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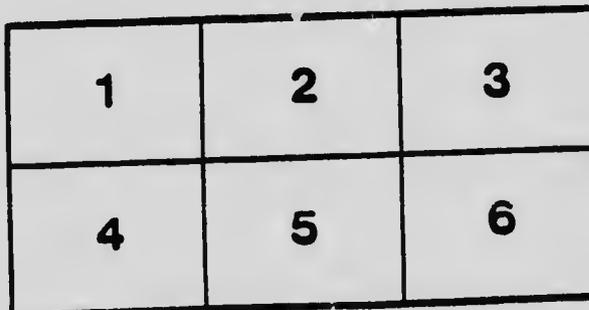
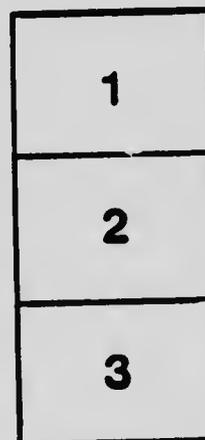
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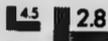
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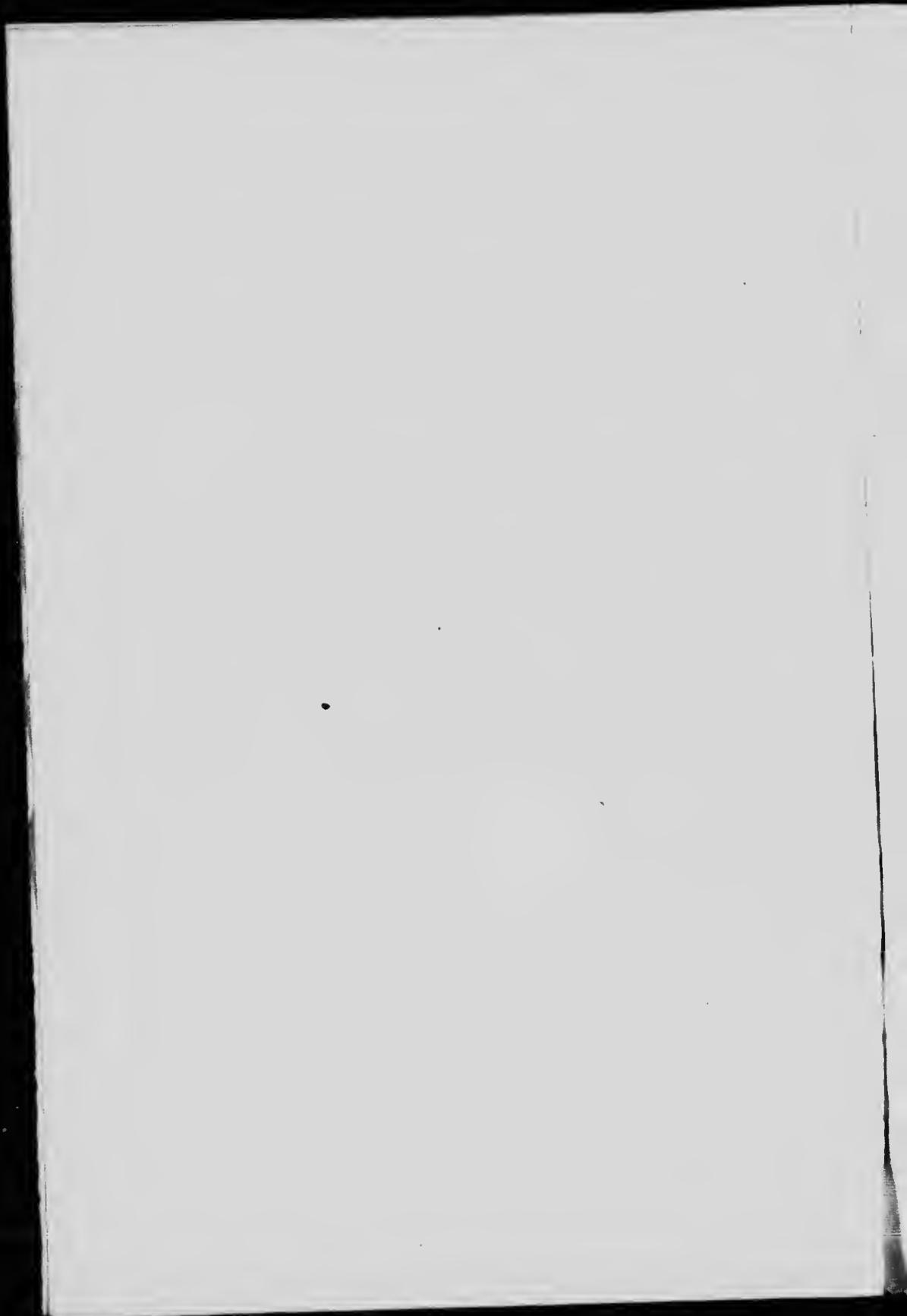
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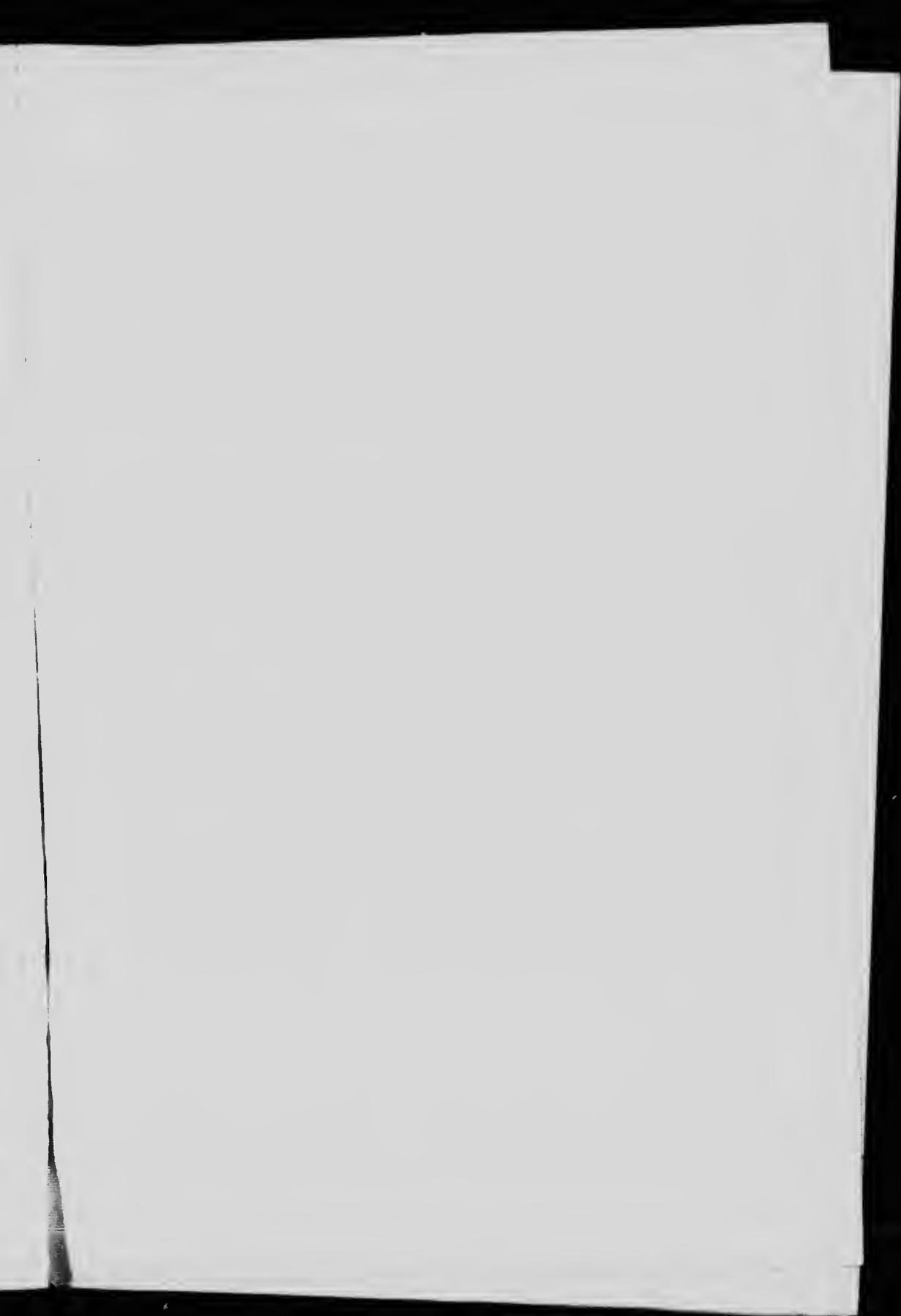
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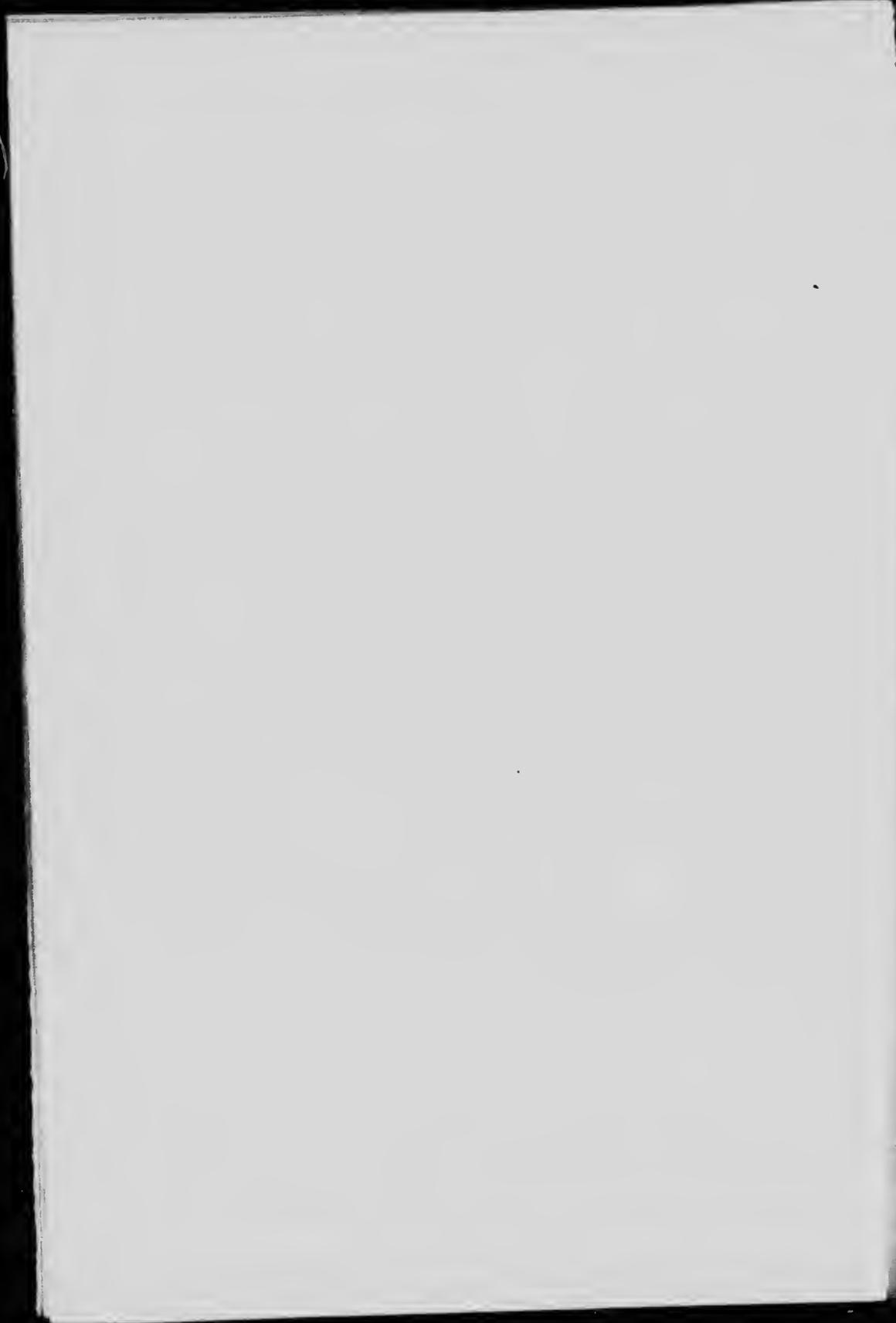


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PHYSICS

BY

CHARLES RIBORG MANN

AND

GEORGE RANSOM TWISS

Authorized for use in the Schools of Quebec

REVISED EDITION

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*PREFACE

THE first edition of this book, published five years ago, was an effort on the part of its authors to introduce into the teaching of Physics a more vital method of presentation than the one then in common use.

The fundamental principle underlying the method of presentation used in both editions of this book is that the study of Science in high schools can be justified only when the pupils gain both knowledge of the subject matter and training in scientific thinking. In conformity with Spencer's definition of Science as classified knowledge, the teaching of subject matter has so dominated elementary instruction in Physics that little attention has been given to training in methods of thought.

The overestimation of the value of mere subject matter, and the prevalence of the custom of testing the results of a teacher's work by examinations on a specifically outlined list of prescribed topics, drove teachers to use methods of teaching that were mainly formal and didactic. Definitions, laws, and principles were simply stated, memorized by the pupils, and justified afterwards if at all by illustrations in the way of experiments and practical applications.

Both educational experience and educational theory show clearly that scientific facts may be memorized, but not mastered in this way. Scientific knowledge is acquired only on the basis of concrete experience by the trying-out process known as the scientific method. Therefore a method of treatment that develops the subject from the concrete experiences of the learner, and gives practice in the framing, testing, and selection of hypotheses appropriate to the solution of definite, concrete problems, is the only method that gives mastery of subject matter.

*The reference to Part II in the Preface applies to the complete book containing Parts I and II.

If the study of Physics is also to give real training in powers of thought and action, it is necessary moreover that the work in hand should appeal to the student as being worthwhile,—it must define in his mind problems that are significant to him; so that the motive that impels him to work is a desire to solve the problems for the sake of knowing the solutions. The solution of scientific problems is always beset with difficulties, and it is in overcoming the difficulties that are inherent in a problem whose solution is significant to the pupil, that real training in power of thought and action is secured. Therefore, the method of treatment that develops the subject as a series of problems that are significant to the pupils is not only the one method that leads to the real mastery of subject matter; it is also the one method that gives him real training in scientific thinking.

In our first book the effort was definitely made to apply this problem method of treatment to the subject matter that was then generally accepted as the necessary content of a first course in Physics. During the five years that have elapsed, teachers have come to recognize more and more clearly the value of this problem method of teaching. The recognition of the fact that the problem must be significant to the pupil has of necessity raised the question whether the subject matter of the old course is the best that can be chosen to impress the student with the significance to him of the laws and principles of Physics. Are such topics as the laws of accelerated motion, the absolute units, and coefficients of expansion, capable of being presented in such a way that they define significant problems in the mind of the average high-school boy or girl just beginning the study of Physics?

Both experience with high school pupils and common sense seem to the authors to answer this question unequivocally in the negative. So a rewriting of the book became a necessity,—an edition in which the attempt should be made to apply the same principles of teaching to subject matter more likely to be significant to the pupils, and so to make more serviceable the new method. The authors believe that the

majority of the teachers of the country now appreciate the value of the problem method of teaching; we believe that they recognize that the old series of topics, which was selected to contain the "Physics every Physicist must know," must give way to a series of topics which contains the "Physics every child should know."

Recognizing that many of the topics which have been considered essential to a course in Physics are necessary and significant to those who are going into technical scientific work, but are neither necessary nor significant to others, we have divided the book into two parts. Part I contains the material that should be significant to everybody. There is enough material here for a full year's work. Those who have completed this part in one year will have satisfied the definition of the unit in Physics as adopted by the North Central Association of Colleges and Secondary Schools.

Part II contains material that may be needed by those who are going on to work in scientific professions, and considerable other material which many teachers desire to place before their pupils. This material is so arranged that it may be used either in connection with that material of Part I to which it is most closely related, or in a later course in which the first course is reviewed and amplified.

This division of the subject matter into two parts is a doubly advantageous one. First, it makes it possible to give all the pupils a significant and learnable course in Physics. Second, those who go on will be able to master the whole subject better if they take it in the order given, because the more abstract and difficult topics come near the end. In other words, the demands on the pupil's powers of abstraction and analysis increase as the argument proceeds. This arrangement, therefore, gives a better preparation for future work than the usual one, which begins with a mathematical treatment of accelerated motion. Those who master both parts will have more than satisfied the new definition of the requirement in Physics of the College Entrance Examination Board.

The material in Part I has been selected not only because it is significant to the pupils, but also because it supplies the basis of an appreciation of the largest and most useful principles of Physics. In his well-known address on the Future of Mathematical Physics, Poincaré has shown that the principle of the conservation of energy and that of least action are the two physical principles most likely to endure. In order to prepare as far as possible for an understanding of the physical meaning of these principles, great emphasis has been placed on energy relations. For the same reason the ideas of relativity involved in Newton's Laws of Motion have been emphasized rather than the quantitative application of those laws to particular cases.

This grouping of subject matter according to the physical ideas of energy and relativity has three decided advantages over other groupings. First, it reduces to a minimum the number of different things to be learned, thereby making possible a great simplification in the treatment, and securing the much-needed repetition of familiar ideas and principles in new relations. The inclined plane, the pulley, the lever, etc., are not separate topics to be learned separately, but special cases of the work principle. Second, the energy relations are more easily grasped by students, because all their motor sensations supply them with those intuitive ideas which are the necessary basis for a clear formulation of the energy relations. The daily experiences thus furnish an easy means of defining significant problems, and so the work is more likely to give real training in power. Third, clear concepts of energy relations are the best possible preparation for future work in Physics,—they are worth infinitely more than a memorized series of definitions in fine logical order.

Practically no use is made of algebraic formulas in Part I. Symbols are omitted because it is important that the pupil's intuitive notions be crystalized in physical concepts before they are reduced to symbols. Although the symbols have been omitted, mathematical reasoning has been employed freely. Therefore the mathematics phase has not

been omitted; but the danger of memorizing formulas whose symbols do not stand for well-developed physical concepts has been reduced to a minimum. The pupils who are ready to use algebraic symbols intelligently will have no trouble in putting the relations into the equation form for themselves. Those who are not able to do this will do better thinking without formulas.

For the same reason, the questions and problems at the ends of the chapters are not mathematical puzzles. They are all real physical problems, and their solution depends on the use of physical concepts and principles, rather than on mere mechanical substitution in a formula.

As practical helps to both pupil and teacher the important facts of each chapter have been gathered together at the end under the caption Definitions and Principles. These may be committed to memory. In the text each paragraph constitutes an argument that begins with concrete experience and ends with the statement of the principle or fact that is under discussion. In order to emphasize the fact, the statement is usually printed in italics. The more general and important of these conclusions are printed in black-faced type.

It is expected that both demonstration experiments and laboratory exercises will be given in connection with this book; but no attempt has been made to specify in the text the particular experiments that should be made. Since most schools are supplied with fairly complete equipment of demonstration and laboratory apparatus, it is believed that each teacher will be the best judge as to the selection of such experiments and the order in which they are to be given. Those who adopt this book will not find it necessary to discard their old equipment and buy a new outfit in order to fit the laboratory work to the method here presented. Those demonstration and laboratory experiments that have proved to be workable and significant to the pupils in connection with courses heretofore given, will be found to be the best for use with this book also.

The authors wish here to express their thanks to Pro-

fessor R. D. Salisbury of the University of Chicago, Editor-in-chief of the Lake Science Series for many valuable criticisms and suggestions. We desire also to thank our colleagues, physicists, psychologists, and school men generally for their courtesy in answering inquiries and giving time to consultations in our endeavor to solve the problem of better methods of teaching the subject of Physics in Secondary Schools.

C. R. MANN.

G. R. TWISS.

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PART ONE

CHAPTER I

GRAVITY

1. **The Regularity of Nature.** Of all the things that happen in our daily lives, none is more familiar than the fall of heavy bodies toward the earth. Even very small children soon become cautious about letting heavy objects drop on their toes, and about falling from high places.

We are so accustomed to seeing things fall that it is difficult to imagine a world in which they would not do so. It would seem strange indeed if stones when released from the hand flew upward or remained floating in the air instead of falling. In the fairy tales of our childhood we have read of such things, but in real life we know of no such exceptions to the usual happenings.

The sun set last night and rose again this morning, and we are sure that it will set again to-night and rise again to-morrow morning. In fact, from all our experiences with Nature we have learned that she always acts in such a perfectly regular way that we can predict what will happen under a given set of circumstances. It is because we can thus predict what will happen under given conditions that we are able to master the forces of Nature and make them work for us. He who knows the ways of Nature and is able to reason most clearly about them is the one who can best control her forces. We study physics in order to learn how to become masters of the forces of Nature.

We can know and control the forces of Nature because Nature always acts in a perfectly regular way.

2. **Gravity.** When you hold any body—a book, a pencil, a chair—in your hand, you “feel the pull of gravity drawing it down.” Moreover you notice that when a body



FIG. 1
PLUMB LINE

is dropped it falls vertically; and that when it is suspended on a string, the string is stretched in a vertical direction. Because of this, every carpenter and brickmason uses his plumb line (Fig. 1) to guide him in erecting vertical walls, or door and window frames. This fact is described by saying that *the force of gravity acts in a vertical line.*

3. Center of Gravity. If we wish to prevent a ruler from falling to the floor, we must counteract the pull of gravity on it by an equal upward push. If this is done by laying it on the table or by holding it in the hand, it is supported at a large number of different points. But the ruler may be upheld in a horizontal position by balancing it on the edge of a knife (Fig. 2). It is then supported at only a few

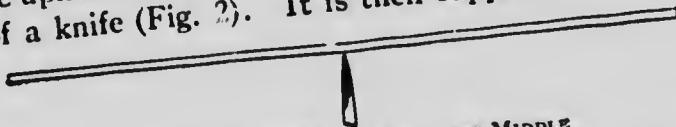


FIG. 2 THE KNIFE EDGE IS IN THE MIDDLE

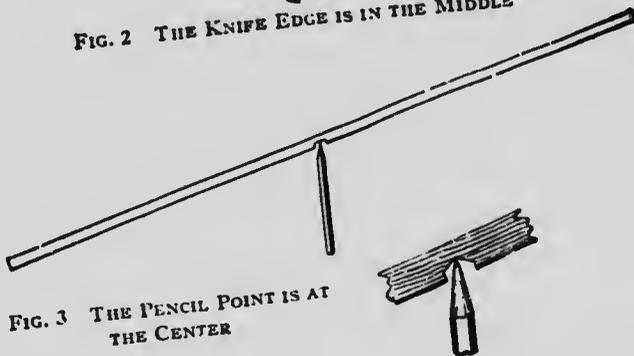


FIG. 3 THE PENCIL POINT IS AT THE CENTER

points along a single line. When it is so balanced, the knife edge is found to be at its middle: just half of the ruler is on each side of the blade, i. e. the two halves are symmetrically placed with reference to it. Thus we can counteract the pull of gravity on the whole stick by applying a support that presses upward against it along a single line at its middle. But we can do more than this. If we bore a small hole in the ruler

so as to reach its center and apply the sharpened end of the pencil at this point, the ruler will balance, although it is supported at this *point* only (Fig. 3).

A square or circular piece of board may be balanced horizontally on the point of a pencil applied at the center of one surface. But if we bore a hole half way through at this point, and thrust the pencil upward into the hole, the piece of board can be balanced on the pencil point not only when it is horizontal but also when it is inclined (Fig. 4). If the pencil is placed at the right point, the board will remain supported and at rest in any position in which it is set. So we see that we can counteract the entire pull of gravity on a body by a single upward push applied at a particular point. This point is called the *center of gravity*.

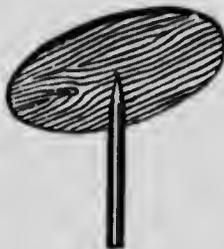


FIG. 4
BALANCED DISK

The word *force* is used to mean either a push or a pull; and the force or pull of gravity on any particular body is called its *weight*. The use of these words, force and weight, enables us to frame the following brief definition of center of gravity.

The center of gravity of a body is that point at which its weight may be counteracted by a single upward vertical force.

4. How to Find the Center of Gravity. If the plumb bob (Fig. 1) be pulled to one side and allowed to swing to and fro like a pendulum, it comes to rest at the middle of its swing where its center of gravity is at the lowest point that it can reach. In other words, *the center of gravity "seeks the lowest level."*

This fact suggests a convenient means of finding the center of gravity of an irregular body. Thus, for example, if we cut from thin metal or cardboard the irregular shaped body *abc* (Fig. 5), and suspend it on a pin passing through a hole near its edge, as at *a*; and if we also hang a plumb line on the pin, the center of gravity of the body will be somewhere in

the vertical line indicated by the plumb line. If we mark this line on the body, and then suspend the body from another point, as *b*, and again draw on it the line marked out by the plumb line, the center of gravity must lie in this line also; and, since it is in both lines, it must be at their intersection. If the experiment has been made carefully, we shall find that the body may be balanced on a pin point applied at this intersection.

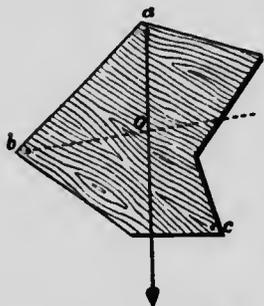


FIG. 5. FINDING THE CENTER OF GRAVITY

This method of finding the center of gravity is based on the fact that no matter how the body is suspended *it remains at rest only when its center of gravity has reached the lowest level possible.*

5. Balancing. Probably every one has tried to balance a long stick or even a pencil vertically on the tip of his finger (Fig. 6). To prevent the stick from falling requires considerable skill and agility on the part of the performer. It is easy to make a bottle stand right side up on a table, but it takes a skillful juggler to balance it on the rim of a plate.

A block of stone on the ground shows no tendency to tip over. Indeed considerable effort is required to overturn it. The tumble jack (Fig. 7) will not remain tipped over; but insists on standing upright.

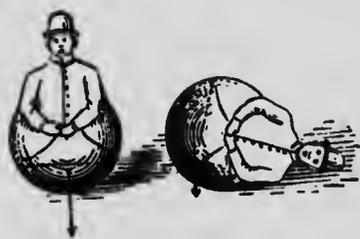


FIG. 7



FIG. 6

A pencil, which can with difficulty be made to stand upright by itself, refuses to upset if two penknives are stuck into it as shown in Fig. 8. Let us find the reason for these facts.

6. Stability. In general we know that a body may be tipped over easily if it stands on a small base, and with difficulty if it stands on a large

base; but this fact alone does not make clear the real reasons for stability.

In the case of the stick on the tip of the finger, the center of gravity is at a higher level than the finger; and, since the base on which the stick stands is small—practically a point—a very slight tipping will cause the center of gravity of the stick to describe an arc *ab* (Fig. 9), about the tip of the finger as a center. By

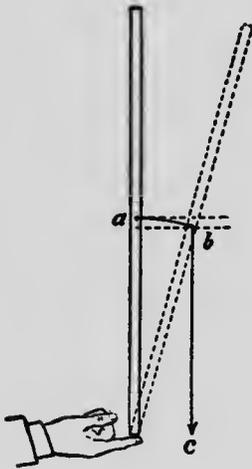


FIG. 9

this motion the center of gravity begins to descend; and it will continue to descend unless the performer takes quick action to prevent it. The stick remains balanced only so long as its center of gravity is at *a*, the highest point of the arc *ab*; for then the vertical line through its center of gravity passes through the point of support.

The case is the same with the bottle on the rim of a plate. Unless the juggler can keep the point of support of the bottle in the vertical line that passes through its center of gravity, over it goes, because its base is but a point. Any rotation about this point gives the center of gravity a chance to descend. Because it is so difficult to keep bodies balanced in this way, we say they are in unstable equilibrium. *A body is in unstable equilibrium whenever it cannot be tipped without lowering its center of gravity.*

In the case of the block of stone on the ground, the base is larger. When the block is tipped up on edge, its center of gravity must be raised to a higher level (Fig. 10); and, if the stone is large and heavy, this operation requires hard work. The

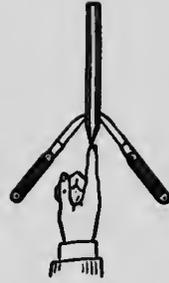


FIG. 8

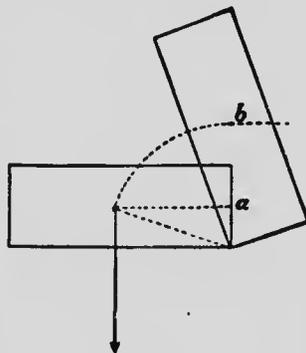


FIG. 10

line drawn from the center of gravity of the stone to that of the earth passes within the base even after the stone has been turned through quite a large angle.

It takes work to tip the stone over because in doing this its center of gravity must be raised to a higher level; on this account the stone, when so placed, is said to be in stable equilibrium. In like manner, the toy (Fig. 7) and the pencil with the knives stuck into it (Fig. 8) are in stable equilibrium when they are standing upright, because then their centers of gravity are as low as possible. Hence the conclusion: *A body is in stable equilibrium whenever it cannot be tipped without raising its center of gravity.*

We can now understand better why the ruler (Fig. 3) or the circular board (Fig. 4) remain balanced in any position when supported on a pencil point applied at the center of gravity. When a body so supported is tipped, its center of



FIG. 11

gravity stays on the pencil point and so neither rises nor falls. If a ball on a level table (Fig. 11) be rolled about, its center of gravity remains over the point of support and so is neither lowered nor raised by the motion; therefore, the ball remains in equilibrium wherever it is placed.

Bodies that remain in any position in which they are placed (Figs. 3, 4, 11), are said to be in neutral equilibrium. *A body is in neutral equilibrium whenever tipping neither raises nor lowers its center of gravity.*

All cases of equilibrium under the action of gravity are included under the following principle:

A body is in equilibrium under the action of its weight when it is so supported that its center of gravity cannot descend to a lower level. This condition is fulfilled when the vertical line through the center of gravity passes within the base or through the point of support.

7. Degree of Stability. When the stone shown in

Fig. 10 has been tipped up on edge (Fig. 12), less work is required to tip it back again. For this reason the stone is said to be more stable in the first position than in the second. The reason for this appears from a study of the two figures, 10 and 12. In order to tip it up on end, its center of gravity had to be lifted through the difference in level ab (Fig. 10); but in order to tip it back again, its center of gravity had to be raised through the smaller difference in level cd (Fig. 12).

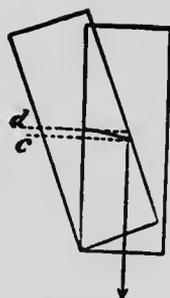


FIG. 12

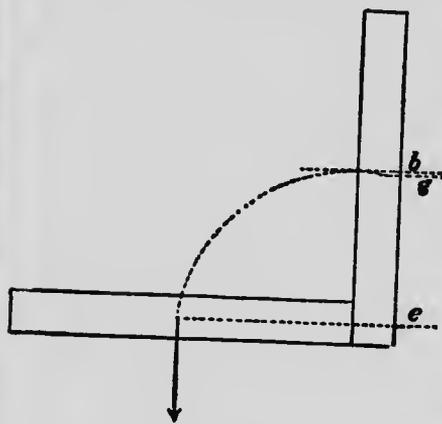


FIG. 13

The stone in Fig. 13 has the same volume and weight as the other, but its base is twice as large and its center of gravity half as high. When lying flat, it is more stable, but when on end it is less stable than the other. In order to tip it up on end, the center of gravity must be lifted through the larger difference in level eb , while in tipping it back, the center of gravity rises

through the smaller difference in level gb . The stability of a body of given weight is therefore greater the larger the base and the lower the center of gravity, because under these conditions the vertical distance through which the center of gravity must be lifted in turning it over is increased.

A block of iron that has the same size and shape as the stone just considered is still more stable than the stone, because it is much heavier than the stone, and therefore a greater weight must be lifted to overturn it. Thus *the stability of a body is greater, the greater the weight and the greater the vertical distance through which its center of gravity must be lifted in tipping it over.*

8. How Gravity Acts. When you stretch a rubber

band, it pulls equally hard on both hands. Now gravity pulls a body toward the earth; but, like the rubber band, it cannot pull the body without pulling the earth just as hard. Hence we may imagine that *the force of gravity acts like an elastic cord stretched between the center of gravity of the body and that of the earth; and so it constantly tends to pull them toward each other along the straight line joining their centers of gravity.*

9. Action and Reaction. When a boy lifts a heavy stone he must stand with his feet on the earth and his hands under the stone, and push downward against the earth with his feet just as hard as he pushes upward against the stone

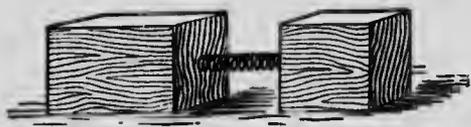


FIG. 14

with his hands. In this, his action is like that of a coiled spring that is compressed between two massive blocks (Fig. 14).

If the spring expands and moves the blocks, it must push on both bodies equally and in opposite directions.

In like manner, when a man slides a heavy box along the floor, he pushes with equal force forward on the box with his hands and backward on the floor with his feet. If his feet slip on the floor, the box does not move. This is because he cannot push any harder against the box than he pushes against the floor, and the greatest force that he can exert on the slippery floor is less than that required to move the box.

Whenever a force acts, two bodies are equally and oppositely affected. This very important fact is known as "Newton's third law of motion." It is usually stated as follows:

"To every action there is an equal and contrary reaction."

10. Mass. If the two blocks (Fig. 14) consist of equal quantities of iron, then, when they are pushed apart by the compressed spring, one moves just as fast as the other. But

if one block contains much more iron than the other, it moves much more slowly than the other. In like manner, when the boy lifts the stone, both the stone and the earth are moved; but the quantity of matter in the earth is enormously greater than that in the stone; therefore the earth's motion is so slow as to be imperceptible.

The word mass is equivalent to the expression, quantity of matter. With the aid of this word we may state our conclusion as follows: *When force acts between two bodies so as to produce motion, both bodies move. If the masses are equal they move equally fast. If their masses are unequal, the greater mass moves more slowly.*

Mass is quantity of matter.

The greater the mass, the slower the motion.

11. Inertia. When a man is standing in a street car and the car starts unexpectedly, he is apparently thrown toward the rear of the car. In reality, the car moves forward under him, while he tends to stay where he was. In order to put his body into motion when the car moves forward, he must push backward with his feet on the floor of the car. On the other hand, when the car stops suddenly, he may fail to stop with it, and so seems to be thrown forward. In order to stop with the car, he must push forward with his feet against the car floor so as to prevent his body from going on. When he jumps from a moving car, he must brace himself in the same way; else his body will go on after his feet stop, and he will fall.

Again, when a man is standing in a moving car, and the car suddenly rounds a curve, the man seems to be thrown toward the side of the car. In reality, the car changes the direction of its motion, while the man tends to go on in the direction in which he was moving. In order that the direction of his motion may be changed when the car turns, he must push sideways against the car. When you swing a stone around in a sling, you feel the force that compels it to move in a curved path. When you let go the sling, the force

ceases; and the stone flies off in the direction in which it was moving at the instant when you let go.

In order to put a football into motion, the player kicks it with his foot. The ball never puts itself into motion. Neither does it stop itself. It goes on unless it is stopped by another player, or by the resistance of the air, or by friction against the earth. When kicked upward, it follows a curved path instead of a straight one, and falls to the earth because its weight is constantly pulling its center of gravity and that of the earth toward each other. We never see a change in the motion of one body without being able to point out some action between it and some other body. So we have come to believe that if a moving body were alone, so that there could be no force whatever to stop it or to change its speed or its direction, it would go on with the same speed and in the same direction forever. This idea is expressed by saying that the body has inertia. This same idea is also expressed in the following statement, which is known as Newton's first law of motion:

Every body continues in its state of rest or of uniform motion in a straight line, except in so far as it is compelled by force to change that state.

Inertia is the inability of a body to change its condition of rest or motion.

12. Universal Gravitation. We know that bodies fall at the tops of high mountains and from balloons; and that occasionally a meteorite, or falling star, falls from an unknown height. We also know that the moon goes around the earth, and that therefore there must be some force acting between the moon and the earth to compel the moon to move in a curved instead of a straight path. Knowledge of this sort led Newton (1642-1727) to wonder whether the same force of gravity, which constantly draws bodies toward the center of the earth, might not extend to the moon, and be sufficient to hold the moon in its curved path around the earth.

After long and careful calculations on the observations of

astronomers, Newton announced his conclusions in the following statement, which is known as the *law of universal gravitation*: *Every body attracts every other body with a force that is directly proportional to the product of the masses and inversely proportional to the square of the distance between their centers of gravity.*

By assuming the truth of this law, astronomers have been able to describe accurately the motions of the heavenly bodies, to predict eclipses and the return of comets, and even to discover new planets. Because predictions based on this law have always come true, we believe that the law is true and that gravity is universal; i. e., that

Every body in our universe attracts every other body and is attracted by them all.

DEFINITIONS AND PRINCIPLES

1. A push or a pull—anything that changes or tends to change a body's condition of rest or of motion—is called a force.
2. The force of gravity acts in a vertical line.
3. The force of gravity on a body is called its weight.
4. The center of gravity of a body is the point at which the weight of the body may be counteracted by a single upward vertical force.
5. The center of gravity of a body seeks the lowest possible level.
6. A body is in equilibrium under the action of its weight when its center of gravity cannot descend to a lower level. This is the case when the vertical line through its center of gravity passes within the base or through the point of support.
7. The stability of a body is greater, the greater the weight of the body and the greater the vertical distance through which its center of gravity must be lifted in tipping it over.
8. The force of gravity acts between a body and the earth

in such a way as constantly to pull the earth and the body toward each other.

9. A body pulls upward on the earth as hard as the earth pulls downward on the body.

10. To every action there is an equal and contrary reaction.

11. Mass means quantity of matter. When a force acts to produce motion, the greater the mass, the slower the motion.

12. Inertia is the inability of a body to change its condition of rest or motion.

13. Every body in the universe attracts every other body and is attracted by them all (universal gravitation).

QUESTIONS

1. Why do you believe that a ball that has been thrown up in the air will come down again?
2. (a) Mention some other things which you are certain will happen.
(b) State why you believe that your predictions will come true.
3. If you hold a large book on your hand, what evidence of the force of gravity do you get?
4. Why is a plumb line useful in building houses?
5. What direction is "vertically downward" to a person who is on the opposite side of the center of the earth? Show by a diagram the position in which he stands compared with your own.
6. Is there any up or down in space apart from the idea of the center of the earth? What direction would be "down" to an inhabitant of the planet Mars?
7. How must a boy place himself so as to lie flat across a horizontal bar? At what point may the entire weight of the boy be supposed to act?
8. What is meant by the center of gravity of a body?
9. Why does a man lean forward when climbing a hill and backward when descending?
10. How does an empty rocking chair act when tipped forward and let go? Explain its action.
11. How would you find the center of gravity of an empty pasteboard box? Prove the correctness of your method.
12. Why does the tumble jack (Fig. 7) insist on standing upright? Compare it with a heavily ballasted sail boat.
13. Where is the center of gravity of a football? Of a tennis racket? Of a derby hat?

14. Why does the pencil in Fig. 8 insist on standing upright while the one in Fig. 6 insists on tipping over?

15. Why is it easier to balance a china bowl on the end of the finger when the bowl is upside down than when it is right side up?

16. Why are racing automobiles made with wheels wide apart? Why is the engine of a boat or automobile placed low down?

17. Why is it safer to sit down in a canoe than to stand up in it?

18. Why are ink bottles often made cone-shaped and with thick bottoms?

19. Describe and explain the action of a marble on a level table. Of a wheel supported on a fixed axle.

20. Make diagrams and explain the relative stability of a brick in three different positions.

21. Is the stability of a box greater when it is empty or when it is full of a heavy substance? Why?

22. If a freight car is to be loaded with kegs of nails and crated sewing machines, how should the load be packed in order that the car may be as stable as possible?

23. A jar is full of water. If a quart of sand is poured into it, some of the water overflows. Is the jar more stable or less stable when the sand is in it? Why?

24. Compare the action of gravity with that of a stretched elastic cord, when connecting (a) two bodies of equal mass, (b) two bodies of unequal mass.

25. When an apple falls from a tree does the earth move toward the apple? If it does move why do we not perceive the motion?

26. What is the correct position in dismounting from a street car? Why?

27. What is the correct position in turning a corner on a bicycle? What is likely to happen in this case if the pavement is wet and the speed is not slackened? Why?

28. Explain some facts similar to the one just mentioned about the bicycle, question 27. (For example, in connection with (a) a circus ring, (b) a railway curve.)

29. Why does an automobile tear up the surface of a road? Why does the mud fly off the wheel? Describe the direction in which the mud flies.

30. Why does a ball roll farther and straighter on a smooth sidewalk than on rough ground? If the sidewalk were very long and perfectly smooth and level, and if the ball were perfectly round and smooth, what would the ball do if started rolling?

31. Place a marble on a card that rests on the rim of a tumbler. You can snap the card away and the marble will fall into the tumbler. Explain.

32. What can you tell about Newton and universal gravitation?

PROBLEMS

1. Given a carpenter's square and plumb line, how can you find out whether the blackboard molding is horizontal?
2. Make a careful examination of a beam balance or of any other form of balance in the laboratory or in a drug or grocery store, and explain how it differs from the balanced ruler (Art. 3) and how it resembles it.
3. Is the center of gravity of a balance beam above, below, or at the line of support? Explain how you found out.
4. Explain why the Leaning Tower of Pisa does not tip over.
5. Explain why a tall slender vase is more likely to be tipped over than a short thick one.
6. Give reasons for the following familiar facts: (a) a man stands in a moving street car with his feet apart, (b) one climbing a step-ladder is more careful not to lean back as he nears the top.
7. If you were alone on a perfectly smooth and slippery horizontal floor at a place near its center, how would you get off? If two boys were there how could they both get off?
8. A fast skater collides with a slow one. Who gets the worse bump?
9. How can you start yourself swinging in a rope swing, or on the rings in the gymnasium, without touching the floor?
10. If all the trains, boats, and animals on the earth should start at a given instant to move eastward and continue moving, would it slow down or hasten the earth's rotation?
11. How might the earth's daily rotation be stopped?
12. How successful was the man who fastened large bellows on the stern of his boat to blow wind into the sail during a calm? If the boat were small how might the bellows be used to move it?
13. Why does a rotary sprinkler rotate?
14. If an electric fan were placed at the rear of a light boat and set in motion, would it move the boat? Would it work better if under the water? Why?

CHAPTER II

WORK AND MACHINES

13. Work. When an expressman lifts a heavy trunk into his wagon he is doing work. The trunk and the earth are being pulled together by gravity, which resists any attempt to separate them. The man, therefore, has to place his hands under the trunk and his feet on the earth and forcibly push them apart, until the trunk has been raised to the desired higher level. If he carries the trunk up stairs he has to do more work than if he merely lifts it into his wagon.

Although we do not as a rule think of it in this way, a man does work whenever he goes up stairs himself, because he is overcoming his own weight in pushing his own center of gravity and that of the earth apart. He readily recognizes, however, that his work is increased when he goes up carrying a pail of water, a package of books, or any other load.

Lifting heavy bodies is not the only thing commonly recognized as hard physical work. Sawing wood, driving nails, hoeing corn, sweeping, scrubbing floors, mowing grass, pumping water, rowing, painting houses, plowing, are all familiar types of work. What do these various activities have in common that makes us class them all as physical work?

A careful analysis shows that in every one of the cases just mentioned something had to be forced some distance against resistance. We thus see that

Work is the action of force through distance.

14. Inclined Plane. Suppose an iceman has to raise a cake of ice (Fig. 15) from the sidewalk into his wagon. Apparently the simplest way is to lift it vertically. But the ice is too heavy for the man to lift. So he gets a plank,

and rests one end of it on the sidewalk and the other on the back of the wagon. He is now able to push the ice up this



FIG. 15 AN INCLINED PLANE

“inclined plane.” The inclined plane is a simple machine. With its help, the man accomplishes an otherwise impossible task.

Is work saved by this machine, or must more work be done by it than if the ice were lifted vertically into the wagon? This question can be answered only by measuring the work done, in each case, and then comparing the results. Before we can make such measurements, we must agree on convenient units in terms of which the forces, distances, and amounts of work may be measured.



FIG. 16

15. Units of Force. The most familiar unit of weight is the pound, which is “the weight in the latitude of London and at sea level of a certain piece of platinum kept in the Standards Office” and known as the British Standard Pound Avoirdupois.

Weight may be measured with a common spring balance, which consists of a coiled spring armed with a pointer that moves over a scale (Fig. 16). This scale forms the front of the case in which the spring is inclosed. It is graduated by hanging on copies of the standard pound, so that it reads pounds-weight and fractions thereof.

Weight acts in a vertical direction; but we can push

or pull horizontally or in any other direction; i. e., a force may act in any direction. Since a spring balance may be used in any direction, force may be measured in pounds by the stretch it produces on a spring balance, the scale of which has been graduated to read pounds-weight, as described above. Hence the definition

A pound-force is any force that stretches a spring balance as far as a pound-weight does.

The pound-force is the unit of force in the British system of weights and measures which is used in the commerce and industries of all English speaking countries; but, on account of its greater simplicity, the "metric system" is everywhere used by physicists and chemists. In his experiments the student will often be required to measure forces with gram-weights and distances with a centimeter rule. *A gram-force is any force that stretches a spring balance as far as a gram-weight does.*

16. Units of Work. Since work is the action of force through distance, and since the British unit of force is the pound, and the unit of distance is the foot, the British unit of work is the foot-pound.

The foot-pound is the work done when a force of one pound acts through a distance of one foot.

Similarly the metric unit of work is the gram-centimeter.

The gram-centimeter is the work done when a force of one gram acts through a distance of one centimeter.

17. Measuring Work on an Inclined Plane. In order to answer the question raised in Art. 14, it is not necessary to measure the force acting on the ice and the dimensions of the inclined plane. We can discover the principle involved by constructing a small model and making measurements on it. For this purpose let the ice (Art. 14) be represented by

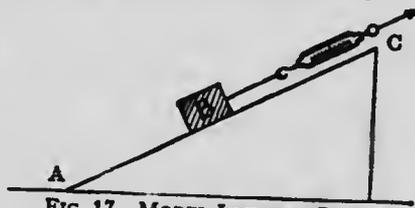


FIG. 17 MODEL INCLINED PLANE

the wooden block B (Fig. 17), which weighs 3 pounds; and let the plane be represented by the board AC , 4 feet long, with one end on the table and the other end supported 2 feet above the table.

To find the number of foot-pounds done in lifting the center of gravity of the block vertically through the 2 feet, we reason as follows:

3 pounds-force lifted 1 foot (3×1) = 3 foot-pounds.

3 pounds-force lifted 2 feet (3×2) = 6 foot-pounds.

For other forces and other distances the reasoning is the same; hence in general we may say that the amount of work is obtained by multiplying together the number of units of force and the number of units of distance or *displacement*—provided always that the force and the displacement are measured in the same direction and in the same system of units.

We abbreviate this rule by writing it

Foot-pounds = Pounds-force \times Feet.

Gram-centimeters = Grams-force \times Centimeters.

Work = Force \times Displacement.

To measure the work done in pulling the block along the plane, up to the height of 2 feet, we attach a spring balance to it and pull it upward along the plane. While the block is moving, we read on the scale of the balance the number of pounds-force that we are exerting, taking care always to keep the balance moving uniformly and parallel to the plane and also to change the position of the eye so as to look squarely at the scale as the balance moves along the plane.

In this case we find that the force indicated by the spring balance is less than 3 pounds, the weight of the block. Suppose it is $2\frac{1}{4}$ pounds. The work is now done by a force of $2\frac{1}{4}$ pounds acting through 4 feet along the plane; therefore, the amount of work is

Work = Force \times Displacement

Work = $2\frac{1}{4}$ (pounds) \times 4 (feet)

Work = 9 foot-pounds.

This is 3 foot-pounds more than was done in lifting the load vertically through the same height.

These figures answer our question. We find that we actually do more work and not less when we push or pull a body up an inclined plane than when we lift it vertically through the same height. The advantage in using the plane lies in the fact that if the body is too heavy to be lifted vertically, the plane enables us to do the work by means of a smaller force exerted through a greater distance.

