with time (in intervals) plotted horizontally and displacements (in squares) plotted vertically. Using the same set of axes, make two graphs for the two independent simultaneous motions in Scene 2. Use one color of pencil for the horizontal displacement as a function of time, and another color for vertical displacement as a function of time.

d) Acceleration due to gravity (optional). The "constant" in Eq. (2) is $\sqrt{\frac{1}{2}a}$; this is the slope of the straight line graph obtained in part a). The square of the slope gives $\frac{1}{2}a$, so the acceleration is twice the square of the slope. In this way you can obtain the acceleration in squares/(interval)^2. To convert your acceleration into ft/sec^2 or m/sec^2, you can estimate the size of a "square" from the fact that the length of the plane is 23 ft (7 m). The time interval in seconds between freeze frames can be found from the slow-motion factor.

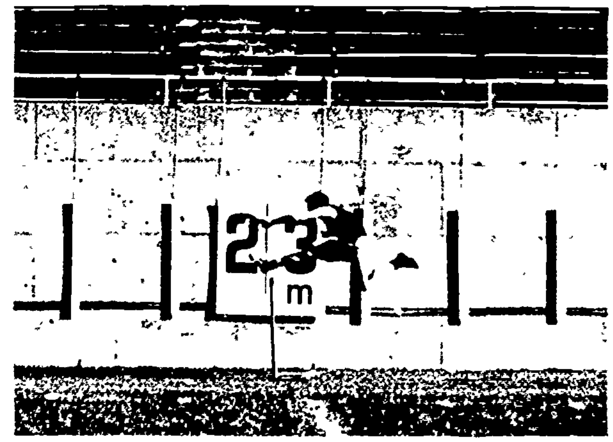
Film Loop 7 Galilean Relativity III — Projectile Fired Vertically

A rocket gun is mounted in gymbal bearings which are free to turn in any direction. When the gun is hauled along the snow-covered surface of a frozen lake by a tractor-like vehicle called a "ski-doo," the gymbals allow the gun to remain pointing vertically upward in spite of some roughness of path. Equally-spaced lamps along the path allow one to judge whether the ski-doo has constant velocity or is accelerating in either a positive or a negative sense. A preliminary run shows the entire scene; the setting, at dusk, is in the Laurentian mountains in the Province of Quebec.



Four events are photographed. In each case the flare is fired vertically upward relative to the ski-doo. Event 1: the ski-doo is stationary relative to the earth. Event 2: the ski-doo moves at uniform velocity relative to the earth. Describe the motion of the flare relative to the earth; describe the motion of the flare relative to the ski-doo. Events 3 and 4: the ski-doo's speed changes after the shot is fired; describe the flare's motion in each case relative to the earth, and also relative to

How do the events shown in this film illustrate the principle of Galilean relativity?



Film Loop 8 Analysis Of A Hurdle Race Part 1

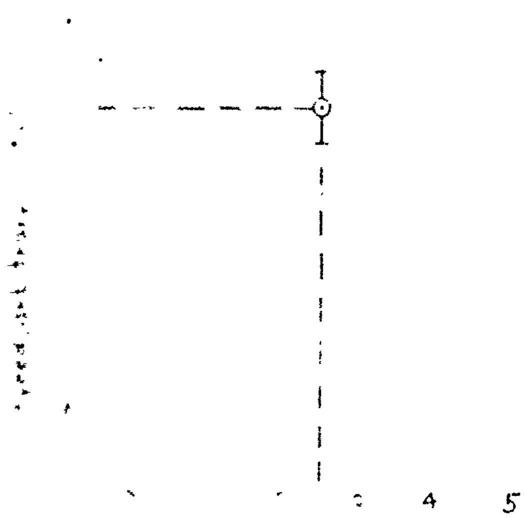
Film Loop 9 Analysis Of A Hurdle Race Part 2

Some preliminary scenes show a hurdle race of regulation length. The hurdles, each 1 meter high, were spaced 9 meters apart. Judging from the number of hurdles knocked over, the competitors were of something less than Olympic caliber! Next, a single runner is shown in medium slow motion during a 50-meter run. Finally, three parts of the run are shown in extreme slow motion for purposes of analysis. The solo runner was Frank White, a 75-kg medical student at McGill University. His time for 50 meters was 8.1 sec.