In doing a given amount of work, the less the force the greater the distance.

18. Useless Work. We had 6 foot-pounds of work to do in getting the block to the desired height, but 3 foot-pounds had to be done to accomplish this with the help of the inclined plane. It was the friction of the block against the board that made it necessary to do the 3 foot-pounds of extra or useless work.

If we mount the block on wheels, and cover the plane with a strip of plate glass, the friction is much reduced, and the force required to pull it uniformly up the plane is found to be about 1.6 pounds. Therefore, the work now done along the plane is

$$\text{Work} = 1.6 \text{ (pounds-force)} \times 4 \text{ (feet)} = 6.4 \text{ (foot-pounds)}.$$

Laboratory experiments with the inclined plane, like the one just described, may be conducted under such conditions that the effects of friction are nearly eliminated. Such experiments, made with various weights and with planes of various heights and lengths, all lead to the following conclusion:

The useful work got out of the machine (work out) is never greater than the total work put into it (work in): in any ideal case, with perfect apparatus, the work got out would be exactly equal to that put in. If we call the force exerted along the plane the effort, and the weight lifted the resistance, this conclusion for the ideal case may be briefly written:

Work out = Work in.

Resistance \times Height = Effort \times Length.

This statement is commonly known as the *Law of the Inclined Plane*. In using it we must always remember that it is strictly true only when there is no friction.

The law of the inclined plane is useful in solving many problems that arise in practical work; for if, of the four factors, resistance, effort, length, and height, any three are known, the fourth may be found by simple arithmetic.

For example, suppose the ice (Art. 14) weighs 200 pounds, that the end of the plank is 3 feet above the sidewalk, and that the plank is 12 feet long. Neglecting friction, how many pounds-force must be exerted in pushing the ice into the wagon?

$$\begin{aligned} \text{Resistance} \times \text{Height} &= \text{Effort} \times \text{Length}, \\ 200 \text{ (pounds-force)} \times 3 \text{ (feet)} &= x \text{ (pounds-force)} \times 12 \text{ (feet)} \\ \text{Hence the effort } x &= \frac{200 \times 3}{12} = 50 \text{ pounds-force.} \end{aligned}$$

Fifty pounds is therefore the least force that may be applied to move the ice uniformly and without friction, up the inclined plane. In the practical case, in which there is friction, a greater force must be used. Hence, for the inclined plane,

Work out is never greater than work in.

With no friction, Work out = Work in. (Work principle.)

19. Work Done With a Fixed Pulley. A single pulley is often attached to a firm support as shown in Fig 18, and used merely to change the direction of a pull. In this case the student may readily find by actual trial and measurement that if the weights of two masses of metal *P* and *Q* are equal, they will balance each other. Since just half of the wheel and also half of the total weight is on each side of the axis, and since they are symmetrically placed with reference to it, the case is similar to that of the balanced ruler (Art. 3).

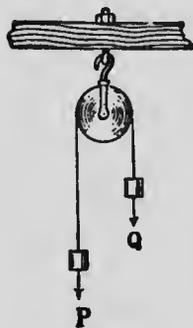


FIG. 18

If Q weighs 90 pounds, and its center of gravity is lifted steadily through 1 foot, the work got out of the pulley in doing this is 90 pounds-force \times 1 foot = 90 foot-pounds. If this work is done by pulling at P , the weight that measures the necessary effort is a little more than 90 pounds. Suppose the required effort is 100 pounds-force: then, since P must descend through 1 foot in order to lift Q 1 foot, the work put into the pulley is 100 pounds-force \times 1 foot = 100 foot-pounds. We find, therefore, as in the case of the inclined plane, that less work is actually got out of the machine than is put in.

From common experience it is natural to suppose, as in the preceding case, that part of the 100 foot-pounds of work put in was employed in overcoming friction and the stiffness of the cord. By perfecting the apparatus and reducing the evident sources of friction, the difference between the work put into the device and that got out of it may be made very small. With the pulley, then, as with the inclined plane, we may conclude that the work done by the device is never greater than the work done on it, but that in the ideal case of no friction or other resistance—

$$\text{Work out} = \text{Work in.}$$

$$\text{Resistance} \times \text{its displacement} = \text{Effort} \times \text{its displacement.}$$

20. Efficiency. In the experiment just described, we found that when we put 100 foot-pounds of work into the pulley we were able, under the given conditions, to get out but 90 foot-pounds; i. e., the useful work got out is 90% of the total work put in. The extra 10 foot-pounds of work put in is useless work.

If the useful work got out of a machine is a large fraction (or per cent.) of the entire work put into it, the machine is said to be very efficient; and this fraction (or per cent.) is used as a measure of its efficiency.

The efficiency of a machine is the ratio of the useful work got out of it to the total work put into it: or more briefly,

$$\frac{\text{Work out}}{\text{Work in}} = \text{Efficiency.}$$

Since the work got out is never greater than the work put in, the efficiency can never be greater than unity; in real cases it is always less than unity.

The definition of efficiency tells us how its numerical value may be found. Determine the work got out and the work put in (both being expressed in foot-pounds or both in gram-centimeters) and divide the former by the latter.

The pulley just considered had an efficiency of 90%, i. e., only 90% of all the work put in comes out in useful form, while 10% of the whole amount employed was done in overcoming internal resistances. This internal work serves no useful purpose, and is therefore waste. It is apparent that the efficiency of a machine is a matter of great economic importance; and any one who discovers a way to increase the efficiency of machinery confers a benefit on mankind.

21. Single Movable Pulley. A fixed pulley enables us to change only the direction of a force. It does not enable us to overcome a large resistance with a small effort as the inclined plane does. We must, in fact, use an effort that is greater than the resistance in order to secure the convenience of pulling in a different direction. With a movable pulley or a combination of movable and fixed pulleys the case is different.



FIG. 19

Fig. 19 represents a fixed pulley combined with a single movable pulley on which is suspended a heavy body Q . First note that the cord is doubled at the movable pulley where the resistance acts; therefore, the end of the cord at which the effort is applied must travel 2 feet for every 1 foot that the center of gravity of Q is lifted. Verify this statement by measuring the distances through which the end of the cord fastened to P travels when the center of gravity of Q is lifted 1

foot, 2 feet, etc. Suppose the weight of Q is 40 pounds. This weight is the resistance to be overcome. Then attach to the end P (Fig. 19) of the cord some body whose weight is just sufficient to keep Q rising with uniform speed after it has been started. The weight of P , which is the measure of the effort, we find to be somewhat more than 20 pounds—say 25 pounds. When the center of gravity of Q rises 1 foot, the work got out is

$$\begin{aligned} &\text{Resistance} \times \text{its displacement, or} \\ &40 \text{ (pounds)} \times 1 \text{ (foot)} = 40 \text{ foot-pounds.} \end{aligned}$$

The work put in is

$$\begin{aligned} &\text{Effort} \times \text{its displacement, or} \\ &25 \text{ (pounds)} \times 2 \text{ (feet)} = 50 \text{ foot-pounds.} \end{aligned}$$

With this combination of pulleys, then, we can overcome a resistance of 40 pounds with an effort of only 25 pounds, but in doing this we do not get out more work than we put in; in fact, we get out 10 foot-pounds less than we put in. After the experience with the inclined plane and the fixed pulley, it is clear that the 10 foot-pounds of unproductive work is expended in overcoming the friction and the stiffness of the cord, and in lifting the movable pulley itself.

If we use pulleys with ball bearings, make the movable pulley as light as possible, and reduce the other causes of friction as far as possible, the useless work may be nearly eliminated. By such experiments, made with various combinations of pulleys, and with various resistances and displacements, we can prove, as in the cases of the fixed pulley and the inclined plane, that *for every ideal case of a combination of pulleys*

$$\begin{aligned} &\text{Work out} = \text{Work in} \\ &\text{Resistance} \times \text{its displacement} = \text{Effort} \times \text{its displacement.} \end{aligned}$$

22. Law of the Pulley. If a man who weighs 150 pounds wants to know whether the pulley (Fig. 19) will enable him to lift a 250-pound stone, he can use the work equation (Art. 21) thus:

Resistance \times its displacement = Effort \times its displacement
 250 pounds \times 1 foot = Effort \times 2 feet.

$$\text{Effort} = \frac{250 \times 1}{2} = 125 \text{ pounds.}$$

Since he weighs 150 pounds, he will be able to lift the stone.

In this case the rope is doubled at the movable pulley; so that the effort must pull the end of the cord through 2 feet for every 1 foot that the resistance moves. Thus when there are two parts of the cord supporting the movable pulley,

$$\text{Resistance} = \text{Effort} \times 2.$$

A similar analysis of cases in which the movable pulley is supported by three, four, or more cords will show that in every case *the value of the greatest resistance that can be overcome with a combination of pulleys is obtained by multiplying together the effort that is applied and the number of cords that support the movable pulley.*

This statement is known as the *law of the pulley*; but like the law of the inclined plane it is only a special case of the general principle that, *with an ideal machine, the work got out is equal to that put in.*

23. The Equal Arm Lever. The lever has been more or less definitely known by all of us from childhood; for nearly every child has played the game of "see-saw," or watched a workman use a crowbar to "pry up" a heavy body.



FIG. 20 THE SEE-SAW

Thus it is known at the outset that if the board (Fig. 20) be balanced at its middle like the ruler in Fig. 2, page 18, its weight is counteracted by the sup-

port or *fulcrum*, and has no influence in turning the board. The effect of friction is very small; so that we may omit the consideration of both the weight of the board and the friction.

If the children sit at equal distances from the fulcrum and if their weights are equal, the board will balance. The two

sides of the see-saw are then symmetrical, just half of it being on each side of the fulcrum. The case is precisely similar to that of the trip scale or equal arm balance (Fig. 21), for in this case also we know from common experience that when the two weights are equal and the arms are equal, the balance will be in equilibrium.

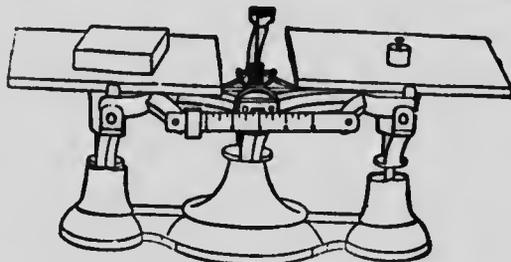


FIG. 21 THE TRIP SCALE

If the see-saw, when balanced with the children on it, as in Fig. 20, be set into motion, work will be done, since the children begin to move vertically. But since the distances of the two children from the fulcrum are equal, it is evident that when the board has been turned through a small angle one rises as far as the other descends, *i. e.*, the vertical displacements of their centers of gravity must also be equal. Because their weights are equal it follows as before that Resistance \times its displacement = Effort \times its displacement.

$$\text{Work out} = \text{Work in.}$$

Thus the lever also acts in accordance with the work principle.

24. Lever With Unequal Arms—First Kind. In the case of the see-saw shown in Fig. 22, the child at one end of the board is able to lift two children, each of his own weight, on the other side, because he is seated twice as far from the fulcrum as they are; and therefore when the see-saw moves, he moves through a vertical displacement which is twice as great as that of the two children.



FIG. 22 LESS FORCE. GREATER ARM

This is like the case in which a man uses a lever with a long effort arm (Fig. 23) to lift a stone whose weight is greater than the force that he applies. To find out how much force x must be applied by the man at the end c in order to

lift a 500-pound stone at the other end b , represent the lever by the straight line bc (Fig. 24). When the man applies the



FIG. 23 THE LEVER

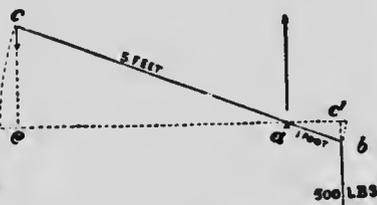


FIG. 24 THE LEVER DIAGRAM

force vertically downward, his hand moves through a vertical displacement ce , while the center of gravity of the stone rises through a vertical displacement bd . Since this ideal lever acts in accordance with the work principle we have,

$$\begin{aligned} \text{Work out} &= \text{Work in} \\ 500 \times bd &= x \times ce. \end{aligned}$$

The values of bd and ce may be determined by direct measurement. However, because the triangles abd and ace are similar, bd and ce are proportional to the arms of the lever ab and ac . Since the arms are more easily measured, it is convenient to use them instead of the displacements. If in the diagram ab represents 1 foot, and we find by measurement that $ac = 5ab$, then ac represents 5 feet. Whence

$$\begin{aligned} \text{Resistance} \times \text{its arm} &= \text{Effort} \times \text{its arm} \\ 500 \times 1 &= x \times 5 \\ x &= 100 \text{ pounds-force.} \end{aligned}$$

From a careful study of this example we see that the mechanical advantage obtained with the lever does not lie in a gain of work, for we actually lose a very little work in overcoming friction and other resistances. It lies in the fact that we may alter the relative magnitudes of the two factors of work (force and displacement) so as to make the force less in any desired ratio, provided we increase the displacement in the same ratio. To state this in another way with special reference to the lever, we may say that *the resistance that may be overcome with a lever is as many times the effort required as*

the effort arm is times the resistance arm. This statement is commonly called the *Law of the Lever*.

25. Lever of the Second Kind. Sometimes a lever is used as shown in Fig. 25. In this case the fulcrum is at one end, the effort is applied at the other end, and the resistance acts at some point between them. A lemon squeezer, or a nut cracker is a lever of this second kind. Let us find how much force must be applied at the effort end of a lever

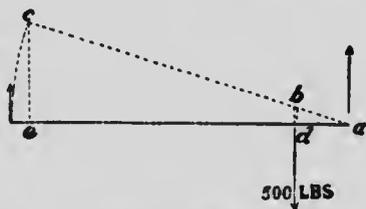


FIG. 25 LEVER OF THE SECOND KIND

6 feet long to lift the 500-pound stone when placed so that its center of gravity is directly over the point *b*, 1 foot from the fulcrum *a*. Since the effort arm is now 6 feet long, and the resistance arm 1 foot long, we have, applying the law of the lever,

$$\text{Resistance} \times \text{its arm} = \text{Effort} \times \text{its arm}$$

$$500 \times 1 = x \times 6$$

$$x = \frac{500 \times 1}{6} = 83\frac{1}{3} \text{ pounds-force.}$$

This problem may also be solved by the work principle (Art. 18). This lever differs from the preceding one in that the effort arm is the whole length of the lever instead of being only a part of it, and that the effort and the resistance act in opposite directions instead of in the same direction.

26. Law of Machines. The work principle has been found to apply to the inclined plane, the pulleys, and the lever. It applies to many other mechanical devices, and so it is often called the *law of machines*. It should be memorized in one of the following forms:

$$\text{Work out} = \text{Work in}$$

$$\text{Resistance} \times \text{its displacement} = \text{Effort} \times \text{its displacement.}$$

27. Force Exerted at the Fulcrum. To know with how much force the fulcrum of a lever must resist when the

lever rests upon it, it is important to note that if the fulcrum of the levers shown in Figs. 20 and 22 is to sustain the seesaw with the children, it must resist the united weights of the children together with the weight of the board itself; and since these weights all act in the same direction, namely, downward, the fulcrum must push vertically upward with a force equal to the sum of all these weights. If the fulcrum pushed up with a force greater than this sum, the entire lever with the children would be lifted upward; if the resistance of the fulcrum were less than this sum they would fall downward.

This fact may be proved by suspending a lever with its

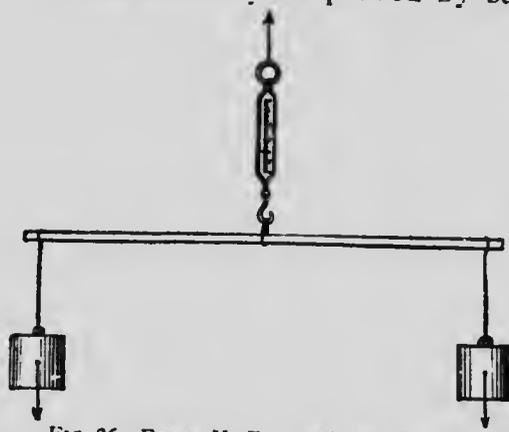


FIG. 26 FORCE UP EQUALS FORCE DOWN

load on a spring balance (Fig. 26). When the lever is not moving bodily upward or downward, the force indicated by the spring balance is just equal to the sum of the weights of the lever and its load. Hence we see that when a rigid body, like a lever, is not moving bodily in a straight line in any direction, the sum of all the forces tending to move it in one direction is equal to the sum of those tending to move it in the opposite direction.

28. The Wheel and Axle. Another type of machine is the wheel and axle. It consists of a large wheel (Fig. 27) and a small cylinder or axle rigidly fastened together and mounted so as to turn about a common axis. In using this machine to draw water from a well, a man pulls on

we see

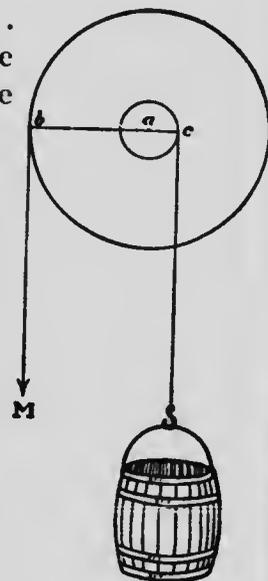


FIG. 27
WHEEL AND AXLE

a rope Mb which has been wound around the wheel so that in unwinding it turns the wheel. The bucket of water is raised by another rope which is wound on the axle at c when the wheel turns. With the aid of the diagram it is evident that for one revolution the displacements of the effort and the resistance are the circumferences of the wheel and the axle respectively, and that the arms of the two forces are the corresponding radii ab and ac . If the bucket of water weighs 40 pounds, and if the radius of the axle is 3 inches and that of the wheel 12 inches, we have for one revolution of the wheel in the ideal case

$$\begin{aligned} \text{Work out} &= \text{Work in} \\ 40 \times 2\pi \times 3 &= \text{Effort} \times 2\pi \times 12 \\ \text{Effort} &= 10 \text{ pounds.} \end{aligned}$$

The law of the lever gives

$$\begin{aligned} 40 \times 3 &= \text{Effort} \times 12 \\ \text{Effort} &= 10 \text{ pounds.} \end{aligned}$$

The law of the lever applies to the wheel and axle and is but a special case of the law of machines.

29. Translation and Rotation. The lever and the wheel and axle differ from the inclined plane and the pulleys in that when they move they turn or rotate about an axis, while in the cases of the inclined plane and the pulleys the motion is in a straight line. Such motion about an axis is called *rotary motion* or *rotation*; and motion in a straight line is called *translatory motion* or *translation*.

In solving problems of the lever we have found it more convenient to use the *arms* of the lever rather than the displacements, although these arms are not always perpendicular to the directions in which the forces act. In order that this term may always have the same meaning, it is defined as follows:—*The arm of a force is the perpendicular distance from the axis of rotation to the line of direction of the force.*

Since the lever and the wheel and axle remain in equilibrium when Resistance \times its arm = Effort \times its arm, this product, force \times arm of force, is a convenient measure of the effective-

ness of a force in producing rotation. This product is called the *moment of force*; hence:

$$\text{Moment} = \text{Force} \times \text{Arm of force.}$$

30. Principle of Moments. Rotation may be either right-handed or left-handed, i. e., clock-wise or counter clock-wise. In order that a lever, a wheel and axle, or any other body mounted on an axis be in rotary equilibrium, it is not enough that the two moments due to the effort and the resistance respectively have the same numerical value; but one must be a right-handed moment tending to turn the body in one direction and the other a left-handed moment tending to turn it in the opposite direction. Hence *a rigid body does not turn about an axis when the moment tending to turn it in one direction is equal to that tending to turn it in the opposite direction.* This statement is known as the *Principle of Moments*. More briefly,

There is rotary equilibrium when Right-handed moment = Left-handed moment.

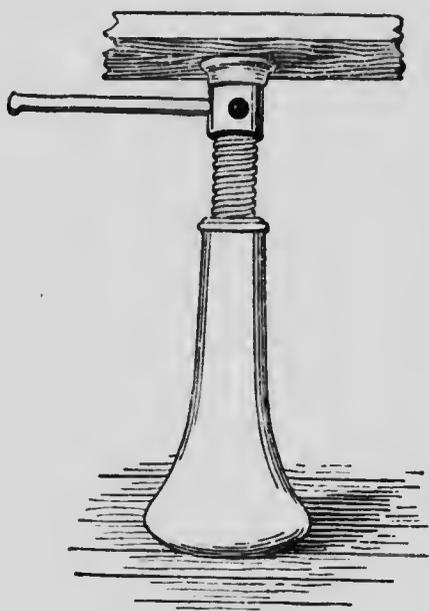


FIG. 23 JACK-SCREW

31. The Screw. The simple machines we have been studying do not enable us to do such heavy work as lifting locomotives or houses. For example, if it is desired to lift a heavy and bulky object like a house, the use of the pulleys, the inclined plane, or the wheel and axle would be inconvenient if not impossible.

The need for doing such work led at an early date to the invention of the screw. Fig. 28 represents a jack-screw such as is used for this purpose. The screw consists of a cylindrical rod of metal

around which there has been cut a groove or thread which rises uniformly a certain distance in every turn about the cylinder. Cut in the iron base or nut is a similar thread which fits the thread of the screw snugly. By reference to Fig. 29 it may be seen that the screw is like an inclined plane wrapped around a cylinder.

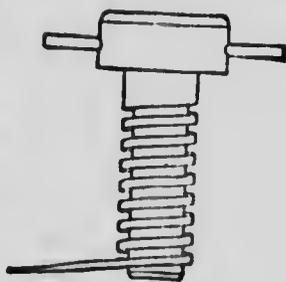


FIG. 29

When the screw is turned once around, it moves upward through a distance equal to that between two successive turns of the thread. This distance is called the *pitch* of the screw. Hence if the top or head of the screw is supporting a weight of 1000 pounds, and if the pitch is 0.05 feet, the work done by the screw when turned once around is 1000 pounds-force \times 0.05 feet = 50 foot-pounds.

A lever may be inserted in a hole in the head of the screw to assist in turning it. Since this lever may be made as long as desired, a small force applied at its end may furnish a large moment of force to turn the screw. Suppose that the length of this lever is 5 feet, let us find what is the least force which must be applied at its end in order to turn the screw when it is lifting the 1000-pound load. The distance through which this force must act is the length of a circumference of a circle of 5-foot radius; i. e., it is $5 \times 2\pi = 5 \times 6.28 = 31.4$ feet. Therefore we have for the ideal case,

$$\begin{aligned} \text{Work out} &= \text{Work in} \\ 1000 \times 0.05 &= \text{Effort} \times 31.4 \\ \frac{1000 \times 0.05}{31.4} &= \text{Effort} = 1.6 \text{ pounds-force.} \end{aligned}$$

In any actual case, the effort would have to be greater than this because of friction. Screws enable us to lift very heavy loads or to produce very large pressures by the application of relatively small forces; therefore they are used in vises and presses of various kinds.

32. Conservation of Work. Every one knows that

if he climbs a hill and coasts down on a sled or a bicycle, some of the work that he did in climbing the hill remains with him when he reaches the bottom and carries him part way up an opposite hill. A child in a swing is a still better example, because in this case the resistance due to friction is less. The work done in raising the center of gravity of the child to a higher level on one side remains with him when he has descended to the lowest level at the middle of his trip, and carries him nearly to the same height on the other side.

In order to discover the principles that are illustrated in such experiences as these, we must produce the phenomena in such a way that the disturbances due to friction are reduced to a minimum. This may best be done by the following experiment, which was first performed by the great Italian philosopher, Galileo (1564-1643).

Make a large pendulum by suspending a heavy ball on a wire from a nail in the wall. The ball will then represent the

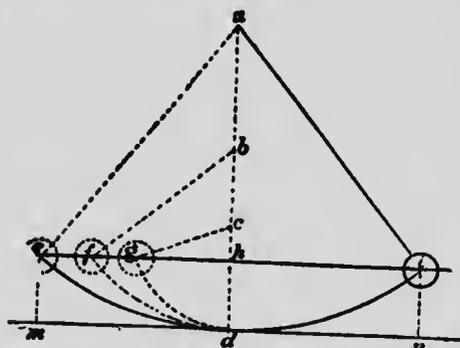


FIG. 30 GALILEO'S PENDULUM

child, and the wire the swing rope. Draw the pendulum bob back and forth, marking the path of its center on the wall (Fig. 30); and, with the help of a carpenter's level, join the ends *ei* of the arc with a horizontal line. Draw another horizontal line *mn* through *d* the lowest point of the arc. If the pendulum bob is now raised till its center is on a level with the upper line *ei*, the work put in is measured by the weight of the bob multiplied by the vertical distance *ni*.

If the pendulum bob is allowed to fall, it descends to the point *d* and rises again until its center is almost but not quite on a level with the line *ei*. Even if we catch the string of the pendulum at some point, as *b* or *c*, so that the pendulum bob rises on the other side of its swing along an arc unlike

that along which it fell, as df , or dg , we find that the center of gravity of the bob does not rise to a higher level than that from which it started. The work thereby got out is measured by the weight of the bob multiplied by the vertical distance me . But since me is never greater than ni , it appears that most of the work put into the bob in lifting it on one side has been stored in the bob during the descent, and got out again when the bob was raised nearly to the same level on the other side. Hence the conclusions:

1. Under the action of gravity alone, the center of gravity of a body never rises to a level higher than that from which it fell.

2. Work done by or against gravity is independent of the path followed and equals weight multiplied by difference of level.

3. Really: Work out is never greater than work in.

4. Ideally: Work out = Work in.

33. **Perpetual Motion Machines.** For centuries inventors have labored to devise a perpetual motion machine, i. e., one that would continue to move forever and to do work without having work done on it. But although thousands of such attempts have been made, none has ever been successful. No one has ever succeeded in making a machine from which he could get out more work than was put in. Therefore the law of machines, namely, that in the ideal case the work out is equal to the work in, has come to be regarded as a universal law of nature. This law finds popular expression in the statement.

"A perpetual motion machine is impossible."

DEFINITIONS AND PRINCIPLES

1. $\text{Work} = \text{Force} \times \text{Displacement}$.
2. In measuring work, force and displacement must be measured in the same direction and in the same system of units.
3. Units of work are the foot-pound and the gram-centimeter.
4. Machines convert small force \times large distance into large force \times small distance, or the reverse.
5. In real machines, work out is never equal to work in.
6. In ideal machines, $\text{Work out} = \text{Work in}$. (Work Principle, or Law of Machines.)
7. $\text{Efficiency} = \frac{\text{Work out}}{\text{Work in}}$.
8. $\text{Moment} = \text{Force} \times \text{Arm of force}$.
9. When Right-handed moment = Left-handed moment, a body does not rotate (Principle of Moments).
10. $\text{Work done by or against gravity} = \text{Weight} \times \text{Difference in level}$.
11. Under the action of gravity alone, a body never rises to a higher level than that from which it fell.
12. A perpetual motion machine is impossible.

QUESTIONS.

1. Mention as many different kinds of mechanical work as you can, and show how each satisfies the definition of work, Art. 13.
2. When you hold a heavy stone motionless in your hand, are you doing mechanical work as defined? Explain your answer.
3. Discuss the scientific knowledge of the old hodcarrier who liked his job because "he only had to carry the bricks to the third story and the man up there did all the work."

4. Where is the reaction that enables you to perform the action of pulling the block B up the inclined plane of Art. 17?
5. If you want to pull a heavy log up the beach with the combination of pulleys in Fig. 19, which pulley would you fasten to the log to get the best effect? Why?
6. A rope passes over a single fixed pulley on the ceiling. A boy on one end is counterbalanced by an iron weight on the other. Explain what happens when the boy climbs the rope hand over hand.
7. A painter sits in a sling that hangs from the movable pulley at Q in Fig. 19. Show whether he moves up or not when he pulls on the end P of the rope.
8. When you shovel coal, do you pull up on the shovel with your left hand as hard as or harder than you push down on its handle with your right?
9. When you sweep a rug with an ordinary broom, does each hand do half the work? If not, show which one does the more.
10. When you cut cardboard with the scissors, why do you open them wide and cut near the pivot?
11. Make a diagram of the whiffletrees of a wagon when arranged so that each of three horses shall pull one third of the load.
12. A man and a boy carry a basket weighing 90 pounds on a pole 3 feet long. When each has hold of his end of the pole, where must the basket be placed so that the man may support 60 pounds and the boy 30 pounds?
13. How is the lever principle applied in rowing a boat?
14. In carrying a pack on a stick over the shoulder, should the pack be carried near the shoulder, or far out on the stick? Why?
15. Explain with a diagram how to use a six-pound flat iron, some strong cord, and a stout 18-inch ruler so as to find the weight of a Christmas turkey.
16. The slider on the trip scale (Fig. 21) is used to determine weights from 5 grams down to 0.1 gram. Explain how this is done.
17. How can the boys on the seesaw (Fig. 20) start it most easily without touching the ground? Explain why.
18. Hold a meter stick horizontally in front of you by resting its ends on the index fingers of your two hands. Draw your hands together so that the stick remains horizontal as the fingers slide under it. Explain why the fingers meet in the middle of the stick.
19. The two blocks of stone shown in Figs. 10 and 13 have the same weight. If you pull up on the left hand edge when you turn them on end as indicated, on which do you have to pull the harder?
20. On which stone do you do the more work in turning it up on end? Why?

21. If in lifting the stone of Fig. 10 you always pull at right angles to its lower face, why do you have to pull with less force the farther the stone is turned? Illustrate with a diagram.
22. Why do door knobs make it easier to unlatch doors?
23. Why does some weight have to be placed on the lower end of a tall ladder when it is being raised to lean against a house?
24. What is the easiest way of raising a telegraph pole into the vertical position without machines to help?
25. Why must the hinges on a farm gate 9 feet wide and 3 feet high be stronger than those on a door of the same weight but 3 feet wide and 7 feet high?
26. When you whittle with a knife, how and where does the handle press on your hand?
27. Why is it a good plan to build railway stations on slightly elevated ground so that the tracks slope gently up to it on both sides?
28. Why is the end board of a wheelbarrow placed as near the wheel as possible?
29. A jar is two-thirds full of water. When you pour sand in until the jar is full, what happens to the center of gravity of the water?
30. What is the source of the work done in changing the center of gravity of the water in question 29?
31. If you drop a marble on the sidewalk from an elevation of 4 feet, why does it not bounce as high as four feet?
32. What do you have to do to the marble in question 31 to make it bounce higher?
33. What is a perpetual motion machine?
34. Why do we say that the man who tries to invent perpetual motion machines is wasting his time?
35. Who was Galileo? What were his most important discoveries?

PROBLEMS

1. A laborer carries 1000 pounds of brick up to a bricklayer working 20 feet above the ground. How much useful work does he do?
2. The laborer mentioned in problem 1 makes 20 trips. If his hod weighs 10 pounds and he weighs 170 pounds, how much useless work must he do?
3. If instead of going up the man hoists the brick with a single pulley in a bucket that weighs 30 pounds, and the bucket makes 10 trips, how much useless work does he save by using the bucket and pulley instead of going up himself?
4. Neglecting all useless work not mentioned in problems 2 and 3, calculate the efficiency of the pulley method of raising the brick and also that of the hod method, and compare the two efficiencies.

5. A boy who can exert a push of 50 pounds along an inclined plane tries to push a 200-pound bag of cement on to a platform 3 feet above the ground. He uses for an inclined plane a plank 8 feet long. (a) Will he succeed? (b) What is the length of the shortest plank with which he will be able to accomplish the work?
6. A smooth road up a hill rises 1 foot in every 10 feet of its length. Neglecting friction, what is the combined weight of a wagon and the heaviest load that can be pulled up the hill by a horse that can pull along the plane with a force of 250 pounds?
7. A boy has a sailboat that weighs 2000 pounds, and wishes to haul it up on a beach that slopes 1 foot in 5. He has some planks, some rollers, a pair of pulleys having 2 sheaves (i. e., wheels) each, and a long rope. Show by diagram and explanation how he can pull the boat up if he is able to pull on the rope with a force of a little more than 100 pounds.
8. If the boy of problem 7 has no pulleys, explain with the help of a diagram some form of wheel and axle or windlass that he might rig up in order to help him do the work.
9. The pitch of the screw of a bench vise is $\frac{1}{4}$ inch and the handle of the vise is 1 foot long. Neglecting friction, with what force would the vise squeeze a board if a man turned the end of the handle with a force of 20 pounds?
10. A crowbar is 5 feet long. Where must the fulcrum be placed in order to pry up a stone weighing 400 pounds by means of a force of 100 pounds exerted at the handle end of the crowbar?
11. When you pull a nail with an ordinary claw hammer, what is the arm of the effort and what that of the resistance?
12. If the resistance arm of the hammer of problem 11 measures 2 inches and the handle is 12 inches long, how much resistance is offered by a nail that requires a force of 25 pounds applied at the end of the handle and perpendicular to it, to pull it out?
13. The length of a bicycle pedal crank is 7 inches and the radius of the front sprocket is 4 inches. When the crank is horizontal and you push down on the pedal with a force of 4 pounds what is the pull on the chain?
14. The radii of the rear sprocket and the rear wheel of a bicycle are 1.4 inches and 14 inches respectively. When there is a pull of 7 pounds on the chain, what is the push back on the road, disregarding friction.
15. With the bicycle of problems 13 and 14, when you push down on the pedal when the crank is horizontal, with a force of 6 pounds, how hard does the wheel push back on the road, disregarding friction?
16. When it requires a force of 80 pounds to lift the handles of a wheelbarrow and the vertical line through the center of gravity of the

barrow and load intersects the bottom of the barrow one-third of the distance between the axle and the handles, what is the weight of the barrow and its load?

17. Two men whose combined weight is 320 pounds have to raise a safe that weighs 1280 pounds to a second story window. What sort of a combination of pulleys will enable them to do it?

18. A bucket used to lift coal from a boat to a dock, weighs 60 pounds and carries 300 pounds of coal each trip. What is its efficiency?

19. Suggest a plan for saving some of the useless work done on the bucket in problem 18.

20. If you weigh 120 pounds, how much work do you do when you go up a flight of stairs 10 feet high?

21. When you come downstairs, do you get back the work done in going up?

22. The hammer of a pile driver weighs 2500 pounds and is lifted 20 feet. How much work is done on it?

23. If the hammer in problem 22 is dropped on the head of a pile, how far will the pile be driven if the average resistance of the pile is 25,000 pounds?

CHAPTER III

MOTION

34. Characteristics of Motion. A man is seated in a slowly moving railway train. How shall we describe his motion? The man by his side might say that he was at rest; another passing him in a faster train moving in the same direction might think that he was going backward; while a pedestrian by the wayside would say he was going forward at a certain speed. Which description is correct?

They are all in some sense correct, because a motion may appear very different from different points of view. A body's motion can be detected and described only when there are other bodies with respect to which it moves. If a body were alone in space, would it be possible to tell whether it were at rest or in motion? Could we tell whether or not our sun is moving rapidly, carrying all the planets with it, if there were no "fixed" stars? A body's motion is always described with respect to some other bodies which are arbitrarily selected as convenient points of reference, and then regarded as stationary. In practical life motions are usually described with reference to points on the earth's surface, which are then considered to be at rest.

This method of describing motions by referring them to some neighboring bodies or points of reference that are then regarded as fixed is a most convenient one for simplifying problems that would otherwise be too complicated to solve. For example, consider the case of a man walking along the street. If we were to describe his motion in full, we should have to take account of the daily rotation of the earth, its yearly revolution about the sun, and any possible motion of the sun, in addition to his personal motion. Such a descrip-

tion, if possible, would be of no practical value for the purposes of daily life. We need only note (1) that the man passes a certain fixed object, as a lamp post on the street, at a certain time; (2) that he moves in a certain direction with reference to the street; and (3) that he moves with a certain speed. For all practical purposes, his motion is then fully described.

Thus, if the man passes the lamp post on the street at 10 a. m. and moves east at the uniform rate of 4 feet a second, we can tell just where he will be at the end of any given number of seconds. For example, at five seconds past 10, he will be $5 \times 4 = 20$ feet east of the lamp post.

The fixed point where the center of gravity of the body is when we begin to consider its motion is called the *origin or point of reference*. The *direction* is determined with reference to a chosen set of points, which are then considered to be at rest. *The speed is the rate of motion.*

Origin, direction, and speed are the three characteristics of motion.

35. Uniform Speed. When we say that the speed of a man is uniform and equal to 4 feet per second, we mean not only that he passes over 4 feet during each second, but also that he passes over 1 foot during each quarter second, $\frac{1}{4}$ foot during each $\frac{1}{4}$ second, and so on. It is perhaps unnecessary to state that no man can walk with a speed that is exactly uniform, nor can he walk exactly in a straight line. Most of the motions that we call uniform are only approximately uniform.

A body has a uniform speed when it passes over equal distances in equal time intervals.

36. How Speed is Measured. When a boy runs 300 feet in 10 seconds at a uniform speed, he moves at the rate of $\frac{300 \text{ (feet)}}{10 \text{ (seconds)}} = 30$ feet per second. Similarly the speed of any moving body may be measured in miles per hour or in centimeters per second. Hence *the numerical value of a speed*

may be found by dividing the distance traversed by the time taken to traverse it. More briefly

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}.$$

This equation defines the magnitude of a uniform speed exactly. Since most speeds are variable, the equation is generally used to calculate the *average speed* of a body that is moving at a varying rate. The Twentieth Century Limited train travels from New York to Chicago, a distance of 990 miles, in 18 hours. During this time it makes a number of stops, so that at different times it is running at speeds that vary from zero up to 60 or 70 miles per hour. Its average speed in miles per hour, however, is all that we care to know ordinarily. Thus

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}; \frac{990 \text{ (miles)}}{18 \text{ (hours)}} = 55 \text{ miles per hour,}$$

the average speed between New York and Chicago.

The average speed is the uniform speed that would enable a body to traverse a given distance in the same time that was actually required to traverse it with the varying speed.

37. The Sum or Difference of Motions. When a man walks in a moving car, he moves with reference to the car, while the car carries him along the track. He therefore has at the same time two independent motions. How does he move with reference to the track? Let us begin to consider his motion at the instant when he is directly over a certain stake that has been driven into the roadbed. If the car is moving northward with a speed of 16 feet per second, and if the man walks toward the front of the car with a speed of 4 feet per second, it is evident that, at the end of one second, he will be $16 + 4 = 20$ feet northward from the stake.

Thus when two motions are in the same direction, they produce the same effect as would a single motion which has that same direction and whose speed is equal to the sum of the two speeds.

Suppose, on the other hand, that the man walks toward the

rear of the car, and that the speeds are the same as in the first case. Then at the end of one second the man will be $16 - 4 = 12$ feet northward from the stake.

This process of finding a single motion that produces the same effect as several independent motions is called the *composition of motions*. The motions that are combined are called the *component motions*. The single motion that would produce the same effect is called the *resultant motion*.

The resultant of two motions in the same direction has their common direction and a speed equal to the sum of their speeds; the resultant of two motions in opposite directions has the direction of the greater and a speed equal to the difference of their speeds.

38. Composition of Motions at Right Angles. Now consider that the man walks eastward across the northward moving car, the two component speeds being the same as before. In this case it is evident that at the end of one second the man will have been carried northward 16 feet, and at the same time will have gone eastward 4 feet across the car; i. e., each component has produced its full effect. The new position at the end of the second will therefore be neither due north nor due east of the point of reference on the track, but will lie somewhere between these two directions. Also his distance from the point of reference will be less than 20 feet—i. e., the resultant speed will be less than the sum of the two component speeds. Since this problem cannot be solved by simple arithmetic, we shall have to use another method which is simple and of wide application.

39. The Graphic Method. On a sheet of paper, starting at any convenient point representing the origin or point of reference, draw a line in the direction of the first motion, making it of such length as to represent the first motion on a scale of convenient size. Thus, in Fig. 32, the point of reference is represented by the point O , and the distance the man travels eastward in one second by the line Ox , which is drawn to the

right on the scale 1 inch = 8 feet. As the distance represented is 4 feet, and as each foot is to be represented by $\frac{1}{8}$ inch, Ox must be $\frac{1}{2}$ inch long. The point x then, represents the point at which the man would have arrived in one second if the car had remained at rest. But the car, in which he was walking eastward, was at the same time moving northward at the rate of 16 feet a second; and so its motion must be represented by the line Oy drawn toward the top of the paper and $\frac{16}{8}$ inches long. If the two motions took place one after the other, the man would have followed either the path represented by Oxp or that represented by Oyp , arriving at the point represented by p in two seconds; but the two motions were simultaneous, so the man was carried northward 16 feet *while* he was walking eastward 4 feet. He therefore actually reached the point represented by p in one second. Moreover, since he was going both eastward and northward *at every instant*, his actual path was neither the broken line Oxp nor the broken line Oyp : but was that represented by the straight line Op . The line Op therefore represents the resultant motion both as to direction and as to distance per second, i. e. as to speed.



FIG. 32

Now although we have found the line Op which *represents* the resultant motion in both direction and speed, we have not yet finished our problem; because *we have not yet found the numerical value of the speed*. To do this we must measure Op and multiply its length by the scale number.

In this case the scale number is 8, because on the scale that we adopted 1 inch = 8 feet. Measuring Op we find it to be $2\frac{1}{8}$ inches long, and since each inch represents 8 feet, the actual distance traveled by the man in one second because of the two simultaneous motions is $2\frac{1}{8} \times 8 = 16.5$ feet. So 16.5 feet is the distance per second, i. e. the speed of the resultant motion. The resultant motion has the direction indicated by the line Op a little east of north.

A line that represents the direction of a physical quantity such as a motion or a force should always be tipped with an arrowhead so as to show which of the two possible directions is meant (Fig. 32).

The graphical solution is based on the principle that each of the component motions produces its full effect in the resultant motion.

40. Parallelogram of Motions. This graphical method of finding the resultant of two motions that are neither in the same nor in opposite directions is often called the *parallelogram of motions*. It may easily be seen (Fig. 32) that the figure $Oxpy$ is a parallelogram of which two adjacent sides Ox and Oy , drawn from the origin O , represent the two component motions; and that the diagonal Op , drawn from the same point, represents the resultant. Op is called the *concurrent diagonal* because it starts from the same point O where the two motions start. We may now state the rule for finding the resultant of two motions.

41. The Parallelogram Rule. 1. *Choosing a convenient scale, represent the two component motions in direction and speed by two lines.* 2. *Taking these two lines as adjacent sides, complete the parallelogram and draw the concurrent diagonal.* 3. *Measure the diagonal and multiply its length by the scale number to find the numerical value of the speed.*

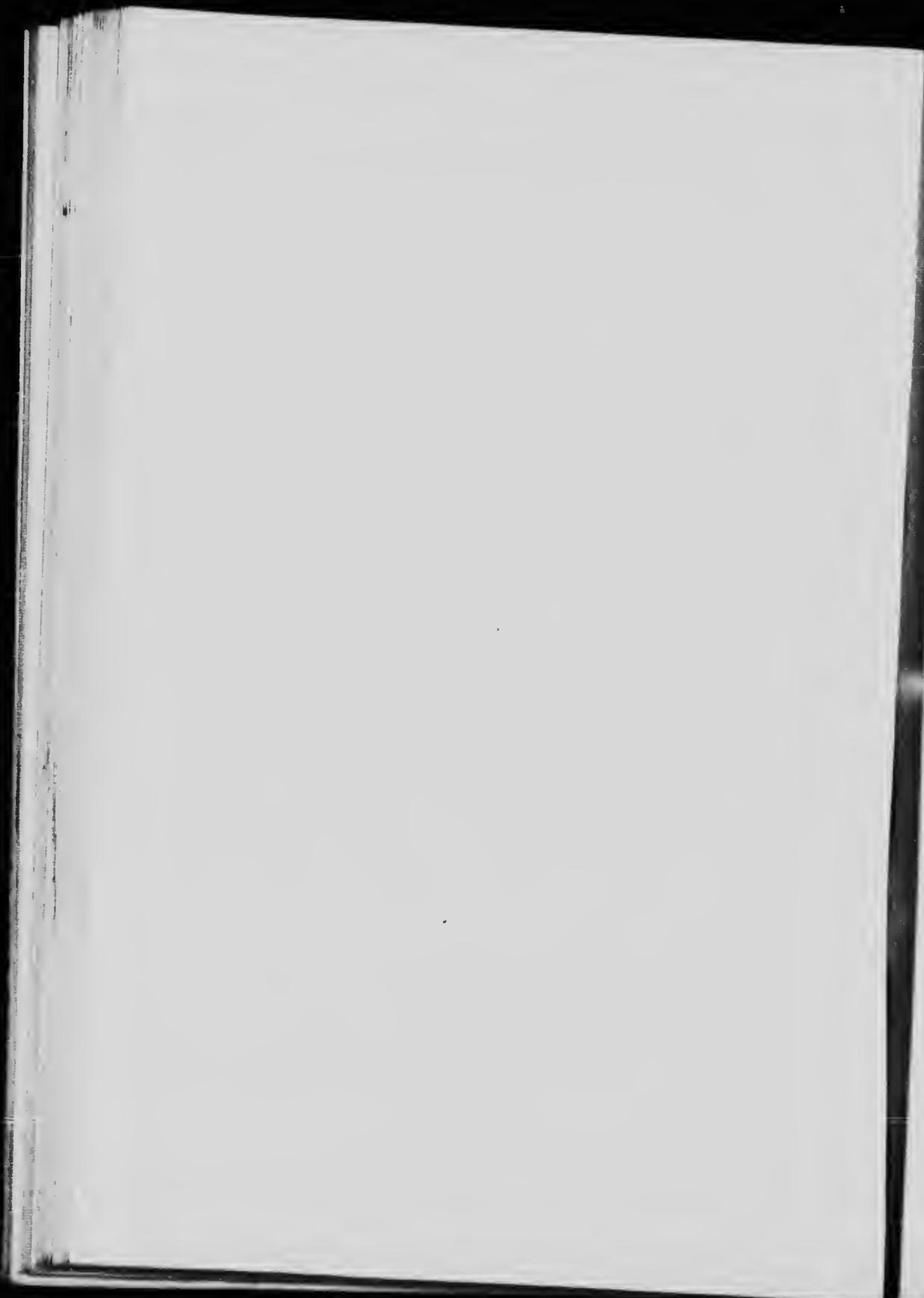
42. Composition of More Than Two Motions. If there are three or more component motions, the resultant of the whole group may be found by first finding the resultant of any two, then the resultant of that and any one of the remaining components, and so on, till all the components have been considered. Thus in Fig. 33, the resultant of Oa and Ob is Od ; and the resultant of Od and Oc is Oe . Hence, Oe represents the final resultant of all three motions Oa , Ob , and Oc . It makes no difference either in what order the components are combined, or whether or not they lie in the same

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PLATE I A TRAVELING CRANE





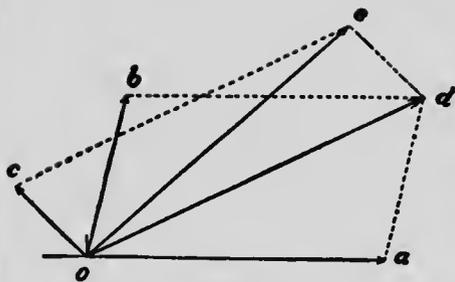


FIG. 33

plane as in this figure. The same rule applies to all cases. This construction is possible because *each component motion produces its full effect in the resultant motion.*

43. Traveling Crane. The composition of three motions is illustrated by a device used in shops where heavy castings or other massive objects have to be lifted and carried from one position in the shop to another. This device (Plate I) is called a traveling crane, and it consists of a steel bridge whose ends rest on little motor cars which run on tracks supported by the side walls of the shop, so that the crane can traverse the shop from one end to the other. The bridge also carries another track, along which another motor car can run across the shop from one side to the other, while the object to be carried may be lifted to any desired height by means of a pulley hanging from the bottom of this car. The motor cars and pulley are operated by electricity, steam or compressed air; and the operator, who rides in the "cage" suspended below the crane, controls them by levers, so that the car carrying the pulley may be made to move either across or along the shop while the weight is being raised or lowered by means of the pulley. Thus the weight may move vertically while the car carries it horizontally across the shop, or the crane may also at the same time carry the weight horizontally along the shop. Therefore, with this device it is possible to combine motions in three directions at right angles to each other.

44. Resolution of Motions. In Art. 18, we learned that the work done against gravity in pulling a body up an inclined plane is equal to that done in lifting the body vertically through a distance equal to the height of the plane. This same result can be obtained in the following way: The

motion of the ice up the plane may be regarded as the resultant of two motions, one horizontal along the sidewalk, and the other vertical into the wagon.

Neglecting friction, practically no work is done in moving the ice horizontally (Art. 32); therefore the work done in sliding the ice up the inclined plane is equal to that done in lifting the ice vertically into the wagon.

The process just considered, in which *an actual motion is conceived to be the resultant of two component motions and is resolved into these components, is called the resolution of motions.* The actual motion is said to be resolved into its components.

To resolve a motion into two components, we must not only know the magnitude and direction of the motion to be resolved, but also either (1) the directions of both components, or (2) the magnitudes of both; or (3) the direction of one and the magnitude of one. Unless these additional data are determined the problem is indeterminate, since any number of parallelograms may be constructed on a given line as a diagonal.

Any motion may be resolved into component motions.

45. Composition and Resolution of Forces. Forces, like motions, have three characteristics, namely, point of application, direction, and magnitude. So it is evident that a force may be represented by a line drawn to scale just as a motion can, the beginning point of the line representing the point of application, the direction of the line the direction in which the force acts, and the length of the line the magnitude of the force. Hence we can construct a *parallelogram of forces* and find the resultant when the components are given; or conversely, the components when the resultant is given, using the same rules that we used for the composition and resolution of motions. To state the rules for the composition and resolution of forces, substitute in the former rules (Art. 41) the word "force" whenever the word "motion" occurs and the word "magnitude" whenever the word "speed" occurs.

Since forces are fully described by the same characteristics

as motion, namely, point of application, direction, and magnitude; and since forces may be compounded and resolved just like motions, it follows also that *each component force produces its full effect in the resultant force.*

Throughout this chapter emphasis has been laid on the fact that when component motions or component forces are combined into resultants, each component produces its full effect. This fact is often called Newton's second law of motion, which is stated thus:

A force has the same effect in producing motion, whether it acts on a body at rest or in motion, and whether it acts alone or with other forces.

46. Work by an Oblique Force. One example will suffice to illustrate the resolution of force. Suppose a boy pulls

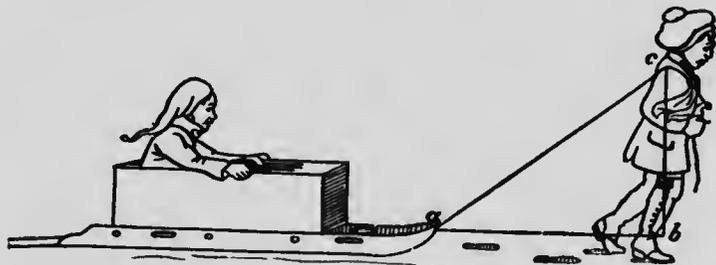


FIG. 34 THE HORIZONTAL COMPONENT DOES THE WORK

a loaded sled along a level road by a rope over his shoulder (Fig. 34). In this case the rope indicates the direction in which the boy pulls, but the sled moves horizontally. We have learned that in measuring work, both the force and the distance must be measured in the same direction. We, therefore, conceive that the boy's pull is composed of two component forces—one horizontal, which does the work, and the other vertical, which lifts up on the front of the sled, but is useless so far as horizontal motion is concerned.

Suppose the boy pulls on the rope with a force of 5 pounds, that the rope is five feet long, and that the end on the boy's shoulder is 3 feet higher than the end at the sled. Half of

the parallelogram for this problem is represented in Fig. 34, the scale used being 1 inch = 4 pounds-force. Hence ac is $\frac{5}{4}$ inch long, and bc is $\frac{3}{4}$ inch long (because the force and the rope have the same direction and the rope rises 3 feet in 5). In measuring ab it is found to be just 1 inch, so the horizontal component of the boy's force is 4 pounds. Therefore for every foot he pulls the sled along the level road, the useful work done is 4 (pounds-force) \times 1 (foot) = 4 foot-pounds.

47. Parallelogram of Forces—Experimental Proof. Fig. 35 shows how the principle of the parallelogram of forces may be verified experimentally. The forces on the spring balances a and b are taken as components, and the parallelogram is constructed according to the rule, on a scale of $\frac{1}{8}$ inch = 1 pound-force. It is then found that the diagonal represents a resultant force of 10 pounds. That this 10 pounds is the correct value of the resultant is proved by the fact that a 10 pound-force is required to produce equilibrium with it. This force is measured by the balance c .

48. Equilibrant. A single force which will just neutralize the effect of a given group of forces is called the *equilibrant of those forces*. *The resultant and the equilibrant of any group of forces are equal and opposite, and act in the same straight line.*

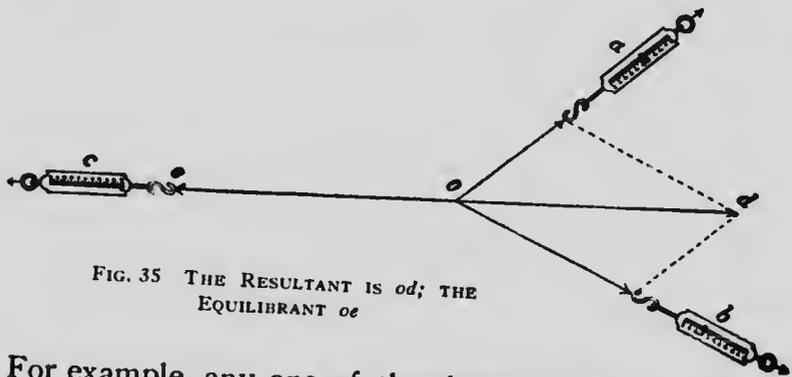


FIG. 35 THE RESULTANT IS od ; THE EQUILIBRANT oc

For example, any one of the three forces exerted by the spring balances a , b , and c (Fig. 35) is the equilibrant of the

other two. Also, c is equal and opposite to the 10 pound-force (represented by the diagonal od) that is the resultant of the two forces a and b .

49. Newton's Laws of Motion. The principles of force and motion that we have been studying in the preceding chapters were summarized by Newton in the following statements, which first appeared in his celebrated *Principia* in 1687. They are known as Newton's Laws of Motion.

1. *Every body continues in its state of rest or of uniform motion in a straight line, except in so far as it is compelled by force to change that state.* (Art. 11.)

2. *A force has the same effect in producing motion, whether it acts on a body at rest or in motion, and whether it acts alone or with other forces.* (Art. 45.)

3. *To every action, there is always an equal and contrary reaction, or the mutual actions of any two bodies are always equal and oppositely directed.* (Art. 9.)

The fact that these laws enable us to predict what will happen under given circumstances not only confirms our belief that they are true, but also enlarges our conceptions of the perfect regularity of Nature. As their meaning becomes clearer, we appreciate more and more the fundamental fact that there is no such thing as an isolated body or action, but that

Everything in the universe is so related to every other thing that not one of them moves without producing an effect, however slight, on them all.

DEFINITIONS AND PRINCIPLES

1. Origin, direction, and speed are the three characteristics of motion.

2. A body has a uniform speed when it passes over equal distances in equal time intervals.

3. Uniform or average speed = $\frac{\text{Distance}}{\text{Time}}$.

4. The resultant of two motions in the same direction has their common direction and a speed equal to the sum of their speeds.
5. The resultant of two motions in opposite directions has the direction of the greater and a speed equal to the difference of their speeds.
6. If two simultaneous motions are represented by two adjacent sides of a parallelogram, the resultant is represented by the concurrent diagonal.
7. Any motion may be resolved into component motions.
8. Point of application, direction, and magnitude are the three characteristics of a force.
9. The principles for the composition and resolution of forces are the same as those for the composition and resolution of motions.
10. A force has the same effect in producing motion whether it acts on a body at rest or in motion, and whether it acts alone or with other forces.
11. Everything in the universe is so related to every other thing that not one of them moves without producing an effect, however slight, on them all.

QUESTIONS AND PROBLEMS

1. What is the world's record for 100-yard dash? How may the speed be determined from the record?
2. If you drop a stone from the rear platform of a moving train, does it strike the ground directly under your hand? Explain.
3. If you stand on the rear platform of a moving train and throw a stone backward with the same speed with which the train is going forward, how does the stone move with reference to the track?
4. Is it easier to walk toward the front or toward the rear of a train when it is running at a high uniform speed?
5. Is it easier to begin walking in a train moving uniformly or in one at rest?
6. Why do we not feel the motion of the earth?
7. Why can you jump farther in a running broad jump than in a standing jump?
8. Why is it easier to ride a bicycle with the wind than against it?

9. If one marble be snapped horizontally from the top of a table and another be dropped from the same height at the same instant, which reaches the floor first? Why?
10. Why does lowering the handles of a wheelbarrow make it easier to go over a bump?
11. Why is it easier to push a baby carriage over bumps when the wheels are large than it is when the wheels are small?
12. When a hunter tries to shoot a flying duck, does he aim directly at it? Why?
13. When shooting at a distant target, a marksman has to aim above the target. Why?
14. Why does a strong side wind interfere with a game of tennis? How should it be allowed for?
15. Why do raindrops make inclined streaks on the window panes of a moving railway car?
16. When a man pushes on a lawn mower in the direction of the inclined handle-bar, into what two components is his push resolved?
17. In pushing a lawn mower rapidly through long grass why does a boy lower the handles?
18. When a fish line with a sinker on it is thrown into a swift stream, the pull of the sinker on the line is the resultant of what two forces? What force is the equilibrant of these two forces?
19. What are the three forces that act on a kite when it is "standing" in the air?
20. What relation must the resultant of any two forces have to the third?
21. Represent by a parallelogram the two forces that support a person who sits in a hammock, and draw the line that represents their resultant.
22. Into what two components is the weight of a wagon descending a hill resolved?
23. A boy flying a kite runs with a speed of 20 feet per second, and the kite rises vertically at the rate of 15 feet per second. Find the resultant speed of the kite.
24. With a diagram show by the resolution of forces why a kite ascends vertically when it is pulled against a horizontal wind.
25. A wind strikes the sail of a boat at an angle of 45° , with a pressure of 2 pounds per square foot. What is the effective pressure perpendicular to the sail per square foot?

CHAPTER IV

PRESSURE IN FLUIDS

50. Water Supply. In the country, wells and springs, when properly located and cared for, may furnish a safe and plentiful water supply for household purposes; but in large cities this is not the case. The problem of providing a plentiful supply of pure water for all purposes, with a pressure sufficient to force it to the tops of tall buildings, is therefore one of the most important of all the problems that a city government must solve. There are two methods of distributing the water; (1) by a gravity system; (2) by a pumping system.

51. Gravity Systems. When a city is so fortunate as to have a lake or reservoir of pure water at a level that is considerably higher than the tops of its highest buildings, it can use a gravity system of water supply. Large pipes called *mains* are laid from the elevated lake or reservoir to the city; and smaller mains branching from these are laid in all the streets. Still smaller pipes, called *service pipes*, lead from the street mains into the houses, and these in turn have branches through which the water flows to the taps or faucets in the different rooms. The water flows through this series of pipes, and is ready to rush out with considerable force through any faucet that may be opened. We say the water does this because it is "under pressure." In order to get a clearer idea of what this statement means, we now take up the study of pressure in fluids, and the methods used in producing and controlling it.

52. Force and Pressure. Let a water-tight cubical box (Fig. 36), that measures exactly one foot along each edge inside, be placed on a horizontal table and filled to the brim

with water. The weight of a cubic foot of water is 62.5 pounds; and therefore the cubic foot of water in the box will press on the bottom with a force of 62.5 pounds. This force will be distributed uniformly over the 144 square inches of its area. Each square inch of the bottom will therefore sustain $\frac{1}{144}$ of the whole weight of the water; or $\frac{62.5}{144} = 0.434$ pounds. Since the force on each square inch of the bottom is 0.434 pounds, the bottom of the box is said to be under a pressure of 0.434 pounds per square inch.

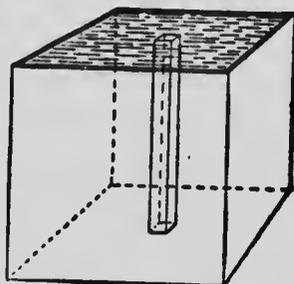


FIG. 36 A CUBIC FOOT OF WATER WEIGHS 62.5 POUNDS

Pressure is force per unit area. It is measured in pounds-force per square inch; or, in grams-force per square centimeter.

53. Pressure and Depth. The cubic foot of water may be thought of as consisting of 144 columns of water, each having a base of 1 square inch and a height of 1 foot, like that shown in Fig. 36. Each square inch on the bottom of the box supports the weight of one of these columns of water, i. e. 0.434 pounds. If the water were only one inch deep, each column would be only $\frac{1}{12}$ foot high, and would weigh only $\frac{0.434}{12} = 0.0362$ pounds. The pressure on the bottom would then be 0.0362 pounds per square inch. If the water were 2.3 feet deep, a column having a base of one square inch would weigh $0.434 \times 2.3 = 0.998$; or, approximately, 1 pound. Therefore, the pressure in water at the depth of 2.3 feet is about 1 pound per square inch.

The relation of pressure to depth in water is numerically simpler when the metric units are used, because one cubic centimeter of water weighs one gram. Reasoning just as before, we find that the pressure in water at a depth of 1 centimeter is 1 gram per square centimeter; at a depth of 10 centimeters it is 10 grams per square centimeter, and so on.

Thus the pressure at any depth in water is due to the weight of the overlying water. It amounts to 1 pound per square inch for every 2.3 feet of depth, or 1 gram per square centimeter for every centimeter of depth. Hence the conclusion:

In water with a free upper surface, the pressure at any depth is proportional to the depth.

54. Pressure and Density. This conclusion would not be true if a cubic inch of water below the surface, where it is under pressure, weighed more than one near the surface. If more water were squeezed by pressure into the space of a cubic inch, the compressed water would weigh more, i. e., would be *more dense* than it was before. But water cannot be compressed appreciably; so a cubic inch of it always weighs about 0.0362 pounds, whether under pressure or not.

The weight per unit volume of a substance is called its density.

A cubic inch of mercury is found to weigh 13.6 times as much as a cubic inch of water. So also a cubic centimeter of mercury weighs 13.6 times as much as a cubic centimeter of water. In other words, the density of mercury is 13.6 times that of water. Therefore, a column of mercury 1 square inch in cross-section and 1 inch high (i. e. 1 cubic inch) weighs $0.0362 \times 13.6 = 0.49$; or, approximately, 0.5 pounds. So also a column of mercury 1 square centimeter in cross-section and 1 centimeter high (one cubic centimeter) weighs $1 \times 13.6 = 13.6$ grams. Hence, reasoning just as with the water, we find that, since mercury also cannot be compressed, the pressure in mercury at rest is 0.5 pounds per square inch for every inch of depth; or 13.6 grams per square centimeter for every centimeter of depth. *The pressure in mercury is thus proportional to the density as well as to the depth.*

Similarly a unit volume of alcohol weighs nearly 0.8 as much as the same volume of water. Alcohol cannot be appreciably compressed, so the pressure in alcohol is $0.0362 \times 0.8 = 0.029$ pounds per square inch for every inch of depth. *The pressure in alcohol is proportional both to the density and to*

the depth. The same reasoning applies to all other liquids. Hence the conclusion:

In any liquid with a free surface, the pressure at any depth is proportional both to the depth and to the density of the liquid.

55. Pressure Independent of Size and Shape of Vessel.

A column of water 2.3 feet high, with a base of $\frac{1}{2}$ a square inch, weighs $\frac{1}{2}$ pound; but the pressure at the bottom is not half a pound per square inch. It is *half* a pound per *half* square inch. Half a pound was the weight of the water borne by half a square inch when the column had a base of 1 square inch. Therefore, the pressure is at the rate of one pound per square inch, just as in the case of a column with a larger base. If the base of the column were 2 square inches, the pressure would be 2 pounds on 2 square inches, or one pound on each inch as before.

Several connecting tubes of various sizes and shapes are filled with water as shown in Fig. 37. If the water in the larger tube produced a greater pressure, the water in the smaller tubes would be pushed up, and the tops of the columns of water would not all be on the same level. When the

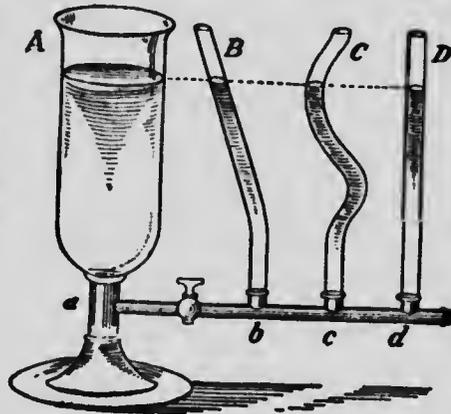


FIG. 37 THE FLUID STANDS AT THE SAME LEVEL IN ALL

water comes to rest after the vessel has been filled, the tops of the columns are all at the same level. The same result is obtained if the vessels are filled with alcohol, oil, mercury, or any other liquid. Therefore;

In any liquid with a free surface the pressure at any given point is independent of the shape and size of the containing vessel, and of the amount of liquid that it contains.

56. Pressure is Independent of Direction. In the experiment just mentioned, the weight of the liquid in the vessel A

causes a pressure vertically downward at the bottom of the tube. This pressure, however, acts horizontally through the connecting tube ab , and balances the pressure produced at b by the liquid in the tube B . This is found to be true always, no matter in what direction the connecting tubes at the bottom may lead, and no matter whether the fluid used is water, oil, alcohol or any other liquid.

The same conclusion follows also from the established fact that a perpetual motion machine is impossible. For if at any point in a liquid at rest the pressure were greater in one direction than in any other, the liquid would move in the direction of the greater pressure. Currents would thus be set up in the liquid; and these currents might be used to drive paddle wheels, so that work would be got out without putting any in. This, we know, is contrary to all experience.

The pressure at a given depth in a liquid at rest is the same in all directions.

We can now understand why the water in the pipes of a gravity system of city water supply is under pressure. The pipes are at a lower level than the surface of the water in the reservoir. The pressure is therefore due to the weight of the overlying water; and, since the pressure does not depend on the shape or size of the containing vessel, or on the direction of the pipe, but only on the difference in level, it makes no difference whether the reservoir is near at hand or far away, so long as the water is at rest. We can therefore determine differences in level in a town, by measuring differences in pressure on the water mains when the water is at rest.

57. Calculation of Liquid Pressure. The principles explained in the last few paragraphs lead to the following rule: **To calculate the pressure at any depth in any liquid, multiply the density by the depth.**

In using this rule the following points should be carefully observed. 1. The depth must be measured on a vertical line drawn from the given point to the level of the free surface of the liquid. 2. If the density is given in pounds per cubic

foot, the depth must be expressed in feet; and the pressure will be in pounds per square foot. 3. If the density is given in pounds per cubic inch, the depth must be expressed in inches; and the pressure will be in pounds per square inch. 4. If the density is given in grams per cubic centimeter, the depth must be expressed in centimeters; and the pressure will be in grams per square centimeter.

58. Pressure Gauges. The principles just discussed suggest a ready means of measuring pressures at faucets. If we fasten a vertical tube to the faucet and note how high the water rises in it, the pressure is 1 pound per square inch for every 2.3 feet that the water rises. This method is convenient for measuring small pressures, but it is impracticable for measuring the pressure of the city water; because this pressure is 30 to 50 pounds per square inch, or even more; so the water column would have to be 70 to 115 feet high in order to measure it.

A shorter tube will serve if we use a denser liquid to measure the pressure. As has just been shown, mercury is such a liquid, a column of mercury 1 inch high giving a pressure of $\frac{1}{2}$ pound per square inch, and a 30 inches high, a pressure of $\frac{1}{2} \times 30 = 15$ pounds per square inch. A mercury column is an *open mercury manometer* (Fig. 38).



FIG. 38 *ab* MEASURES THE PRESSURE

For measuring fluid pressures greater than 15 pounds per square inch, a pressure gauge (Fig. 39) is usually preferable to a mercury column. The fluid whose pressure is to be measured is admitted through the pipe *A* into the curved metal tube *BDE*, which is somewhat flattened so that it has an elliptical cross section. When filled with a fluid under pressure, such a tube tends to straighten itself, because this allows it to become larger in volume. In doing this, the end *E* moves to the right, and turns the hand before the dial. By comparison with a mercury manometer, the scale on the dial is graduated to read pounds per square inch. This type of gauge is much

used on steam boilers, hot water heaters, force pumps, and other machines where it is necessary to watch the pressures.

59. Tap Pressures. If now we measure the pressure of the water at different taps in the school building, by means of a mercury manometer or a pressure gauge, we find that the pressure is greatest in the basement, and that it gradually diminishes as we go up to higher floors. By this means, the pressure will be found to change in just the manner that the foregoing discussion leads us to expect, i. e., about 1 pound per square inch for every 2.3 feet difference in level; increasing as we go down, and decreasing as we go up.

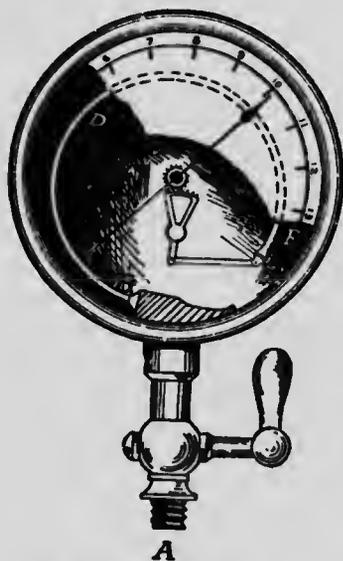


FIG. 39 PRESSURE GAUGE

This change in the water pressure is due to the weight of the water column in the pipes above the level of the taps. From the observed pressures it is easy to calculate how high we could go before we reached an elevation where there would be no pressure at all.

60. Pressure Variations Because of Flow. The principles just discussed are true for water at rest. Most of us have been annoyed, when trying to draw water from a tap on one of the upper floors of a house, by having the water suddenly stop running because some one had opened a faucet on a lower floor. On summer evenings, when lawn sprinklers are being used freely about the neighborhood, the water usually fails to flow from faucets higher than the second floor. But late at night, when little water is being used and few taps are open, the pressure makes the water flow forcibly again.

In order to see how the pressure changes when the water is flowing, let the apparatus shown in Fig. 40 represent a gravity

system of water supply. R is the reservoir; IO , the supply pipe; and the vertical tubes at a , b , and c , are the pipes that carry the water up into the buildings. The heights of the water in these vertical tubes indicate the pressures in the supply pipe at the points a , b , and c .

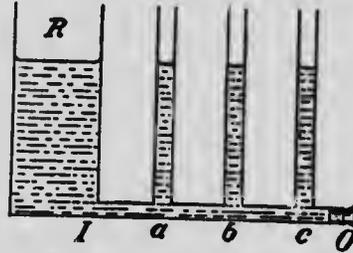


FIG. 40 NO FLOW: UNIFORM PRESSURE

When the water is not flowing from the end O , it stands in all the vertical tubes at the same height as it does in the reservoir R . This indicates that when no taps are open, the pressure all along the supply pipe is the same as it is at the end I , through which the water is supplied (cf. Art. 55). On the other hand, when the end O is open, so the water can flow out there, the pressure is no longer the same at all points along the pipe; but falls off as the distance from the reservoir I increases. This is indicated by the decreasing heights at which the water stands in the vertical tubes a , b , c (Fig. 41). From this illustration it is clear that when water is flowing through a pipe, its pressure gradually decreases, being greatest at the point where it flows in, and least at the opening where it flows out.

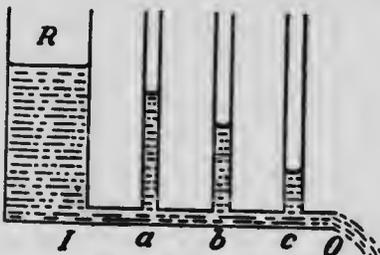


FIG. 41 PRESSURE FALLS WITH FLOW

The experiment just described furnishes a picture of the way the water pressure changes at the taps in the building. When a number of taps are open, the water escapes easily and the pressure in the neighborhood becomes small. Farther away from the open taps the pressure is greater; and when all the taps are closed, the water comes to rest, and the pressure all along the mains becomes the same.

61. Other Systems of Water Supply. The gravity system of water supply is the most economical one when it is available, because the work of moving the water is done by

gravity, which makes no charge for its labor. Some cities, like Denver and Los Angeles, are situated near a satisfactory supply of water at a higher level in the mountains, so that a gravity system is possible. In other cities, like Chicago, St. Louis, and Cleveland, water can be secured only at the expense of work. We may now inquire how this work is done and how it is measured.

62. Wells and Cisterns. In thinly settled districts, the water supply is drawn from individual wells and cisterns.

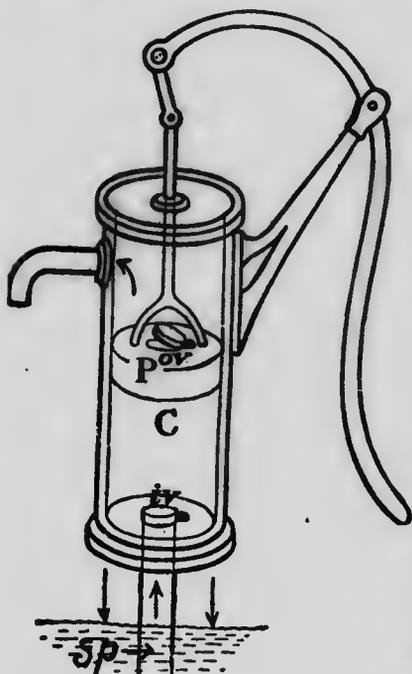


FIG. 42 LIFT PUMP

The work of raising the water from the well was originally done by hand with a pail or bucket on the end of a rope. This simplest of all methods has been made easier by the use of a long lever called a well-sweep; or of a wheel and axle (Fig. 27), a pulley, or a chain pump. The principles on which these devices depend have been discussed in preceding chapters. Because of well-nigh universal experience in raising water from wells, men have come to recognize the fact that work must be done on water if we would raise it from a lower to a higher level. *The useful work done in lifting the water is measured by the product of the*

weight of the water lifted and the vertical distance through which it is lifted.

63. Lift Pump. Besides these primitive and direct methods of lifting water in buckets, there are many machines by means of which this work can be done more conveniently. Among the simplest of these is the ordinary lift pump. This

was known and used in Greece in the time of Alexander the Great (B. C. 350). The diagram (Fig. 42) shows how it is made and how it acts. It consists of a hollow cylinder C at the bottom of which is a valve iv , opening upward like a trapdoor and called the inlet valve. Fitting closely into the cylinder is a piston P , perforated by a hole over which is fitted another valve ov , also opening upward and called the outlet valve. A long pipe sp , called the suction pipe, extends into the water below. When the piston P is lifted, the air in the suction pipe sp pushes up the inlet valve iv , and forces itself into the cylinder C . When the piston starts down, the inlet valve iv closes by its own weight, so that the air inclosed in the cylinder cannot return into the suction pipe. As the piston descends, the air in the cylinder C forces the outlet valve ov open, and passes through the piston. When the piston comes up again, this air is lifted out; and more air is pushed up from the suction pipe into the cylinder. When, after several strokes, all the air has been pumped out of the suction pipe, the water is forced into the cylinder as the piston rises, passes through the piston when it is pushed down, and is lifted out when the piston rises again just as the air was.

But what force is it that pushes the air and the water into the suction pipe, and causes it to lift the inlet valve and flow into the cylinder? The celebrated Greek philosopher, Aristotle (384-322 B. C.), and his followers offered in explanation the saying that "Nature abhors a vacuum"; but the reader will readily recognize that this is no explanation at all.

64. Air Has Weight. Any one who has tried to walk against a stiff breeze, or who has seen the havoc wrought by a gale or a tornado, or watched the windmills spinning around and doing work, must have realized the fact that air, though invisible, is a form of matter just as truly as water and lead are; and that therefore it must have weight. No one seems to have recognized the fact, however, until Galileo proved it by weighing a glass globe, forcing more air into it, and weighing it again. The difference between the two weights, he rightly

ascribed to the weight of the air that had been added. He did not discover that the weight of the air had anything to do with Nature's alleged horror of a vacuum. He was astonished when informed that a lift pump had been made with a suction pipe about forty feet long, and that no amount of pumping would cause the water to rise higher than about thirty-three feet. Since a vacuum remained in the cylinder and upper part of the suction pipe, he was led to remark that "the horror of a vacuum was a force that had its limitations and could be measured by the height of a column of water that it would raise."

Galileo's friend and pupil, Torricelli (1608-1647), took advantage of this suggestion, and concluded that the weight of the atmosphere was the cause of the rise of the water column in the suction pump.

65. Torricelli's Experiment. Reasoning that, since a given volume of mercury weighs 13.6 times as much as the same volume of water, the pressure of the atmosphere ought to be sufficient to balance that of a column of mercury only about one-fourteenth ($\frac{1}{13.6}$) as long as the water column, he caused two of his pupils to carry out the experiment, which has since been known by his name.

A glass tube, about 33 inches long was closed at one end and completely filled with mercury. When the open end of the tube had been closed by the finger, and the tube inverted, it was supported in a vertical position with the open end in a dish of mercury. On removing the finger, the mercury sank down a little way in the tube, and, after a few oscillations, came to equilibrium with the surface of the mercury inside the tube about 30 inches (76 centimeters) above that of the mercury in the dish. The modern barometer is simply one of Torricelli's tubes, conveniently mounted so that it will not get broken.

The atmosphere exerts a pressure equal to that of a mercury column nearly 30 inches high.

66. Why the Water Rises in the Pump. The reason why the water rises in the suction pipe of a pump, and why it does not rise to a greater elevation than about 34 feet, should now be clear. These phenomena result from the fact that a fluid remains at rest when at any given point the pressure is the same in all directions; and that it moves in a particular direction only when the pressure is greater in that direction. Hence when the pressure in the top of the suction pipe is diminished by pumping out some of the air, the pressure of the atmosphere on the water in the well is greater than the air pressure in the suction pipe; so it drives the water up the pipe. The water in the pipe stands at such a height that the pressure at the bottom of the pipe *inside* is equal to the atmospheric pressure *outside*.

67. Pumping Systems. In cities, individual wells and cisterns cannot be used; and when a city has in its vicinity no hills or mountains where a reservoir can be built, it cannot have a gravity system of water supply. In such cases, the water is taken from a lake or river or from large wells and the pressure in the city mains has to be secured by means of pumps.

The ordinary lift-pumps cannot be used for this purpose because the water has to be forced into the mains against the pressure that is due to the columns of water standing in the pipes of tall city buildings.

68. Force Pump. Fig. 43 is a diagram of the simplest kind of pump that is used for this purpose. Machines of this type are called *force pumps*. The force pump differs from the lift pump in that the piston has no hole in it; and the outlet valve *ov* is at the same end of the cylinder as the inlet valve *iv*; but it, of course, opens outward. When the piston *P* is

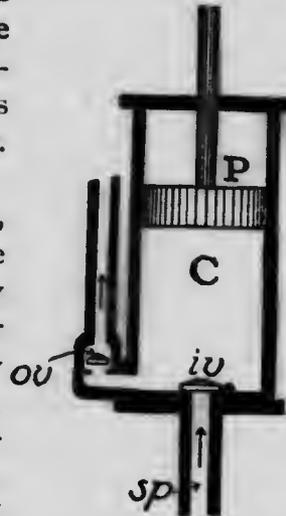


FIG. 43 FORCE PUMP

raised, water is pushed into the cylinder by the atmospheric pressure outside; and when the piston is pushed down, the inlet valve is closed and the water is pushed out through the outlet valve, the pressure depending on the force used in pushing it.

In order to design a pump for a city system we must know what relation exists between the pressure desired in the city mains and the force that must be used in the pumps to produce it. We must also know how the pressure produced by the pump distributes itself through the system of pipes.

69. Pascal's Principle. In order to find the answer to this question return to the model of a gravity system (Art. 60).

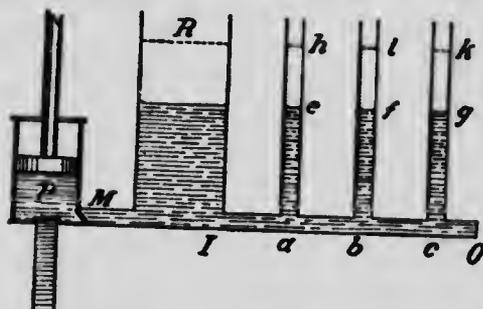


FIG. 44 PRESSURE RISES THE SAME IN ALL

The pressure in the system of tubes will not be changed if we add on one side of the larger tube R another tube M to which is attached the force pump P (Fig. 44). If P is at the same level as the tube IO , the pressure at P is the same as that in IO ; namely, that measured by the height ae , bf , cg of the water columns.

If now the pump P be set to work, water will be forced into the apparatus, causing all the water columns to rise from the level eg to the level hik . The increase in pressure is measured by the rise in level eh , and it is the same for all points in the tubes; i. e., the pressures at P , at O , at a , at e , at g , have all increased by the same amount. Thus the pressure added at P has caused the same increase in pressure at all points in the system of pipes. Hence, when the water is at rest, the pressure due to the pump is transmitted undiminished to all other parts of the system. The effect will be the same if the vertical tubes (Fig. 44) are all closed at e , f , and g , etc. Hence the following conclusion, which was first announced by Pascal and is known as Pascal's Principle.

A pressure exerted on any part of a fluid enclosed in a vessel is transmitted undiminished in all directions, and acts with equal force on all surfaces of equal area, in directions perpendicular to those surfaces.

70. Hydraulic Machines. The meaning of Pascal's Principle may be made clearer by considering its application to a simple machine. Thus, if we have a vessel (Fig. 45) consisting of a large and a small cylinder connected by a pipe and each fitted with a water-tight piston, and if the areas of these pistons are 1 square inch and 100 square inches respectively, then a force of 1 pound exerted upon the smaller piston will produce a pressure of 1 pound per square inch on the larger piston, or a total force of 100 pounds. Thus the total force transmitted to any surface by a fluid is directly proportional to the area of that surface. "Hence" said Pascal, "it follows that we have in a vessel full of water a new principle of mechanics and a new machine for multiplying forces to any degree we choose."

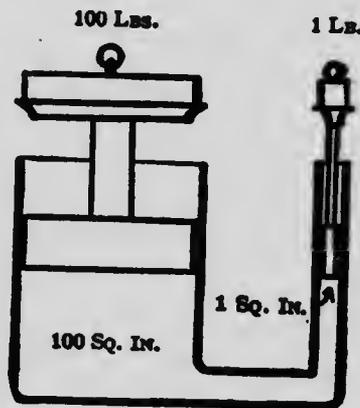


FIG. 45 ONE POUND CAN LIFT 100 POUNDS

71. The Mechanical Advantage of a Hydraulic Machine. Since the pressures on the two pistons are proportional to their areas, the mechanical advantage gained by means of a hydraulic machine of this sort is equal to the ratio of the area of the larger piston to that of the smaller, i. e., *the resistance that may be overcome by the larger piston of a hydraulic machine is to the effort applied to the smaller piston, as the area of the larger piston is to the area of the smaller.*

72. Work Done by a Hydraulic Machine. With regard to the work done it should be noted that if in the example just

mentioned the small piston is pushed through a distance of 1 foot, the large piston will be displaced through only 0.01 foot, because the liquid forced out of the small cylinder into the larger has to spread out over an area 100 times as great. Therefore, if we multiply the forces by the corresponding displacements, we find that the resulting amounts of work are equal. $1 \text{ (pound)} \times 1 \text{ (foot)} = 100 \text{ (pounds)} \times 0.01 \text{ (foot)}$. It can easily be shown that this is true no matter what the areas of the pistons are and no matter what the force and displacement of the smaller piston are; so that *every hydraulic machine conforms to the general law of machines* (Art. 26.)

73. The Hydraulic Press. The principle of Pascal is extensively applied in a class of machines of which the *hydraulic press* (Fig. 46) is a

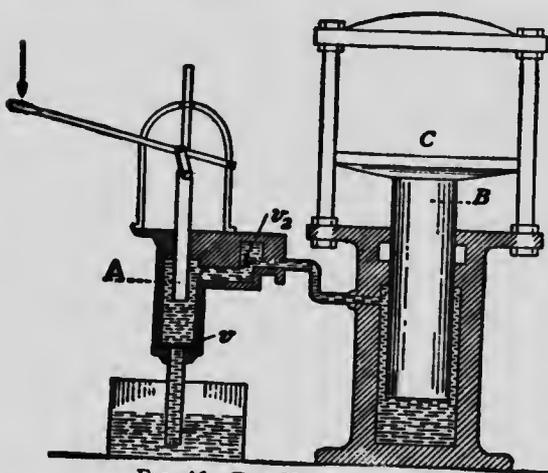


FIG. 46 THE HYDRAULIC PRESS

type. It consists of a large, strong cylinder connected by a pipe with a force pump (Fig. 43). The piston of the large cylinder has an area many times larger than that of the pump. The pump plunger *A* is worked by means of a lever and forces water or oil into the large

cylinder, causing the large piston *B* to rise. Thus a bale of cotton, or whatever substance is to be compressed is squeezed between the pressure head *C* of the large piston, and the heavy frame above it. *Hydraulic jacks*, used for lifting very heavy weights, work on the same principle; and *hydraulic elevators* are operated by the ordinary pressure in the city water mains.

74. Equalizing Pressure. In Art. 60 it has been noted that the pressure in water mains varies as faucets are opened

and closed at different points. In order to allow for these changes, there must be some flexibility or spring introduced somewhere in the system. Water itself is almost incompressible, so the sudden starting and stopping of the flow would cause serious jarring and result in leaky pipes. Two devices for giving flexibility or spring are in common use; (1) the standpipe, and (2) the air cushion.

75. The Standpipe. This is simply a large vertical steel pipe (Fig. 47), open at the top, and connected at the bottom with the city pipe system and the pump. Fig. 44 shows a model of such a system. Since it is open at the top, a sudden flow of water that produces a change in pressure simply raises or lowers the level of the water in the standpipe. The pipe also serves as a reservoir from which the city can be supplied for a time if the pumps break down.

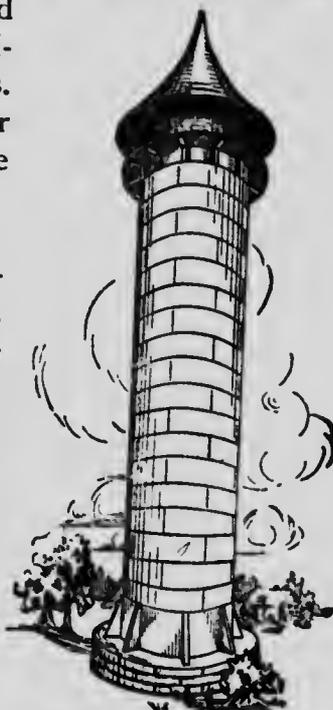


FIG. 47 A TALL PIPE, LARGE PRESSURE

76. The Air Cushion. This consists of a dome-shaped metal chamber filled with air and connected to the water mains as shown in Fig. 48. Unlike water, air is easily compressed; so when the pressure in the pipes changes, the air expands or is compressed, introducing the necessary elasticity into the system. All fire engines, force pumps and atomizers have air cushions, which serve to keep the water flowing continuously between strokes. In houses the water pipes are usually carried a few inches higher than the faucets (Fig. 49), so that the air confined in the closed end may act as a cushion

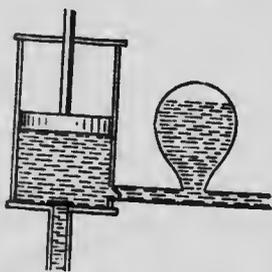


FIG. 48 THE AIR DOME

and take up the shock that would result from suddenly closing a faucet while the water was running. *Fluids, like solids, have inertia, and tend to keep on moving when once they are started.*

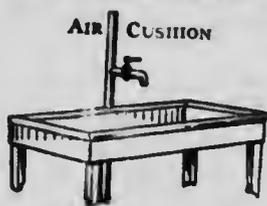


FIG. 49 FAMILIAR AIR CUSHION

77. Spring of Air. Boyle's Law.

In order to understand fully the action of the air cushion it is necessary to find out how the volume of a given quantity of air changes as the pressure changes. The English scientist, Robert Boyle

(1627-91), first discovered the relation we are seeking, and we cannot do better than follow his experiments. He took a glass tube (Fig. 50), "which by a dexterous hand and the help of a lamp, was in such manner crooked at the bottom that the part turned up was almost parallel to the rest of the tube." The shorter leg was closed and the longer open.

Mercury was poured in and the tube tipped and shaken until the mercury stood at the same level ab (Fig. 50) in both legs of the tube. The columns of mercury in the two legs then balanced each other, and the pressure of the air in both was that of the atmosphere. The barometer showed that the atmospheric pressure at the time was equal to 29 inches of mercury. At this pressure the length of the column of air confined in the short leg, ad , was 12 inches. More mercury was then poured into the long leg, till the column h was 29 inches long; so that the pressure on the confined air was increased by 29 inches of mercury, and was therefore twice 29 inches. When the confined air column was under this pressure, its length cd was 6 inches; i. e., when the pressure had been doubled, the volume was reduced to one-half. Another 29 inches of mercury added to h made the pressure three times as great as at first, and reduced the volume of confined air to 4 inches, or one-third; and so on.



FIG. 50 BOYLE'S TUBE

As a result of extended experiments like these, Boyle announced the following law, which has since been verified by a great many experiments, and found to be approximately true for all gases.

The volume of a given mass of gas, at a constant temperature, is inversely proportional to the pressure that it supports.

78. Pressure and Depth in the Atmosphere. When the French philosopher, Pascal (1623-1662), learned of Torricelli's experiments (Art. 65), he reasoned that if one were to ascend a mountain with a Torricellian tube, the mercury column should fall; because the pressure of the air at the greater elevation should be less, since there would be less air overlying the mountain top than there was over the plain. When the experiment was tried, the mercury column was three inches shorter at the top of the mountain, but resumed its previous length when brought down again to the plain. Hence the atmospheric pressure decreases as we ascend.

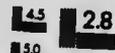
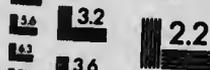
Since air is easily compressed, the atmospheric pressure cannot be proportional to the depth of the air, as it is proportional to the depth in liquids. It is possible to calculate, with the help of Boyle's law, how the pressure changes with the altitude; so that a measurement of the pressure enables us to determine the altitude of mountains. The pressures are measured with a barometer.

79. The Mercurial Barometer. The ordinary mercurial barometer, which is an instrument of great precision and of inestimable practical value, is simply a Torricellian tube in which the dish for the mercury is replaced by a flexible bag of chamois skin. The tube and bag are enclosed in a metal case which is fitted with a very accurate scale, by means of which the height of the mercury column may be measured. Since the height of the mercury varies in direct proportion to the pressure of the atmosphere, this height is taken as a measure of the atmospheric pressure. For example, 29 inches of mercury represents a comparatively low pressure, while 31 inches represents a high pressure.



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Since changes in the weather are caused by the passing of areas of low pressure in the atmosphere, the barometric column falls when one of these areas is approaching, and rises again when the low pressure area passes and a high pressure area takes its place.

By means of barometers and other instruments, read simultaneously at scores of stations. the United States Weather Bureau officials are able to map the weather conditions of the entire country every eight hours; and thus, as the areas of low or of high pressure travel across the country, taking with them their characteristic weather conditions, the forecast official announces by telegraph the probable time of their arrival at any given place and the kind of weather that may be expected to accompany them. These weather forecasts and storm warnings, which would be impossible without the barometer and thermometer, save many lives and much property annually.

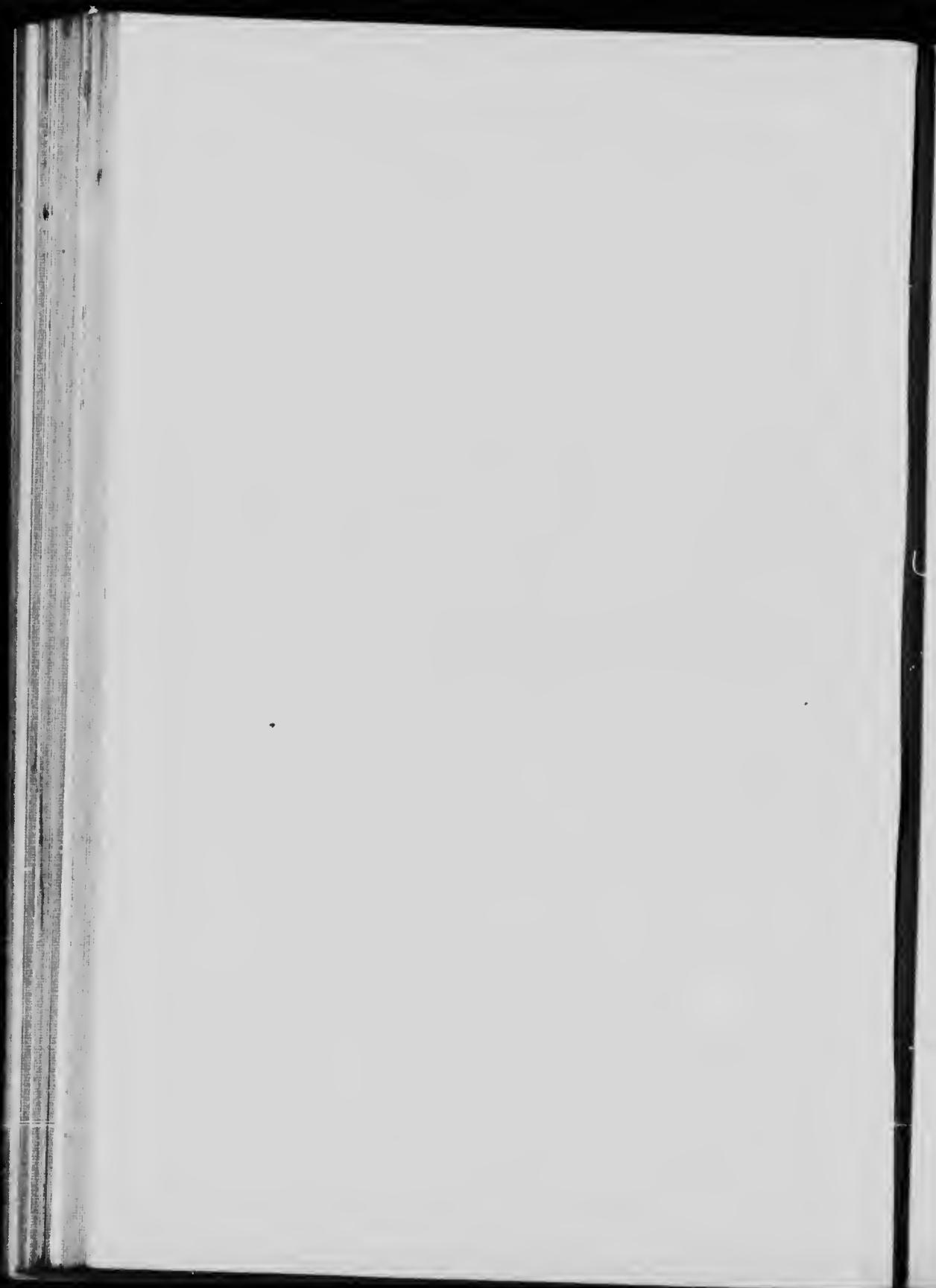
80. Calculation of Atmospheric Pressure. Since the pressure of the atmosphere exactly balances the pressure of a column of mercury having a certain length, we can calculate this pressure in pounds per square inch by calculating the pressure due to the weight of this mercury column. Thus, at sea level, the average height of the barometer column is 30 inches; and, since a column of mercury 1 inch high gives a pressure of nearly 0.5 pound to the square inch (Art. 54), *the average pressure of the atmosphere is approximately $0.5 \times 30 = 15$ pounds to the square inch.*

This pressure amounts to a little more than one ton per square foot; or to 1 kilogram per square centimeter. Like pressure in liquids it is the same in all directions at a given point.