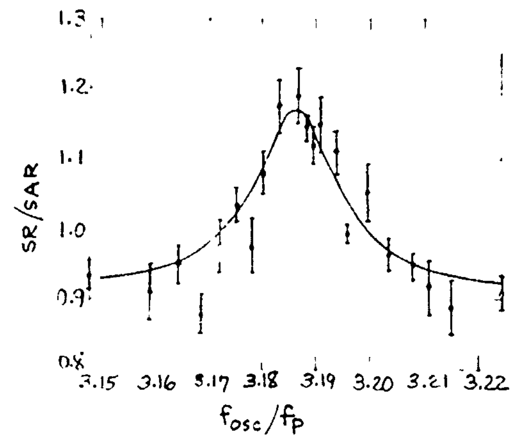
To study the runner's motion, measure the average speed for each of the 1-meter intervals in the three slow-motion scenes.

We are interested in how the speed varies during the run; therefore, you need only calculate relative values of speed, in whatever units you find convenient. The slow-motion factor of 80 is given for orientation and need not be used for this part of the analysis. We assume you are using a "dragstrip" to measure time intervals. Then the time is measured in "cm" (distance between marks on the moving piece of paper).

Whatever method you choose for measuring the time intervals, the small but significant variations in speed will be lost in the experimental uncertainty unless you work very carefully. Repeat each measurement three times, reading to the nearest half-millimeter on the dragstrip. Use the average times to compute the speeds. For example, if the time for the interval 2 m to 3 m is measured as 13.7 cm, 12.9 cm and 13.25 cm, the average time is 13.28 units and the speed is (100 cm)/(13.28 cm) = 7.55 units. This is plotted at the mid-time of the interval. The error bar is based on the spread of the observed times. The worst values are about 0.4 unit away from the average, this error of 0.4 unit out of 13.28 units is about 3 out of 100, or 3%. The speed is subject to the same percent error as is the time, and 3% of 7.55 is 0.2. We plot the point as 7.55 ± 0.2 units (Fig. 1).



You are in the best tradition of experimental science when you pay close attention to limits of error. Only then can you decide whether some of the seemingly small changes in the runner's speed are really significant. Your graph is likely to be at least as good as those research workers draw conclusions from. Thus in Fig. 2 a research team has plotted a



Stroboscopic Coincidence Positive Muons in Bromoform
f_{osc} = 48.63 Mc/Sec

quantity designated as "SR/SAR" which depends on a ratio f_{osc}/f_p (to appreciate the point we are making, it is not necessary that you know anything at all about the experiment as such). The peak at 3.19 in Fig. 2 is significant, even though some of the plotted points have error bars representing limits of error as large as 5%.

Scene 1 shows the runner's motion from 0 m to 6 m. Mark the dragstrip paper when the seat of the runner's shorts just clears the far (left-hand) edge of the vertical red meter-marks. (What are some other possible reference points on the runner that could be used? Are all reference points equally useful? Would the near edge of the meter-marker allow as precise a measurement as does the far edge?) Use a ruler or meter stick to measure each of the six dragstrip intervals corresponding to 0-1, 1-2, 2-3, 3-4, 4-5 and 5-6 m. Mark the dragstrip in this way three times and average your results for each interval. It might improve your accuracy if you form a grand average by combining your averages with those of your lab partner (assuming that he used the same dragstrip). Calculate the average speed for each interval, and plot a graph of speed versus displacement. Estimate the limit of error for a typical point and add similar error bars to each plotted point. Draw a smooth graph through the points. Discuss any interesting features of the graph.

One might assume that any push of the runner's legs comes only between the time when a foot is directly beneath the runner's hip and the time when that foot lifts off the ground. Study the film carefully; is there any relationship between your graph of speed and the way the runner's feet push on the track?

The initial acceleration of the runner can be estimated if you find the time for him to travel from the starting point to the 1-meter mark. For this you must use a clock or a watch with sweep second hand, and you must use the slow motion factor to convert apparent time to real time. Calculate the average acceleration, in m/sec^2, during this initial interval of about 1.4 m. How does this forward acceleration compare with the magnitude of the acceleration of a freely falling body? How much force was required to give the runner this acceleration? What was the origin of this force?

Scene 2 and Scene 3 are on a second loop which is a continuation of the first loop. In Scene 2, the hurdler moves from 20 m to 26 m, clearing a hurdle at 23 m. In Scene 3, the runner moves from 40 m to 50 m, clearing a hurdle at 41 m and sprinting toward the finish line at 50 m. Plot graphs of these motions, and discuss any interesting features.

Additional Suggestions For Activities

Growth of a tree

A growth vs. age graph for a tree makes an interesting display. Get a cross-section of a tree trunk, perhaps from your biology department, a local tree trimming company or a science museum. Start at the middle of the cross-section and measure how many millimeters per year the tree grew. Make a graph of growth vs. age for the tree. What might a very narrow ring indicate? If you know for sure when the tree was cut down, you can check with a local newspaper office on when there were particularly bad droughts, rains, etc., and see if the tree rings are good indicators of these.

Extrapolation

Many arguments regarding private and public policies depend on how people choose to extrapolate from data which they have gathered. Do some reading in magazines and make a report about the problems of extrapolating in various situations.

For example:

1. the population explosion;
2. the number of students in your high school ten years from now;
3. the number of people who will die in traffic accidents over the next holiday weekend;
4. the number of lung cancer cases that will occur next year among cigarette smokers;
5. how many gallons of punch you should order for your school's Junior Prom.

If you would like to become more proficient in making your statistics support your pet theory—and more cautious about common mistakes—you will enjoy reading How to Lie with Statistics by Darrell Huff, W. W. Norton and Company.

Clocks

Find out when the first pendulum clock was constructed and by whom. Try making a simple pendulum clock on the basis of drawings you find in your reading. Read the article about the prize that was offered for the development of the chronometer, for determining longitude when at sea, in the four-volume series, The World of Mathematics, edited by James Newman.

Science fiction stories related to Unit 1

Just after the American Civil War, Jules Verne, a Frenchman, wrote A Trip From the Earth to the Moon and A Trip Around the Moon. Both are available in paperback from Dover Publications, New York. Find out what sort of scientific background Verne had for writing these stories. You will find that he made an incorrect prediction about what would happen to a passenger inside a free projectile traveling from the earth to the moon.

Edgar Rice Burroughs, who wrote Tarzan, also wrote At the Earth's Core, a story about a land at the center of the earth, where daytime is eternal and the land and sea are placed as though they were on the inside of a beachball. It is an excellent story of the kind that invites speculation about which of the author's assumptions are scientifically possible and which are not.

A "tin can" planetarium, a simple device for projecting star images, can be made by following the instructions given in an article in The Science Teacher, November, 1950. The finished instrument consists of a flashlight bulb shining at the center of a surrounding tin can. The light passes through small holes and shines on the walls of the surrounding room. The small images of the bulb's filament resemble stars.

Table 1

A GUIDE FOR PLANET AND ECLIPSE OBSERVATIONS

Check your local newspaper for local eclipses times and extent of eclipse in your locality.