81. The Magdeburg Hemispheres. The phenomena of atmospheric pressure were very thoroughly investigated by Otto von Guericke (1602-1686), an eminent civil engineer, and burgomaster of Magdeburg. Guericke made many experiments, one of the cleverest of which was that of pumping the



PLATE II THE MADDEBURG EXPERIMENT



air out of a pair of hollow iron hemispheres having smooth rims which fitted very accurately together. When the air was pumped out of these, it was found, as Guericke expected, that great force must be exerted in order to separate them; because the pressure due to the weight of the air held them together. This experiment was made by Guericke in the presence of Emperor Ferdinand II and the Reichstag, with hemispheres 1.2 feet in diameter. The force of sixteen horses was required to separate them. Plate II is a photograph of the picture that appeared in Guericke's book.

82. How Animals Sustain Atmospheric Pressure. If the pressure of the atmosphere is about one ton on each square foot, how are we able to withstand so great a pressure on our bodies? The reason is that our blood and tissue cells contain air at the same pressure as the air outside our bodies. The presence of this air can be demonstrated in an experiment with the "hand glass." This is a bell jar (Fig. 51), which fits on the plate of the air pump, and has an opening at the top to which the palm of the hand can be fitted air tight.



FIG. 51 HAND GLASS

When the air is pumped out of the jar, the hand is not only pushed down with great force by the weight of the overlying air, but also the fleshy part of the palm swells out and extends through the opening into the receiver. This is because the pressure of the outside atmosphere has been removed from the palm, and the air within the hand, being free from outside pressure below, expands and distends the cells in which it is confined. This is one reason why aeronauts and mountain climbers often suffer great inconvenience. As they ascend, the pressure of the atmosphere diminishes so rapidly that the blood is forced to the surface by the pressure of the air within the tissues.

83. Floating. Archimedes' Principle. The importance of boats, both for business and pleasure, gives point to

the study of the principles of flotation. What determines how far a boat will sink in water? How must a submarine be built that it may be able to dive? What makes a balloon float in the air? These questions may be answered by applying to this problem the principles we have already learned.

Let Fig. 52 represent a vessel, filled with liquid to the level gh , in which a rectangular solid $cdef$ is conceived to be submerged; and let us find whether the liquid exerts any force which tends to move the solid.

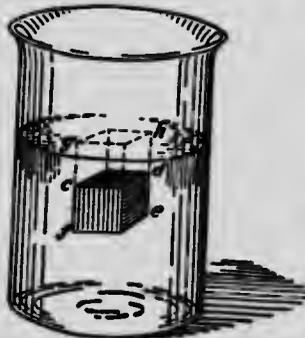


FIG. 52 THE CUBE IS BUOYED UPWARD

The resultant of all the horizontal forces exerted by the liquid on the solid is zero, because every such force is opposed by an equal and opposite force at the same depth on the opposite side. The force on the top cd is equal to the weight of a column of liquid represented by $ghdc$, and it acts downward. The force on the bottom fe is equal to the weight of the column of liquid represented by $ghfe$. According to Pascal's principle (Art. 69), the liquid exerts this force upward on the solid. The resultant of the upward and downward forces is equal to their arithmetical difference, which is equal to the weight of a volume of the liquid equal to the volume $cdef$. But $cdef$ is the volume of the body, which is the same as that of the liquid displaced by it. Therefore, the liquid exerts on the solid an upward force equal to the weight of the liquid displaced.

The foregoing argument does not depend for its conclusion on the kind of fluid, nor on the depth to which it is submerged, nor on the size and shape of the submerged body. The principle that we have just reached was discovered by Archimedes of Syracuse (287?-212 B. C.), who announced it substantially as follows:

A body immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced.

84. Boats and Balloons. Applying this principle to a boat, we learn that the boat will sink in the water until the weight of the water displaced by the boat is just equal to the total weight of the boat. If the boat is loaded, its total weight is greater; therefore, it sinks deeper so as to displace a greater weight of water, and thus produce a buoyant force sufficient to balance the increased weight. The submarine boat (Fig. 53) must be so constructed that its total weight is not quite equal to the weight of an equal volume of water. It is provided with air-tight compartments into which water may be admitted to increase its weight and make it sink. When this water is expelled by means of strong pumps, the boat

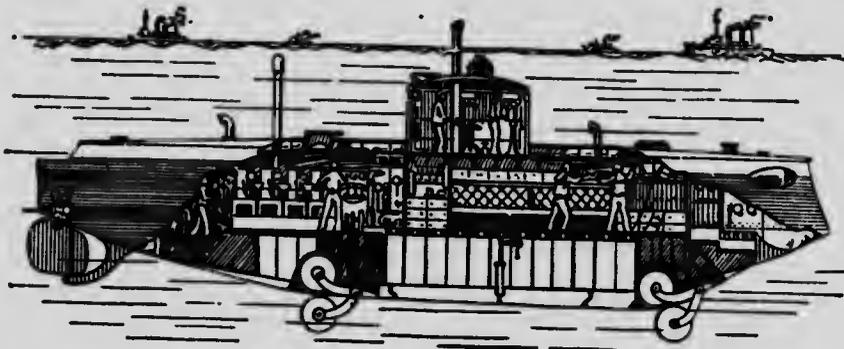


FIG. 53 WEIGHT OF THE SUBMARINE = WEIGHT OF WATER DISPLACED

rises again. The devices for admitting and expelling the water are under the control of the men in the boat.

Balloons are filled with hydrogen or illuminating gas, which is much lighter than air, so the balloon and the gas together weigh less than the large volume of air which it displaces. When the balloon has risen to an elevation where the air is less dense than near the ground, so that the balloon and its load weigh just as much as the displaced air, it floats along with the air currents and neither rises nor sinks. If the aeronaut wishes to ascend, he throws out a little of the sand which he carries for ballast, thus making the weight of the balloon less than the buoyant force of the air. When he wishes to descend, he pulls a cord which opens a valve at the

top of the balloon and lets out some of the gas. This diminishes the volume of the balloon, and makes the buoyant force less than the weight of the balloon.

85. Relative Density or Specific Gravity. In Art. 54, we learned that a cubic inch of water weighs 0.0362 pound, and a cubic inch of mercury weighs 0.49 pound; i. e., the mercury weighs 13.6 times as much as the same volume of water. This fact is generally expressed by saying that the mercury is 13.6 times as dense as water,—or more briefly, that its *specific gravity* is 13.6. So likewise, if we find that a piece of brass weighs 17 pounds and an equal volume of water weighs 2 pounds, then the brass is $\frac{17}{2} = 8.5$ times as heavy as the same volume of water; i. e., its specific gravity is 8.5.

The specific gravity of a substance is its weight divided by the weight of an equal volume of water.

86. Specific Gravity by Archimedes' Principle. Archimedes' Principle furnishes a convenient method of determining the specific gravity of a substance that does not dissolve in water, because it tells us that a body immersed in water is buoyed up by a force just equal to the weight of the water displaced. Since the volume of water displaced is the same as the volume of the immersed body, the buoyant force is just equal to the weight of an equal volume of water. If then a body whose density is desired is weighed in air, and then weighed suspended in water (Fig. 54), it weighs less in water by an amount just equal to the weight of its own volume of water. The weight in air, divided by the loss of weight in water, is therefore the specific gravity.

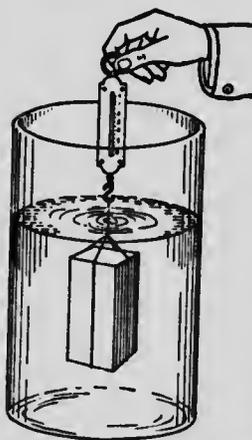


FIG. 54 IT WEIGHS LESS IN WATER

It is to be noted that this process of weighing in air and

then in water is simply a convenient way of finding the weight of an equal volume of water.

$$\text{Specific gravity} = \frac{\text{Weight in air}}{\text{Loss of weight in water}}$$

87. Why Some Bodies Float. In Art. 4 we have learned that the center of gravity of a body always seeks the lowest possible level. Yet, if we push a block of wood down to the bottom of a jar of water and let it go, it rises to the surface; i. e., its center of gravity goes up. When mercury is poured into a jar partly full of water, it sinks to the bottom, raising the center of gravity of the water to a higher level.

If the mercury stayed at the top of the water, the common center of gravity of the jar, the mercury, and the water, would evidently be higher up than it is when the mercury is at the bottom. Likewise, if the wood stayed at the bottom of the jar of water, the common center of gravity of the jar, the water, and the wood would be higher up than it is when the wood is at the top. The common center of gravity of a collection of several different bodies is at the lowest possible level, only when the denser substances are at the bottom, and the less dense ones are on top. So if, in any collection of bodies some are fluids, the less dense ones float upward, and the more dense ones sink downward; because

The center of gravity always seeks the lowest possible level.

DEFINITIONS AND PRINCIPLES

1. Pressure is force per unit area. It is measured in pounds-force per square inch or grams-force per square centimeter.

2. Density is weight per unit volume. It is measured in pounds per cubic inch or grams per cubic centimeter.

3. In a liquid with a free surface the pressure at any depth is proportional to the depth and the density of the liquid.

4. In a liquid with a free upper surface the pressure at any depth is independent of the shape or size of the containing vessel.
5. When water is flowing in a pipe, the pressure gradually decreases, being greatest at the end where the water flows in, and least at the end where it flows out.
6. Work must be done in raising water to a higher level.
7. In raising water to a higher level, Work done = weight of water raised \times difference in level.
8. Air has weight.
9. Normal, sea level, atmospheric pressure is 15 pounds to the square inch.
10. A pressure exerted on any part of a fluid enclosed in a vessel is transmitted undiminished in all directions and acts with equal force on all surfaces of equal area in directions perpendicular to those surfaces. (Pascal's Principle).
11. In the ideal hydraulic machine, Work out = work in.
12. The volume of a given mass of gas at a constant temperature is inversely proportional to the pressure it supports. (Boyle's Law).
13. A body immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced.
14. The specific gravity of a substance is its weight divided by the weight of an equal volume of water.
15. The center of gravity of a collection of bodies is at the lowest possible level when the denser bodies are below and the less dense ones are above.

QUESTIONS

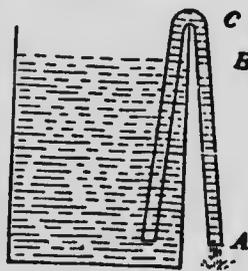
1. Explain the difference between the pressure on the bottom of a cistern and the total force on the same.
2. What is the cause of the pressure in a fluid (i. e., a liquid or a gas) when at rest in an open vessel?
3. What is the relation between this pressure and the depth at any point within a liquid having a free upper surface?
4. What is the cause of this simple relation (question 3), between the pressure and the depth in a liquid?
5. At what depth in water is the pressure equal to 1 pound per square inch? 10 pounds per square inch?
6. At what depth (in meters) is the pressure in water equal to 100 grams? 500 grams?

7. What is the density of water in pounds per cubic foot? In pounds per cubic inch? In grams per cubic centimeter?
8. Why will boards placed over swampy ground enable a person to walk safely over it, when otherwise his feet would sink in at every step?
9. Why is the water more likely to penetrate into the ears during a deep dive than during a shallow one?
10. Must the lower portions of the wall of a standpipe be made stronger than the upper portions? Why?
11. Does coffee stand at the same level in the spout of a coffee pot as it does in the pot itself? Why?
12. Is the pressure at the base of a dam 80 feet high greater when the dam holds a lake 30 miles long than it is when the lake is only half a mile long? Why?
13. How can you determine the difference in level between two faucets in a building with an ordinary pressure gauge?
14. Can you make a satisfactory measurement of difference in level, as in question 13, when some one is drawing water from a tap in the basement? Why?
15. Describe the action of an ordinary lift pump?
16. How would you calculate the work done per stroke in lifting water from a cistern with an ordinary lift pump?
17. Why did Galileo conclude that Nature's horror of a vacuum had its limitations?
18. Why does the water rise in the suction pipe of a pump?
19. Why are not barometers filled with water?
20. How does the barometer in a balloon car act when the balloon is ascending uniformly?
21. What sort of weather does a falling barometer forecast? Why?
22. Why do corks float on water?
23. How are balloons and submarines made to rise or sink?
24. Why is it easier to float in water when the lungs are well filled with air?
25. Why is it easier to swim in salt water than in fresh water?
26. A boat builder objected to placing the lead ballast of a boat on the bottom of the keel because the "water took the heft all out of the lead." He wanted the lead up in the boat. Was he right?
27. A disk of soft leather attached to a string makes a "sucker," because when pressed against any flat object like a brick or a flat stone it clings to the object hard enough to lift it when the string is lifted. Is the object pulled or pushed up? Explain the phenomenon.
28. Explain any methods that you know for proving Archimedes' principle by experiment.
29. When you begin to pump up an empty bicycle tire, it is not difficult to push the piston. As the tire grows full, it is difficult to do this. Explain.

30. How is the pressure in the water system of your town obtained?
31. Does the water run faster from a faucet near the pumping station or standpipe than from one at the same level but far away? Explain.
32. Fill a glass with water, hold a wet card over the top, invert the glass, and then withdraw the hand. Explain what happens.
33. Fill a large bottle with water, invert it, note the process by which it is emptied, and explain.
34. Why can the bottle be emptied more quickly and with less splashing if tilted gradually than if quickly inverted and held upside down?

PROBLEMS

1. What is the pressure in pounds per square foot on the bottom of a vessel containing water to a depth of 1 foot? 5 feet?
2. What is the pressure in kilograms per square centimeter on a dam when the depth of water is 10 meters? 20 meters?
3. At what depth in mercury is the pressure equal to 136 grams per square centimeter? To 272?
4. At what depth in alcohol is the pressure equal to 1.6 grams per square centimeter? To 8 grams per square centimeter?
5. What is the difference in level between two taps in a house when the pressure of the water at the upper tap is 5 pounds per square inch less than it is at the lower tap?
6. A cubical water tank measures 5 feet along each edge inside, and its center is 50 feet above the water in the supply source. How many foot-pounds of work are done in pumping it full of water?
7. Does it make any difference in the amount of work done in problem 6 whether the pipe from the pump enters the tank at the top or at the bottom? Explain.
8. A standpipe on a city water supply system is 50 feet high and 6 feet in diameter. The pipe from the pump enters at the bottom. How many foot-pounds of work are done in pumping it full of water?
9. In a siphon, when the barometer reads 30 inches and the top of the tube *C* is 6 inches above the level *B* of the water in the jar, what is the water pressure at *B*?
10. In the siphon, when the end of the tube *A* is 14 inches below *C* what is the water pressure at *A*? What is the resultant pressure in the direction *CBA*?
11. How much work is done per stroke by a pump whose piston has an area of 40 square inches and a stroke of 2 feet if the piston pressure is 40 pounds to the square inch?



THE SIPHON

12. The small piston of a hydraulic press has an area of 2 square inches, and the large piston an area of 250 square inches. What force applied to the small piston will cause the large one to exert a force of 12,500 pounds?
13. If the lever of the hydraulic press (Fig. 46) is 2 feet long and the distance from the fulcrum end to the plunger is 6 inches, what force will the plunger *A* exert on the water in the small cylinder if the handle is pushed down with a force of 100 pounds?
14. In problem 13 what force will the piston *B* exert if its area is 300 square inches and that of the small one *A* is 3 square inches?
15. If the piston *A* in problem 14 moves 5 inches at each stroke, how many strokes would be required to lift the piston *B* 10 inches?
16. At a time when the barometer stands at 30 inches, an empty bottle is inverted and pushed below the surface of a body of water until it is half full, no air being allowed to escape from it. What is the pressure in the bottle? How far below the surface is it?
17. When the air in the air dome of a fire engine pump has been reduced to $\frac{1}{4}$ of its original volume, what is the pressure in the dome at the point where the water leaves it?
18. A rowboat weighs 250 pounds. How many cubic feet of water does it displace when floating?
19. If you weigh 125 pounds and can just float with your nose out in fresh water what is your volume?
20. A block floats half in and half out of water. What is its specific gravity?
21. A piece of glass weighs 25 grams in air and 15 grams in water. What is its specific gravity?
22. A submarine has a volume of 4000 cubic feet. How much must it weigh out of water?
23. When air weighs 1200 grams per cubic meter how much load can a balloon bag support when it contains 300 cubic meters of gas that weighs 750 grams per cubic meter?
24. The weight of a steamer is 6000 tons and when loaded it displaces 10,000 tons of water. How heavy a load can it carry?

CHAPTER V

WATER POWER

88. Moving Water Has Power. No one can go wading in a swiftly running brook, or even hold his hand in the stream of water rushing from a tap, without realizing that moving water has power. That it can do work, the havoc wrought by floods and freshets bears convincing testimony. A slowly flowing river or quiet lake or pond do not often impress us with their power of driving mills. It is only when a river plunges over a ledge and makes a rapid or a waterfall, or when the water from the lake runs through a mill-race to a mill at a lower level, that the power of moving water can be utilized to drive machinery and do mechanical work.

Rapidly moving water may be made to saw wood, grind corn, or furnish electric light for streets and houses. Because of this, *a waterfall or a rapid in a river is a possession of great value to any community.*

We shall now consider some of the devices that are used to utilize the power of running water and make it do mechanical work.

89. Overshot Wheels. Most children have amused themselves with toy water wheels. They are made by fastening a number of blades or paddles around the rim of a wooden disk mounted on an axle. When the wheel is held so that the blades dip in running water, the wheel turns.

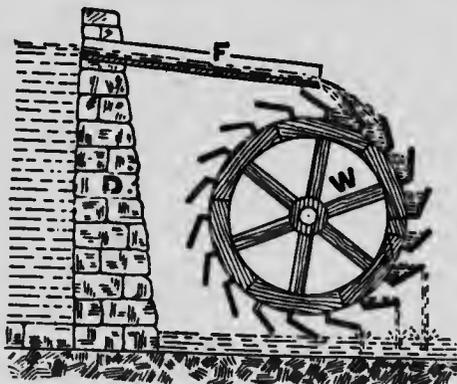


FIG. 55 WATER FALLS—WHEEL TURNS

Old fashioned water wheels, built on this plan, were used to drive flour mills and sawmills. A dam was built in a river, holding back the water, and keeping it at a level higher than the wheel. The water was then led through a pipe or flume

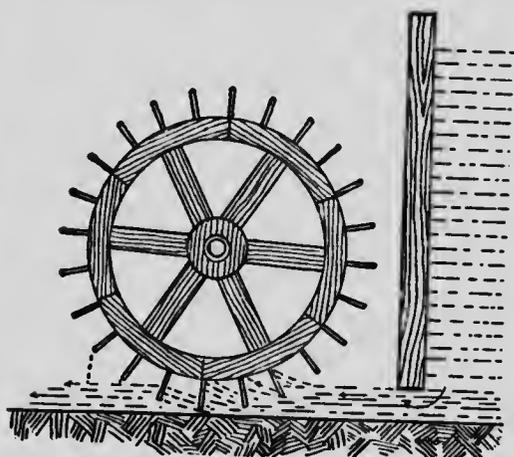


FIG. 56 RUNNING WATER PUSHES IT

F (Fig. 55) from near the level of the top of the dam *D*, and allowed to fall on the paddle wheel *W*. Because the water falls over the wheel from above, this sort of wheel is called an *overshot wheel*. The weight of the water in the buckets on one side causes the wheel to turn; and as the axle is fixed to the wheel, it turns

and transmits the motion to the machinery in the mill. Water can do work on such a wheel when it falls on the wheel from above, so that its weight pulls down the buckets on one side of the wheel as the water descends from the higher to the lower level.

90. Undershot Wheels.

The undershot wheel (Fig. 56), as its name implies, differs from the overshot wheel in that the water runs under it instead of over it. In this case the wheel is driven by the horizontal pushes which the water gives to the blades of the wheel.

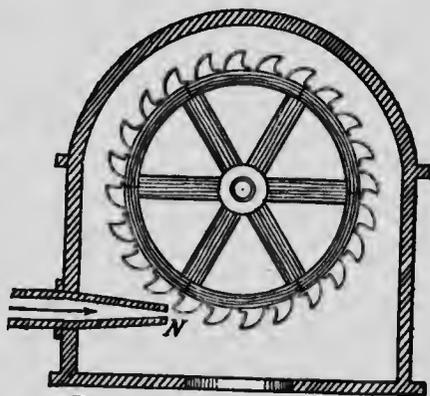


FIG. 57 PELTON WATER WHEEL

In the modern water motor of the Pelton type the water rushes out from a nozzle *N* (Fig. 57), strikes against blades or buckets on the rim of the wheel, and gives up part of its own motion in turning the wheel.

In the case of the water wheel, the water flows in a direction parallel to the flat sides of the wheel. The blades are set at right angles to the flat side of the wheel, so that the water strikes perpendicularly against them and pushes them in the direction in which the water flows.

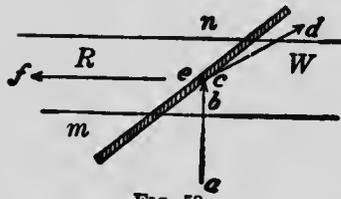


FIG. 58

91. **Turbines.** The toy pinwheel and the farm windmill are familiar types of *turbines*. The wind does not blow in a direction parallel to the flat side RW (Fig. 58) of the wheel, but in the direction ab at right angles to it. Each blade mn is set at an angle with the flat side RW of the wheel. When the wind strikes the blade mn in the direction ab , it is deflected in the direction cd , thereby pushing the blade in the direction ef , and so turning the wheel.

Niagara Falls power plants are driven by water turbines. The water is led near the top of the falls into a large steel pipe P (Fig. 59). The turbine is placed at the bottom of this pipe, where the water under heavy pressure flows with great force through the turbine T , causing it to revolve rapidly, turning the shaft S and driving the dynamo D .

Fig. 60 shows a simple model of a water turbine. A small metal disk T , cut and bent like a pinwheel or an electric fan, is mounted on a wire AB and arranged so that it rotates freely inside of an ordinary lamp chimney P . When water is

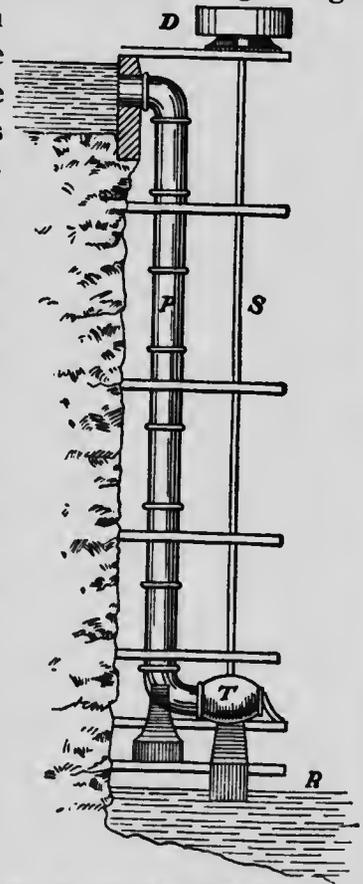


FIG. 59 NIAGARA POWER TURBINE

kept running through the chimney, the wheel turns, driving the small pulley at *B*, to which small machinery may be attached.



FIG. 60 TOY TURBINE

In real turbines the water is led in at a number of curved inlets or passages *B* (Fig. 61) which project it against the blades of the turbine *T* in the direction most favorable for turning the wheel. The direction in which the water flows as it passes through the machine is changed as indicated by the arrows in the figure.

As with all other machines, *the important thing about water motors is their efficiency.* We must therefore learn how to measure both the work done on the machine, and the useful work done by it (Art. 20).

92. Measurement of Work Done by Water. In Art. 62, we have seen that work must be done on water when it is raised from a lower to a higher level, and that this work is measured by the product of the weight of the

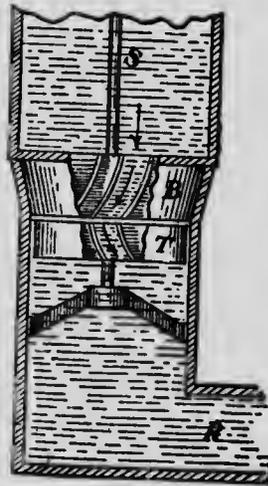


FIG. 61 WATER TURBINE

water raised and the distance through which it is raised. Conversely, when water does work simply by its weight, as in the overshot wheel (Fig. 55), the work done by the water is measured by the product of the weight of the water that falls, and the vertical distance through which it descends. When, however, work is done by projecting a stream of water under pressure against the blades

on the wheel of a motor, it is not so convenient to measure the work in this way. We can best find out how to do this in the latter case by first considering the converse problem of measuring the work done in forcing water against pressure.

Consider the force pump (Fig. 43), the area of whose piston is 100 square inches and the length of whose stroke is 20 inches. If the pump is to be used to force water into the mains of a city water system against a pressure of 60 pounds per square inch, the total force that must be applied to the piston to move it is 100 (square inches) \times 60 (pounds per square inch) = 6000 pounds. When the pump makes one stroke, this force acts through a distance of 20 inches = $\frac{20}{12}$ feet. The work done per stroke is therefore force \times distance; or, 6000 (pounds) \times $\frac{20}{12}$ (feet) = $10,000$ foot-pounds.

In practical work it is convenient to rearrange the factors involved in this calculation. Thus we had: Work = Pressure (lbs. per sq. in.) \times Piston area (sq. in.) \times stroke ($\frac{\text{in.}}{12}$)

But piston area \times stroke = volume of the cylinder in cubic inches. So the work done per stroke may be obtained by multiplying the pressure by the volume of water moved against this pressure each stroke. If the pressure is measured in pounds per square inch, the volume must be expressed in cubic inches divided by 12, so that the result may be expressed in foot-pounds.

If the pressure is measured in grams per square centimeter, and the volume in cubic centimeters, the result will be expressed in gram-centimeters.

The reasoning just given holds for other fluids than water, hence: *the work done by a fluid when a volume of it flows under pressure through any machine is measured by the product, pressure \times volume, or*

$$\text{Fluid Work} = \text{Pressure} \times \text{Volume.}$$

If the work is to be calculated in foot-pounds, the pressure must be in pounds per square inch, and the volume in cubic inches divided by 12; or, the pressure must be in pounds per

square foot, and the volume in cubic feet. If the work is to be calculated in gram-centimeters, the pressure must be in grams per square centimeter, and the volume in cubic centimeters.

93. Applications. In order to illustrate the use of this principle, let us find out how much work must be done per day by the pumps of a city water plant if they have to pump 1,000,000 gallons a day against a pressure of 60 pounds to the square inch. Since there are 231 cubic inches in a gallon, the total volume to be pumped per day is 231,000,000 cubic inches. The pressure is 60 pounds per square inch. Therefore, the work to be done is $\frac{231,000,000}{12} \times 60 = 1,155,000,000$ foot-pounds.

A second problem will show how the metric units are used. How much work is done on a water motor by the water while 200,000 cubic centimeters of water flow through it, the water being under a pressure of 3000 grams per square centimeter? Fluid work = 200,000 (cubic centimeters) \times 3000 (grams per square centimeter) = 600,000,000 gram-centimeters.

94. Power. How large an engine will be needed to do the work of pumping 1,000,000 gallons a day against a pressure of 60 pounds to the square inch? If time were of no importance, it could be done by one man working with a hand pump. If the volume of his pump cylinder were 77 cubic inches, he would do $\frac{77}{12} \times 60 = 385$ foot-pounds of work each stroke. We have just found that the amount of work to be done is 1,155,000,000 foot-pounds. So if a man can make 10 strokes a minute, he does the work at the rate of 3850 foot-pounds per minute. At this rate, it would take him $\frac{1,155,000,000}{3850} = 300,000$ minutes, or more than 200 days.

The work must, however, be done in 24 hours, i. e., at the rate of about 48,000,000 foot-pounds an hour; or 800,000

foot-pounds a minute. It would therefore take more than 200 men, working at the hand pumps, to supply the water demanded each day. So we need something much more powerful than one man to do this work at the required rate. We need an engine of at least 200 man-power.

Power is the rate of doing work. It is determined by dividing the work done by the time taken to do it.

$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

Since power is measured by dividing the work done (foot-pounds) by the time required to do it (seconds), *the unit of power is either the foot-pound per second, or the gram-centimeter per second.*

95. Calculation of Water Power. One method of calculating water power is illustrated in the following example. In the great turbines at Niagara, the difference in level between the surface of the water above, and the turbine *T* (Fig. 59) below, is 146 feet. The water pressure at the turbine is therefore (Art. 53) $\frac{146}{2.3} = 62.5$ pounds per square inch.

When 6,000,000 cubic inches of water have flowed down the pipe, the work put into the turbine is (Art. 92):

$$\begin{aligned} \text{Fluid work} &= \text{Pressure} \times \text{Volume.} \\ &= 62.5 \text{ (lbs. per sq. in.)} \times \frac{6,000,000 \text{ (cu. in.)}}{12} \\ &= 31,250,000 \text{ foot-pounds.} \end{aligned}$$

If 6,000,000 cubic inches of water flow down the pipe each second (volume per second), 31,250,000 foot-pounds of work are put into the turbine each second; i. e. the power supplied to the turbine is 31,250,000 foot-pounds per second. Hence *the power supplied by a fluid when a certain volume flows each second at a given pressure through a machine is measured by the product of the pressure and the volume per second, or*

$$\text{Fluid Power} = \text{Pressure} \times \text{Volume per second.}$$

If the power is to be calculated in foot-pounds per second, the pressure must be in pounds per square inch and the volume per second in cubic inches per second divided by 12; or, the

pressure must be in pounds per square foot, and the volume per second in cubic feet per second.

If the power is to be calculated in gram-centimeters per second, the pressure must be in grams per square centimeter, and the volume per second in cubic centimeters per second.

96. Horsepower. In solving engineering problems, like the one just considered (Art. 95), the foot-pound per second (or the gram-centimeter per second) is too small a unit for convenience; because the power of waterfalls and steam engines is generally large. For this reason Watt, the inventor of the modern steam engine (1736-1819), introduced a unit called the *horsepower*, which is approximately the rate at which an average horse would work. He selected this unit because, before he invented the steam engine, horses in treadmills were much used as a source of power; and his engines had to be built to replace a certain number of horses. After suitable experiments with horses he defined a horsepower as a power of 33,000 foot-pounds a minute. This is equal to 550 foot-pounds a second, or about 7,620,000 gram-centimeters a second.

The horsepower is equal to 550 foot-pounds a second.

The man pumping (Art. 94) did 385 foot-pounds of work in 6 seconds. His power was therefore $\frac{385}{6} = 65$ (nearly) foot-pounds per second; or roughly, $\frac{1}{3}$ horsepower.

The horsepower of the turbine (Art. 95) is found to be 31,250,000 (foot-pounds per second)

$$\frac{550 \text{ (foot-pounds per seco.)}}{31,250,000} = 5680 \text{ horsepower.}$$

Similarly, the horsepower of an engine that would be able to do the pumping for the waterworks considered in Art. 94 is

$$\frac{800,000 \text{ (foot-pounds per minute)}}{33,000 \text{ (foot-pounds per minute)}} = 24.2 \text{ horsepower.}$$

A 25-horsepower engine would do the work. Many automobile engines have much higher horsepower than this. It is important to note carefully the distinction between

work and power. *Work is measured in foot-pounds, but power is measured in foot-pounds per second.* This distinction is like that between distance and velocity. Distance is measured in feet, but velocity is measured in feet per second.

97. Work Done by a Water Motor. Brake Test. Before we can determine the efficiency of a water motor we must find out how much work we can get out of it in a given time. To do this fasten to the shaft *S* (Fig. 62) of the motor a small

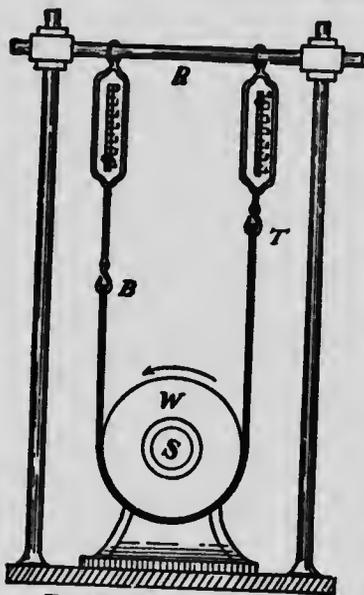


FIG. 62 FRICTION BRAKE

wheel or pulley *W*, which has a rim two or three inches wide. About this pulley pass the leather belt *BT* which is about as wide as the pulley. Fasten the ends of the belt to two spring balances which are supported from the rod *R*. Raise the rod until the friction of the belt slows the motor down to about its normal working speed. Because the motor is running and rubbing against it, one end of the belt *B* will pull harder on its spring balance than the other end *T*, and the difference in the readings of the two balances will measure the pull of the motor on the belt. Suppose this difference or pull to be 5.3 pounds. The distance through which this pull is exerted in a single revolution of the motor is the circumference of the pulley *W*. If the radius *r* of the pulley is $\frac{1}{8}$ foot, this distance is $2\pi \times \frac{1}{8} = 1.05$ feet. The work done in one revolution of the axle is then measured by the product, force \times distance; or 5.3 (pounds) \times 1.05 (feet) = 5.56 foot-pounds. If the motor makes during the test 1200 revolutions, the total work done is $5.56 \times 1200 = 6672$ foot-pounds.

If the motor did this work in 120 seconds, the power of the motor is $\frac{6672}{120} = 55.6$ foot-pounds per second. But as 550

foot-pounds a second is one horsepower, the motor was working at the rate of approximately $\frac{1}{10}$ horsepower.

This device used in measuring the work done by the motor is called a *brake*. The power as determined by the brake is called the *brake horsepower*. Hence the rule:

To find the brake horsepower of a motor multiply together the number of pounds pull on the brake, the number of feet in the circumference of the pulley, and the number of revolutions per second; and divide by 550.

The Efficiency of a Water Motor. We can now determine the efficiency of the motor, since we have found out how much useful work it can do. If, while the measurement just described was being made, 3300 cubic inches of water passed through the motor, and if the water pressure where the supply pipe entered the motor was found to be 60 pounds to the square inch, the work done on the motor was (Art. 92),

$$\text{Fluid Work} = \text{Pressure} \times \text{Volume}$$

$$\text{Fluid Work} = 60 \text{ (lbs. per sq. in.)} \times \frac{3300 \text{ (cu. in.)}}{12}$$

$$\text{Fluid Work} = 16,500 \text{ foot-pounds.}$$

The efficiency of the motor was, therefore,

$$\frac{\text{Work out}}{\text{Work in}} = \frac{6672}{16,500} = 40\% \text{ efficiency.}$$

The efficiency is here expressed in the usual way as work out divided by work in.

Both these amounts of work were done in the same time, namely 120 seconds. The value of the fraction will not be changed if we divide both numerator and denominator by 120

$$\text{(seconds). But } \frac{6672 \text{ (foot-pounds)}}{120 \text{ (seconds)}} = \text{power of the motor,}$$

$$\text{and } \frac{165,000 \text{ (foot-pounds)}}{120 \text{ (seconds)}} = \text{power supplied by the water.}$$

Hence we conclude:

The efficiency of a motor is found either by dividing the work out by the work in, or by dividing the power out by the power in.

DEFINITIONS AND PRINCIPLES

1. Water flows from a higher to a lower level, or from a higher to a lower pressure when it does work.
2. Fluid Work = Pressure \times Volume that flows.
3. Power = $\frac{\text{Work}}{\text{Time}}$.
4. Fluid Power = Pressure \times Volume per second.
5. Work is measured in foot-pounds. Power is measured in foot-pounds per second.
6. One horsepower = 550 foot-pounds per second.
7. Brake horsepower = pounds pull on brake \times number of feet in circumference of pulley \times revolutions per second \div 550.
8. Efficiency of a motor = $\frac{\text{Work out}}{\text{Work in}}$ or $\frac{\text{Power out}}{\text{Power in}}$.

QUESTIONS

1. What conditions are necessary to a water power site?
2. How is an overshot wheel placed with reference to the water that drives it?
3. Is it necessary to have a dam for an undershot wheel? Why?
4. If you entirely submerge a toy water wheel in a running brook will the wheel turn? Why?
5. Why does the turbine turn when entirely submerged in running water?
6. Why does turning the propeller of a motor boat make the boat go?
7. Why does an electric fan make a breeze when it is rotating rapidly?
8. How may the wind be made to do work?
9. If water were carried from the mill-pond to an overshot wheel through a siphon 20 feet high, instead of through a straight flume, what would be gained? Why?
10. Does it require more power to go up a flight of stairs in 10 seconds than to go up the same flight of stairs in 20 seconds? Why?
11. Do you do more work when you go up a flight of stairs in 10 seconds than when you go up the same flight of stairs in 20 seconds? Why?
12. When you get into a bath, the level of the water rises in the tub. Whence comes the work that lifts the water to the higher level?
13. If the same amount of water flows from a mill-pond each second, does the water have greater power if it flows over the top of the dam than it does if it flows through a gate at the bottom? Why?

14. Is one man able with a hand pump to pump 1,000,000 gallons of water into a tank 50 feet from the ground? How?
15. Can one man pumping 200 days do as much work as 200 men pumping one day? Why?
16. If the one man and the 200 men of question 15 do the same amount of work, have they the same power? Why?
17. Why are eleven men digging a trench for one hour better than one man digging it for eleven hours?
18. Before the invention of the steam engine, what were used to pump out mines?
19. How many foot-pounds of work can an average horse do per hour?
20. How did Watt define the horsepower?
21. When you hire a number of horses, do you pay for them by the horse or by the hour? Why?
22. Could 25 horses make an automobile go as fast as a 25-horsepower engine can? Why?
23. If 25 horses are hitched to one end of a rope and an automobile having a 25-horsepower engine is fastened to the other end, when the horses pull in one direction and the automobile in the opposite direction, which will win the tug of war?
24. How could you apply a brake to a windmill to measure its power?
25. If the windmill of question 24 runs a pump, how would you measure the power of the combination, windmill and pump?
26. If you measure the power of the windmill alone with a brake (question 24) and the power of the combination by the pressure and volume of the water pumped per second, would the results be the same? Why?
27. The ratio of the two powers in question 26 would be the efficiency of what?
28. Why is a pipe of large diameter better than one of small diameter to bring the water to the nozzle *N* of the water wheel shown in Fig. 57?
29. What is the advantage of measuring the efficiency of a motor by the ratio of power out to power in, instead of by the ratio of work out to work in?
30. What is the efficiency of a water motor that is running fast but doing no work?
31. If a water motor is loaded so heavily that it cannot turn, although the water is running through it, what is its power?
32. What is the efficiency of a motor under the conditions of question 31?

PROBLEMS

1. If 100 cubic feet of water flow each second over a dam 20 feet high, what is the available power?
2. If 100 cubic feet of water flow each second through a gate at the bottom of the dam (problem 1) what is the available power in foot-pounds?
3. What power must an engine have in order to fill a tank 5 feet square by 4 feet deep and 60 feet above the level of a lake in 10 minutes?
4. What horsepower can be had from a waterfall 10 feet high, if 20 cubic feet of water per second go over it?
5. How much of the power, problem 4, will be available for useful work with a water wheel that has an efficiency of 70%?
6. How much work is done on a water motor through which 120 cubic feet of water flow at a pressure of 55 pounds per square inch?
7. If in problem 6 the water flows through the motor in 3 minutes, what is the horsepower supplied to it?
8. If the efficiency of the motor of problem 7 is 60%, how many horsepower can it supply for operating machinery?
9. What is the horsepower of a fire engine that can throw 6600 pounds of water every 2 minutes to a height of 100 feet?
10. A mine is 275 feet deep and water is flowing into it at the rate of 120 cubic feet per minute. What is the necessary horsepower of a pump that will keep it dry?
11. The piston of a force pump has an area of 60 square inches and a stroke of 18 inches. If it works at a pressure of 45 pounds per square inch, how much work does it do per stroke?
12. What must be the horsepower of a pump that will supply 5 million gallons of water per day at a pressure of 72 pounds per square inch?
13. If the pump of problem 12 has an efficiency of 90%, what horsepower must be supplied to it by the engine that drives it?
14. The radius of the pulley of a water motor is 3 inches and the measured friction-force of a brake against it is 10 pounds. If the pulley makes 1500 revolutions per minute, what is the brake horsepower of the motor?
15. When the motor (problem 14) was running at 1500 revolutions per minute, 60,000 cubic inches of water were found to be running through it per minute at a pressure of 66 pounds per square inch. What horsepower was supplied to it?
16. What was the efficiency of the motor (problems 14 and 15)?

17. A standpipe 115 feet high holds when full 30,000 cubic feet of water. If a pump at the bottom pumps water into it through a pipe that leads into the standpipe at the top, how many foot-pounds of work must the pump do in filling the empty pipe?

18. What must be the horsepower of the pump that will fill the standpipe of problem 17 in one hour?

19. If the pipe from the pump entered the standpipe of problem 17 at the bottom instead of at the top, how many foot-pounds of work must the pump do in filling the empty pipe?

20. What must be the power of the pump under the conditions of problem 19?

21. A football that weighs 0.6 pound and has a volume of 432 cubic inches is pushed under water. With how many pounds force does it push up when submerged?

22. How many foot-pounds of work would be done in pushing the football (problem 21) 10 feet deeper?

CHAPTER VI

HEAT

98. Importance of Heat. Few animals and plants live in the extreme polar regions because of lack of heat. But while a certain amount of heat is necessary to life, fire destroys it. Conditions most favorable to life are found where heat and cold are not extreme. Men can live in comfort in regions where the yearly range in temperature is large,—say from 30° below zero to 110° above, Fahrenheit,—only because they have learned to control heat, and to keep the range of temperature in their houses much smaller than it is out of doors.

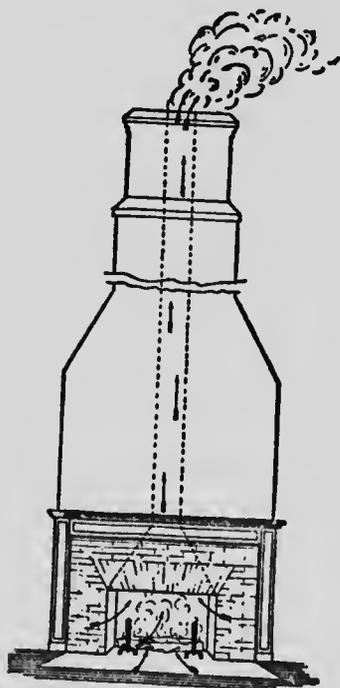


FIG. 63 THE HEAVY FLUID
DISPLACES THE LIGHTER

Heat not only keeps us warm and makes vegetation flourish; but when properly controlled, it also cooks food, drives engines, smelts ores, and in a thousand different ways helps to carry on the world's work. When fire gets beyond control, however, it becomes a destructive agent. For these reasons, the problems that must be solved in order to control heat effectively are among the most important of the problems of science.

99. Fireplaces. The primitive savage built his fire in the middle of his hut or wigwam, and provided an opening in the roof for the escape of the smoke. The more intelligent and progressive races gradually learned that a fireplace and a chimney (Fig. 63) afford a better means of controlling the

fire and carrying off the smoke; for to do this there must be a steady "draft," and there can hardly be a steady draft without a chimney. There is a common impression that the chimney "draws" the smoke up. Let us see if this impression is correct.

100. Air Expands When it is Heated. A flask (Fig. 64) is fitted with a stopper through which a slender glass tube passes. A drop *a* of liquid colored so as to be easily seen is placed in the tube, enclosing a definite quantity of air at atmospheric pressure in the flask. If the flask full of air be warmed with the hand or a burner, the drop of liquid moves upward in the tube. Since the air in the flask is still at atmospheric pressure, we see that it takes up more space when it has been warmed without changing its pressure. *Air expands when it is heated at constant pressure.* Since the whole body of heated air in the flask fills a larger space than it did when cold, one cubic inch of space contains less of the hot air than it held of the cold before. Consequently:

When the pressure remains the same, hot air weighs less per cubic inch than cold air. Or,

The density of hot air is less than that of cold air at the same pressure.

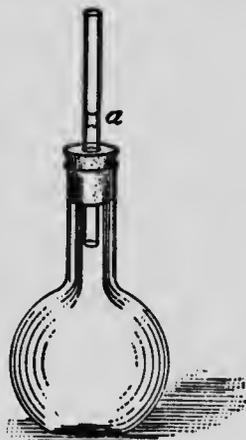


FIG. 64

101. Why Smoke Goes Up the Chimney. When a fire is started in the fireplace (Fig. 63), the air about the fire becomes heated, expands, and becomes less dense than it was before. The volume of warmed air about the fire then weighs less than an equal volume of the cold air by which it is surrounded. The heated air is, therefore, in the same condition as the gas in a balloon: its weight is less than that of the cold air it displaces. So the hot air is pushed upward by a force that is equal to the difference between its weight and that of an equal volume of the colder air (Art. 83).

Since the chimney is directly over the fireplace, the heated air from the fire is pushed up the chimney, which soon becomes filled with hot air. The entire volume of heated air in the chimney is then pushed up, just as the smaller volume about the fire was: but since this volume is larger, the upward pressure is greater, and the air moves more rapidly, making a strong draft. A tall chimney can hold a larger volume of hot air than a shorter one of the same diameter can; so, other things being equal, *the taller the chimney, the stronger the draft.*

In the time of Aristotle (B. C. 350), hot air was said to rise because of its "levity," just as a stone falls because of its "gravity." We now understand that "levity" is due to differences in density. Although gravity is constantly pulling down on everything, it pulls on a given volume of a denser substance, like mercury, with greater force than it does on the same volume of a less dense substance, like water. When mercury is poured into water, the mercury sinks to the bottom, thus pushing the water to a higher level. Oil is less dense than water; so when oil and water are poured into the same vessel, we say the *oil rises* on the water. Really, the water is pulled down under the oil by its greater weight, thereby pushing the oil up. It is only when the denser mercury is below the less dense water, or the still less dense oil is on top of the water, that *the center of gravity of the combination mercury-water, or water-oil, is at the lowest possible level.* (Art. 87).

So it is with the draft in the chimney. The hot air is not drawn up; it is pushed up by the denser cold air, which forces its way underneath because it is pulled downward more strongly than is the hot air by the force of gravity. *It is only when the denser and heavier cold air is underneath, that the center of gravity of the combination is at the lowest possible level.*

102. Stoves. Though the open fire is very pleasant to look at, it is not an economical or efficient means of heating a room, because much of the heat goes up the chimney and is wasted. It is also inconvenient for cooking. The need

for a more efficient means of controlling the heat led to the invention of stoves. For heating houses, however, these too are inconvenient and inefficient; because it is necessary to have a separate stove in each room which is to be heated. Modern houses are generally heated by one central stove or furnace in the basement, from which the heat is distributed to the various parts of the house. This heat is carried either by hot air, by hot water, or by steam.

103. The Hot Air Furnace.

Fig. 65 shows the arrangement of a hot air furnace. A fire is kept burning in the firepot *F*; and the smoke passes up the chimney through the smoke pipe. The arrows show how the air moves around the fire-box through the furnace. It enters cold at *C*, is heated by contact with the firebox, and is pushed up the pipes to the various rooms by the denser cold air outside.

In this type of heater, then, the air moves through the air-jacket and through the flues into the rooms for the same reason that the smoke and hot gases from the fire move up the chimney. The volume of hot air in the furnace jacket and hot air flues weighs less than an equal volume of the colder air by which the heater is surrounded.

It is therefore pushed upward by the cold air which settles down under it; and since the cold air is continually being heated as it passes around the firebox, the circulation continues as long as the fire burns.