Year	Mercury Visible for about one week around stated time.	Venus Visible for several months around stated time.	Mars Very bright for one month on each side of given time. Observable for 16 months surrounding given time.	Jupiter Especially bright for seven months beyond stated time.	Saturn Especially bright for two months on each side of given time. Visible for 13 months.	Lunar Eclipses	Solar Eclipses
	Mercury and Venus are best viewed the hour before dawn when indicated as a.m. and the hour after sunset when indicated as p.m.						
1968	late Sept.: p.m. late Oct.: a.m				mid Nov.: overhead at midnight	Oct. 6	
1969	mid Jan.: p.m. late Feb.: a.m. early May: p.m. mid June: a.m. early Sept.: p.m. mid Oct.: a.m. late Dec.: p.m.	late Feb.: p.m. mid May: a.m.	mid July: overhead at midnight	late Apr.: overhead at midnight	late Nov.: overhead at midnight		Sept. 11 partial in western U.S.
1970	mid Feb.: a.m. late Apr.: p.m. early June: a.m. mid Aug.: p.m. late Sept.: a.m. early Dec.: p.m.	early Nov.: p.m. mid Dec.: a.m.		late May: overhead at midnight	early Dec.: overhead at midnight	Feb. 21 Aug. 17	Mar. 7: total in Fla., partial in eastern and southern U.S.
1971	mid Jan.: a.m. late Mar.: p.m. mid May: a.m. late July: p.m. mid Sept.: a.m. late Nov.: p.m.		early Sept.: overhead at midnight	late June: overhead at midnight	late Dec.: overhead at midnight	Feb. 10	
1972	early Jan.: a.m. mid Mar.: p.m. early May: a.m. mid July: p.m. late Aug.: a.m. early Nov.: p.m. mid Dec.: a.m.	mid May: p.m. early Aug.: a.m.		late July: overhead at midnight		Jan. 30 July 26	July 10 partial in northern U.S.
1973	late Feb.: p.m. late Apr.: a.m. late June: p.m. early Aug.: a.m. mid Oct.: p.m. early Dec.: a.m.	late Dec.: p.m.	late Nov.: overhead at midnight	early Sept.: overhead at midnight	early Jan.: overhead at midnight	Dec. 10	
1974	mid Feb.: p.m. late Mar.: a.m. early June: p.m. mid July a.m. late Sept. p.m. early Nov. a.m.	early Mar.: a.m.		mid Oct.: overhead at midnight	late Jan.: overhead at midnight	June 4 Nov. 29	
1975	late Jan.: p.m. early Mar.: a.m. mid May: p.m. early July: a.m. mid Sept.: p.m. late Oct.: a.m.	mid-late July: p.m. early Oct.: a.m.		early Nov.: overhead at midnight	early Feb.: overhead at midnight	May 25 Nov. 18	
1976	mid Jan.: p.m. late Feb.: a.m. early May: p.m. mid June: a.m. late Aug.: p.m. early Oct.: a.m. mid Dec.: p.m.		late Jan.: overhead at midnight	early Dec.: overhead at midnight	late Feb.: overhead at midnight		
1977	early Feb.: a.m. early Apr.: p.m. late May: a.m. mid Aug.: p.m. late Sept.: a.m.	early Mar.: p.m. mid Apr.: a.m.				Apr. 4	

Table 2

FAVORABILITY OF OBSERVING METEOR SHOWERS

The best time for viewing meteor showers is between midnight and 6 a.m., in particular during the hour directly preceding dawn.

Quadrantids Jan. 3-5 Virgo	Lyrids Apr. 19-23 Lyra	Perseids July 27-Aug. 17 Perseus	Orionids Oct. 15-25 Orion	Leonids Nov. 14-18 Leo	Geminids Dec. 9-14 Gemini	Year
Rises in the east around 2 a.m., upper eastern sky at 5 a.m.	Rises in the east around 10 p.m., western sky at 5 a.m.	Rises in the east at 10 p.m., towards the west at 5 a.m.	Rises in the east at midnight, directly overhead at 5 a.m.	Rises in the east at 2 a.m., upper eastern sky at 5 a.m.	Rises in the east at 8 p.m., towards the far west at 5 a.m.	
Good	Good	Through early August, after Aug. 10	Good	Good	Good	1968
Poor	Good	Aug. 3-17	After Oct. 20	Good	Good	1969
Good	Poor	July 27-Aug. 11	Oct. 18-25	Poor	Poor	1970
Good	Good	July 27-Aug. 2 Aug. 7-17	Good	Good	Good	1971
Good	Good	Aug. 2-17	Oct. 15-20	Nov. 14-16	Good	1972
Good	Apr. 21-23	July 27-Aug. 9	Good	Good	Poor	1973
Poor	Good	Aug. 7-17	Good	Good	Good	1974
Good	Good	Good	Oct. 21-25	Poor	Dec. 9-12	1975
Good	Good	July 27-Aug. 5 Aug. 12-17	Good	Good	Good	1976
Poor	Good	Aug. 3-17	Oct. 15-21	Good	Good	1977

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