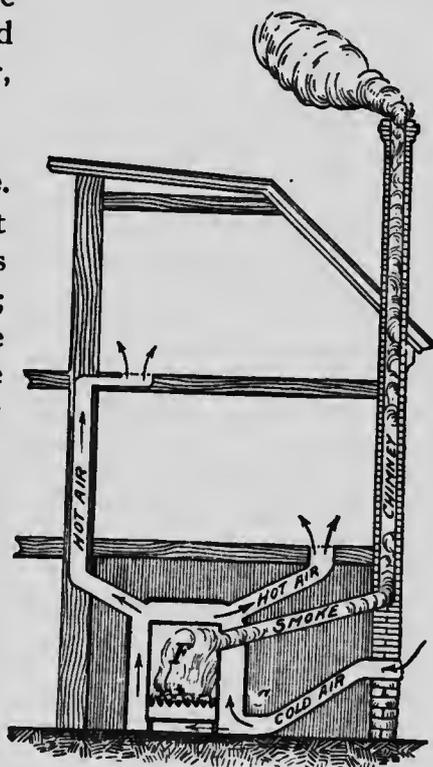


FIG. 65 HOT AIR HEATER

104. Ventilation. In the cover of a pasteboard box (Fig. 66), cut two holes about $\frac{3}{4}$ inch in diameter and several inches apart. Place a short lighted candle near one of the holes and cover both candle and hole with a lamp chimney. Place a second lamp chimney over the other hole and thrust into it from the top a piece of smoldering cotton waste, or better, a Chinese "joss stick." The smoke will go down the second chimney and up the first. The volume of air in the first chimney is hotter and less dense than the surrounding air, which, therefore, pushes its way underneath. Since the

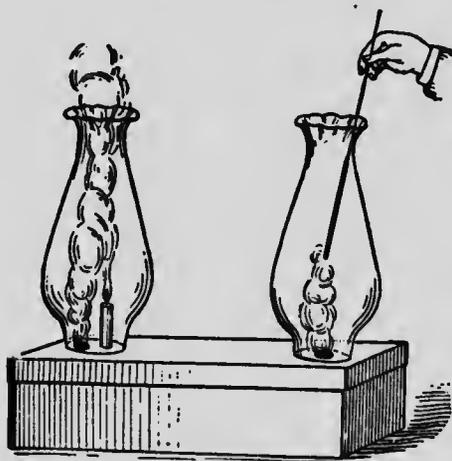


FIG. 66 HEAT MAKES IT CIRCULATE

only way to get under the first chimney is to go down through the second, the cold air follows this path. The smoke serves merely to show how the air is moving.

The ventilation of school buildings, theaters, and churches is accomplished by maintaining a circulation of air after the manner illustrated by this simple experiment. In many cases, however, the simple heating of the air does not produce a sufficiently rapid circulation, so fans, driven by electric motors or engines, are used to make the air move faster. The members of the class should investigate the system of ventilation in the school building and find out the manner in which the circulation of air is maintained. For proper ventilation about 3000 cubic feet of fresh air per person should pass through the room each hour.

Winds are produced in much the same manner as furnace drafts are. The unequal heating of the air over various portions of the earth's surface causes inequalities in the density of the air, and thus sets up a circulation. The currents at the bottom of the air move from the areas of higher

pressure toward those of lower pressure, and the excess of air flows off in the opposite direction, forming the upper currents.

105. Hot Water Heating. The arrangement of a kitchen hot water heater is shown in Fig. 67. Cold water enters the boiler near the bottom through a pipe that passes into it at the top. From the bottom of the boiler a pipe is led in a coil around or over the fire and back to the top of the boiler. This pipe leaves the fire at a higher level than that at which it approaches. The water circulates as indicated by the arrows.

The circulation of the water may be observed conveniently by making a model of the heater out of glass tubing and introducing a few drops of ink in the heating pipe. Still more simply, these currents may be seen in a beaker of water when it is being heated over a flame. A few scrapings of blotting paper in the water enables them to be seen more easily. If the flame be applied to the water at the top of the beaker, no such currents are set up.

By filling the flask (Fig. 64) with water and heating it, we find that water also expands when it is heated. Therefore, a cubic inch of hot water weighs less than the same volume of cold water, i. e., *hot water is less dense than cold water*. When a small volume of water in the beaker becomes warmer than the surrounding water, it also becomes less dense. The denser water then forces its way underneath and pushes the warmer water up. Thus the circulation is started and maintained in water just as it is in air. The center of gravity of the water is not at the lowest possible level unless the colder water is at the bottom and the hot water on top.

A hot water system for heating houses works like the

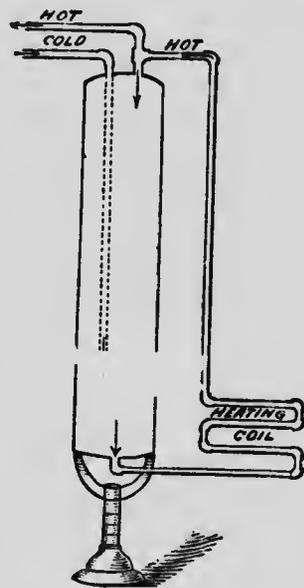


FIG. 67 WATER HEATER

kitchen heater. The heating coils are in the furnace in the basement. Each radiator is connected with these coils in the same manner as the kitchen boiler is connected with its coil. The hot water flows into the radiator and heats it, thus warming the room. It then passes out at the bottom and back to the furnace to be reheated.

106. Convection. In the devices we have been studying, heat is absorbed from a fire by either air or water, and carried along by the air or water to the place where it is wanted. The process by which heat is carried by currents set up in a fluid because of differences in density, is called *convection* of heat.

Convection is the process by which heat is carried from hotter bodies to colder bodies by a moving fluid.

107. Conduction. The handle of a silver spoon becomes hot very quickly if the bowl of the spoon is placed in a cup of hot tea. One end of an iron poker becomes too hot to touch when the other end has been in the fire for a few minutes. So long as one end is hotter than the other, heat creeps along the metal from the hot end toward the colder end.

In stoves and furnaces the heat passes through the iron walls of the firepot from the fire inside to the colder air or water outside. The process continues as long as the inside is hotter than the outside. In all these cases the metals do not move along with the heat; but the heat flows, or is conducted, through them. This process of the transfer of heat is called *conduction*.

Conduction is the process by which heat is transferred from hot bodies to cold bodies through substances that are at rest.

108. Good and Bad Conductors. When milk is heated in a metal pan over a hot fire, it is easily scorched; because the fire is very hot and the metal pan offers little resistance to the flow of heat from the fire to the milk. So it is customary to

place an asbestos mat between the flame and the pan. Asbestos offers such a high resistance to the passage of heat that the heat flows through it slowly, and the top of the mat remains at a much lower temperature than that of the flame below. Hence, the heat does not flow into the milk too fast to be distributed through it by convection currents, before any of it gets burned. Asbestos is also much used to cover steam pipes and boilers.

Brick, wood, and glass offer resistance to the passage of heat. They are therefore excellent materials for building houses that will hold the heat during the winter, and keep it out during the summer. Bricks are also used in building furnaces and chimneys. They resist the flow of heat to such an extent that a very hot fire may be kept in the furnace without heating the outside too much. In other words, a large difference in temperature may be maintained between the inside and the outside, and yet relatively little heat passes through the walls and escapes.

The fireless cooker consists of two boxes of wood or metal, one inside the other, separated by a space which is packed with excelsior, glass wool, or some granular substance that prevents the circulation of the air between the boxes. Such a layer of still air prevents the escape of the heat from the hot food that is placed inside the smaller box to be cooked. In like manner, the walls of a refrigerator are double; and the space between is usually filled with charcoal, which keeps the air there still, so that the heat does not flow through easily. The thermos bottle consists of a metal case containing two glass bottles, one within the other, and separated by a space from which the air has been pumped out. This vacuum prevents the flow of heat either into or out of the inside bottle. Anything that offers large resistance to the flow of heat is called a *bad conductor of heat*.

Conversely, stoves, steam radiators, and boilers are made of iron, because iron offers little resistance to the passage of heat. The inside and the outside of the iron shell have nearly the same temperature, because the heat passes easily

through the iron and escapes into the room. Metals offer little resistance to flow of heat; they are therefore called *good conductors of heat*.

109. Temperature. Every one has some idea of what is meant by "hot" and "cold." Yet if we take three basins of water, one hot, one lukewarm and one cold, and place the right hand in the hot water and the left in the cold, and then transfer both hands to the lukewarm water, the latter will seem cold to the right hand and hot to the left. So it appears that we cannot always rely on our sensations of warmth for accurate information about differences in temperature.



FIG. 68
GALILEO'S
THERMOM-
ETER

In Art. 100 we learned that air expands when heated. This fact suggests that the expansion of an enclosed mass of air may give more reliable information about temperature. We owe this suggestion to Galileo, who made one of the first thermometers ever used. He blew a bulb on the end of a glass tube of small bore, and, after warming the bulb, placed the open end of the tube in a vessel of colored water (Fig. 68). As the air in the bulb cooled, the liquid rose in the tube; and when the bulb was warmed again, the air expanded and the liquid went down. The ordinary thermometers now in use do not differ from this one in principle. A small bulb is blown on the end of a tube of fine bore, and filled with alcohol or mercury, which have been found more convenient than air. The open end of the tube is sealed, and the tube mounted in a frame which carries the scale.

110. Temperature Scales. Galileo's thermometer furnishes us with means of detecting changes in temperature, but it does not tell us definitely how great a change in temperature is indicated by a given change in the height of the liquid in the tube. In order to make a temperature scale, we arbitrarily select two different temperatures that are fixed

and easily obtained, and then agree to divide the temperature interval between them into some definite number of temperature steps or degrees.

The scale used in American households was devised by Fahrenheit (1686-1736). He chose the temperature of the human body as one fixed point and called it 100° . For the other fixed point, he chose that of a freezing mixture of ice and salts and called it zero, because it was the lowest temperature then known. He divided this interval into 100 steps or degrees. On this scale the temperature at which water freezes is 32° , and the temperature of boiling water under normal barometric pressure (30 inches of mercury, Art. 80) is 212° . It was soon found to be more convenient and accurate to graduate these thermometers by placing them in melting ice and in the steam of boiling water, and marking the points where the mercury stands 32° and 212° respectively. It was then found that the temperature of the human body was 98.4° according to this scale.

Another temperature scale, which is generally used in physical laboratories is called the *Centigrade scale*. On this scale the temperature of melting ice is called 0° , and that of boiling water 100° . Since both scales are in common use, we distinguish them by using F. for Fahrenheit and C. for Centigrade. It is well to remember that $0^{\circ}\text{C.} = 32^{\circ}\text{F.}$ and $100^{\circ}\text{C.} = 212^{\circ}\text{F.}$; hence a difference in temperature of 100 Centigrade degrees is equal to $212 - 32 = 180$ Fahrenheit degrees; or 5 Centigrade degrees make 9 Fahrenheit degrees, and 1 Centigrade degree = 1.8 Fahrenheit degrees.

111. Expansion. The ordinary mercury thermometer shows us that mercury expands when heated and contracts when cooled, much as air does. Water, alcohol, metals and nearly all substances are found to be affected in the same way. In building a railway it is necessary to leave small spaces between the rails in order to allow for their expansion in summer. Steel bridges, for the same reason, have their ends supported on rollers, so that they can expand and con-

tract. If hot water is poured into a cold thick glass tumbler, the glass will probably crack, because the inside expands before the outside can get heated.

While most substances expand when heated and contract when cooled, they are not all affected equally by the same change in temperature. 100 feet of steel rails increase in length about half an inch when heated from 10° C. below zero (-10° C.) to 30° above. If the rails were aluminum, they would expand about twice this amount for the same rise in temperature. Brass rails would expand about three quarters of an inch under the same conditions.

112. Exceptional Expansion of Water. Water is one of the few substances that do not always contract when cooled. It contracts as it is cooled until it reaches the temperature of 4° C. (about 39° F). When cooled further, it expands to the freezing point. When it freezes, it expands still further, so that ice is less dense than water. On this account ice floats, about one-seventh projecting above the water. It is well for us that ice acts in this exceptional manner; for if it should sink, lakes and rivers in latitudes where there is much freezing would become solid cakes of ice.

113. The Heating and Cooling Process. If a small beaker full of hot water be placed in a larger beaker of cold water, the hot water gets colder, and the cold water hotter until both have the same temperature. If a small beaker full of water be placed in a larger one of the same temperature, neither changes its temperature.

If a room is cold, it may be warmed only by bringing into it something hot—a stove, a steam radiator, or hot air from the furnace. Heat then passes from these hot bodies to the air and the colder bodies in the room; and if no heat were allowed to escape, the process would continue until everything in the room had reached the same temperature. The process of heating or cooling therefore implies the existence of at least two bodies at different temperatures. One is

heated at the expense of the other. Heat given up by the hot body is absorbed by the colder one, since it always flows from bodies at higher temperatures to bodies at lower temperatures.

The heating or the cooling process consists in the transfer of heat between bodies at different temperatures.

Heat given up by the hot body is absorbed by the colder body.

114. Boiling. Every housekeeper knows that a kettle of water when placed on the stove will come to a boil sooner when the kettle is covered than when it is not. In order to learn the reason for this, we shall have to study the processes of changing water into steam, and steam into water.

Place an uncovered beaker of water over a flame, insert a thermometer, and watch what happens. As the water gets hotter, it begins to "sing," and we note that bubbles are forming at the bottom and starting upward through the water. At first the bubbles do not reach the surface, but disappear shortly after leaving the bottom of the beaker. As the water gets hotter, the bubbles go higher before they disappear. At last they reach the surface and break through into the air. The water is then said to *boil*.

During this process the mercury has been gradually rising; but when the boiling begins, it remains stationary, no matter how hard the water boils, and notwithstanding the fact that heat is constantly being supplied to it from the burner. If the thermometer be held in the steam just above the boiling water it shows that the temperature of the steam is the same as that of the boiling water.

Boiling is the process in which bubbles of steam form at the bottom of heated water, float up, and break through the surface.

The temperature of boiling water remains stationary.

The stationary temperature at which boiling takes place is called the boiling point.

The temperature of the steam is the same as that of the boiling water.

115. Heat of Vaporization. Whenever the burner is removed, the boiling ceases, i.e., the bubbles of steam are no longer formed in the water; but when the burner is replaced under the beaker, the steam bubbles at once begin to form again. Steam does not form unless heat is being added. Therefore, *heat must be supplied in order to change water into steam at the same temperature.*

The heat absorbed when water is changed into steam is called the heat of vaporization.

We can get a very crude idea of how much heat is required to change a gram of boiling water into steam, by putting a measured quantity of water, say 1 pound (= 1 pint) at 32° F.,

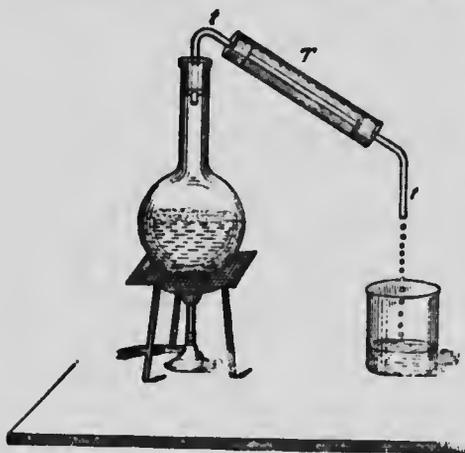


FIG. 69 CONDENSING STEAM GIVES UP HEAT

into an open beaker over a steady flame, and noting the time taken to heat it to boiling. Then, after the water has boiled for an equal length of time, weigh it, and find out how much has passed off as steam. If we assume that the same amount of heat goes into the water each second, we find that approximately the same amount of heat is required to convert 3 ounces of boiling water into steam, both at 212° F., as is required to raise the temperature of 1 pound of water from 32° to 212° F.

116. Condensation. If a cold plate be held in the steam above the beaker of boiling water, it soon becomes covered with drops of water. The steam is cooled by the plate, and *condenses* into water again. If water is boiled in a flask (Fig. 69) which has a glass tube *t* fitted through the stopper, the steam may be caught and led away. If the tube *t* passes through a larger tube *T* filled with cold water, the steam condenses, and hot water comes out at the other end. The

temperature of this hot water will be nearly 212° F.; yet the water in the tube T rapidly becomes hot, proving that *steam in condensing to water gives up a large amount of heat.*

To find out how much heat is given up by the steam in condensing, we conduct the steam from the flask into a beaker (Fig. 70) containing a measured quantity of water at 32° F., and note how much water is condensed from steam in heating the cold water to boiling. Thus if we have 1 pound of water at 32° F., and if we pass steam into it until no more steam condenses, we find that we have about 1 pound and 3 ounces of boiling water. The additional 3 ounces represent the amount of steam that has been condensed. So we see that the heat given up in condensing 3 ounces of steam into water is approximately equal to that required to heat 1 pound of water from 32° to 212° F. *This is the same amount of heat that was required to change 3 ounces of water into steam (Art. 115).* Hence the conclusion:

The heat absorbed by the vapor while the liquid is vaporizing is given up again by the vapor while it is condensing.

When water is converted into steam, impurities in the water that do not vaporize readily are not carried away with the steam. So water may be purified by vaporizing it and then condensing it. This process is called *distilling*. The apparatus shown in Fig. 69 is a simple form of *still*. Water so purified is called *distilled water*.

117. Unit Quantity of Heat. The experiments just described lead to a result that cannot yet be easily stated because we have not yet selected a unit in terms of which to measure a

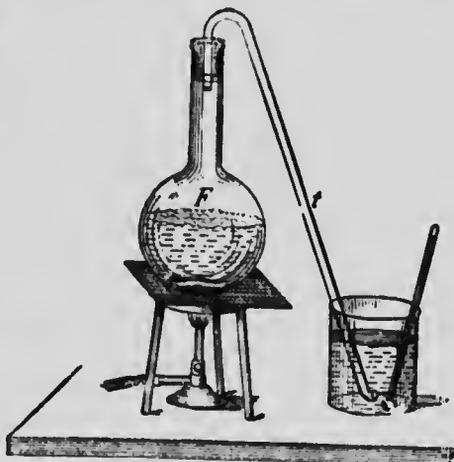


FIG. 70 HOW MUCH STEAM IS CAUGHT?

quantity of heat. Temperature is measured with a thermometer; but every one knows that it takes more heat to bring four quarts of water to the boiling point than it does to bring one quart to the same temperature. So quantity of heat is not the same as temperature, and hence it cannot be measured with a thermometer only.

The experiments of Arts. 115-6 suggest a convenient unit—namely, the quantity of heat that is required to heat a unit quantity of water through one degree of temperature. Since we have two temperature scales as well as two units of weight, there are two heat units in common use. The first is used by engineers, and the second by scientists in the laboratory.

The British Thermal Unit (B. T. U.) is the quantity of heat that is required to change the temperature of 1 pound of water 1° F.

The gram-calorie is the quantity of heat that is required to change the temperature of 1 gram of water 1° C.

118. Heat of Vaporization of Water. In the experiment with steam (Art. 115) we found that 1 pound of water was heated from 32° to 212° F.—i. e., through 180° F.—by the heat given up from about 3 ounces of condensing steam. The heat received by the water was 1 pound \times 180° F. = 180 B. T. U. Since this number of heat units was derived from 3 ounces of steam, each pound (16 ounces) of steam would have supplied $180 \div \frac{3}{16} = 960$ B. T. U.

Accurate measurements show that it requires 967 B. T. U. of heat to convert one pound of water at 212° F. (the boiling point) into steam at the same temperature. *The heat of vaporization of water is 967 B. T. U. per pound. In the metric system it is 536 gram-calories per gram.*

We begin now to see how a cover on a kettle prevents the escape of heat when the water is boiling. When the water passes into steam, it absorbs a large amount of heat; and if the steam is allowed to escape into the room, this heat escapes with it. The cover prevents the escape of the steam with its

heat. This fact, however, does not give the full explanation that we are seeking. We must first discover what happens while the water is coming to a boil.

119. Evaporation. Water that is left standing in an open dish in a warm room soon dries up. Wet clothes are hung out of doors or in a hot room when we wish to get the water out of them—i. e., to “dry” them. It is thus a familiar fact that water passes into water vapor—i. e., *evaporates*—not only when boiling, but also at all ordinary temperatures.

Without water, plants and animals cannot live. Large areas of land would be uninhabitable if there were no rain. Rains are produced by water that has evaporated from the oceans, lakes, rivers, and moist lands. When the sun shines on the surface of a body of water it supplies heat, which hastens the process. The water vapor rises from the surface of the water and moves off in all directions. It is also carried along by winds. When anything happens to cool it sufficiently, it condenses into *clouds*, which are made up of tiny drops of water or of tiny particles of ice. When these drops or particles become heavy enough, they fall as rain or snow. Rains supply rivers, which drive mills, so evaporation not only helps to supply the water that supports life; it also helps to do the work of the world.

120. Cooling by Evaporation. Whenever our hands are moist and we allow them to dry in the air, they are cooled by the evaporation. If the hand is wet with alcohol or ether, the sensation of cold is more marked than when water is used, because the evaporation is more rapid. If a pitcher of water is wrapped with a wet cloth and set in the breeze on a hot day, it will be kept cool if the cloth is kept moist. A thermometer whose bulb is covered with a piece of wet muslin will indicate a lower temperature than one not so wrapped, so long as the muslin remains wet.

When in a hurry to dry wet clothes we hang them by the fire or in the sunshine. We do this because we know that

heat must be supplied when a liquid evaporates, and that the process may be hastened by supplying the heat freely.

Conversely, by hastening the evaporation by means other than heat, low temperatures may be obtained; for heat is always absorbed during evaporation. This fact finds practical application in the manufacture of ice, and in cold storage plants. Ammonia or carbon dioxide gas is condensed into a liquid by means of a powerful force pump driven by a steam engine. The liquefied gas is then allowed to escape through a valve into a system of pipes from which the air has been pumped. These pipes pass back and forth in a large tank filled with salt water. The heat required for vaporizing the liquid carbon dioxide or ammonia is taken from this brine, which is thus cooled until its temperature is several degrees below 0° C. It does not freeze, because the freezing point of brine is much below 0° C. The pure water to be frozen is placed in large sheet-iron molds, which are submerged in the cold brine and are kept there until the water in them has given up so much of its heat to the colder brine that it freezes into solid cakes.

In the processes just described, the marked cooling effect of vaporization shows that *large amounts of heat are absorbed when a liquid evaporates.*

121. Saturated Vapor. No one thinks of hanging clothes out to dry in a fog. The fog, like rain clouds, is made up of tiny drops of water floating about in the air. The presence of these drops of water shows that evaporation has stopped; so the clothes will not dry. The atmosphere contains all the water vapor it can hold, so it does not take up any more.

If a bottle partly filled with water is left standing without a cork, the water finally evaporates and leaves the bottle dry. But if the bottle is kept tightly corked, the water will stay in it for months, or even for years. The water evaporates in the bottle until the space in the upper part of the bottle contains all the water vapor it can hold; then, since the cork prevents the escape of any vapor, evaporation ceases. In

other words, there is a limit to the amount of water vapor that a given space can hold. When a given space contains as much water vapor as it can hold, the water vapor there is said to be *saturated*.

122. Dew Point. On a warm, moist day, when the temperature is say 80° F., any object but little colder than the room, like a pitcher of cold water at a temperature of about 60° F., soon becomes covered with drops of water. It is often said that the pitcher "sweats," but the water on it does not come from inside the pitcher. It is condensed from the atmosphere on the outside. But the water vapor becomes saturated before it condenses; so when the water vapor in the atmosphere is plentiful, it becomes saturated and condenses at a fairly high temperature (60° F. say).

In a steam-heated house in winter, clothes dry quickly, because the air is dry, and evaporation takes place quickly. Also, throats become parched, and people grow restless. Although the temperature of the room may be 80° F., no water condenses even on so cold an object as a pitcher of ice water (32° F.). We know that it is very cold out doors when the water vapor in such a room condenses into ice crystals and paints "Jack Frost's pictures" on the window panes. When the water vapor in the atmosphere is rare, it must be cooled to a rather low temperature before it becomes saturated and begins to condense.

Combining the conclusions of the last two paragraphs, we see that there are different amounts of water vapor in the atmosphere on different days, and that the *more plentiful the water vapor, the higher the temperature at which it becomes saturated and begins to condense*. Hence, the temperature at which the water vapor becomes saturated and begins to condense furnishes a clue to the amount of water vapor in the air. This temperature is called the *dew point*, because a familiar case of the condensation of water from saturated vapor is found in the deposition of dew.

The dew point is the temperature at which water vapor becomes saturated and begins to condense.

123. Conditions of Saturation. Take two barometer tubes bb' (Fig. 71), and with a bent tube, squirt a little water into the lower end of one of them under the mercury, taking care not to admit air. The water rises through the mercury, collects on top, and some of it vaporizes, until the top of the tube is filled with water and saturated water vapor. The column of mercury and water in this tube now stands at a lower level than it does in the other, which shows that the *water vapor exerts a pressure* which pushes the mercury column down. This pressure may, therefore, be measured by the difference ct in the heights of the two mercury columns (Fig. 71).



FIG. 71

If the tube containing the water be raised and lowered as far as possible without getting it out of the mercury; or if it be tipped sideways, the volume occupied by the water and the saturated vapor may be varied. But so long as the temperature remains constant, the difference in level of the tops of the two columns does not change; showing that *the pressure of the saturated vapor in contact with its liquid remains constant as the volume changes*. As the volume in the top of the tube is increased, more water evaporates; as that volume is decreased, some of the water vapor condenses, and so keeps the pressure constant.

If the tube with the water in it be heated, the column falls at once, as shown in b'' (Fig. 71). This shows that *an increase in temperature causes more water to evaporate, and so produces an increase in the pressure of the saturated vapor*. Many other experiments of this sort have been made and all lead to similar results. Hence the conclusions:

A liquid continues to evaporate until the vapor about it is saturated.

A vapor in contact with its liquid in a closed vessel quickly becomes saturated.

A vapor in a closed vessel exerts a pressure on the walls of the vessel.

The pressure exerted by a given saturated vapor in contact with its liquid in a closed vessel increases as the temperature rises, but depends only on the temperature.

We can now answer in full the question as to why the teakettle comes to a boil sooner when the cover is on. It is because the teakettle is then a closed vessel, containing water and water vapor. *Evaporation from the surface of the water continues until the water vapor in the top of the kettle is saturated; then it stops.* If the cover is off, evaporation will not stop until the entire room becomes filled with saturated water vapor. Evaporation always requires heat, and so long as it goes on, it cools the water. If the water is to be heated quickly, we put a cover on the kettle, and this prevents the evaporation.

124. Pressure and Temperature of Saturated Water Vapor. Since the pressure exerted by a given saturated vapor in a closed vessel changes as the temperature changes, but depends only on the temperature, the relation between pressure and temperature can be determined by experiments similar to those just described. For water vapor, the results are given for reference in the following table. The temperatures are in centigrade degrees, and the pressures in centimeters of mercury.

Temperature	Pressure	Temperature	Pressure
0.....	0.5	100.....	76.0
20.....	1.7	120.....	149.1
40.....	5.5	140.....	271.8
60.....	14.9	160.....	465.2
80.....	35.5	180.....	754.6
90.....	52.5	200.....	1169.0

125. Boiling Point. From the table, note what the pressure of the saturated water vapor is at 100° C. What relation is there between that pressure and the normal barom-

eter pressure? You may have heard that it is not possible to cook eggs by boiling them on high mountains, because the water does not get hot enough. The following experiment will help us to find the reason for this interesting fact.

Fit a laboratory boiler (Fig. 72) with a thermometer and a pressure gauge, and boil water in it. Then cork the outlet *O* loosely, so as to allow the steam to escape but slowly

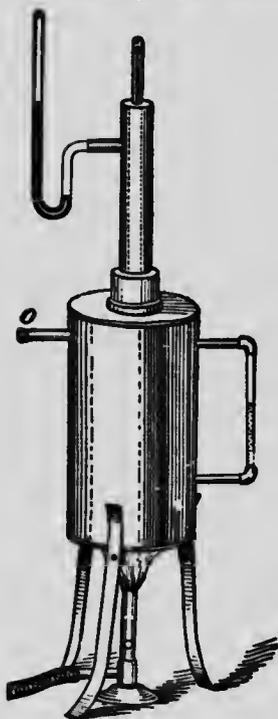


FIG. 72 THE BOILING POINT RISES

under pressure. Watch the thermometer and the gauge as the heating goes on. *The thermometer rises 1° C. for an increase in pressure of about 3 centimeters of mercury. So an increase in the pressure on the surface of the water raises the boiling point.* Conversely, diminishing the pressure lowers the boiling point. On high mountains the pressure of the atmosphere is low, so that water boils at a temperature which is not high enough to cook eggs.

That water boils when its temperature is raised until the pressure of the saturated vapor is equal to the pressure of the surrounding atmosphere may readily be appreciated from common sense reasoning. For it is plain that ebullition (boiling) is different from evaporation in that the steam escapes in bubbles from the midst of the liquid instead of from the surface only. Now if the

surrounding pressure were greater than the pressure of the steam in these bubbles, the bubbles would be unable to expand and float to the surface. On the other hand, if the external pressure were less than that of the steam composing the bubbles, the water would flash into steam instantaneously, as it sometimes does with explosive violence when a defective boiler gives way. Hence the following definition:

The boiling point is the temperature at which the pressure of the saturated vapor is equal to the surrounding pressure.

126. Relative Humidity. Returning to the question of the humidity of the air, if the temperature of the room is 20°C ., and if the water vapor in it were saturated, how much pressure would the water vapor exert? The table, Art. 124, gives the number—namely, 1.7 centimeters of mercury. But suppose the dew point was found to be 0°C . Then the water vapor actually present in the air will not be saturated until cooled to 0° . At this temperature it exerts a pressure of only 0.5 centimeters of mercury. Thus the water vapor, if saturated, would exert as great a pressure as 1.7; but it actually does exert a pressure of only 0.5. *The ratio of the pressure that the water vapor actually exerts, to the pressure it would exert if saturated at the given temperature, is called the relative humidity.*

In the case just considered the relative humidity is $\frac{0.5}{1.7} = 0.29$ or 29%. This means that the air contains only $\frac{29}{100}$ of the water vapor that is needed for saturation at 20° .

The humidity of the schoolroom or home should not be allowed to fall below 50%. Out doors it is generally higher than this. In the best modern public buildings, heating plants are equipped with devices for supplying the necessary moisture to the air.

Relative humidity is the fraction obtained by dividing the pressure of saturated water vapor at the dew point, by its pressure at the temperature of the air.

127. Freezing. Ice cream is frozen by surrounding the cream with a mixture of ice and salt. The salt makes the ice melt; and as the ice melts, the cream freezes. In order better to understand this process, fill a beaker with cracked ice, place a thermometer in it, and heat it slowly over a flame. As the ice melts, the thermometer indicates 0°C . As the heating continues, more ice melts; but the temperature remains stationary at 0°C . It thus appears that *heat is absorbed in the process of changing ice into water, just as it is absorbed when liquids evaporate.*

Conversely, heat must be taken from water to cause it to change from water at 0°C . to ice at the same temperature. *The heat given up by a liquid in freezing, or that absorbed by a solid in melting, is called heat of fusion.*

128. Heat of Fusion of Ice. To find out how much heat is absorbed by ice in melting, put about 2 pounds of water in a beaker and warm it to 104°F . Then drop in $\frac{1}{2}$ pound of dry cracked ice, and stir till all the ice is melted. During the process the water cools to 60° . In the process 2 pounds of water have been cooled 44°F .; so $2 \times 44 = 88$ B. T. U. of heat have been given up by the water. This heat has been absorbed by the $\frac{1}{2}$ pound of ice in melting, and in heating the $\frac{1}{2}$ pound of melted ice from 32° up to 60° . But $\frac{1}{2} \times 28 = 14$ B. T. U. were used in heating the melting ice to 60° . Hence, $88 - 14 = 74$ B. T. U. were required just to melt $\frac{1}{2}$ pound of ice. The heat required to melt 1 pound is therefore $74 \times 2 = 148$ B. T. U.

A more accurate determination shows that

*The heat of fusion of ice is 147 B. T. U. per pound. Or,
The heat of fusion of ice is 80 gram-calories per gram.*

In freezing ice cream, therefore, every pound of ice which is melted absorbs 147 B. T. U. of heat from adjacent objects, largely from the cream. When water is frozen, 147 B. T. U. of heat must be extracted from every pound. This fact has an important bearing on climate, in that large amounts of heat are given out by the water and absorbed by the air when lakes freeze over, making the cold weather less severe. All substances absorb heat when melting and give up heat when solidifying. The heat of fusion for different substances is different. For lead it is 5 and for silver 21 gram-calories per gram.

129. Specific Heat. Does it require the same amount of heat to warm different substances through the same temperature interval? For answer, place a 1-pound iron weight in a beaker containing 1 pound of water, and heat

to boiling. The iron and the water then have the same temperature, namely 212° F. Now remove the weight and cover the beaker to prevent evaporation, and observe which gets cold faster. The iron does, largely because it contains less heat than the water. Numerous experiments of this sort show us that different substances require different amounts of heat to raise their temperatures 1°.

The specific heat of a substance is the number of B. T. U. required to raise one pound of the substance 1° F. Or,

The specific heat of a substance is the number of gram-calories of heat necessary to raise the temperature of one gram of the substance 1° C.

The numerical value of the specific heat of any substance may be determined by experiment in a number of different ways. One of the simplest of these is illustrated by the following example: 100 gm of aluminum clippings at 98° C. are stirred into 200 gm of water at 2° C.; and the mixture comes to the temperature of 11.5°. If h represents the specific heat of aluminum, the heat given up by it in cooling to 11.5 is

$$\begin{aligned} &\text{Specific heat} \times \text{grams} \times \text{change in temperature} \\ &h \times 100 \times (98^\circ - 11.5^\circ) \end{aligned}$$

The heat absorbed by the water in warming to 11.5 is

$$\begin{aligned} &\text{Specific heat} \times \text{grams} \times \text{change in temperature} \\ &1 \times 200 \times (11.5^\circ - 2^\circ) \end{aligned}$$

The heat absorbed by the water must be equal to that given out by the aluminum; so that we may form the equation, $h \times 100 \times (98 - 11.5) = 1 \times 200 \times (11.5 - 2)$ or $h = 0.219$. This means that it requires 0.219 gram-calories of heat to warm 1 gram of aluminum 1° C.

The following are the values of the specific heat of some of the more common substances. Water 1.00; ice, 0.50; glass, 0.19; iron, 0.11; copper, 0.09; silver, 0.06; gold, 0.03. These numbers mean that it takes 1 gram-calorie of heat to heat 1 gram of water 1° C.; half a gram-calorie to heat 1 gram of ice 1° C.; 0.03 gram-calorie to heat 1 gram of gold 1° C., etc.

It will be noted that water and ice have much larger specific heats than the other substances. This fact is impor-

tant in determining climatic conditions in the neighborhood of large lakes and oceans. Because water absorbs a large amount of heat when being warmed, and gives up an equally large amount when being cooled, lakes and oceans cool slowly in winter and warm up slowly in summer, thus serving to equalize seasonal temperatures. That household comfort, the hot-water bottle, is perhaps a more familiar example of the value of the high specific heat of water.

DEFINITIONS AND PRINCIPLES

1. Nearly all substances expand when heated and contract when cooled.
2. Convection is the process by which heat is carried from a hot body to a colder body by a moving fluid.
3. Conduction is the process by which heat is transferred from hot bodies to cold bodies through substances that are at rest.
4. The temperatures of melting ice and the steam from water boiling at normal barometer pressure are the two fixed points selected for temperature scales.
5. $0^{\circ}\text{C.} = 32^{\circ}\text{F.}$ $100^{\circ}\text{C.} = 212^{\circ}\text{F.}$
6. Water contracts while being cooled to 39°F. ($= 4^{\circ}\text{C.}$), but when cooled further it expands until it freezes.
7. The heating or the cooling process consists in the transfer of heat between bodies at different temperatures.
8. Heat moves from the hot body to the colder body.
9. The British Thermal Unit (B. T. U.) is the amount of heat required to raise the temperature of 1 pound of water 1°F.
10. The gram-calorie is the amount of heat required to raise the temperature of 1 gram of water 1°C.
11. The heat of vaporization of steam is 967 B. T. U. per pound, or 536 gram-calories per gram.
12. Liquids evaporate at all temperatures.
13. A liquid continues to evaporate until the space over it becomes saturated.

14. A vapor in contact with its liquid in a closed vessel soon becomes saturated.

15. The pressure exerted by a given saturated vapor increases as the temperature rises but depends only on the temperature.

16. The boiling point is the temperature at which the pressure of the saturated vapor is equal to the surrounding pressure.

17. The dew point is the temperature at which water vapor becomes saturated and begins to condense.

18. The heat of fusion of ice is 147 B. T. U. per pound or 80 gram-calories per gram.

19. The specific heat of a substance is the number of B. T. U. necessary to raise the temperature of 1 pound of the substance 1° F.; or it is the number of gram-calories of heat necessary to raise the temperature of 1 gram of the substance 1° C.

QUESTIONS

1. Why are the chimneys of factories usually very tall?
2. Is the smoke from a fire pulled or pushed up a chimney? Why?
3. If your fireplace smokes, what might you do to stop it? Explain fully.
4. How are tissue paper balloons made to ascend? Is there any limit to the altitude they will reach?
5. In boiling a soup bone on a gas stove why should the dish be covered and the gas turned low, after the water begins to boil?
6. Why can vegetables be cooked more efficiently in a fireless cooker than on a red hot stove?
7. What makes a wood fire snap and crackle?
8. When a glass is filled with cold water from the top and allowed to stand and warm up to the temperature of the room, why do bubbles of air collect on the inside of the glass?
9. Which heats a room better, an open fire in a fireplace or a fire in a stove? Why?
10. Could a hot air furnace placed in the attic be used to heat a house? How?
11. Why is the ice always placed near the top of a refrigerator?
12. In the kitchen boiler (Fig. 67), why does not the cold water inlet pipe end at the top of the boiler?

13. Is it desirable to have a fireplace in a room that is heated by hot air from a furnace, even though no fire is ever built in it? Why?
14. A room may be ventilated by opening a transom over a door or the top of a window on one side and opening a window at the bottom on the opposite side. A board is often placed in front of the opening on the sill to deflect the cold air upward. Explain.
15. A stove will distribute the heat more comfortably in a room if a cylindrical jacket, open at top and bottom, is placed around it. Why?
16. If there is a ventilating shaft in a schoolroom next to a chimney, will this shaft work on a cold day when the chimney is not hot?
17. How will the ventilating shaft of question 16 operate when the air outside the school building is warmer than that inside?
18. Why is ventilation by opening windows and by heated air stacks generally inadequate for schoolrooms?
19. Why are asbestos mats useful when heating milk over a gas stove?
20. Why are steam pipes often covered with asbestos?
21. Why is iron better than brick or porcelain as a material for stoves?
22. Force a piece of ice to the bottom of a test tube of water with a piece of lead. Apply a flame at the top. Does the ice melt rapidly? Why?
23. Allow the ice to float at the top of the test tube of question 22 and apply the flame at the bottom. Is the effect the same as in question 22? Why?
24. Why was Galileo's thermometer unsatisfactory as a temperature measurer?
25. The grate bars in furnaces are not rigidly fastened to the frames in which they are set. Why?
26. Why do telegraph wires that are strung in winter sag in the summer?
27. When pouring hot preserves into glass jars, it is a good plan to wrap the jars in a hot cloth. Why?
28. What is ordinarily the temperature of the water at the bottom of a pond that is frozen over?
29. What prevents a pond from freezing solid?
30. Why do water pipes burst when the water in them freezes?
31. What influence has the melting and freezing of water upon the making of soils from rocks?
32. Why are bubbles of steam formed at the bottom of a kettle of water over a fire?
33. Why do the bubbles of steam (question 32) rise in the water?
34. Why do the steam bubbles (question 32) disappear before reaching the surface before the water comes to the boiling point?
35. If water is brought to the boiling point and then removed from the stove does it continue to boil? Why?

36. Why are burns from steam more painful and injurious than burns from hot water at the same temperature?
37. Would a teakettle be more efficient if it had a cover to the spout as well as to the kettle itself? Why?
38. The water at the top of a waterfall is able to do work. How did it get this ability?
39. What is the difference between a fog and a cloud?
40. What determines whether water vapor in the air shall return to the earth as rain or snow or sleet?
41. When a moist wind from the ocean sweeps against a mountain chain it is forced up as if ascending a high inclined plane. In these high altitudes it is cooled. What happens to the moisture in it?
42. Why is the rainfall of California abundant, while that of Arizona and New Mexico is scanty?
43. Mexicans cool their drinking water by setting it in a current of air, in the shade, in jars of porous earthenware. Why is this method effective?
44. Why does water evaporate more rapidly from a shallow pan than from a bottle? From a lake than from a puddle? When the wind is blowing than when the air is still? When the temperature is high than when it is low? When the air is dry than when it is moist?
45. Does dew "fall"? Why?
46. Why does more dew form when the air is moving gently than when it is perfectly still? On a clear night than on a cloudy one?
47. Why does more dew form when the air is moist than when it is dry? On a cool night than on a warm one?
48. What circumstances determine whether there shall be dew or frost?
49. Why does dew form only at night?
50. Why does moist air when heated become "dry," although no moisture has been precipitated from it?
51. What does a relatively high dew point tell us of the amount of moisture in the air?
52. Why is it not possible to boil eggs on the top of Mont Blanc?
53. In his celebrated climb up the Righi, why did Mark Twain stop every little while to "boil his thermometer?"
54. When a bottle has been sterilized by boiling it, and is then drained and set aside with a tuft of cotton in its neck, the inside becomes coated with moisture. Why?
55. Why does ice cream freeze in a freezer?
56. Why do not icebergs melt before they reach the temperate zones?
57. Why is it cooler near the sea in summer, and warmer near the sea in winter than it is farther inland?

58. Does a large lake that freezes over in winter often "hold back the spring" for towns near it? Why?
59. Why is a bottle of hot water better than a hot stove lid for keeping your feet warm when you go sleigh riding?
60. Which cools faster, a cup of hot tea or the tea that remains in the teapot? Why?
61. When you have poured all the hot tea from a teapot, which cools the faster, the tea in the last cup poured, or the empty teapot? Why?

PROBLEMS

- How many B. T. U. are given up by 1 pound of melted lead when it solidifies (Art. 128)?
- A silver teaspoon that weighs 30 grams and is at a temperature of 20°C is put into a cup of hot tea at a temperature of 91°C . How many gram-calories of heat does the spoon absorb in becoming heated to 90°C ?
- If the cup of problem 2 contains 252 grams of tea, how much will the temperature of the tea be lowered because of having heated the spoon? (Art. 129)
- A cubic foot of air at ordinary temperature weighs approximately .07 pound. What is the weight of the air in a chimney whose flue is 10 square feet in cross section and whose height is 100 feet?
- When the air in the chimney of problem 4 has been heated until each cubic foot has expanded to $1\frac{1}{2}$ cubic feet, and the excess of air has flowed out at the top, what is the weight of the hot air in the chimney?
- What is the total force that pushes the hot air up the chimney (problems 4 and 5)?
- When a Fahrenheit thermometer reads 86° on a hot day, what does a Centigrade thermometer read?
- What is the temperature of the blood (98.2°F .) on a Centigrade thermometer?
- The temperature of a room is 20°C . What does the Fahrenheit thermometer read?
- Steel rods expand about $\frac{1}{800}$ inch per foot for every rise of 1°C in temperature. How much longer is an 80-foot steel girder in summer when its temperature is 40°C . than in winter when its temperature is 10°C ?
- How many B. T. U. are given out by a steam radiator when 25 pounds of steam have been condensed into water in it?
- How many B. T. U. are carried into the kitchen by the steam when one quart of water has been allowed to boil away?
- Steam from boiling water is passed into a beaker containing 1072 grams of cold water (Fig. 70). How many grams of water are there in the beaker when its temperature has risen 10°C ?

14. What is the dew point directly under the lid of a kettle of boiling water?

15. When the temperature of the air is 20°C . and the dew point is 0°C , what is the relative humidity (Art. 126)?

16. At what temperature does water boil under a pressure of 85 centimeters of mercury?

17. How many pounds of ice are needed to cool 5 gallons (40 pounds) of water at 65°F . to 32°F .?

18. A half cup of cold water at 10°C is poured into an equal quantity of hot tea at 98°C . What is the temperature of the resulting beverage?

19. A hot water bottle containing 2 quarts of water at 200°F . together with an iron stove cover that weighs 4 pounds and is heated to a temperature of 400°F . are placed side by side. When both have cooled to 100°F ., which has given up the more heat? How many B. T. U. more?

CHAPTER VII

HEAT AND WORK

130. Heat from Work. When a cent is rubbed hard on anything rough like the carpet, it becomes warm. Tools become hot when cutting wood and metal. Two pieces of ice may be melted by rubbing them together. Sparks fly from an emery wheel when a steel tool is being ground.

In all these cases not only is heat developed, but work is done in forcing something through some distance, against resistance. Since in these cases no heat is supplied from bodies at a higher temperature, and since the temperature rises only when work is done, we conclude that the work is the source of the heat. Many other familiar phenomena indicate that the temperature of a body may be raised by doing work on it. Hence the conclusion:

Work may be converted into heat.

131. Work from Heat. A steam engine can do work only when there is a hot fire under the boiler. A gasoline engine will drive an automobile or a boat, but only when it is constantly supplied with heat by exploding gasoline in its cylinders. All engines are devices for doing work with heat.

The way in which the heated steam in the cylinder of a steam engine does work in pushing the piston may be understood by recalling the experiments in Arts. 100 and 125. When the air in the flask is heated, it expands and pushes the drop of liquid upward in the tube for some distance against the pressure of the atmosphere. If the water in the closed laboratory boiler (Art. 125), is heated sufficiently, the steam will push the mercury out of the gauge, thereby doing work because of the heat from the burning gas. In these experiments, heated air or steam expands and pushes the liquid,

just as it pushes the piston in a steam engine. In all these cases we get work from heat. Hence the conclusion:

Heat may be converted into work.

132. Relative Efficiencies of Teakettles. Since heat and work are convertible, the most important thing to be known of any device for utilizing heat is, "What proportion of the heat put in is actually utilized; or, in other words, what is its efficiency?"

In the household the relative efficiencies of teakettles and of gas burners is important, just as in a factory the efficiencies of the furnaces and of the boilers are important. The methods of determining these efficiencies are similar. Let us therefore find out which of two teakettles is the more efficient. To do this we must measure the amount of heat that goes into the water in each kettle from the same burner in a given time under exactly the same circumstances.

Into each kettle put 2 quarts of water at the same temperature. Place a thermometer, F. or C., in the first one, set it over a burner, and allow it to heat for five minutes. Note the rise in temperature during this time. Do exactly the same with the second kettle. Then in each case the number of B. T. U. of heat absorbed by the water is equal to 4 pounds (2 quarts) \times rise in temperature. Since each was exposed to the same flame for the same time, we may assume that they received equal amounts of heat; and, therefore, the kettle that transmitted the larger number of B. T. U. into the water that it contains, is the more efficient.

133. Relative Efficiencies of Burners. When we wish to compare the efficiencies of burners we must know not only how much heat gets into the water, but also how much gas is consumed by each burner. So we have to test each burner during the experiment. For example, by burning 1 cubic foot of gas in a Bunsen burner, 4 pounds of water were heated from 50° F. to 122° F., i. e., through a range of 72°. The heat absorbed was 4 (pounds) \times 72 (°) = 288 B. T. U.

With this burner and kettle, then, we get 288 B. T. U. per cubic foot of gas.

On repeating the experiment with the same kettle and a burner like those used on gas stoves, we find that a larger amount of heat is given to the water by burning 1 cubic foot of gas. The numbers of B. T. U. thus obtained, however, give us only the relative efficiencies of the Bunsen burner and the gas stove burner. They are relative, because we have measured the useful heat obtained in *B. T. U.*, and the heat supplied in *cubic feet of gas*. To give actual efficiencies, both must be expressed in the same units; so we must find how many B. T. U. can be obtained by burning 1 cubic foot of gas.

134. Heat of Combustion. The heat that is given out by fuels when burning is called their *heat of combustion*. The

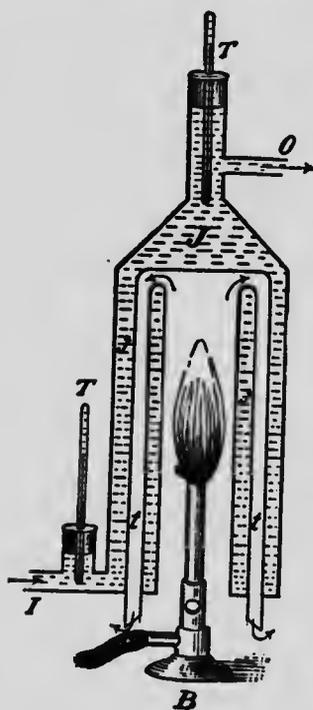


FIG. 73 CATCHING HEAT FROM GAS

amount of the heat of combustion of the laboratory gas may be found by surrounding the burner (Fig. 73) with a water jacket *J*. The hot gases from the flame pass out through tubes *tt* which are also surrounded with water. Water flows in at the bottom of the jacket, and out at the top, and the thermometers *TT* give the temperature of the water as it enters and as it leaves. By noting the difference in temperature on the thermometers and measuring the water that flows through while 1 cubic foot of gas is burned, the heat of combustion may be determined.

Thus in an experiment the lower thermometer registered 50° F. and the upper one 104° F. While 1 cubic foot of gas was burning, 11 pounds of water flowed through the jacket, thereby being warmed through 54° . Hence the number of B. T. U.

given out by burning the cubic foot of gas was

$$11 \text{ (pounds)} \times 54 \text{ (}^\circ\text{)} = 594 \text{ B. T. U.},$$

which is the heat of combustion of 1 cubic foot of this gas.

In like manner coal may be burned in a suitably constructed water jacket and its heat of combustion determined. The average heat of combustion of coal is 15,500 B. T. U. per pound. This is equal to 7800 gram-calories per gram, or 3,500,000 gram-calories per pound.

135. Thermal Efficiency. The efficiency of the kettle can now be expressed as the ratio of useful heat got out to total heat put in. Since the water absorbed 288 B. T. U. when 1 cubic foot of gas was burned, and since the cubic foot of gas supplied 594 B. T. U. in burning, the efficiency of the kettle and burner taken together is

$$\frac{\text{Useful Heat out } 288 \text{ (B. T. U.)}}{\text{Total Heat in } 594 \text{ (B. T. U.)}} = 53\%.$$

Thermal efficiency of a heating process is the fraction that what proportion of the total heat supplied is expended for useful purposes, or

$$\text{Thermal Efficiency} = \frac{\text{Heat out}}{\text{Heat in}}$$

136. Early Steam Engines. In olden times all work was done by men and animals, or by wind and water power. Industry and commerce were conducted on a relatively small scale, and no need for greater power was felt. About 1600, however, the need for a stronger and more reliable source of power developed; so attention was turned to steam, and efforts were made to harness it and make it do work.

One of the early steam pumps, built by a mechanic named Newcomen in 1705, is shown in Fig. 74. A cylinder *C*, open at the top, was fitted with a piston *P*, which was hung on a chain from one end of the "walking beam," and counter balanced by the weight *W* and the pump rod *H*. When steam was admitted to the cylinder at *I*, it pushed the piston up. The steam was then shut off and cold water was sprayed

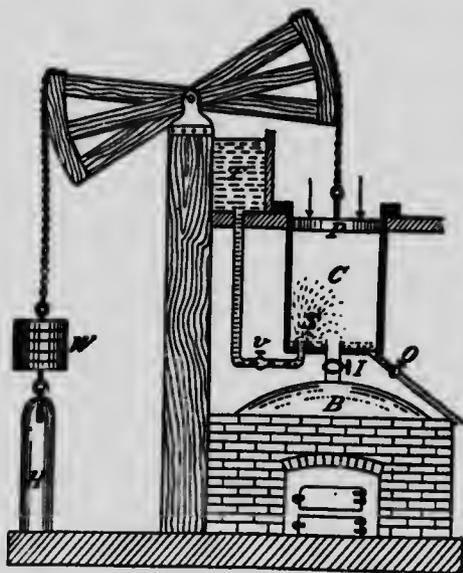


FIG. 74 NEWCOMEN'S ATMOSPHERIC ENGINE

into the cylinder at *S*. This cold spray condensed the steam; a partial vacuum was produced in the cylinder; and the pressure of the atmosphere pushed the piston down again. The water was then allowed to flow out of the cylinder at *O*, and the process was repeated, each stroke of the piston *P* giving one stroke to the pump rod *H*.

This engine was found to be very wasteful of steam. No one seems to have thought of measuring

its efficiency, in order to find out how wasteful it was, and how it might be improved until James Watt attacked the problem.

137. How Newcomen's Engine Wasted Heat. Watt began his experiments in 1763 on a small model of a Newcomen engine in the physical laboratory at the University of Glasgow, where he occupied the position of instrument maker. He was surprised at the amount of steam that was needed to fill the cylinder and push the piston up. He began to make measurements, and discovered that the amount of steam that had to be admitted to the cylinder to push the piston up once was sufficient to have filled it about four times with steam at the pressure maintained in the boiler.

Watt concluded that this great waste of steam was due to its condensation when it entered the cold cylinder. The cylinder was always cold when the steam entered it, because cold water had just been sprayed into it; so the heat of the steam which should all be used in doing work was in large part wasted in reheating the cylinder.

To utilize the heat in the steam, it must not be cooled before it has done its work. But after the hot steam has done its work in pushing the piston up, it must be got rid of by condensing it so that the air pressure can push the piston down again. In order to condense the steam, it must be cooled. If it is cooled and condensed in the cylinder, the cylinder must be reheated at every stroke, hence the waste.

To avoid the necessity of cooling and reheating the cylinder at every stroke, Watt reasoned that it was necessary to connect the cylinder with a second one, which was kept cold, and into which the steam should flow and be condensed. Accordingly, he attached to the cylinder of the Newcomen engine a second cylinder *D* (Fig. 75), which was kept cold by a spray of cold water. He called this cooling chamber the *condenser*.

138. How Watt's Condenser Increases Efficiency. Having reached this conclusion, Watt built the engine after the following plan. Steam from the boiler entered the cylinder *C* (Fig. 75), through the valve *I*, and pushed up the piston *P*. Then *I* was closed, and the steam, while still hot, was allowed to flow through the valve *O* into the cold condenser *D*, where it was condensed by a spray of cold water. The steam was pushed from *C* into *D* because *D* was so cold that the pressure of the saturated water vapor in *D* was less than the atmospheric pressure that was pushing down on the piston *P* (Art. 123).

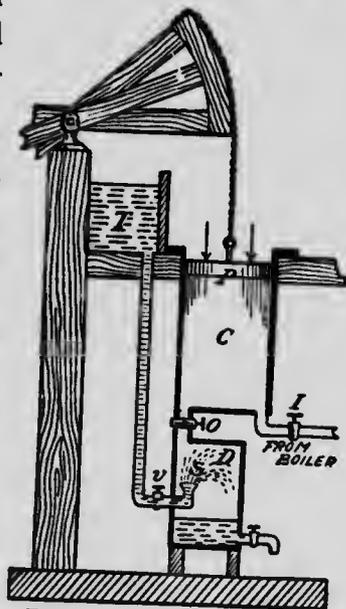


FIG. 75 THE CONDENSER *D* SAVES HEAT

139. Watt's Double-Acting Engine. The addition of the condenser to the Newcomen engine greatly increased its efficiency. Watt saw, however, that the open-top cylinder

was objectionable, because the cylinder walls were cooled by contact with the air while the piston P was down. He

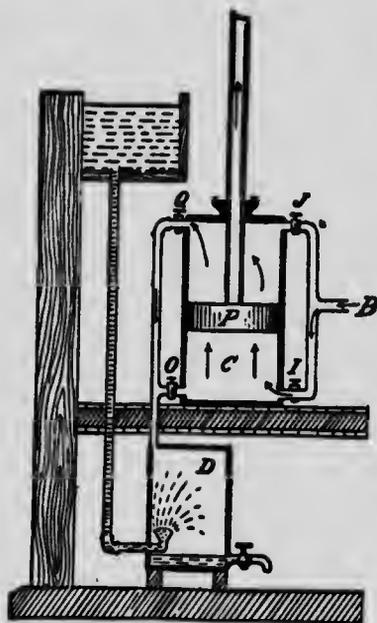


FIG. 76 WATT'S DOUBLE-ACTING ENGINE

therefore made another engine with a closed cylinder C (Fig. 76), in which steam was admitted first at I to push the piston up, and then at J to push it down. There were also two valves O and Q in the pipes to the condenser. These valves had to be worked so that I and Q were open and J and O shut when the piston went up, and vice versa when the piston came down. The valves were worked by a system of levers connected to the piston rod.

In order to keep the cylinder as hot as possible, Watt built a second cylinder around the first, and kept the space between (J , Fig. 77) filled with hot steam from the boiler. This device is called a *steam jacket*. In this form, Watt's engine does not differ essentially from a modern condensing steam engine.

140. Work by Expanding Steam. When driving an engine, the steam enters the cylinder at nearly boiler pressure. If the valve were left open during the entire stroke of the piston, as described in Art. 136, the steam would have the same high temperature and pressure when it left the cylinder that it had when it entered. It would therefore expand suddenly into the condenser at this high pressure, and all the heat that it gave up to the condenser would be wasted. In order to use as much

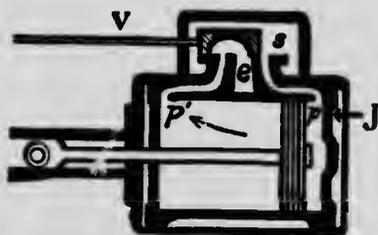


FIG. 77 THE PISTON STARTS BACK

as possible of this heat, Watt invented the "automatic cut-off."

This device consists of an inverted metal box, called the *slide valve*, that may be slid back and forth inside the steam chest *s* (Fig. 77) by means of the valve rod *V*. When the box is in the position shown in the figure, the steam from the steam chest passes through the port *p* and pushes the piston to the left. Meanwhile the exhaust steam is escaping through the port *p'* and the hollow of the slide valve out through the opening. The position of the slide valve when the piston starts forward is shown in Fig. 78. The slide valve moves so as to close the passage from *s* to *p'* when the piston has made about $\frac{1}{4}$ of a stroke.

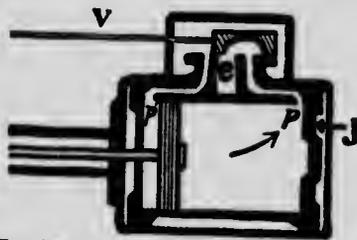


FIG. 78 THE PISTON STARTS FORWARD

When the steam from the steam chest is thus "cut off," the steam that has entered the cylinder has a greater pressure than that required to move the piston; so it expands and pushes the piston through the remaining $\frac{3}{4}$ of its stroke. While the steam is expanding and doing this work, not only is its pressure reduced, but also it becomes cooler. The heat lost by the steam in cooling is the heat that has been converted into useful work. The automatic cut-off thus gives the steam a chance to expand and cool in the cylinder, thereby allowing it to convert into work a large amount of heat which would otherwise be carried into the condenser or into the air, and be wasted.

When steam expands in an engine, it cools and gives up the heat that does the work.

141. Horsepower of an Engine. The two important questions about an engine are: 1, What is its horsepower? 2, How efficient is it? We shall now take up these questions in order. The method of calculating the horsepower of an engine is like that of calculating the horsepower of a pump (Art. 94). The average working pressure in pounds per

square inch multiplied by the volume of the cylinder in cubic inches divided by 12 gives the number of foot-pounds per stroke. This number multiplied by the number of strokes per minute gives the number of foot-pounds per minute; and this last divided by 33,000 (Art. 96) gives the horsepower. The following data were obtained in a test on a locomotive running at 60 miles per hour. The calculation illustrates the method of finding the power of the engine.

Average working pressure	53.7 lbs. per square inch.
Length of stroke	24 in.
Area of piston	283.5 sq. in.
Single strokes of piston	520 per min.

$$\text{Horsepower} = 53.7 \times \frac{283.5 \times 24}{12} \times 520 \div 33,000, \text{ or}$$

$$\text{Horsepower} = \frac{53.7 \times 567 \times 520}{33,000} = 480 \text{ (nearly).}$$

Since this was a locomotive, and there were two cylinders working under exactly the same conditions, the horsepower of the locomotive was $480 \times 2 = 960$.

For accurate measurements, the average working pressure is obtained by means of an ingenious pressure gauge invented by Watt for the purpose, and called a "steam indicator." So the horsepower found in this way is known as the "indicated horsepower." On account of friction in the moving parts of the engine the actual horsepower as obtained by a brake test is somewhat less than the indicated horsepower. For a rough calculation of horsepower the average working pressure may be found approximately by taking half the difference between the boiler pressure and the condenser pressure as found from reading the steam gauges.

142. Pounds of Coal per Horsepower-Hour. In order to determine how efficient the locomotive is, we must calculate the work done by it in a certain time,—say one hour,—and then find the weight of the coal burned by it in the same time. If the work is calculated in foot-pounds, the number obtained is inconveniently large. Hence it is customary to

measure such large amounts of work in a new unit called the horsepower-hour. *The horsepower-hour is the amount of work done in one hour at the rate of one horsepower.* One horsepower-hour = 33,000 (foot-pounds in one minute) \times 60 (minutes) = 1,980,000 foot-pounds.

Since the horsepower of the locomotive was 960 (Art. 141), it did 960 horsepower-hours of work in one hour. In the same test it consumed 2880 pounds of coal in one hour; so $\frac{2880}{960} = 3$, the number of pounds of coal burned per horsepower-hour.

With stationary engines in the best modern power plants, the consumption of coal is about 1 pound per horsepower-hour; and therefore, since they do the same amount of work with the expenditure of $\frac{1}{3}$ the amount of coal, these power plants are about 3 times as efficient as a locomotive.

143. Relative and Actual Efficiencies. A comparison of the pounds of coal per horsepower-hour tells us how efficient one power plant is when compared with another, but gives us no definite idea as to what the actual efficiency of either of them is. In order to know the real efficiency (Art. 20), we must compare, not work out with coal burned, but work out with work in.

The first step in measuring the actual efficiency of an engine has been taken. In Art. 134 we learned that a definite number of heat units is liberated when one pound of coal is burned. As there stated, the heat of combustion of coal is 15,500 B. T. U. per pound. We may therefore reduce the pounds of coal to the equivalent number of B. T. U., and express the efficiency by comparing work out with heat in.

144. Joule's Experiment. The next step in determining the actual efficiency is to find whether a definite number of foot-pounds is equivalent to 1 B. T. U. This problem, because of its great practical importance, has engaged the attention of the best scientific minds since the time of Watt;

but it was not satisfactorily solved until the middle of the nineteenth century. A definite solution was obtained in 1842

by James Prescott Joule (1818-89) of Manchester, England. Joule measured, in British Thermal Units, the heat that was produced when a definite number of foot-pounds of work were done in stirring up water with a paddle wheel.

The paddle wheel (Fig. 79), was turned by weights *PP* that descended and unwound cords from the shaft on which the wheel was mounted. The water was kept from following the revolving paddles *a* by means of fixed paddles *b* attached to the inside of the vessel.

The number of foot-pounds of work done was equal to the number of pounds in the two weights, multiplied by the distance they descended; and the number of B. T. U. produced

was equal to the number of pounds of water in the vessel multiplied by the number of Fahrenheit degrees through which the temperature of this water was raised. In this experiment great care was taken to make all the measurements accurately, and to prevent any of the heat from being lost. As a result of this and many experiments of the same sort Joule reached the following conclusion, which is known as Joule's Principle: *When heat is obtained from work or work from heat, the number of units of work is always proportional to the number of units of heat.*

145. Mechanical Equivalent of Heat. The number of work units that correspond to a heat unit is called the *mechani-*

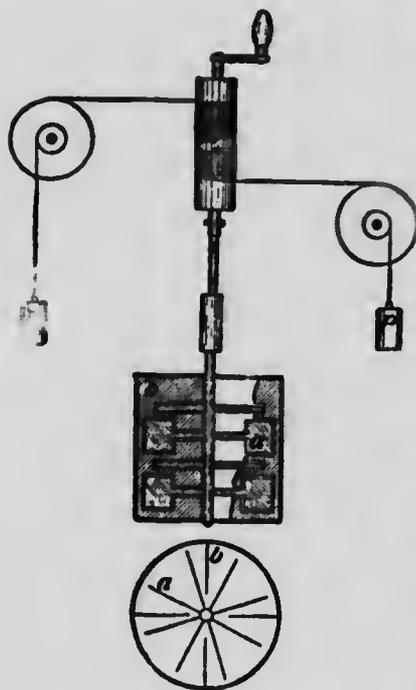


FIG. 79 JOULE'S APPARATUS

cal equivalent of heat. Its numerical value, as found by Joule and verified by many others, is

1 British thermal unit = 778 foot-pounds

1 gram-calorie = 42,700 gram-centimeters.

We can now calculate the number of foot-pounds or the number of horsepower-hours that are represented by the heat of a pound of average coal. Thus—

$15,500 \left(\begin{smallmatrix} \text{B. T. U. for a} \\ \text{pound of coal.} \end{smallmatrix} \right) \times 778 \left(\begin{smallmatrix} \text{foot-pounds} \\ \text{for a B. T. U.} \end{smallmatrix} \right) = 12,000,000$ (nearly) foot-pounds for a pound of coal. Since 1 horsepower-hour = 1,980,000 foot-pounds, or approximately 2 million, the 12 million foot-pounds corresponding to 1 pound of coal is equal to 12 million

$\frac{12 \text{ million}}{2 \text{ million}}$, or 6 horsepower-hours. Therefore,

The mechanical equivalent of average coal is 6 horsepower-hours per pound.

146. Efficiency of an Engine. Since we now know how much work a pound of coal represents, we can find the actual efficiency of any engine when we know the number of pounds of coal that it requires per horsepower-hour. The stationary engine with its furnace and boiler consumed 1 pound of coal per horsepower-hour; and since 1 pound of coal represents 6 horsepower-hours, the work put in is represented by 6 H. P. H. for every pound of coal, therefore,

$$\frac{\text{Work out}}{\text{Work in}} = \frac{1}{6} = 16\frac{2}{3}\%, \text{ the Efficiency.}$$

Since the locomotive was only $\frac{1}{3}$ as efficient as the stationary plant (Art. 142), its efficiency is $\frac{1}{3}$ of $16\frac{2}{3}\% = 5\frac{1}{2}\%$ (nearly).

147. Energy. If you measure the length of a table and find it to be 60 inches, and then measure it in centimeters, and find it to be 152.4 centimeters, you conclude that 1 inch = $\frac{152.4}{60} = 2.54$ centimeters. Whenever we measure the same length in terms of these different units, we get the same relation 2.54 to 1, between the units.

When work is converted into heat, as in Joule's experiments (Art. 144), in such a way that we can measure all the work done in foot-pounds, and all the heat obtained in B. T. U., we always find the number of foot-pounds is 778 times as great as the number of B. T. U. Because we always find this same number, we conclude that we are really measuring the same thing in terms of two different units. This thing that remains the same whether it is measured in foot-pounds or in B. T. U. is called *energy*.

Work and heat are different forms of energy.

In Art. 19 we learned that when the block had been pulled up the inclined plane, work had been done on it; and that when it slid down, it could do work. Similarly, in Arts. 88-91, we saw that water could do work in driving mills, if it fell on a wheel from a higher level, or rushed under pressure through a turbine. In Art. 140 we found that hot steam in an engine cylinder could expand and do work. All these things—the lifted block, the running water, the expanding steam—have capacity for doing work, because they have either had work done on them, or have been heated. Since heat and work are different forms of energy, we may say these things have capacity for doing work because they have been stored with energy.

Energy means capacity for doing work.

Energy may be measured either in work units or in heat units.

In every transformation of work into heat or of heat into work, the amount of energy remains constant.

148. Law of Machines Amplified. In Chapter II we learned that, because of useless work done against friction, we never get out of a machine all the work that we put into it. Only in the ideal case may we say that the work out is equal to the work in. We can now understand that the work done against friction and similar resistances within a machine is converted into heat, and that this heat is the exact equivalent of the work that seems to disappear. In other words, the sum of the work got out and the work-equivalent of the heat got out is exactly equal to the work put in. So the energy

that seemed to disappear in doing useless work was not put out of existence, but was changed into the form of heat. Since, when work is done with the help of a machine, some of the energy is converted into heat that cannot again be used for doing work, we can see why it is not possible to get out of a machine as much work as is put into it.

$$\text{Work out} + \text{Heat} = \text{Work in.}$$

149. Sources of Heat. Coal, gas, oil, and wood are generally considered our most plentiful sources of heat. Electricity generated by water power is now being much used to produce high temperatures in electric furnaces and smelters. Food is the source of heat and muscular work in men and animals.

Throughout the last two chapters we have been constantly reminded of the facts that unless we have a hot body and a cold body, we cannot make heat work for us, and that heat is always flowing from hot bodies to colder ones. Heat phenomena occur only when there are at least two bodies at different temperatures.

If we should ever burn up all the coal and wood and other fuel in the world, so that we could no longer build fires and produce differences in temperature, everything would soon come to the same temperature and further work become impossible, unless there were some other source of heat. We will find that the final source of heat is the sun.

Coal was made from the plants of past ages, and has been called "buried sunshine" since plants grow and furnish wood and food only because the sun shines. Without sunshine, winds would cease to blow and water would cease to evaporate. There would be no clouds to send down rain, and no streams to descend in waterfalls and drive motors. We can thus trace all our work back to the sun.

The sun is the source of the world's energy.

DEFINITIONS AND PRINCIPLES

1. The heat of combustion of gas is approximately 600 B. T. U. per cubic foot.
2. The heat of combustion of average coal is 15,500 B. T. U. per pound.
3. Thermal efficiency = $\frac{\text{Useful heat out}}{\text{Total heat in}}$.
4. When steam expands and does work, it cools and gives up the heat that does the work.
5. The horsepower-hour is the work done in an hour at the rate of 1 horsepower. It is 2,000,000 foot-pounds, nearly.
6. 1 pound of coal = 12,000,000 foot-pounds.
7. The best modern stationary engines burn one pound of coal per horsepower-hour. Their efficiency is therefore $\frac{1}{12}$.
8. 1 B. T. U. = 778 foot-pounds.
9. 1 gram-calorie = 42,700 gram-centimeters.
10. Energy means capacity for doing work.
11. Energy may be measured either in work units or in heat units.
12. In every transformation of work into heat or of heat into work, the amount of energy remains constant.
13. Work out + Heat = Work in.
14. The sun is the ultimate source of the world's energy.

QUESTIONS

1. Why does a nail become hot when rapidly hammered?
2. Why must an ax be kept wet with cold water while it is being ground?
3. If you wish to boil 4 potatoes would you use a 2-quart thick iron kettle full of water? Why?
4. How may the heat of combustion of gas be determined?
5. How would you determine the thermal efficiency of a small engine boiler heated by a gas burner?
6. How did Newcomen's engine waste heat?
7. Why did Watt's condenser save heat?

8. What made Watt think that a double-acting steam engine would be more efficient than the Newcomen engine?
9. Why does a steam jacket increase the efficiency of a steam engine?
10. Who was James Watt and what were his most important inventions?
11. Why does the automatic cut-off make the steam engine more efficient?
12. What is the source of the heat developed in a bicycle pump while it is being used to pump up a tire?
13. Why does the air escaping from the valve of a bicycle tire feel cool?
14. Why is the work done by an engine measured in horsepower-hours and not in horsepower?
15. Do you burn coal or gas in your kitchen stove at home? Which is for you the more economical?
16. Why do we say that 1 B. T. U. is equivalent to 778 foot-pounds?
17. Do the terms "energy" and "work" have the same meaning? Why?
18. What is the heat of combustion of coal?
19. What is the mechanical equivalent of a pound of coal expressed in horsepower-hours?
20. What is the efficiency of a locomotive that burns 3 pounds of coal per horsepower-hour?
21. Describe the transformations of energy in Joule's experiment on the mechanical equivalent of heat.
22. Count Rumford, who was superintending the boring of cannon for the Bavarian government in 1798, noticed the great amount of heat developed, and was the first to attribute it to the mechanical work done. He made a rough experiment to determine the heat developed in boring a bronze block, but did not measure the work. Can you outline a rough method for measuring the heat and the work in this process and comparing them?
23. Why is the efficiency of a machine always less than 1?
24. Since the work out is less than the work in, is it proper to say that some work has been lost?
25. In view of our knowledge of the mechanical equivalent of heat what is the complete statement for the law of machines?
26. A circular saw is turned by a water wheel and saws up a log. Trace this energy, through all its changes, back to the sun.
27. A boat is propelled by a steam engine. Trace the energy back to the sun.

PROBLEMS

1. If the furnace in your house burns 200 pounds of coal a day, and its efficiency is 50%, how many B. T. U. are liberated in the house?
2. If gas yields 600 B. T. U. per cubic foot, and costs 75 cents per thousand feet, how much will it cost to heat 6 pints (i. e., 6 pounds) of water from 42° F. to the boiling point with a burner and kettle having a combined efficiency of 50%?
3. What is the horsepower of an engine whose piston area is 80 square inches and stroke 16 inches if it works under an average pressure of 66 pounds per square inch and makes 400 strokes per minute?
4. What is the efficiency of an engine and boiler that works with 192 horsepower while consuming 384 pounds of coal per hour?
5. How many B. T. U. can be obtained by burning 768 pounds of average coal?
6. The water at Niagara falls 49 meters. If none of the heat generated by the fall were dissipated and the temperature of the water were 10° C. at the top, what would the temperature of each pound at the bottom be?
7. Sir Humphry Davy melted two pieces of ice by rubbing them together at 0° C. How much work did he do to melt 10 grams of ice?
8. When you heat a quart of water from 52° F. to 212° F. in order to make afternoon tea, how many foot-pounds of energy are put into the water?
9. How many loads of coal, each weighing 4 tons, could be lifted through a vertical distance of 15 feet by the energy put into the water in problem 8?
10. When you use 5 cubic feet of water for a hot bath, and the water has been heated from 42° F. to 102° F., how many B. T. U. of energy have been added to the water?
11. If the average temperature of the ocean is 50° F., how many B. T. U. would be given up by each cubic yard of water if the temperature of the ocean should fall 5° F.?

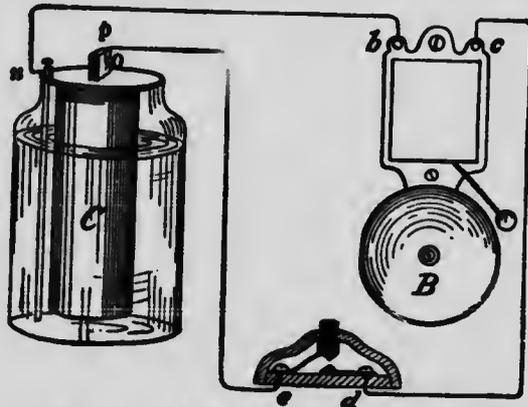
CHAPTER VIII

ELECTRIC CURRENTS

150. Electric Currents. In a general way all are familiar with electric currents, since they are now so generally used to operate door bells, electric lights, the telephone, the telegraph, and trolley cars. The vast network of wires which is spread all over the country and through city streets has taught every one that the electric current flows along metal wires. We know that these wires have to be suspended from glass knobs on poles, or coated with waxed thread, in order to prevent the escape of the electricity from the wire. We know that electricity comes from a battery or from a dynamo in a power-house. We also know that electric currents are dangerous, and that, when not properly controlled, they sometimes set fire to houses and even kill men and animals.

Yet notwithstanding this general familiarity with electric currents, there are relatively few whose knowledge is sufficiently definite to enable them to repair a door bell when it gets out of order.

151. The Door Bell. The arrangement of an electric door bell is shown in Fig. 80. From one terminal of the battery *n*, a wire runs to the bell at *b*. This wire is continued without break through the driving mechanism of the bell, comes out at *c*, and ends at *d*, where it is fastened to



the lower spring of the push button. Another wire begins at e , where it is fastened to the upper spring of the push button, and proceeds back to the other terminal p of the battery. When we push the button, the bell B rings; and we say that *an electric current is flowing in the circuit.*

The door bell thus consists of several parts; namely, a battery, a metallic circuit, and an electric bell. Let us see how each of these parts is made and how it works.

152. Simple Voltaic Cell. The simplest form of electric battery is the one invented about the year 1800 by Alessandro Volta, who was professor of physics at the University of Pavia, Italy. It consists of two metal plates, one of copper Cu and the other of zinc Zn , placed near together but not in contact, in a jar containing dilute sulphuric acid (Fig. 81). This battery is called *the Simple Voltaic cell.*



FIG. 81 SIMPLE VOLTAIC CELL

As soon as the plates are immersed in the acid, bubbles begin to rise from the zinc. These bubbles are bubbles of hydrogen gas; and they indicate that a chemical action is taking place. The zinc is being dissolved, and the hydrogen is being set free from the acid. No such bubbles rise from the copper plate; which shows that if there is any chemical action there, it is not so strong as that taking place at the zinc plate. In other words,

The chemical action at one plate is stronger than that at the other.

If each plate is connected by means of a wire with one of the binding posts of an electric bell, the bell rings; showing that an electric current is flowing through it. But if the copper plate is replaced by a zinc plate, so that the cell consists of two zinc plates in the acid, the bell, when connected with the plates as before, does not ring. Although the chemical action of the acid on the zinc goes on, this action is the same on both plates, and no electric current is produced.

If a cell is made of two copper plates in acid, and if the plates be connected with the bell as before, the bell does not ring. In this case again the chemical action is the same on both plates, and no current flows. Current may be obtained from a cell made with a zinc and a carbon plate, or from one made with a zinc and a platinum plate, or from one made with a zinc and a mercury plate. In each of these cases the acid acts more strongly on the zinc than on the other plate. The plates used in making an electric cell are called *electrodes*. *In order to produce a current, the electrodes must be made of two materials on which the acid acts differently.*

It is customary to call one of the electrodes of a cell *positive*, and the other *negative*. By general agreement, *the zinc is always called the negative electrode*. The other electrode (copper, carbon, etc.) is the positive. We generally consider that *the current flows in the metallic circuit outside the cell from the copper (positive) to the zinc (negative)*.

A voltaic cell consists of a pair of electrodes of different materials immersed in a fluid which acts chemically on one of the electrodes more strongly than on the other.

153. Polarization. If the simple voltaic cell is left connected to the bell for a few seconds, the bell ceases to ring, even though the circuit through it is not broken. Examination of the cell then shows that the copper plate is covered with bubbles. These are found to be bubbles of hydrogen, and they stick to the copper plate and become more numerous the longer the current flows. As they increase in number they form a coat on the copper, so that the acid cannot touch it. Hence the current through the bell gradually grows weaker; until at length it is too weak to ring the bell at all. The cell is then said to be *polarized*.

The bubbles collect on the copper plate only while the current is flowing. They are made of the hydrogen set free at the zinc. When no current is flowing they rise through the acid; but when the current is flowing, the hydrogen travels toward the copper plate and forms bubbles on it. Polarization

can be prevented either by continually brushing the bubbles away by some mechanical means; or by surrounding the copper plate with chemicals which, because they combine easily with hydrogen, catch it on its way to the copper. One of the most useful of the cells in which polarization is prevented by chemical means is the *gravity cell*.

154. The Gravity Cell. In the gravity cell (Fig. 82) a copper electrode is placed at the bottom in a solution of

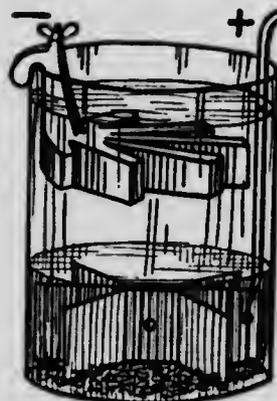


FIG. 82 THE GRAVITY CELL

copper sulphate. The zinc is placed at the top in dilute sulphuric acid. The dark blue copper sulphate solution is denser than the acid, so it remains at the bottom of the cell by its own weight; hence the name, *gravity cell*. When the hydrogen which is traveling toward the copper plate comes into this copper sulphate solution, it exchanges places with the copper there, and remains in the solution, while the displaced copper is deposited on the copper plate. So the hydrogen bubbles are prevented from reaching the copper electrode, and the cell does not polarize.

A gravity cell keeps in better condition if its poles are kept connected with a long wire when the cell is not in use. If plenty of copper sulphate crystals is kept in the cell it will last a long time with little attention, and will give a very steady current. For this reason gravity cells were generally used in telegraphic work until the dynamo-electric machines were perfected.

155. The Leclanche Cell. In this type of cell (Fig. 83) one electrode is carbon and the other zinc. The active fluid used is a strong solution of "sal ammoniac" (ammonium chloride). The carbon electrode is often packed in a porous cup with a black powder called manganese dioxide, which

partially prevents polarization. The cell polarizes rather quickly, however, in spite of the manganese dioxide, and so cannot be used when steady currents are needed for long time. Cells of this type are generally used for operating door bells and telephones.

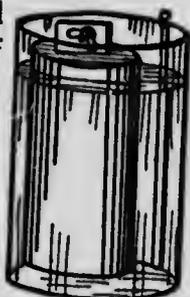


FIG. 83

The Dry Cell is a form of Leclanche cell. The outer shell is a cylinder made of zinc, which serves as one electrode. The other electrode is a carbon stick which is placed in the center. The space between is packed with a paste made largely of water, ammonium chloride and plaster of Paris. Dry cells are ready for use, cheap, easily portable, and they can furnish rather strong currents for a short time. They are therefore the most popular form of voltaic cell.

156. Electromotive Force. In their action electric currents are somewhat analagous to water currents flowing in pipes. Water flows in a pipe only when it is forced to do so by a difference in pressure, such as may be developed by the pump *P* (Fig. 44). An electric current flows in a wire when the ends of the wire are connected with the electrodes of a voltaic cell. We may therefore conceive that the chemical action in the cell develops a difference in electric pressure between the electrodes of the battery, and imagine that the electric current is maintained by this force. Such a difference in electric pressure, whether developed by the chemical action in a cell or by some other means, is called *electromotive force*. It is usually denoted by the letters *E. M. F.* We may therefore describe the action of a cell thus:

In a voltaic cell, chemical action develops an electromotive force (E. M. F.) which drives the electric current through the circuit.

157. The Complete Circuit. Returning now to the electric bell (Fig. 80) we note that when a door bell is connected with a battery through a push-button as shown in the figure, the metallic path from the copper or carbon electrode back to

the zinc is not complete unless the button is pressed down so that the metal spring *s* is in contact with the metal strip *d*. The bell will not ring unless this metallic path outside the battery is unbroken, from the copper or carbon electrode back to the zinc.

So also the electricity must have an unbroken path through the acid inside the cell from the zinc to the carbon or copper. To prove this, leave the carbon or copper plate in the jar of acid; and, without disconnecting the wires, remove the zinc to another jar of acid. In this case, although the external path for the current is complete, no current flows, because there is no continuous liquid conductor between the two plates; and so the current cannot flow from the zinc to the carbon or copper inside the cell. We see therefore that the current cannot flow and ring the bell unless it has a continuous conducting circuit from zinc to copper through the fluid inside the cell, and from copper to zinc through the metallic circuit outside the cell.

There is no current without a complete conducting circuit.

158. Conductors and Insulators. An air-gap is not the only thing that will stop the current. If a layer of mica, pitch, glass, rubber, paraffin, or oil be introduced anywhere in the circuit, the current refuses to flow through it. For this reason substances of this sort are called non-conductors or *insulators*.

In the transmission of electric currents from place to place, insulators are just as important as conductors. Since the earth, the bodies of animals, and all moist objects conduct electricity fairly well, it is necessary to separate or insulate a wire conductor from them by means of non-conductors, in order that the electricity may go on along the wire instead of escaping to the earth. For this reason, electric wires are supported on knobs of glass or porcelain; or covered with paraffined cloth, rubber, or silk.

Both conductors and insulators are necessary for carrying an electric current.

159. How the Current Rings the Bell. We have thus far used the ringing of the bell as an indication of the presence of the electric current in the circuit. Let us now examine the bell and see how it works. On tracing the path of the current through the ringing device we note that it enters at *a* (Fig. 84) and passes around two coils of wire *ss* that are placed on iron rods. From these it passes to the iron bar or *armature b*, to which the clapper is attached. It then flows through a spring that presses against a screw at *c*; and from *c* back to the battery.

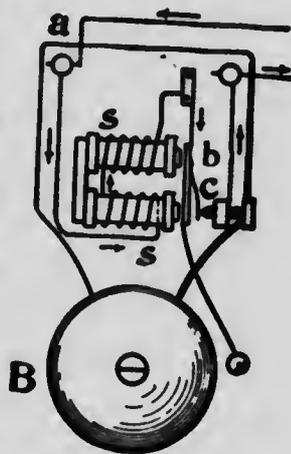


FIG. 84
THE ELECTRIC BELL

On closing the circuit at the push-button, we see that the armature is at once drawn toward the coils, causing the clapper to strike the bell. This motion removes the spring from the screw at *c*, breaking the circuit there, and the armature is pushed back again by the spring on which it is mounted. But as soon as the spring strikes the screw at *c*, the circuit is closed again, and the armature once more flies toward the coils. Every time the armature is drawn toward the coils, the clapper hits the bell; so the bell continues to jingle as long as the push-button is held down.

If we hold the armature away from the coils, so as to keep the circuit closed at *c*, and then hold the blade of a knife near the ends of the coils while the current is flowing, we find that the knife is attracted toward them. Nails likewise are attracted, and the iron armature is drawn strongly toward the coils whenever the circuit is closed, but ceases to be attracted when it is broken. Hence the conclusion:

The current makes the coils attract iron.

160. Magnets Point North and South. Since magnets attract iron, the fact that the coils attract iron suggests that they become magnets when the current is flowing in them.

In order to test this suggestion we shall have to find out whether the coils have the other properties of magnets as well as that of attracting iron.

If a slender magnet is hung on a fine thread tied about its center, or supported at its middle on a needle point so that it can rotate freely in a horizontal plane, it turns and comes to rest when pointing in a north and south direction. When so supported, a magnet is called a *magnetic needle*. The fact that the magnetic needle points north and south is of the greatest possible service to sailors, because it enables them to determine directions on the high seas. The pocket compass and the mariner's compass consist of a magnetic needle suitably mounted in a brass case. The compass became known to European sailors about the year 1100 A. D. Be-

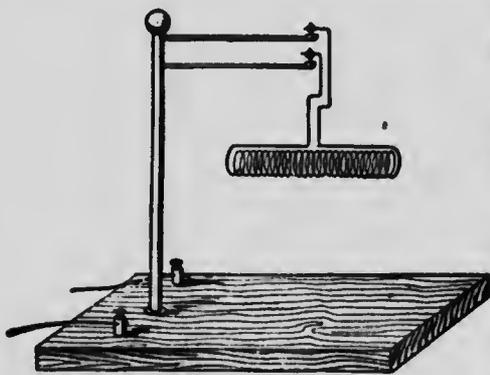


FIG. 85 THE COIL POINTS NORTH

(Fig. 85) is found to turn about and point north and south when a current is flowing through it.

A magnetic needle points north and south.

The current makes the coil point north and south.

cause it made navigation safer, commerce was able to develop as it has, and the voyages of Columbus were possible.

If a coil of wire is really magnetic when carrying a current, it should point north and south when free to do so. A coil of wire suspended so that it can rotate in a horizontal plane

161. Magnetic Poles. If a piece of iron be held near either end of a compass needle, the needle is attracted toward the iron. But when two magnetic needles are brought near together, the ends that point north repel each other; the ends that point south repel each other; and the north-pointing end of either magnet attracts the south-pointing end of the

other. This property of the magnet is called *polarity*. The end that points toward the north is called a north pole, and the other end is called the south pole.

Like poles repel and unlike poles attract each other.

If the coil carrying the current (Fig. 85) be tested for polarity, it is found to act like the magnet in this respect also. The north-pointing end of the coil is repelled by the north pole of a magnet; its south-pointing pole is repelled by the south pole of the magnet; and when either pole of the coil is brought near the end of the magnet that has the opposite kind of polarity, the two unlike poles attract each other.

If, instead of a magnet, a second coil carrying a current be brought near the first, the two act exactly like two magnets. Hence

When carrying a current, a coil has magnetic poles.

162. Magnetic Field. If a magnet be placed under a piece of cardboard, and if iron filings be scattered over the card, then, when the card is gently tapped, the filings arrange themselves in a regular pattern (Fig. 86). If a small pocket compass be placed on the card at any point, the magnetic needle points in the same general direction as the curve marked out by the filings at that place. A compass needle at a given place points in the direction in which the magnetic force acts at that place. The curves therefore show the direction in which the magnetic force acts at the various points about the magnet.

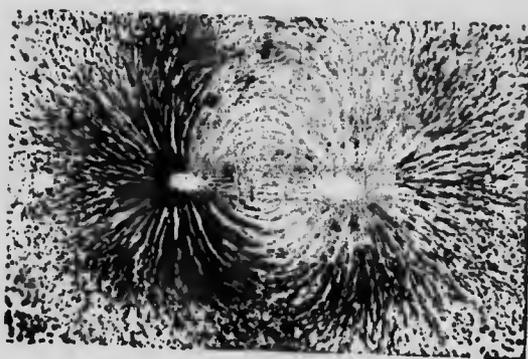


FIG. 86 MAGNETIC FIELD OF FORCE

The iron filing curves and the action of a small compass needle around the magnet also show that the magnetic force

extends to a considerable distance from the magnet in all directions. This fact is described by saying that the magnet is surrounded by a *field of force*.

The space which surrounds a magnet, and through which its magnetic force acts, is called a magnetic field of force.

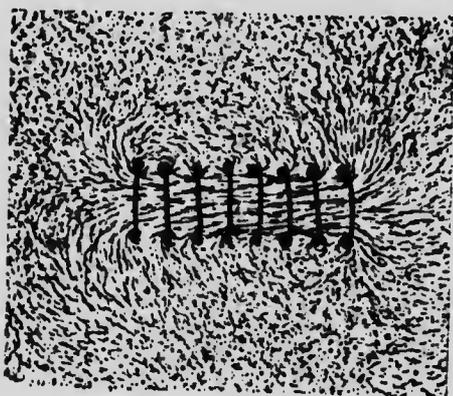


FIG. 87 THE COIL HAS A FIELD OF FORCE

If a card be placed over a coil of wire carrying a current, the iron filings will trace similar curves on it. If the coils of wire are passed through holes in the card, as in Fig. 87, better curves may be obtained. The small compass needle when in the neighborhood of the coil acts just as it does when near a magnet. Hence

When carrying a current, a coil is surrounded by a magnetic field of force.

Since the current makes the coil act in every way like a magnet, we conclude that—

A current-bearing coil is a magnet.

163. The Electro-Magnet. Although the current-bearing coil acts just like a magnet, it is not a very strong one. It will barely support iron nails. But if an iron rod be placed in it, the magnetism is much increased. It will now attract iron more strongly than does the bar magnet or the magnetic needle. Such a bar of iron in a coil is called a *core*. The addition of the iron core strengthens the magnetic field. A coil with an iron core is called an *electro-magnet*.

When the current ceases to flow through the coils of an electro-magnet, its magnetism disappears; hence, the electro-magnet is much more useful than the steel magnet, because it can be magnetized and demagnetized at will. This fact enables us to explain the action of the electric bell. The coils with iron cores in them are electro-magnets. When the circuit

is closed, these electro-magnets draw the armature toward them and make the clapper strike the bell. The motion of the armature breaks the circuit, the magnetism vanishes, and the armature is pushed back by a spring. This motion closes the circuit again; and the operation is repeated, until the circuit is broken by letting go the push-button.

164. Oersted's Experiment. The fact that the current has a magnetic field was discovered by Oersted, a Danish physicist, in 1819. While experimenting before his class, he happened to hold a wire carrying a current directly over and parallel to a compass needle. The needle immediately turned out of its north-south direction; its north pole moving, say to the west. When the wire was held below the needle and parallel to it, the needle turned from its north-south direction, but the north pole now moved to the east. In either case, if the direction of the current was reversed, the direction of the deflection of the needle was also reversed. After a careful study of this action, the following rules have been framed to describe it.

A compass needle tends to set itself at right angles to a wire carrying a current.

When we look along the wire in the direction in which the current is flowing, the north pole of the needle is deflected in the direction of the movement of the hands of the clock.

165. Henry's Discovery. Oersted's discovery attracted a great deal of attention, because scientists at once recognized that it furnished a means of signaling at a distance. The early attempts to construct an instrument that would do this failed, because when several hundred feet of wire were introduced in the circuit, the current would not operate an electro-magnet of the kind then used.

The honor of finding out how to make the electro-magnet work at a distance belongs to Joseph Henry, an American. The early coils consisted of a single layer of bare wire wound like a screw thread around an iron core covered with paper.

Henry discovered that if he insulated his wires by covering them with silk, and then wound many turns of such insulated wire on the core, as thread is wound on a spool, his magnet would work at great distances from the battery. Thus Henry discovered that, with a given current,

The greater the number of turns of insulated wire in the coil of an electro-magnet, the stronger its magnetic field.

Electro-magnets like those which Henry made give still stronger effects at a distance when the number of cells in the circuit is increased. But increasing the number of cells increases the strength of the current; i. e. with a given electro-magnet,

The stronger the current, the stronger the magnetic field.

The electro-magnet consists of a coil of insulated wire wound on an iron core.

The strength of the electro-magnet may be increased by winding more turns of wire on its coils and also by sending a stronger current through them.

166. The Telegraph. The modern telegraph was made possible by the discovery made by Henry. In its simplest form it consists of a battery *B* (Fig. 88), a key *K*, and a sounder *S*. The essential parts of the sounder (Fig. 89), are the electro-magnet *M*, the bar of iron *A* (called the armature), and the brass lever *L*. When the key is pushed down, current flows in the circuit; and the

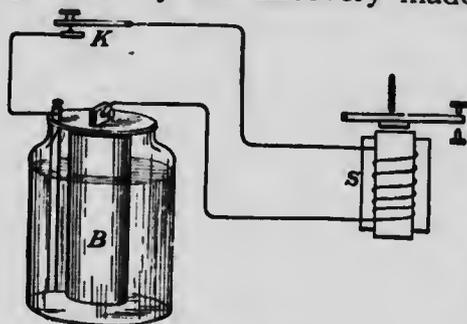


FIG. 88 SIMPLE TELEGRAPH

electro-magnet draws the armature down, making *L* strike the stop *P*. When the circuit is broken, *L* is forced up by a spring *S*, and strikes the stop *Q* with a click. So closing and opening the circuit at *K* (Fig. 88) produces clicks at the sounder *S*, which may be many miles away, provided wires connect it with the battery.

One voltaic cell will operate the telegraph sounder when it is near by. But, as the early experimenters found, when several miles of wire intervene between battery and sounder, the effect is much weaker, because the electromotive force of the battery cannot drive enough current through the long wire to make the sounder click vigorously.

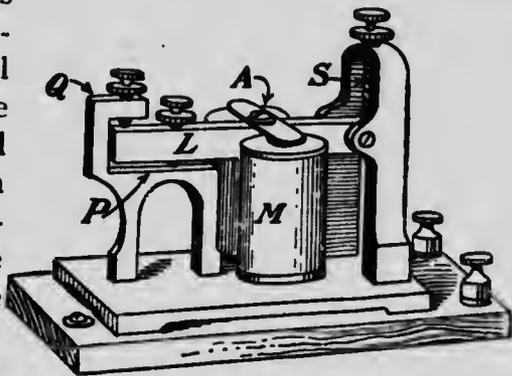


FIG. 89 TELEGRAPH SOUNDER

This falling off of the current when the "line" is lengthened can be studied if we introduce into the circuit something that will show how the current varies as more wire is added. Such an instrument is the *galvanometer*.

167. Galvanometers and Ammeters. The simplest form of galvanometer consists of a single wire placed above and parallel to a magnetic needle (Art. 164). When a current flows in the wire, the magnetic field of the current tends to turn the needle into an east-west position; while the magnetic field of the earth opposes this motion, because it tends to keep the needle pointed north and south. The two fields thus tend to turn the needle into directions at right angles to each other. The stronger the current, the stronger is the action of its field; and the more the needle is deflected out of the north-south direction. The size of the deflection therefore indicates roughly the strength of the current. The instrument is much more sensitive if the wire is wound into a coil so that it passes over the needle a number of times.

Another form of galvanometer is shown in Fig. 90. It consists of a coil of wire suspended between the poles of a horseshoe magnet *NS*. The current enters the instrument at *E+*, passes into the coil through the thin metal ribbon *R* by which the coil is suspended, and passes out below by a

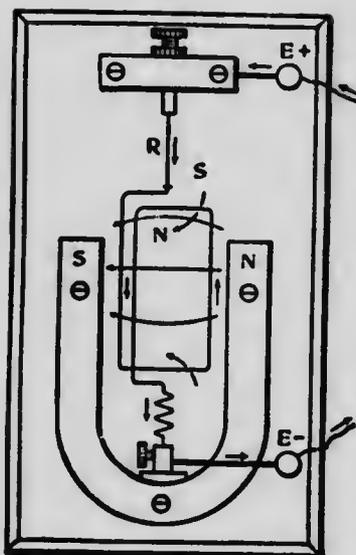


FIG. 90 D'ARSONVAL GALVANOMETER

coiled wire. When the current is flowing through the coil the latter becomes a magnet and tends to turn around with its flat sides (faces) toward the poles of the magnet. As it turns, it twists the ribbon *R*, and this twist in the ribbon opposes the turning produced by the current; so the coil turns until the twist produced by the current is just balanced by the twist in the ribbon. The stronger the current, the more the ribbon will be twisted before the two twists are balanced and the coil comes to rest. This

kind of instrument is called a *D'Arsonval galvanometer*.

The commercial instruments used in comparing current strengths are really D'Arsonval galvanometers. The arrangement of the coil *C* between the poles of the magnet *NS* is shown in Fig. 91. When the current flows, the coil turns; and winds up a spiral spring *S* like the hair-spring in a watch. The turning effect of the current is balanced by the tension of this coiled spring. When the current ceases to flow, the spring untwists and brings the

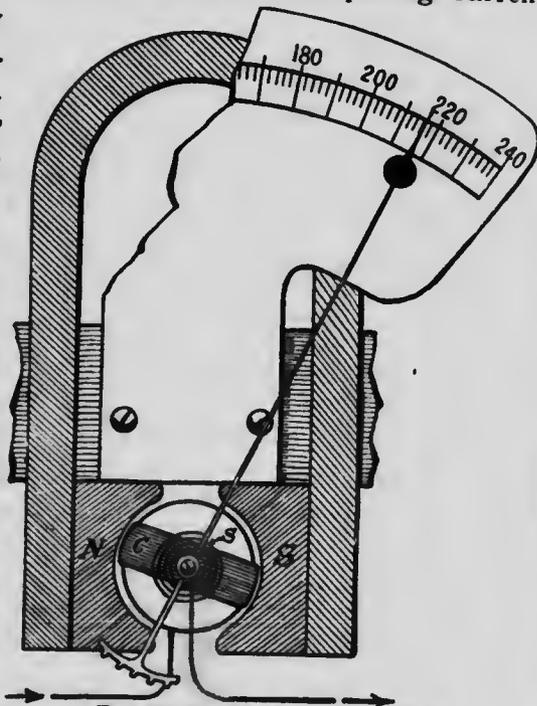


FIG. 91 INTERIOR OF AN AMMETER

coil back to its original position. The coil carries a pointer *P* by which its motion can be observed. This instrument is called an *ammeter*.

168. Resistance of Circuits. We can now study the changes produced in the strength of the current in the telegraph circuit by the addition of a long wire between the battery and the sounder. If a suitable galvanometer or ammeter be placed in the circuit when the wire is short, the pointer is deflected through a certain angle, corresponding to the strength of the current. But when the extra wire has been introduced, the deflection of the galvanometer is much smaller, showing that the current is then much weaker.

This fact is described by saying that the wire *offers resistance* to the passage of the current. So long as the electromotive force of the battery remains the same, it can drive only a smaller current through this greater resistance. The case is analogous to the flow of water in pipes. A given pressure can drive a larger quantity of water per second through a short pipe than through a longer pipe of the same size, because the resistance of the long pipe is much greater. Hence, other things being equal, *the longer the wire the greater the resistance*.

If the extra wire added be replaced by a wire of the same length, but of smaller diameter, the deflection of the galvanometer is still further reduced. The fine wire offers a greater resistance to the current than the coarse one, and so less current flows through it. This is again similar to the flow of water in pipes. A pipe of small diameter offers a greater resistance to the flow of water than a larger pipe of the same length, because the area of the cross-section of the pipe is smaller, and the friction of the water in the small pipe is therefore greater. Thus, for a wire of given length and material, *the thinner the wire, the greater the resistance*.

With constant electromotive force, the greater the resistance, the smaller the current.

169. Good and Poor Conductors. If, in the experiment just described, the added wire was of copper, and if the copper wire be replaced by an iron wire of the same length and diameter, the deflection of the galvanometer is still further reduced. The electromotive force of a given battery can force less current through the iron than through the copper. This means that, other things being equal, the iron wire has a higher resistance than the copper.

If we shorten the iron wire in the circuit until the galvanometer shows the same deflection as it did when the copper wire was in circuit, we can find out what length of iron wire has the same resistance as a given length of copper wire. If the wires have the same diameter, the iron wire will be found to be about one-sixth as long as the copper wire of equal resistance. Hence, under like conditions, iron has a resistance about six times as great as that of copper.

If a German silver wire of the same diameter is used instead of the copper wire, the length of German silver wire that gives the same deflection to the galvanometer will be about one-twentieth of the length of the copper wire. Under like conditions, therefore, German silver has a resistance 20 times as great as that of copper.

Copper is therefore said to be a good conductor of electricity and German silver a bad conductor; so copper is commonly used for electric circuits, since it is generally desirable to have their resistance low. German silver wire is used to introduce resistance into circuits in order to reduce currents that are too strong for convenient use. From the foregoing we see that

Different substances have different relative resistances.

170. Adding Electromotive Forces. If the telegraph sounder will not work at a distance when two or three cells are used, we may be able to make it work by adding other cells. If the copper of one cell be connected to the zinc of the next (Fig. 92), the electromotive force of each is added to that of the others, thereby increasing the electrical pressure

in the circuit. If this increased electromotive force is still insufficient to work the sounder, other cells may be added in



FIG. 92 CELLS IN SERIES

the same way, until the electromotive force becomes sufficient to force enough current through the circuit to make the sounder work properly.

When the zinc of one cell is connected to the copper of the next and so on, as shown in Fig. 92, they are said to be *arranged in series*. When cells are arranged in series, the electromotive force of the battery is equal to the sum of the electromotive forces of all the cells.

If a suitable galvanometer or ammeter be placed in the circuit, we can see that the current increases as more cells are added. As the cells are added, the deflection in the galvanometer increases by about the same amount, if the circuit otherwise remains the same.

With constant resistance, the greater the electromotive force the greater the current strength.

171. Comparison of Electromotive Forces. The principle just stated (Art. 170) enables us to compare the electromotive forces of different cells in the following way. Place one gravity cell in circuit with an ammeter and a fixed resistance that is large enough to make the deflection small and note the deflection. If the gravity cell be replaced by a dry cell, other things remaining the same, the deflection will be about $1\frac{1}{2}$ times as great. The dry cell sends about $1\frac{1}{2}$ times

as strong a current through the same circuit; so it has about $1\frac{1}{2}$ times as high an electromotive force as the gravity cell.

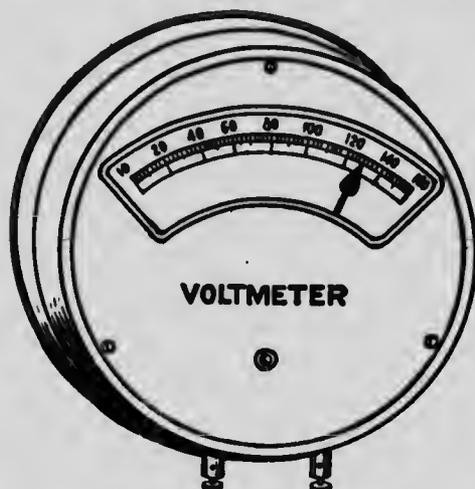


FIG. 93 STATION VOLTMETER

with the movable coil. Since the entire resistance of the voltmeter is large, the current that flows through it is weak. Since the resistance in the instrument is fixed, the size of the deflection produced when its terminals are connected directly to the poles of a battery (Fig. 94), with nothing else in the circuit, depends only on the electromotive force of the battery.

172. Unit Electromotive Force. The instrument just described will be more useful if supplied with a scale that will enable us to compare electromotive forces in terms of a convenient unit. The unit of electromotive force commonly used is the *volt*. The simple voltaic cell and the gravity cell furnish

Electromotive forces may be compared by comparing the currents that they send through a circuit of fixed resistance.

The commercial instruments for measuring electromotive force operate in the way just described. They are called *voltmeters*. The voltmeter (Fig. 93) is like the ammeter (Art. 167) but has a wire of high resistance in the circuit

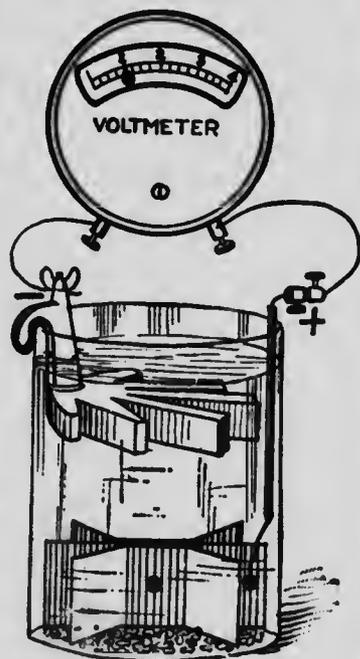


FIG. 94 IT MEASURES E. M. F.

electromotive forces that are nearly equal to 1 volt (more accurately, 1.08 volts). The Leclanche cell, when in good condition, gives an electromotive force of about 1.4 volts; and the dry cell one of about 1.5 volts.

The unit of electromotive force is the volt.

173. The Scale of the Voltmeter. The scale of a voltmeter may now be constructed as follows: Attach the terminals of the voltmeter to the poles of a good gravity cell, and mark the position of the pointer 1.08 volts. Then add a second gravity cell in series. The deflection will now be twice as great, and the position of the pointer should be marked 2.16 volts. More cells may be added, marking the successive positions of the pointer to correspond to the voltages, which are determined in each case by multiplying 1.08 by the number of cells in circuit. Having thus located a series of points that correspond to known voltages, the scale may be completed with the help of an ordinary inch or centimeter rule.

174. How the Current Produces Rotation. If we pass the current from a single gravity cell through the coil of a D'Arsonval galvanometer (Fig. 90), one face of the coil becomes a north pole and the other a south pole; so the coil turns through a right angle, and stops with its north face next the south pole of the magnet. If we reverse the current in the coil, its magnetic poles will be reversed also; so that each pole of the coil will be facing a like pole of the magnet. The magnetic forces will now cause the coil to face about, so that each of its poles will be adjacent to an unlike pole of the magnet. When the coil rotates through a half turn, it does not stop at the instant when it reaches the position in which its poles are opposite the unlike poles of the magnet. On account of its inertia, it goes beyond that position, until the magnetic force and the twisting force of the suspending ribbon stop it and bring it back. After a few vibrations it settles into the position just mentioned. If we can manage to reverse the current just as it passes this position, and if we can also arrange

the coil so that it does not twist the suspending ribbon, then instead of vibrating and settling in the definite position mentioned, it will go on around through half a revolution more. On account of its inertia, it can not stop itself; and, if we again reverse the current just at the right instant, it will continue to rotate through another half turn. Thus it appears that if we can reverse the current just at the end of each half turn, and if we can rid the apparatus of the twisting of the suspension, we may produce continuous rotation.

175. Principle of the Electric Motor. These conditions can be fulfilled by the following arrangement. Instead of being hung on a metal ribbon, the coil is mounted on a horizontal shaft XX (Fig. 95). In order to bring the current

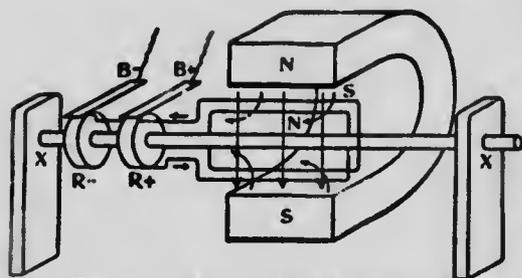


FIG. 95 THE COIL IS FREE TO ROTATE

into the coil, metal rings RR are placed on the shaft near one end, and one end of the wire from the coil is soldered to each ring. In order to let the current in at one of these collecting rings and out at the other, battery wires are attached to two light metal springs, $B+$ and $B-$, called *brushes*, one of which rubs lightly against each of the collecting rings. In making the apparatus, it is important to remember that the steel shaft XX is a conductor; if the collecting rings were in metallic contact with it, the greater part of the current would take the short cut along the steel shaft from one ring to the other, and thence back to the battery. Therefore, the collecting rings must be mounted on a sleeve of hard rubber, which insulates them from the armature shaft, and from each other.

By first touching the brush $B+$ to ring $R+$, and the brush $B-$ to ring $R-$; and then at the right instant reversing the brushes so that the brush $B+$ touches $R-$ and the brush $B-$ touches $R+$, we can make the coil rotate continuously.

We may avoid the inconvenience of having to change the brushes back and forth every half turn by discarding one of the rings, splitting the

other ring parallel to the shaft XX , and attaching the two ends of the coiled wire to the two separated halves of the ring. The brushes must now touch opposite points of the split ring. This

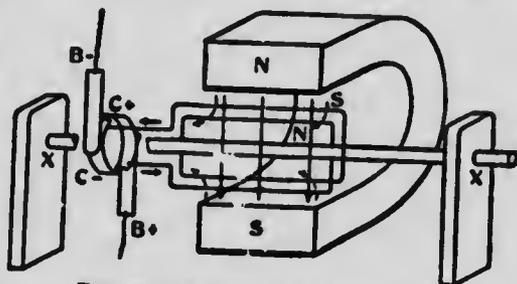


FIG. 96 THE MOTOR PRINCIPLE

arrangement is shown in Fig 96, the shaft being broken away and the split ring ($C+$, $C-$) being enlarged for the sake of clearness.

If the brushes are properly placed, then at the instant when the armature comes into the position in which its poles (i. e., its flat faces) are nearest the attracting poles of the magnet, the half ring $C+$ will shift from the brush $B+$ to the brush $B-$; and at the same time the half ring $C-$ will shift from the brush $B-$ to the brush $B+$. The result is that the current through the coil is reversed at just the right instant, and the coil continues to rotate as long as the necessary current is supplied. This apparatus is now a toy electric motor. This split ring device is called a *commutator*. The rotating coil is called the *armature*; the magnet is called the *field magnet*.



FIG. 97 A MODERN COMMUTATOR

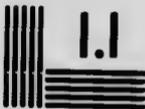
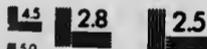
176. From Toy to Practical Machine. This toy is very weak, being barely able to run itself; to say nothing of driving machinery. In Art. 163 we learned that the magnetic effect of a current was increased by placing a bar of soft iron in the coil. So the motor can be made stronger by filling the armature with iron.

In like manner the strength of the field magnet can be increased by substituting an electro-magnet for the steel magnet, and sending the current through the magnet coils



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before it goes to the armature. The number of poles in the field may also be increased to four or more. Finally, more coils can be wound on the armature, so that while the current is being reversed in one it may be flowing in another.

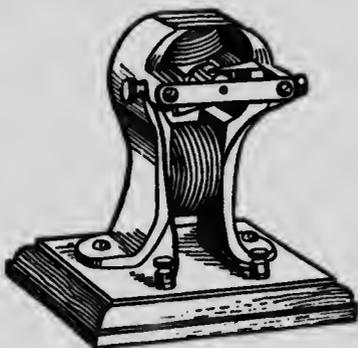


FIG. 98 TOY MOTOR

Fig. 98 shows the well known toy motor which has three coils on its armature. There must be at least as many segments on the commutator as there are coils on the armature.

An electric motor thus consists essentially of a stationary electro-magnet called the *field magnet*, a rotating electro-magnet called the *armature* and a sliding contact device, which leads the current into the armature, and is called a *commutator*.

When a suitable electric current is passed through the motor, *the motor transforms the energy of the current into mechanical work.*

177. Internal Resistance. When we try to run the toy motor (Fig. 98), with two or three gravity cells, we find that it will not go. A single dry cell will operate it successfully, two dry cells will make it hum. The addition of several more gravity cells, which increases the electromotive force in the circuit, still does not make the motor go.

If the voltage of the two gravity cells in series be measured with a voltmeter, it will be found to be 2.16 volts. The dry cell has a smaller electromotive force (1.5 volts) than the two gravity cells. Yet one dry cell runs the motor, and the two gravity cells do not. The gravity cells do not furnish enough current, but the dry cells do. Thus, although the two gravity cells have the greater voltage and the resistance outside the battery through the motor is the same in one case as it is in the other, the current from the two gravity cells is much weaker than that from one dry cell.

To account for this, recall Art. 157, in which it was shown that when a current flows in a circuit it must also flow through the battery—i. e., no current flows unless there is a complete conducting circuit. Hence the reason for the difference in the action of the gravity and the dry cells must be sought in that portion of the circuit which lies inside the cells themselves. The cell itself offers resistance to the flow of current. This "*internal resistance*" in a gravity cell is usually rather large, while that of the dry cell is very much smaller. So, even with a small external resistance in circuit, gravity cells cannot give strong currents, because their internal resistances are large, and the current has to flow through these large resistances.

Since a complete conducting circuit is necessary for the flow of current, and since the electromotive force must overcome both the external and internal resistance of a circuit, *the current strength depends on the total resistance in circuit.*

178. Need of Stronger Currents. We have learned in Art. 156 that the various forms of voltaic cells derive their electricity from chemical action. In this action, the zinc in the cell is gradually consumed. Therefore, if cells are used as a source of current, zinc must be supplied, just as steam must be supplied to keep a steam engine going, or gas or gasoline to keep a gas engine running.

The amount of zinc consumed in furnishing weak currents such as are used for door bells, is small; so the cost of zinc is not excessive. But the cost of zinc is so much greater than that of coal, gas, or oil; that it would be a great deal more expensive to do large amounts of work with a motor that is run by consuming zinc in a battery, than to do it with an engine that is run by burning coal or gas under a boiler. Thus the motor would be of little practical value unless we could generate electric currents in large quantity and at reasonable expense. We shall therefore next inquire how this is done

DEFINITIONS AND PRINCIPLES

1. In a voltaic cell, chemical action develops an electromotive force which drives the electric current through the circuit.
2. The zinc is always the negative electrode of a cell.
3. The current flows in the external circuit from copper (or carbon) to zinc.
4. Electric currents flow only in completely closed conducting circuits.
5. A magnet suspended so that it can turn freely, points north and south. (Magnetic needle).
6. The north-pointing end of a magnet is called the north pole, and the south-pointing end is called the south pole.
7. Like magnetic poles repel each other and unlike poles attract.
8. A magnet is surrounded by a magnetic field of force.
9. A coil carrying an electric current is surrounded by a magnetic field of force and acts exactly like a magnet.
10. A compass needle tends to set itself at right angles to a wire carrying an electric current.
11. When we look along a wire in the direction in which an electric current is flowing, the north pole of the needle is deflected in the direction in which the hands of a clock move.
12. A coil of wire wound on an iron core is an electro-magnet.
13. The greater the number of turns in the coil and the greater the current strength, the stronger is the electro-magnet.
14. The resistance of a wire is proportional to its length, inversely proportional to the area of its cross-section, and depends on the material of which it is made.
15. With constant electromotive force, the smaller the resistance, the greater the current strength.
16. With constant resistance, the greater the electromotive force the greater the current strength.

17. The unit of electromotive force is the volt. The electromotive force of a gravity cell is 1.08 volts.

18. When cells are connected in series, both their electromotive forces and their internal resistances are added together.

19. The current strength depends on the total resistance (internal + external) in circuit.

20. By means of the electro-magnet and the electric motor, the electric current may be made to do mechanical work.

QUESTIONS AND PROBLEMS

1. When you press the pushbutton of a door bell, the bell rings. Why?
2. If you wanted to make an electric battery, what materials would you secure?
3. How would you construct a cell that would furnish small currents continuously?
4. Why do telegraph lines fail to work after a severe storm when the wires are down?
5. Why are telegraph and telephone wires strung on glass supports?
6. Is it possible to use the wires of barbed-wire fences for telegraph or telephone lines? Why?
7. Would a battery made of two jars of acid with a plate of copper in one and a plate of zinc in the other furnish a current to ring a bell? Why?
8. If you place a slip of paper between the springs in the pushbutton of a bell, will the bell ring when the button is pushed? Why?
9. Why was the term electromotive force invented?
10. What similarity is there between the flow of water in pipes and the flow of electricity along wires? Art. 156.
11. Why can birds perch on electric light wires without harm, when the same wires, if broken down, might kill a horse?
12. In trolley car lines the electricity is carried back to the power house through the rails. Why is it not dangerous to step on the track?
13. Why is the third rail on an electric railroad dangerous?
14. How can you find out whether or not the blade of your knife has become magnetized?

15. If the blade of your knife has become magnetized, how can you tell which end is a north pole?
16. Do the lines of force about a steel magnet extend beyond the space where the iron filings indicate them? Prove the correctness of your answer.
17. Can a horseshoe magnet be used for a compass? Why?
18. Could you make a telegraph instrument, using a common steel horseshoe magnet instead of an electro-magnet?
19. If you have a pocket compass, can you tell whether a current is flowing in an electric light wire? How?
20. If you have built a telegraph line between your home and your chum's home and the sounder will barely work, what could you do to make it work better?
21. Why is a telegraph sounder less likely to work on a long line than on a short one?
22. Are dry cells or gravity cells better in the long run for operating your telegraph line (question 20)? Why?
23. What is the effect of increasing the number of cells on a telegraph line?
24. How may the effect of adding cells to a telegraph line be shown?
25. How would you test a dry cell to find out whether or not it is "used up?"
26. How would you make a simple galvanometer that would enable you to determine which of a number of cells were in the best condition?
27. Why are electric wires so frequently made of copper?
28. Why are iron wires used for telegraph lines, while copper wires are used for long distance telephone lines and for trolley lines?
29. Of what material, usually, is the wire used in the coils of electric heaters? Why?
30. Why are the coils in electric heaters often wound on asbestos covered rods?
31. How could you make an ammeter if you had a pocket compass and some wire?
32. How could you make a voltmeter if you had a horseshoe magnet and some wire?
33. Why must the voltmeter have a high resistance?
34. How would you make a scale for your voltmeter (question 32)?
35. What changes have to be made in a D'Arsonval galvanometer in order to be able to make the coil rotate continuously?
36. For what purpose is a commutator used?

37. What could be done to the toy motor (Fig. 98) to make it more powerful?

38. Why will two dry cells run a toy motor very rapidly, while three gravity cells having the same voltage as the two dry cells will not move it?

39. Would six gravity cells run the motor better than three? Why?

40. The principle of the electric motor was known many years before motors came into general use. What was the cause of the delay in its introduction?

CHAPTER IX

INDUCED CURRENTS

179. Faraday's Discovery. The principles that enable us to generate strong currents at a reasonable cost were discovered by Michael Faraday (1791-1867) in 1831, but they were not applied to practical machines until about the year 1870. Faraday himself was content to leave to others the practical applications of the great discovery he made. We shall be able better to appreciate the importance of this discovery if we first study Faraday's experiments.

The apparatus (Fig. 99), differs in no essential way from that used by Faraday. A coil *S* of many turns of fine wire is connected to a sensitive galvanometer *G*. A steel magnet *M* is pushed into the coil. While the magnet is moving, the

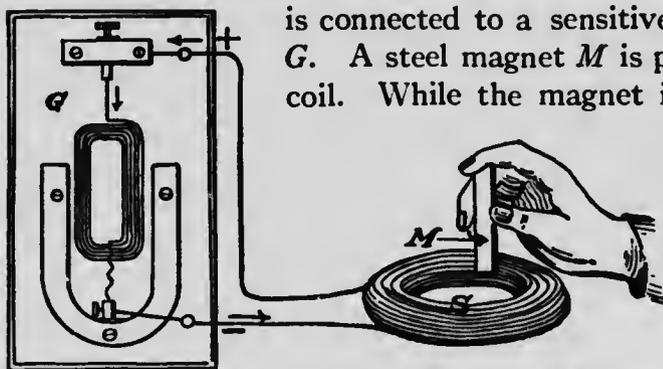


FIG. 99 THE MOVING MAGNET GENERATES A CURRENT

coil of the galvanometer moves, showing the presence of a current in the circuit. As

the magnet stops, the galvanometer coil returns to its original position, showing that the current also has stopped.

As the magnet is being pulled out of the coil *S*, the galvanometer again indicates the presence of a current in the circuit; but the current flows in a direction opposite to that in which it flowed when the magnet was being pushed into the coil. Whenever either pole of the magnet is pushed into the coil, or pulled out of it, the galvanometer shows a current in the circuit; but only so long as the magnet is in motion.

Thus Faraday discovered that

An electric current flows in a coil when the pole of a magnet is moving through it.

The current ceases when the motion stops.

180. Faraday's Interpretation. In Art. 162 we learned that if a steel magnet is covered with a piece of cardboard and iron filings are scattered over the card and the card gently tapped, the filings arrange themselves in curves, as shown in Fig. 86. When a single magnet is used, these curves appear to begin at one pole of the magnet and to end at the other. We also learned that when a small pocket compass is set at various points on the card, its needle points in the direction of these curves at that point; showing that the space about the magnet is filled with magnetic forces, whose directions are indicated by the curves. Faraday called these curves traced by the filings, *lines of magnetic force* because they show the direction in which the magnetic force is acting at any point in the field.

If we place two magnets under the card with their unlike poles toward each other, and let the iron filings trace the direc-

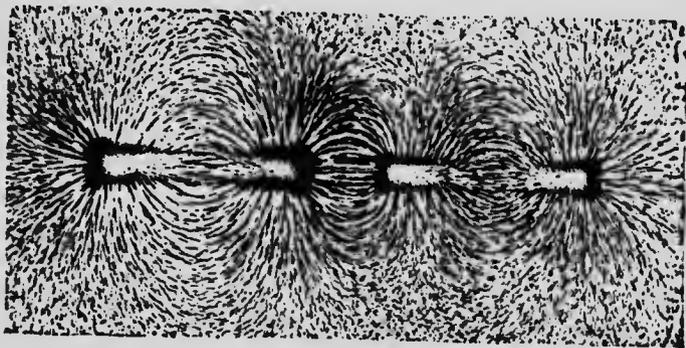


FIG. 100 THE LINES PULL UNLIKE POLES TOGETHER

tion of the lines of force, we get the result shown in Fig. 100. Since some of the lines of force seem to begin on one magnet and to end on the other, the curves suggested to Faraday that the magnetic lines of force act as though they were elastic

bands stretched between the two poles and trying to contract and pull the magnets together.

When two like poles are placed near together, we obtain the curves shown in Fig. 101. In this case none of the lines of

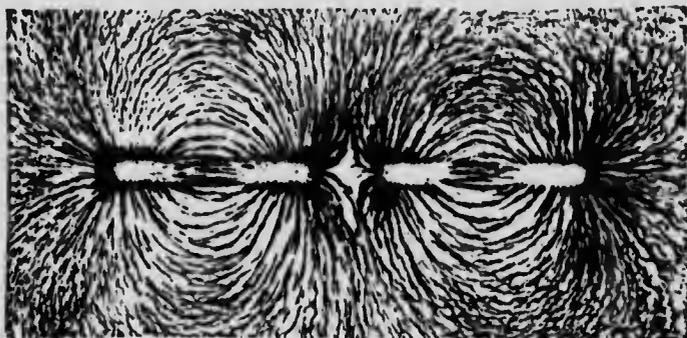


FIG. 101 THE LINES PUSH LIKE POLES APART

either magnet enter the other. Like magnetic poles always repel each other; and the curves suggest the idea that the repulsion is due to the action of the lines of force, which seem to be pushing sideways on each other, thus driving the magnets apart.

Since Faraday was not able to conceive how magnets could attract or repel each other when there was absolutely no connection between them, he supplied a connection by imagining that *every magnet is surrounded with invisible lines of force which produce the magnetic attractions and repulsions by pulling on the magnets or pushing against one another.*

181. Cutting Lines of Force. Having thus formed a clear mental picture of the lines of force about a magnet, Faraday saw that when one end of a magnet is pushed into a coil, the wires in the coil cut across these lines of force. If, instead of a coil, a single wire, whose ends are connected to the terminals of a sensitive galvanometer, is moved in the field, a current flows when the wire moves so as to cut across the magnetic lines of force; but when the wire is moved so as to follow along those lines, no current flows in the circuit.

The electric currents that flow in a wire when it cuts lines of magnetic force are called *induced currents*.

Since the flow of an electric current is always due to an electromotive force, Faraday conceived that *the cutting of lines of magnetic force by a wire induces in the wire an electromotive force, which drives a current through it.*

182. Increasing Induced Electromotive Force. If the like poles of two magnets be pushed into the coil at the same time, the galvanometer (Fig. 99) gives a larger deflection than when only one is thrust into it. The larger deflection indicates that a stronger current is flowing. Since the resistance in the circuit (that of galvanometer and coil) has not been changed, the stronger current implies that a greater electromotive force must have been induced. When two similar magnets are thrust into the coil, the wires in the coil cut twice as many lines of force as before, and the induced electromotive force is much greater.

If we thrust a single magnet into the coil twice as rapidly as the two were pushed into it, the deflection in the galvanometer is exactly the same. So we can increase the induced electromotive force either by cutting more lines in a given time, or by cutting the same number of lines in less time.

If the coil consists of a single large loop, four or five inches in diameter, the galvanometer does not give so great a deflection when the magnet is pushed into the loop as when a smaller loop that fits the magnet closely is used. The small loop is closer to the magnet, where the lines of force are closer together; it therefore *cuts more lines per second*.

If the same wire is wound into two small loops parallel to each other and near together, the galvanometer gives a greater deflection; and when the wire is wound into a coil with a large number of turns parallel to one another and fitting closely about the magnet, the electromotive force induced by thrusting the magnet into this coil is much stronger. Each turn of wire cuts the same number of lines per second,

and so the same electromotive force is induced in each; and the electromotive forces of all are added together. Hence *the greater the number of turns in the coil, the greater the induced electromotive force.*

All of these devices—stronger magnetic field, faster motion, moving conductors close to the magnetic pole, more turns in the coil,—are but devices for cutting more lines of force per second; and they all increase the strength of the induced electromotive force. Hence the conclusion:

The intensity of an induced electromotive force is proportional to the number of lines of force cut per second.

183. Direction of an Induced Current. In Art. 179 we found that when one pole of a magnet was pushed into a coil, the galvanometer was deflected in a certain direction, say to the right. When an electric current of whatever origin, flows in a coil, the faces or flat sides of the coil act like magnet poles (Art. 167). In order to find out which face of the coil becomes a north pole when the north pole of the steel magnet is thrust into the coil, a battery may be so connected in the circuit, with the coil and galvanometer, that the galvanometer deflects to the right. A pocket compass will then indicate which end of the coil is a north pole.

Suppose it is found that when the battery current is passing through both coil and galvanometer, it causes the galvanometer to deflect to the right. If the upper face or end of the coil at the same time is found to be a north pole, then when the battery is removed and an induced current in the coil also deflects the galvanometer to the right, the induced current has the same direction as that from the battery, and so makes the upper face of the coil a north pole. Interpreting the deflections of the galvanometer in this manner, we find that when a north pole of a magnet approaches one end of the coil, that end itself becomes a north pole, because of the induced current that flows in the coil. When the north pole of the magnet is drawn away from one end of the coil, that end of the coil becomes a south pole. Since like poles repel each

other and unlike poles attract, the end of the coil repels the approaching north pole and attracts the receding one.

Similarly, when a south pole of a magnet approaches one end of a coil, that end becomes a south pole, and so repels; and when the south pole of the magnet is drawn away from one end of the coil, that end becomes a north pole, and so attracts. In all cases,

The direction of an induced current is such that its magnetic field opposes the motion of the magnet that produces it. (Lenz's law.)

184. Currents Induced by Currents In Art. 162 we learned that a coil through which a current was flowing acts in every way like a magnet. We may, therefore, expect that if we move such a current-bearing coil either into or out of another coil, we shall get effects precisely similar to those obtained by moving the magnet. The apparatus for the experiment is shown in Fig. 102. When we pass the current through the coil *P*, and then bring it quickly near the coil *S*, the galvanometer gives a deflection in a certain direction, say to the

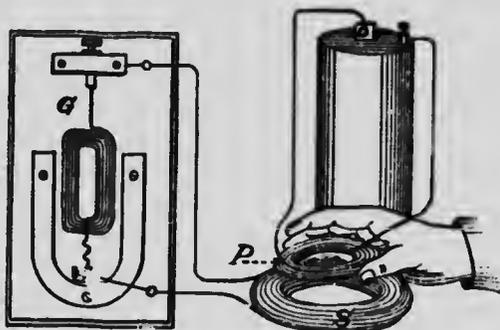


FIG. 102 THE MOVING COIL GENERATES A CURRENT

right. Withdrawing the coil quickly gives a deflection to the left. When we investigate the direction of the induced current as in Art. 183, we find that the direction is always such that the magnetic field of the induced current opposes the motion, just as it did with the magnet.

A slow motion of the coil gives a smaller deflection than a quick one, showing again that the faster the lines of force are cut, the greater the induced electromotive force.

A stronger current or more turns of wire in the coil *P*, increases the strength of its magnetic field, i. e., the number of

lines of force about it (Art. 182). The deflections are also increased, when P , with its stronger field, is brought up to S with the same speed as before.

The deflections are also increased when the iron core C (Fig. 103) is placed inside the coils, other circumstances remaining the same as before. An iron core strengthens the magnetic field, and so increases the number of lines of force about the coil (Art. 163).

All these observations show that *in the matter of inducing electromotive force, current-bearing coils and electro-magnets act just like steel magnets.*

185. Making and Breaking the Circuit. When the coil P is left lying in S , with the iron core C in the center (Fig. 103),

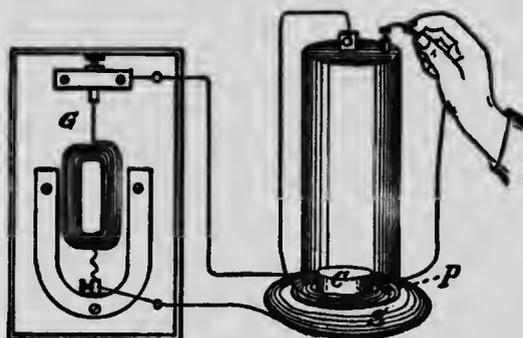


FIG. 103 MAKING OR BREAKING THE CIRCUIT INDUCES CURRENT

and the circuit through P is suddenly broken, we get the largest effect of all. Breaking the circuit by disconnecting the wire withdraws the magnetic lines of force from the coil S more quickly than they can be withdrawn by moving P . Conversely,

making the primary circuit by connecting the wire again pushes the magnetic lines of force through S more quickly than it can be done by moving P ; therefore, more lines are cut per second and the induced electromotive force is greater.

The coil P through which the current from the battery is sent is called the *primary* coil; the coil S in which the electromotive force is induced is called the *secondary* coil. When no current is flowing in the primary, practically no lines of force are passing through the secondary. When the circuit through the primary is closed, a very large number of lines of force is passing through the secondary. Thus the number of lines of force passing through the secondary has been changed.

Whenever a wire loop cuts a line of force, that line must have passed from the outside of the loop to the inside, or vice versa. So by cutting the line, the number of those that pass through the loop has been changed. So "cutting lines of force" has the same effect as "changing the number of lines of force that pass through a loop"; and either expression may be used to describe the operation.

186. Principles of Induced Electromotive Force. The results of our study of induced electromotive force may be stated in the following three principles which are sometimes called the *laws of induced currents*.

1. An electromotive force is induced in a conductor whenever it cuts magnetic lines of force.

2. The greater the number of lines of force cut per second, the greater the induced electromotive force.

3. The direction of the induced current is always such that its magnetic field opposes the motion that produces it.

187. The Dynamo. We can now understand the construction of a dynamo. In Fig. 104 *N* and *S* represent the

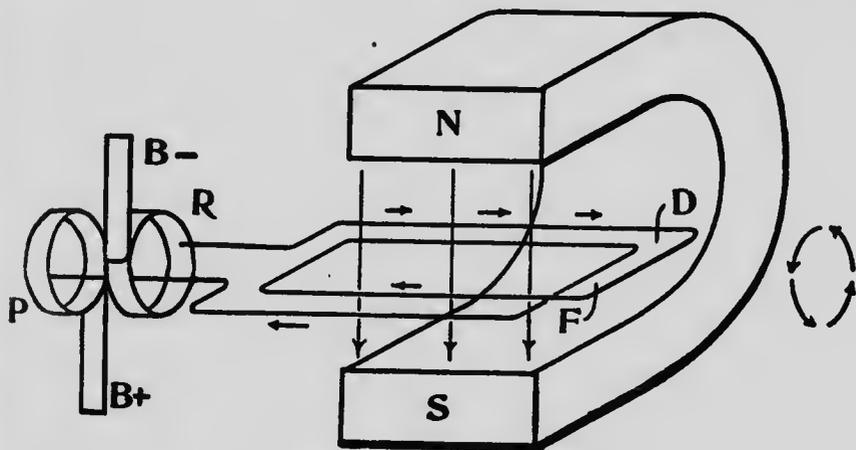


FIG. 104 THE DYNAMO DIAGRAM

two poles of the field magnet, their lines of force being indicated by the long vertical arrows. *FD* represents a single

coil of wire, RP a pair of collecting rings, one soldered to each end of the wire from the coil FD , and $B+$ and $B-$ a pair of brushes attached to the terminals of the external circuit around which the current is to be sent. The shaft and bearings are omitted for the sake of clearness (cf. Figs. 104 and 95).

The coil FD being in the position shown, the greatest possible number of lines of force pass through it. When the coil is turned through a quarter of a revolution in the direction of the curved arrows (seen at the right of the diagram), its plane will be vertical, and the wires cut across all these lines of force. This turning of the coil has the same effect as withdrawing a north pole from the upper face of the coil. Therefore an induced current will circulate around the coil in such a direction as to make the face D a south pole, and the other face F a north pole. This induced current will flow onward from $B+$ around the external part of the circuit, which for simplicity is not shown in the diagram, returning to the coil through brush $B-$ and collecting ring R .

When the coil FD (armature) has turned through the second quarter revolution, its plane will again be horizontal and its wires will again have cut all the lines of force that now pass through it. But, since it has turned completely over, the lines of force from N now enter the other face F ; so this motion has the same effect as that of pushing a north pole into the face F of the coil. Since pushing a north pole into the face F has the same effect in the coil as has withdrawing a north pole from D , the induced current will continue to flow around the coil in the same direction as before.

During the third and the fourth quarter revolution the lines of force from the north pole of the magnet are withdrawn from the face F and pushed in to the face D . Both of these motions produce an induced current that flows around the coil in the same direction, but this direction is the reverse of what it was during the first half turn. So the current in the external circuit flows in one direction during one-half of the

revolution, and in the opposite direction during the other half. Such a current is called an *alternating current*.

The electromotive force of the dynamo is produced by rapidly cutting lines of magnetic force with a rotating coil.

188. Direct Current Dynamo. Dynamos that furnish direct currents, like those from batteries, differ from the "alternators" mainly by having "commutators" like direct current motors (Fig. 96). At the end of each half turn, the commutator changes the direction of the alternating current in the armature, so that the current in the external circuit flows all the time in the same direction.

189. Greater Power in the Dynamo. The power and efficiency of a dynamo are increased by the means previously described in the case of the motor (Art. 176). The field magnets are electro-magnets, and instead of two poles there may be four or more. They are designed so as to give a magnetic field with as many lines of force as is possible.

The armature consists of many coils wound on a soft iron core. The coils must be wound in slots in the core, and strongly bound in their places; for if they were not held firmly in the slots, the magnetic forces that tend to stop their motion would combine with the reaction due to inertia and the rapid rotation (Art. 11) to pull them out of their places. The insulation of the coils should also be as perfect as possible.

Large dynamos often are as powerful as 7500 horsepower steam engines; and, since they may be run by steam engines or by water wheels, they generate electricity at relatively small expense. So Faraday's discovery of induced currents (Art. 179) has led to the solution of the problem of supplying cheap and powerful currents (Art. 178); thereby bringing the motor and the electric light into practical use, and laying the foundations of the enormous, modern, electrical industries.

190. Source of Energy in the Dynamo. When a magnet is thrust into a coil, causing an induced current to flow in it,

the direction of the current is always such as to oppose the motion (Art. 183). If the ends of the coil are not connected, no induced current can flow. There is then no magnetic opposition to the motion, and so less force is required to move the magnet back and forth through the coil. If a model dynamo, such as is used for demonstration purposes, be run by hand when it is furnishing no current and also when it is furnishing current, the fact that more force is required in the latter case is very noticeable.

More force, however, means more work done in driving the machine. Because the induced currents flow in such a direction as to oppose the motion, work must be done to overcome this opposition, and this work is the source of the current.

The essential parts of a dynamo are: (1) *a rotary coil called an armature*; (2) *a stationary magnet called the field magnet*, and (3) *a sliding contact device for carrying the current from the armature to the external circuit*.

The dynamo generates an induced current when its armature coils cut the magnetic lines of force of its field magnets.

The energy of an induced electric current is derived from the mechanical work done in overcoming the resistance of the current's own magnetic field.

191. The Induction Coil. The induction coil (Fig. 105) is an instrument frequently mentioned in the papers and maga-

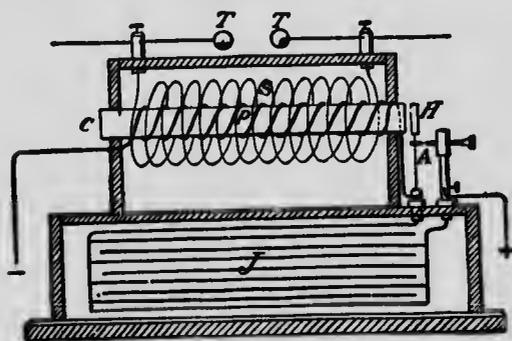


FIG. 105 INDUCTION COIL DIAGRAM

zines, because it is used in producing X-rays, and furnishing the sparks used in wireless telegraphy. It was invented by an American, Charles G. Page, in 1838. Its essential parts are:

(1) an inner coil *P* called the *primary*, consisting of a few turns of coarse wire; (2) a core *C* made of straight soft iron wires, and placed

inside the primary; (3) an outer coil *S*, called the *secondary*, made of a great many turns of fine wire, whose ends lead to a pair of insulated knobs or points *TT*, and (4) a device *HA* for rapidly making and breaking a strong electric current which is sent through the primary.

When the contact points *A* are pressed together, the current from the battery enters at +, flows through the primary *P*, and back to the battery. The spring that holds the two contact points together carries a piece of soft iron *H* on its upper end where it is directly in line with the iron core. When the circuit from the battery is closed, *C* becomes an electro-magnet and draws *H* toward it, thereby opening the circuit at *A*. Then *C* loses its magnetism and *H* flies back again, closing the circuit at *A*. Thus *H* keeps itself vibrating, and automatically opens and closes the primary circuit, exactly as the armature of the electric call bell does (Art. 159). Whenever the circuit through the primary coil is closed or opened, a spark passes between the knobs *TT*.

Large induction coils are placed on a box *J* filled with sheets of tinfoil separated by sheets of paraffined paper. Every alternate sheet of tinfoil is connected to one of the contact points *A*, the other sheets being connected to the other contact point, as shown in the diagram. This device is called a *condenser*, and it serves to reduce the sparking at the points *A* when the circuit is broken there. This sparking is objectionable because it burns out the contact points, and because it prolongs the time of breaking the circuit, thereby reducing the intensity of the induced electromotive force; and consequently, the length and brightness of the sparks at *TT*.

Induction coils have been made to give sparks six or eight feet long. A coil that gives a 40-inch spark produces an electromotive force equal to that of from 60,000 to 100,000 voltaic cells and contains over 250 miles of wire in the secondary coil. Large induction coils must be made with great care, especially with regard to the insulation, which would otherwise be punctured by the great electrical pressures.

The principles explained in Art. 185 enable us to see how the induction coil works. Closing the circuit through the primary has the same effect as introducing a strong electro-magnet inside the secondary very quickly; and opening the circuit through the primary has the same effect as quickly withdrawing the electro-magnet. The secondary has a very large number of turns; therefore the induced electromotive force is very great.

192. The Telephone. Although Faraday realized that his discovery of induced currents (Art. 179) was an important one, he never dreamed that it would some day make it possible to talk between New York or Boston and Chicago. Yet such is the case; and the telephone has now come into such general use that every one is familiar with it and appreciates its enormous value in daily life. It is hard to understand how people ever got on without it.

The essential parts of the telephone are the "transmitter" and the "receiver." Directly behind the mouthpiece *M* (Fig. 106) of the transmitter, is a diaphragm or disk *D* of thin

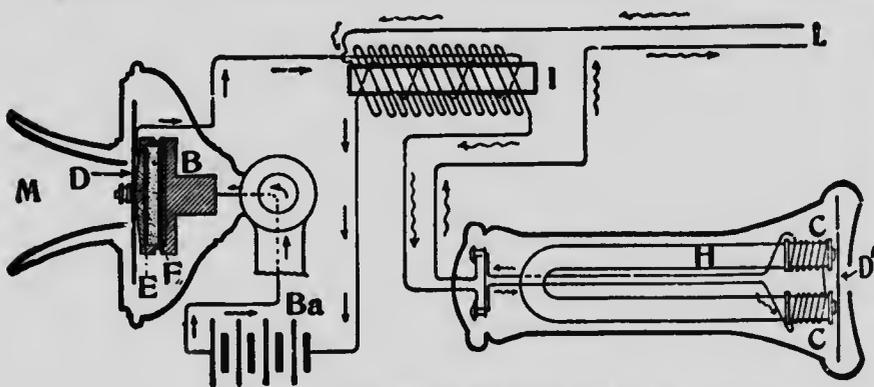


FIG. 106 DIAGRAM OF TELEPHONE CIRCUIT

sheet iron. A smaller disk *E* of hard carbon is firmly attached to the center of the diaphragm *D*. A second similar disk *F* of carbon is fastened to the plate *B*, which is rigidly connected with the frame of the transmitter. The two carbon disks *E* and *F* are insulated from each other, and the space between them is filled with granules of hard carbon.

Current from the battery *Ba* flows through the plate *B*, the disk *F*, the carbon granules, the disk *E*, and the primary of a small induction coil *I*, as shown in the figure.

When you talk into the transmitter, the sound sets the diaphragm *D* into vibration, so that it alternately increases and decreases the pressure on the grains of carbon between *E* and *F*. These alternations of pressure in some way alter the resistance of the carbon granules, decreasing it when the pressure increases, and increasing it when the pressure decreases. These variations in the resistance of the carbon granules produce variations in the strength of the electric current flowing through them, and through the primary of the induction coil. The variations of current strength produce corresponding variations in the number of lines of force that pass through the secondary of the induction coil. Therefore induced alternating electric currents, varying both in strength and in time of vibration with the vibrations of the speaker's voice, are sent chasing one another along the line wire to the distant receiving instrument.

The receiver consists of a steel magnet *H*, whose poles are surrounded with the coils *CC*. Close to the poles is a diaphragm *D'* of thin sheet iron, held in a hard rubber case so that it cannot touch the magnet. The coils *CC* are connected with the secondary of the induction coil *I*, and with the line *L* to the other end of the line.

When the pulsating electric currents from the induction coil flow through the coils *CC*, they produce variations in the strength of the magnetic field of the magnet *H*. These variations in the strength of the field cause the disk *D'* to be alternately attracted and repelled in time with the vibrations of the speaker's voice, making the diaphragm *D'* vibrate and reproduce the vibrations of the transmitter diaphragm *D*. An ear near *D'* then hears sounds similar to those sent in at the other end of the line.

DEFINITIONS AND PRINCIPLES

1. A magnetic field is filled with lines of magnetic force.
2. The stronger the field, the greater the number of lines of force.
3. An electromotive force is induced in a conductor whenever it cuts magnetic lines of force.
4. The greater the number of lines of force cut per second, the greater the induced electromotive force.
5. The direction of the induced current is always such that its magnetic field opposes the motion that produced it. (Lenz's Law).
6. The energy of an induced current is derived from the work done in overcoming the opposition of its own magnetic field.

QUESTIONS AND PROBLEMS

1. Who was Faraday and what were some of his most important discoveries?
2. An electric current may make iron magnetic. Can an electric current be obtained with the help of a magnet? If so, how?
3. In what direction does a compass needle point when it is near a magnet?
4. How do we find the direction of the magnetic lines of force at a certain point near a magnet?
5. Have two magnets when placed close together more lines of force about them than one alone has? Prove the correctness of your answer.
6. When a magnet pole is passed quickly through a coil whose terminals are not connected together, do we get an induced current in the coil? Why?
7. If one moving conductor cuts 10,000 lines of magnetic force per second while another cuts 20,000 lines per second, how does the number of volts of induced electromotive force in the second case compare with that in the first?
8. If the resistance of the second coil in question 7 is twice as great as that of the first, how will the induced currents in the two cases compare?

9. Why does increasing the number of turns of wire in a coil make it possible to induce a greater electromotive force in the coil with a given magnet?

10. Why does increasing the strength of a magnet make it possible to induce a greater electromotive force in a given coil? Prove the correctness of your answer.

11. When the north pole of a coil approaches one end of another coil, in which direction does the current induced in the second coil flow? Why?

12. An induced current can do work. What work had to be done in order to give the current this ability?

13. Does it require more work or less work to push a magnet into a coil when its terminals are connected together than when they are disconnected? Why?

14. How long does an induced current flow?

15. Why may a greater electromotive force be induced with an electro-magnet than with a steel magnet?

16. Why may a greater electromotive force be induced by making and breaking the circuit of the electro-magnet than by moving it? Prove the correctness of your answer.

17. Which parts of a dynamo should be made of iron and which of copper?

18. Why are there more coils than one on the armature of a dynamo?

19. If your dynamo should give an electromotive force of 125 volts and it gives only 90 volts, what is the simplest thing you can do to it to bring up the voltage?

20. Does it require less power to run a dynamo when it is supplying current than when it is not? Why?

21. Two toy motors are belted together. If one is driven by a current, and the other has its terminals connected to those of a galvanometer, what will happen? Why?

22. If two motors have their terminals connected by wires, and one of them is driven by a belt connected with a hand rotator or a small steam engine, what will happen?

23. How is the spark coil on a gasoline engine made and how does it operate?

24. Why is it objectionable to run alternating current light mains on the same pole with telephone wires?

25. Why is it possible to get a very high electromotive force with an induction coil?

26. If an alternating current were sent through the primary of an induction coil and the circuit was not broken, would we get sparks from the terminals? Why?

27. Would a dynamo supply current if its armature were held stationary and the field magnets revolved? Prove the correctness of your answer.

CHAPTER X

ELECTRIC POWER

193. Electroplating. If two electric light carbons are connected by means of wires to the terminals of a battery and then placed in a solution of copper sulphate, the one fastened to the negative terminal soon becomes "plated" with copper. If a silver nitrate solution is used instead of one of copper sulphate, silver will be deposited instead of copper. The current decomposes a solution containing a salt of any metal such as sodium chloride (common salt), copper sulphate, or silver nitrate, and deposits the metal on the negative electrode. This process of depositing metals by the current is called *electroplating*.

Electroplating is extensively used in making gold and silver plated jewelry, nickel-plated parts of bicycles and machinery, copper "electrotype" plates from which books are printed, etc. Fig. 107 shows an electroplating bath. It is usually a large vat, containing a solution of some compound of the metal that is to be deposited. Three copper rods, or "bus bars," are laid on the top; and two of these, $B+$, $B+$, are connected with the $+$ terminal of a dynamo, the other, $B-$, with the $-$ terminal.

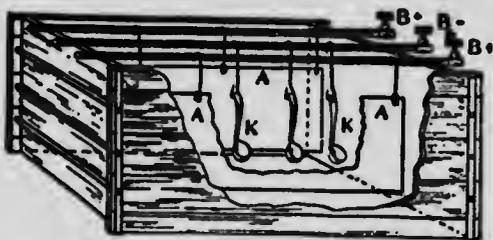


FIG. 107 ELECTROPLATING BATH

From the $+$ bus bars are suspended large plates AA of the metal to be deposited, and from the $-$ bar are hung the articles KK to be plated. When a current of the proper strength is passed, the metal is evenly deposited from the

solution on the articles suspended from the negative bar, giving them the desired coating.

194. Electrolysis. The process by which a salt in solution is decomposed by passing an electric current through it is called *electrolysis*. The solution that is decomposed while conducting the current is called an *electrolyte*. The vessel in which the action takes place is called an *electrolytic cell*. The plate or electrode that is connected to the positive terminal of the battery is called the *anode*. The negative electrode, on which the metal is deposited, is called the *cathode*. The current in an electrolytic cell always flows from the anode to the cathode, or *the positive current and the metal go together*.

If two copper plates are weighed and placed in a copper sulphate solution, and if a current is then passed through them for some time—say half an hour—we find, on weighing the plates again, that the negative plate has gained in weight and the positive plate has lost. So the current makes the copper anode dissolve into the solution, and deposits copper from the solution on the cathode. The amount of metal in the solution remains fairly constant.

Faraday made several electrolytic cells with copper plates in a solution of copper sulphate, and arranged them in series with a battery and a galvanometer, so that the current had to go through one after another. After the current had flowed through them all for a given time, he found that the same amount of copper was deposited in each of the cells. When he allowed the current to flow twice as long through the same circuit, twice as much copper was deposited in each cell. When he increased the electromotive force in circuit, by adding more batteries until the galvanometer showed that the current strength was doubled, twice as much copper was deposited in each cell each second.

After many experiments of this kind, Faraday concluded that the same quantity of electricity was always required to deposit 1 gram of copper from the solution; no matter whether that quantity of electricity flowed rapidly in a strong current,

or slowly in a weak current. So he conceived that *the number of grams of metal deposited in an electrolytic cell is a good measure of the quantity of electricity that has passed.*

195. Current Strength. The Ampere. The strength of a current of water is measured by the quantity of water that flows past a given point in one second. Similarly, the strength of a current of electricity is measured by the quantity of electricity that flows past a given point in a second. Since a quantity of electricity may be measured by the number of grams of copper that it deposits, the strength of an electric current may be measured by the number of grams of copper that it deposits in a second. This method of measuring current strength is the one that is used in defining the unit of current strength, which is called the *ampere*.

A steady current has a strength of 1 ampere when it deposits silver from a solution of silver salt at the rate of 0.001118 grams per second.

The same current will deposit copper from a solution of a copper salt at the rate of 0.000329 grams per second. At this rate it would take 50.7 minutes to deposit a gram; so we may think of an ampere as the strength of a current that would deposit a gram of copper in about $\frac{1}{2}$ of an hour.

Since Faraday, in the experiments described in Art. 194, found that, when a number of electrolytic cells were arranged in series, the same amount of copper was always deposited in each, we conclude that

At a given instant, the current strength is the same at all points in a series circuit.

196. The Ammeter. The measurement of current strength by electrolysis requires considerable skill, and is a slow and troublesome process. To avoid this, galvanometers of the type shown in Fig. 93 are made, with scales so graduated that the current strength may be read directly in amperes. In order to make the scale, the instrument may be placed in a circuit with an electrolytic cell containing copper sulphate.

The position of the pointer is marked on a blank card which is to serve as a scale. After a steady current has flowed twenty minutes or so, the amount of copper deposited is determined by weighing. The weight of copper deposited, divided by the number of seconds during which the current was passing, gives the amount of copper deposited in 1 second; and this, divided by 0.000329, gives the number of amperes. This number is placed opposite the mark at which the pointer stood during the experiment.

This operation has to be repeated several times with currents of different strengths. When the numbers of amperes that correspond to several different points have been thus determined, the rest of the scale can be marked proportionally with the help of an ordinary inch or centimeter rule. After the scale has been marked on the card, the instrument may be placed in any circuit through which a current is flowing, and the number of amperes of current will be told by the number on the scale where the pointer comes to rest.

Such a galvanometer, graduated to read amperes, is called an *ammeter*. It is a very useful instrument, for it indicates all the time just how strong a current is flowing through it. It differs from the voltmeter in that its resistance is very low, while that of the voltmeter is very high (Art. 171), and in that its scale is graduated so that it reads amperes instead of volts. The ammeter is placed in series in the circuit, so the whole current passes through it. Since a knowledge of the "voltage" and "amperage" is necessary for the proper management of the current, both voltmeters and ammeters are to be seen on all switchboards in power houses and electric light stations.

197. Unit of Resistance. The practical unit of resistance is the *ohm*. It is a resistance equal to that of about 152 feet of number 18 copper wire, or 25 feet of number 18 iron wire, or 7.6 feet of number 18 German silver wire. The ohm is defined as follows:

The ohm is the resistance at 0° C. of a column of pure mercury 106.3 centimeters long and one square millimeter in cross section.

198. Ohm's Law. We have already learned (Art. 170) that, when other things are the same, the current strength increases as the electromotive force is increased by adding more cells. In Art. 168 we learned that, other things being the same, the current strength decreases when the resistance in circuit is increased. Since we have now selected units in which to measure current strength, electromotive force, and resistance, we can readily make measurements to determine how these factors are related in an electric circuit.

Such measurements were first made by a German physicist, George Simon Ohm (1789-1854), and the relation which he found is called Ohm's Law. It is

$$\text{Current in amperes} = \frac{\text{Electromotive force in volts}}{\text{Resistance in ohms}}$$

$$\text{Amperes} = \frac{\text{Volts}}{\text{Ohms}}$$

199. Lamps in Series. Amperes. Suppose we first construct a miniature electric light plant, by connecting five or six dry cells in series, and passing the current through two or three "3-volt" lamps *L*, also arranged in series (Fig. 108). The lamps will light up. In order to measure the strength of current, place a suitable galvanometer or an ammeter *A* in the circuit, between the battery and the first lamp, and note the deflection. Suppose the deflection means 0.2 ampere. Then change the position of the ammeter, so that it is between the first and second lamp. Its reading is the same as before.

Wherever the ammeter is placed in the circuit, provided the circuit is not otherwise changed, the same current strength of 0.2 ampere is found. So when we wish to measure current strength the *ammeter may be placed anywhere in the circuit.* Hence, as Faraday concluded from his experiments in electrolysis (Art. 194),

At a given instant the number of amperes of current is the same through every complete cross section of a given circuit.

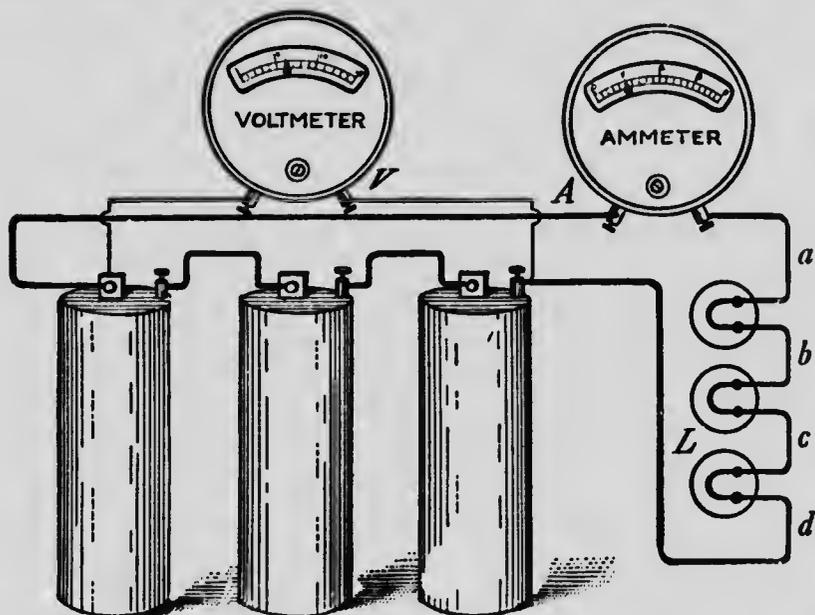


FIG. 108 THE CELLS AND THE LAMPS ARE IN SERIES

200. Lamps in Series. Potential Difference. If we touch the terminals of the voltmeter (Art. 171), or of a suitable galvanometer, to the terminals of the battery (Fig. 108), we get a deflection which measures the voltage of the battery. If the voltmeter terminals be touched to the circuit at the points *a* and *d*, its deflection measures the voltage between those two points. Suppose this deflection means 9 volts. If the 3 lamps are all alike, then, when the terminals of the voltmeter are applied at the points *a* and *b* (at the terminals of the first lamp), its deflection is one-third as large as before, showing that the difference in electric pressure between these points is 3 volts. The differences in pressure between *b* and *c*, and between *c* and *d* are also 3 volts each; i. e., it requires a difference in pressure of 9 volts to drive a current of 0.2 ampere through 3 lamps, and 3 volts is required for each lamp. The difference in electric pressure between two points on a circuit is called *Potential Difference* (*P. D.*).

The difference in electric pressure between two points on an electric circuit corresponds to the difference in water pressure between two points on a pipe in a water system, as shown by the difference in the level of the water in two vertical pipes connected at those points (Art. 60).

201. Definition of the Volt. In Art. 172, the volt was mentioned as the unit of electric pressure, but was not there defined

A volt is the electromotive force that will drive a current of 1 ampere through a resistance of 1 ohm.

202. Measurement of Resistance. The current through the lamps in the experiment in Art. 199 was found to be 0.2 ampere, and the total fall of potential in the circuit was 9 volts (Art. 200); therefore (Art. 198),

$$\text{amperes} = \frac{\text{volts}}{\text{ohms}}, \text{ or } 0.2 \text{ (ampere)} = \frac{9 \text{ (volts)}}{x \text{ (ohms)}}. \quad x = 45 \text{ ohms.}$$

Thus the total resistance of the lamps is 45 ohms.

The resistance of each lamp is found by applying Ohm's law to each lamp separately. Thus

$$0.2 \text{ (ampere)} = \frac{3 \text{ (volts)}}{x \text{ (ohms)}}. \text{ Hence, } x = 15 \text{ ohms for each lamp.}$$

Since there are 3 lamps in series, the total resistance in circuit is $3 \times 15 = 45$ ohms. We thus find that the resistances of 1, 2, and 3 lamps are 15, 30, and 45 ohms respectively; and that the P. D. is 3 volts for 1 lamp, 6 volts for 2 lamps, and 9 volts for 3 lamps. Experiments and calculations of this kind with all sorts of lamps and with other resistances as well, has led to the following conclusions:

1. *The resistance between any two points of a circuit may be found by dividing the number of volts P. D. between those points by the number of amperes of current in the circuit.*

2. *When lamps are arranged in series their resistances are added together.*

3. The $P. D.$ between two points on a circuit is proportional to the resistance between the same points.

203. Lamps in Parallel. The arc lamps commonly used to light streets are generally arranged in series as just described.

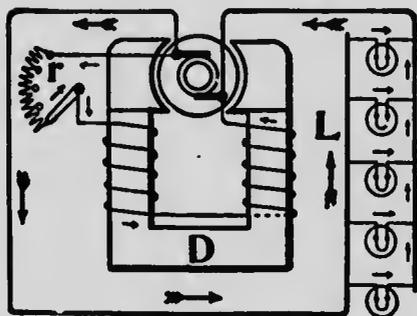


FIG. 109 LAMPS IN PARALLEL

Incandescent lamps used in houses are arranged "in parallel" (Fig. 109). Two heavy wires, called *mains*, run from the dynamo D to the lamps L ; and one terminal of each lamp is attached to each of the mains, as shown in the figure.

The arrangement may be imitated with the cells and the miniature lamps L (Fig. 110). If two cells will not light all the lamps, other pairs of cells should be added in "parallel"—i. e., with the free zinc of each pair of cells connected to one main and the free carbon of each pair to the other main. For simplicity only 3 single cells are shown in parallel in the figure.

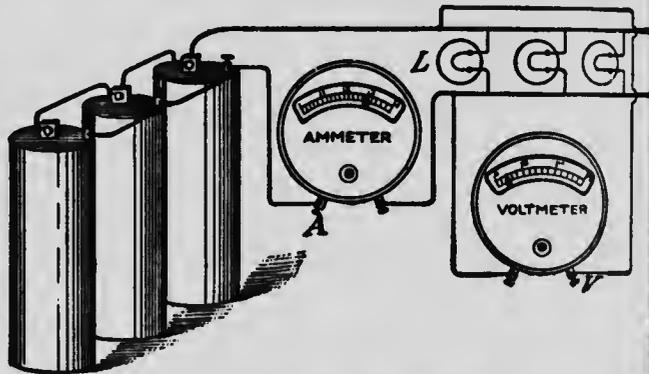


FIG. 110 THE CELLS AND THE LAMPS ARE IN PARALLEL

With 3 pairs of cells in parallel, the voltmeter indicates 3 volts pressure between the mains, wherever it is applied.

When one lamp only is in circuit, the ammeter A shows a current of 0.2 ampere. When a second lamp is added, the current strength in the mains increases to 0.4 ampere. The addition of the third lamp increases the current to 0.6 ampere. Since the voltage remains constant and the number of amperes

increases as lamps are added, it must be that *the addition of lamps in parallel reduces the resistance in circuit.*

If the ammeter be placed between one terminal of a lamp and one of the mains, it indicates that 0.2 ampere is flowing through each lamp. So the lamps are somewhat similar to tubes through which water can flow from one water main to another. When a water main and a sewer are connected

by a number of small pipes with valves in them (Fig. 111), each pipe, when its valve is open, allows a certain number of gallons of water to flow through it each second. The

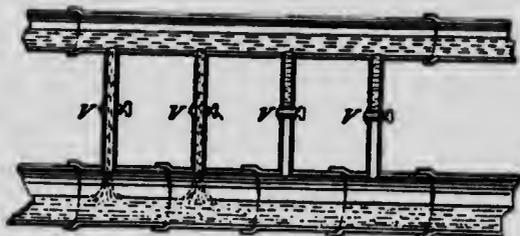


FIG. 111 MORE OPEN VALVES, MORE WATER FLOWS

greater the number of open valves, the greater the number of gallons of water that flow each second from the water main to the sewer; and the less the resistance to the flow. So it is with the lamps in parallel. Each lamp can carry a current of 0.2 ampere; so when one lamp is in circuit only 0.2 ampere of current flows. When 2 lamps are in circuit, 0.4 ampere flows; and so on. Since the voltage remains constant, it is evident from Ohm's law that the resistance of two lamps in parallel is only half the resistance of one; the resistance of three lamps in parallel is only one-third the resistance of one. Hence the conclusion:

When a number of equal resistances are placed in parallel, the joint resistance of all is equal to the resistance of one of them divided by their number.

204. Cells in Parallel. In Art. 177 we learned that the internal resistance of a cell prevented us from getting a large current from it. The internal resistance of cells acts like any other resistance; so the total internal resistance of a battery may be reduced by placing the cells in parallel—i. e., connecting all the negative terminals with one wire and all the positives with the other.

For example, three dry cells in parallel will give the same voltage as one, but the joint internal resistance of the three is only one-third that of one. For this reason it was suggested (Art. 203) that if one pair of cells would not light the three lamps in parallel, other pairs of cells be added in parallel.

205. Electrical Power. In Art. 156 electric pressure was shown to be analogous to water pressure; and in Art. 195 the analogy between the quantity of electricity that flows per second—i. e., the strength of the electric current—and the quantity of water that flows per second was pointed out. In Art. 95 we learned that water power is measured by the product of the water pressure and the quantity of water that flows each second. Hence just as

Water power = water pressure \times quantity of water per second, so

Electric power = electric pressure \times quantity of electricity per second.

The unit of electric pressure is the volt; and the unit of quantity of electricity per second—i. e., of current strength—is the ampere: therefore,

$$\text{Electric Power} = \text{Volts} \times \text{Amperes.}$$

We have 1 unit of electric power when a current of 1 ampere flows under a pressure of 1 volt. This unit of electric power is called the *watt*. Hence,

$$\text{Watts} = \text{Volts} \times \text{Amperes.}$$

206. Efficiency Test of an Electric Motor. As with simple machines, water motors, and steam engines, the most important thing about electric machines is the efficiency. The efficiency of an electric motor may be determined by a method analogous to that used in the case of the water motor (Art. 97).

Suppose that we have bought a 110-volt motor that is built to develop two horsepower, and we wish to test its power and efficiency in order to see whether it does what is claimed for it. The voltmeter V , whose terminals are

attached to those of the motor (Fig. 112), measures the P. D. at the motor. It should read 110 volts. The ammeter *A*,

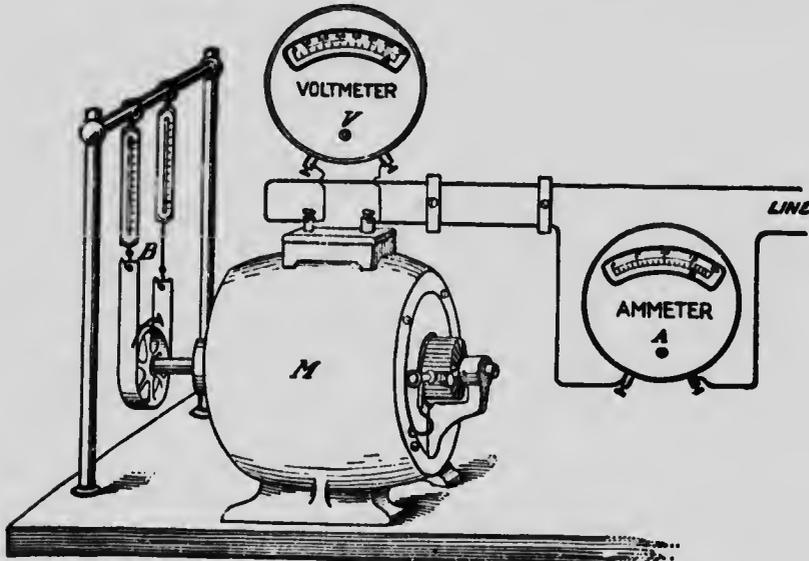


FIG. 112. MEASURING THE EFFICIENCY OF THE MOTOR

placed in the power circuit in series with the machine, measures the number of amperes flowing through the motor. Suppose it reads 16 amperes. Then the power supplied to the motor (power in) is

$$110 \text{ (volts)} \times 16 \text{ (amperes)} = 1760 \text{ watts.}$$

A brake (Art. 97) is applied to the axle of the motor and the readings made, exactly as they were for the water motor (Art. 97). Let us suppose these readings to be as follows:

Circumference of brake wheel, 2 feet; revolutions per minute, 360; pull on brake, 82.5 pounds. Then the power obtained from the motor is

$$82.5 \text{ (pounds)} \times 2 \text{ (feet)} \times 360 \text{ (rev. per min.)} = 59,400 \text{ foot-pounds per minute.}$$

Dividing this by 33,000 foot-pounds per minute (Art. 96) to reduce it to horsepower, we get 1.8 horsepower.

So 1760 watts of electric power was supplied to the motor to make it do work at the rate of 1.8 horsepower. This result enables us to compare the efficiency of this motor with

that of others; but it does not state what the real efficiency of this motor is; because the power in is expressed in watts, and the power out is expressed in horsepower.

In Art. 145 we learned that there was a definite relation between the foot-pound and the B. T. U. The electric current heats the filaments of incandescent lamps. We can therefore find out whether a definite number of watts is equivalent to a horsepower if we can determine whether a given number of watts always produces the same number of B. T. U. per second. This question will be answered crudely in the next article.

207. Number of Watts for 1 B. T. U. per Second. An ordinary 16-candle-power 110-volt electric lamp is placed in a jar containing a measured amount of water and a thermometer (Fig. 113). The heat from the lamp warms the water.

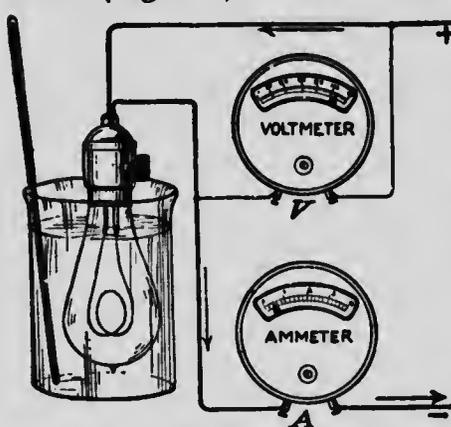


FIG. 113 1100 WATTS=1 B. T. U. PER SECOND

If the jar contains 2 pounds (1 quart) of water and if a Fahrenheit thermometer is used, the temperature of the water rises about $1\frac{1}{2}^{\circ}$ F. per minute—i. e., the water is heated at the rate of 3 B. T. U. a minute.

A voltmeter V and an ammeter A measure the electric power supplied to the lamp. If the voltmeter reads 110 volts, and the ammeter reads $\frac{1}{2}$ ampere, the power supplied is (Art. 205) 110 (volts) \times $\frac{1}{2}$ (ampere) = 55 watts. Hence, roughly, 55 watts = 3 B. T. U. per minute; or 1100 watts = 1 B. T. U. per second.

The first determination of this relation was made more accurately by the same Joule who made the first determination of the relation between the B. T. U. and the foot-pound. The apparatus (Fig. 114) does not differ in principle from that used by Joule. A coil of platinum wire is placed in a jar

containing a measured quantity of water and a thermometer. A voltmeter V , and an ammeter A , arranged as shown in Fig. 113, measure the number of watts of electric power used in heating the coil. The number of B. T. U. given up by the coil to the water in a certain time is obtained by multiplying the number of pounds of water in the jar by the number of degrees F. rise in temperature.

Joule's experiments have been repeated many times by many other scientists, using different current strengths and different kinds of coil. The results of all of these experiments show that there is a constant ratio between the heat unit and the unit of electric power; and they give the accurate value of this ratio as

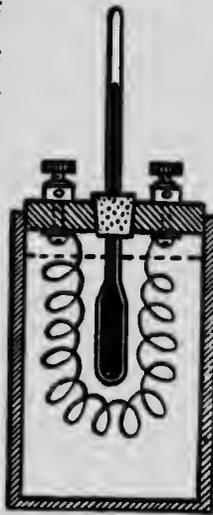


FIG. 114 JOULE'S CALORIMETER

$$1055 \text{ watts} = 1 \text{ B. T. U. per second.}$$

$$4.2 \text{ watts} = 1 \text{ gram-calorie per second.}$$

208. Number of Watts in a Horsepower. Since 1 B. T. U. = 778 foot-pounds, we have 1055 watts = 1 B. T. U. per second = 778 foot-pounds per second. Hence, 1 foot-pound per second = $\frac{1055}{778} = 1.356$ watts. But (Art. 96) 1 horsepower = 550 foot-pounds per second. Therefore 550 foot-pounds per second = $550 \times 1.356 = 746$ watts, i. e.,

$$1 \text{ horsepower} = 746 \text{ watts.}$$

The brake horsepower of the motor is 1.8 (Art. 206). Therefore the power out for this motor is $1.8 \times 746 = 1342.8$ watts. The power in is 1760 watts. Hence (Art. 97)

$$\text{the efficiency} = \frac{1342.8}{1760} = 76\%. \text{ The best electric motors}$$

have efficiencies of from 90 to 95 %.

The watt is a rather small unit to use in calculations where

large amounts of electrical power are used. So a larger unit, called the *kilowatt* is generally used.

$$1 \text{ kilowatt} = 1000 \text{ watts.}$$

In practical work it is often necessary to make rough calculations quickly. For such calculations it is convenient to remember that roughly

$$1 \text{ kilowatt} = 1 \text{ B. T. U. per second} = 1\frac{1}{3} \text{ horsepower.}$$

209. Electrical Energy. The Kilowatt-Hour. It is important to note that the watt and the kilowatt are units of power, not units of energy. They measure the rate at which electrical work is done. The unit of energy is obtained as in Art. 142, where we found that the unit of work used in calculation for large steam engines was the work done in one hour at the rate of one horsepower. In like manner, the unit of electrical work is the *kilowatt-hour*.

The kilowatt-hour is the electrical work done in 1 hour at the rate of 1 kilowatt.

Smaller units are sometimes needed, and then the *watt-hour* or the *watt-second* are used. In terms of these units, the approximate relations between work, heat, and electrical energy (Art. 208) (1 hour = 3600 seconds) are:

$$1 \text{ kilowatt-hour} = 3400 \text{ B. T. U.} = 1\frac{1}{3} \text{ horsepower - hours.}$$

When electrical energy is converted into heat, as in Joule's experiment (Art. 144), in such a way that we can measure all the electrical work done in watt-hours, and all the heat obtained in B. T. U., we always find that the number of B. T. U. is 3.4 times as great as the number of watt-hours. Hence, as in Art. 147, we conclude that we are measuring the same thing—energy—in terms of different units. Hence the conclusion:

Electrical work is a form of energy.

210. Cost of Different Forms of Energy. Most transactions in the industrial world are carried on in terms of energy. The cost of energy is thus a matter of great importance, and a study of the relative prices of the different forms leads to

many interesting problems. So the following table is added, giving roughly the present valuation of raw energy.

Coal at \$4.00 a ton furnishes 30 horsepower-hours for 1 cent.

Gas at 85 cents per 1000 cubic feet furnishes 3 horsepower-hours for 1 cent.

Electricity at 4 cents per kilowatt-hour furnishes $\frac{1}{3}$ horsepower-hours for 1 cent.

Human labor at 25 cents an hour furnishes $\frac{1}{25}$ horsepower-hour for 1 cent.

In the cases of the first three, it is not possible to convert all the energy into useful work. If we take into account the efficiencies of steam and gas engines and electric motors (Arts. 146 and 208), and the cost of building and maintaining them, we get the following figures:

Large steam engine.....	$\frac{1}{2}$ cent per horsepower-hour.		
Large gas engine.....	2 cents "	"	"
Electric motor.....	2 cents "	"	"
Horse and wagon	15 cents "	"	"
Laborer with pulley.....	\$2	"	"
Laborer with hands.....	\$3	"	"

Since the energy required to do a given piece of mechanical work—measured in foot-pounds—costs about 500 times as much when derived from men as it does when derived from coal, the great economic importance of coal becomes apparent.

211. Conservation of Energy. In Art. 145 we learned that when work is transformed into heat, the number of foot-pounds of work done is always 778 times as great as the number of P. T. U. of heat secured. We therefore concluded that we must be measuring the same thing in terms of different units; and called this same thing energy.

We have now learned (Art. 207) that there is a similar constant ratio between units of heat and of electricity, showing again the presence of this constant something called energy. These facts lead to the following general conclusion, which is called the *Principle of the Conservation of Energy*.

In every physical process in which energy is transformed from one form into another, the amount of energy remains constant.

DEFINITIONS AND PRINCIPLES

1. A current has a strength of 1 ampere when it deposits from a solution of a silver salt 0.001118 grams of silver per second.

2. The ohm is the resistance at 0° C. of a column of pure mercury 106.3 centimeters long and one square millimeter in cross-section.

$$3. \text{ Amperes} = \frac{\text{Volts}}{\text{Ohms}} \quad (\text{Ohm's Law.})$$

4. At a given instant the number of amperes of current flowing is the same through every complete cross section of a given circuit.

5. The potential difference (P. D.) between two points on a circuit is proportional to the resistance between those points.

6. The volt is the electrical pressure required to drive a current of 1 ampere through a resistance of 1 ohm.

7. When lamps are arranged in series their resistances are added together.

8. When several equal resistances are placed in parallel, their total or joint resistance is equal to the resistance of one of them, divided by their number.

9. The watt is the unit of electrical power.

$$10. \text{ Watts} = \text{Volts} \times \text{Amperes.}$$

$$11. 1 \text{ horsepower} = 746 \text{ watts.}$$

12. The units of electrical energy are the watt-hour and the kilowatt-hour.

$$13. 1 \text{ kilowatt-hour} = 3400 \text{ B. T. U.} = 1\frac{1}{3} \text{ horsepower-hours.}$$

14. Electrical work, like heat and mechanical work, is a form of energy.

15. In every physical process in which energy is transformed from one form into another the amount of energy remains constant (Conservation of Energy).

QUESTIONS

1. If you wished to silver plate a spoon, what materials would you have to procure?
2. What would happen in an electroplating cell if the current were reversed?
3. One of two spoons is kept in a plating solution for 4 hours with a current at a certain strength, and the other for 8 hours with the current at half that strength. What are the relative amounts of metal deposited on the two spoons?
4. Three cells *A*, *B*, and *C*, are connected in series with a motor *M*. If an ammeter placed in the circuit between *A* and *M* reads 2 amperes, what would it read between *A* and *B*? Between *B* and *C*? Between *C* and *M*?
5. If you have a galvanometer for testing the strength of the current flowing through an electroplating bath, how could you make a scale that would indicate the number of amperes of the current?
6. In an electric light circuit, when the lamps are in parallel, why does the current strength increase as more lamps are lighted?
7. Are electric light bills made out in terms of kilowatts or of kilowatt-hours? Why?
8. The P. D. on a trolley line is 500 volts. Are more amperes of current required to drive the car up hill than to run it along a level track? Why?
9. Is it better in your town to drive dynamos with water motors or with steam engines? Why?
10. Are electric motors ever used to propel ocean liners? Why?
11. Is there any relation between electric work and the various forms of energy? Prove the correctness of your answer.
12. Which has the greater power, a current of 100 amperes at 110 volts or a current of 10 amperes at 1100 volts? Why?
13. Which of the currents in question 12 can do the more work in an hour? Why?

PROBLEMS

1. If you wish to deposit 1 gram of silver on a spoon, with a current of 1 ampere, how long must the current flow?
2. What is the strength of the current furnished by a dynamo having an E.M.F. of 110 volts and an internal resistance of 1 ohm if it flows through an external resistance of 10 ohms?
3. How many dry cells in series will be needed to light 5 toy glow lamps in series if the P. D. between the terminals of each lamp must be 3 volts?
4. What is the resistance of a toy lamp that takes a current of 0.2 amperes at a pressure of 3 volts?

5. A dry cell tested with a voltmeter is found to have an E. M. F. of 1.5 volts. When its terminals are joined directly with those of an ammeter, which has practically no resistance, the ammeter reads 7.5 amperes. What is the internal resistance of the cell?

6. What current strength is maintained through a small motor having a resistance of 13 ohms by a series of 10 cells, each having an E. M. F. of 1.5 volts and an internal resistance of 0.2 ohm?

7. If 20 16-candle-power electric lamps, each having a resistance of 220 ohms, are joined in series, what is the resistance between the terminals of the series?

8. If the 20 lamps in problem 7 are placed in parallel between the two mains from a dynamo, what is their joint resistance?

9. If the P. D. between the mains in problem 8 is 110 volts, how many amperes of current flow through the circuit?

10. How many watts of electrical power are required for a common 16-candle-power carbon glow lamp taking a 0.5 ampere current at a pressure of 110 volts?

11. When electric energy costs 10 cents a kilowatt-hour, how much does the lamp of problem 10 cost per hour?

12. An electric arc lamp takes 10 amperes of current at a P. D. of 110 volts. How many B. T. U. of energy are radiated from it per second?

13. An electric heater supplies heat at the rate of 680 B. T. U. an hour. How many watts of power does it require?

14. What must be the brake horsepower of a steam engine that is required to run a 6714 watt dynamo, if the efficiency of the dynamo is 90%?

15. What is the efficiency of a motor that is found to take 7460 watts of electrical power and to develop 9 horsepower in a brake test?

16. How many B. T. U. are liberated in an electric baking oven taking 0.1 kilowatt for an hour?

17. How many kilowatts of available energy are there in a waterfall 20 feet high over which water flows at the rate of 600 cubic feet a second?

18. If all the water of problem 17 flowed through a turbine having efficiency of 60%, what would be the power of the turbine in kilowatts?

19. If a dynamo driven by the turbine of problem 18 has an efficiency of 90%, what would be its power?

20. Find the number of watts consumed by a series of 15 arc lamps each requiring 45 volts pressure and a current strength of 9 amperes.

21. What horsepower must be supplied to a dynamo having an efficiency of 90% if it is to light a series of 20 arc lamps each requiring 10 amperes current at 50 volts P. D.?

22. How many watts of power are required to operate 128 glow lamps in parallel, each taking $\frac{1}{2}$ ampere current at 110 volts P. D.?

23. Allowing an efficiency of 75% for the dynamo and belt, what is the horsepower of the engine that lighted the lamps in problem 22?

24. What current will be supplied to a lamp circuit by a dynamo having an output of 18,800 watts and an E. M. F. of 125 volts?

25. How many lamps may be operated in parallel with a current from a dynamo of 150.5 amperes if each lamp requires $\frac{1}{2}$ ampere?

26. What is the resistance of a line on which there is a "drop" or P. D. of $12\frac{1}{2}$ volts when it carries a current of 150.5 amperes?

27. How many watts are lost in the line mentioned in the preceding question? How much heat is produced per second?

CHAPTER XI

SOUND AND WAVE MOTION

212. Origin of Sound. If you place your hand on your chest when you are talking or singing, you feel a vibration. If you touch a piano string or a bell or a drum when it is sounding, its vibrations may be felt. If the string is vibrating violently, its vibrations may even be seen. When the vibrations cease, the sound ceases also.

When you hear a sound,—a spoken word, a whistle, a shout,—you are perfectly certain that something has vibrated near by to produce the sound. Although the fact that *sound originates at a vibrating body* is familiar, few have a definite idea as to just what the sound vibrations are like, or as to how sound travels from one place to another.

213. Natural Periods of Vibration. In Arts. 4 and 32, attention was directed to the vibrations of bodies that swing back and forth after they have been pulled from their positions of equilibrium and let go. The rope swing and hammock are familiar cases of bodies that vibrate in this way. Because of his experiences with swings and hammocks, every child has felt this rhythmic motion called *vibration*, and knows that it consists in the continued repetition of the same motion in the same interval of time. Because the motion is thus repeated in a definite time interval, it is called *periodic motion*. The time required for a single swing is the *period*.

A swing with long ropes vibrates more slowly than one with short ropes, i. e., its period is longer. Yet any swing always has a particular period which is characteristic of it. If we change the length of the swing, we also change its period. Similarly, an empty rocking chair, when tipped and let go, vibrates in a particular period which is always the

same. If some one sits in the chair, the mass of the vibrating body is greater and the period of vibration is longer. A particular tuning fork always has the same period of vibration; the shorter and stiffer the fork, the more rapidly it vibrates. A meter stick, when clamped at one end and set into vibration, always vibrates in the same period; when clamped in the middle, it vibrates in a faster period. In fact, everything that can vibrate has a particular period in which it vibrates most easily. The particular period in which a body vibrates most easily is called its *natural period*.

214. Vibrations That Produce Sound. The vibrations of swings and pendulums do not ordinarily produce sound. A sudden blow of a hammer produces one click, but no sustained tone. If the corner of a card is held so as to strike the spokes of a wheel when it is rotating slowly, we hear a separate click when each spoke hits the card. As the wheel is rotated more rapidly, the clicks become more rapid, until at length they blend into a low tone.

If we mount a disk pierced with circular rows of equidistant holes (Fig. 115) on the axle of a hand rotator or a small motor, and blow a stream of air against the disk as it rotates, a puff of air passes through each hole as it passes the end of the air pipe. When there are but few puffs per second, no sound is heard; but as the disk rotates more and more rapidly, the puffs come faster and faster, until we hear a low note. The faster the disk turns, the higher the pitch of the note. This apparatus for producing tones is called a *siren*.

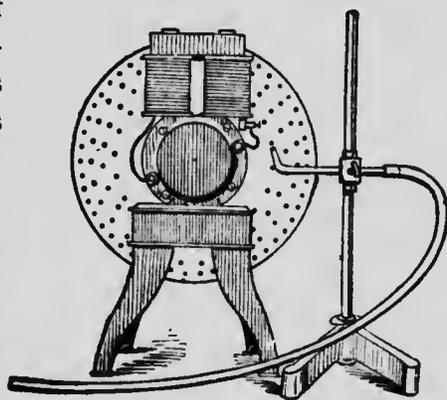


FIG. 115 THE SIREN

If we multiply the number of holes in a row by the number of revolutions that it makes in a second when a cer-

tain tone is being produced, the result is the number of puffs per second which produce that tone. By this instrument, it has been shown that the puffs do not produce a continuous tone until they come at the rate of at least 30 per second. They then combine to form the lowest audible tone. More rapid puffs give tones of higher pitch; and we can hear shrill tones that result from vibrations as fast as 35,000 a second.

Thus a single sudden impulse, or a series of irregular impulses may make a *noise* that can be heard; but a *sustained tone* is produced by a series of periodic impulses which proceed from a body that makes at least 30 vibrations per second. The number of vibrations per second is called the *frequency*. *The pitch of a tone is determined by the frequency.*

The greater the frequency, the higher the pitch.

215. Period and Frequency. When the puffs from the siren have a certain frequency, say 50 (vibrations) per second, the time between puffs—i. e., the period of the vibration—is $\frac{1}{50}$ second. If the frequency is 100, the period is $\frac{1}{100}$ second; and so on. Hence

The period is the reciprocal of the frequency.

216. Sound Spreads in Every Direction. When a band is playing everybody in its neighborhood can hear it. A good speaker is heard by every one in his audience, even by those behind him. The whistle of a locomotive may be heard for a long distance round about the engine in every direction. *Sound spreads out in every direction from the vibrating source.*

217. Sound Travels in Air. If a small bell is suspended by means of soft elastic yarn inside a sealed jar connected with a good air pump, and the air is pumped out of the jar, no sound can be heard when the bell is shaken. When a little air is admitted to the jar, the sound may be heard faintly; as more air is admitted, the sound becomes louder. This experiment shows that

Air transmits sound; and it is ordinarily the medium that conveys it to our ears.

218. Speed of Sound. In a thunderstorm, the lightning is always seen before the thunder is heard. The farther away the lightning is, the longer the interval between seeing the flash and hearing the rumble. When you watch a carpenter driving a nail at a distance, you hear the blow of his hammer an instant after you have seen the hammer strike. When shouting to get an echo from a distant hill, a few seconds intervene between giving the shout and hearing the echo. From many such experiences as these we know that *sound takes time to travel from one place to another.*

The speed of sound may be measured roughly by striking a hammer against a board at a distance from a large surface—like the flat wall of a large building—which gives an echo, and noting the time that elapses between striking the board and hearing the echo. In that time the sound has traveled to the wall and back; therefore, twice the distance to the wall, divided by the time, gives the speed of sound.

Many measurements of the speed of sound have been made under different weather conditions, and these show that

The speed of sound in air at 0°C. is 1088 feet per second (33,170 centimeters per second).

The speed of sound increases 2 feet per second (60 centimeters per second) for every degree centigrade that the temperature rises.

219. Sound Makes Bodies Vibrate. When a piano is being played, it often happens that a picture frame, or some small ornament on or near the piano, buzzes or vibrates when some one particular note is struck. A church window often responds in the same way to some particular note of low pitch from a powerful organ. If you sing close to the mouth of a wide-mouthed quart bottle, you may find by trial a particular note which will set the air in the bottle into vibration, thereby greatly increasing the intensity of the sound. The particular note which does this has the same pitch as

that which the bottle itself gives out when sounded by blowing gently across its mouth.

The same phenomenon may be observed by holding down a key of the piano, so as to lift the muffler from the corresponding string, and then singing a loud, sustained tone of the same pitch as that which the string gives out when struck. The string may be distinctly heard giving out this tone after the singer has ceased to do so.

A still more remarkable case of the same sort may be shown with a pair of large tuning forks that are adjusted so as to have the same period of vibration. Mount these forks on hollow boxes, which re-enforce the sound after the manner of the bottle in the experiment just described. Place these boxes from 15 to 30 feet apart with their open ends facing each other, and sound either one of the forks. The other fork then begins to vibrate, and gives out the same tone. The vibrations may be made visible by hanging a glass bead on a fine thread so that it just touches a prong of the responding fork. When the fork vibrates, the bead shows it by bouncing away. If a piece of beeswax be stuck on the end of one of the forks, so as to make it vibrate more slowly, the other fork no longer responds.

Thus sound that starts from one body may do the work of setting another body into vibration, even though it be some distance away. In other words,

Sound transmits energy from one body to another.

220. How One Fork Makes the Other Vibrate. We can get an idea of how the sound from one fork sets the other into vibration in the experiment just described (Art. 219), from the following simple experiment. *A* and *B* (Fig. 116), are two meter sticks exactly alike, each clamped in a vise at the same points on the sticks, so that their vibration periods are equal. They are connected by a cotton cord by which any motion of one stick may be transmitted to the other. If one of these sticks is set into vibration, it gives a series of periodic jerks to its end of the cord. If we take hold of the string

we can feel these periodic impulses traveling along it to the other stick. If, however, the period of one stick be length-

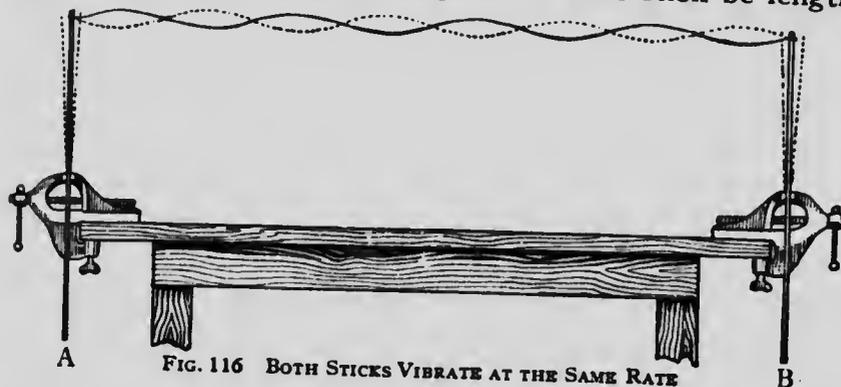


FIG. 116 BOTH STICKS VIBRATE AT THE SAME RATE

ened or shortened by clamping it higher or lower in its vise, neither stick will respond to the periodic impulses from the other. In this case the natural period of the second stick does not agree with the period of the impulses that it receives from the string. These impulses do not come at the right instants, and so fail to set the second stick into vibration.

The action of the periodic impulses of the thread on the second stick is like that of a boy when he pushes another boy in a swing. The swing makes one vibration back and forth in a certain period. If the boy times his pushes so that they have the same period as the swing,—giving it a little push in the right direction every time it passes him,—he soon has it swinging high. But if his pushes are so timed that some of them push backward when the swing is moving forward, very little motion results.

So the second stick is set into vibration when it is given a series of properly timed impulses, which are carried from one stick to the other along a string. This process by which one body is set into vibration by impressing on it a series of periodic impulses, is called *resonance*. *In order that a body be set into vibration by resonance, the period of the impulses given it must be the same as its natural period.*

Since (Art. 219), a tuning fork may be set into vibration by vibrations from another fork of the same period, when

there is no string between them, the periodic impulses must be carried from one fork to the other through the air. Hence the conclusion:

Sound is transmitted in a series of periodic impulses in air.

The way in which periodic impulses carry energy from one place to another may be understood most easily from a study of waves on the surface of water.

221. Water Waves. When a pebble is thrown into a pond, a disturbance is produced which spreads out over the surface of the water in circles about the place where the pebble struck. Its first effect is to push aside the water,



FIG. 117 WAVES CARRY ENERGY

heaping it up into a circular ridge about the place where the pebble fell. This circular ridge of water at once begins to expand into a larger circle. It is followed by a second circular ridge of water, which expands in the same way. This action is repeated a number of times; and the water surface is soon covered with a series of equidistant circular swells, separated by circular troughs (Fig. 117), all constantly expanding away from the center of disturbance.

These swells travel over the surface of the water at the same speed, and keep the same distance between them. Such swells and troughs are called *waves*. The motion on the surface of the water as the waves pass over it is called a *wave motion*.

222. What Waves Do. If we dip the end of a long pole into the water, and then move it rhythmically up and down, we start a series of circular waves like those started by the pebble. When a fish nibbles at the bait, the float on the surface of the water bobs up and down, and becomes the

center of a similar series of waves. A wind blowing over a lake soon ruffles the water into waves. A steamer plowing its way through the water is another familiar source of waves. Unless work is done on the water in giving it a vibratory motion, no waves appear.

Energy is expended when waves are started.

If the shore is near by, the waves soon reach it and break. Any one who has bathed in the surf, or watched the waves pounding on a rock bound coast, knows that waves give up energy when they break. If the shore is far away, the waves started by the pebble or the stick simply die out, having used their energy in overcoming the friction of the water. In every case, waves travel on until the energy used in starting them is spent.

Waves carry energy from one place to another.

223. Characteristics of Waves. Suppose an instantaneous photograph were taken of a train of waves while it is traveling along the surface of a pond; or suppose that it were suddenly frozen. We should then find that the surface of the water was curved so that a slice or section of it would look like Fig. 118. Such a curve is called the *shape* of the wave. Some parts of the wave are above the level of the water when at rest, while other parts are equal distances below it. The parts above this level are called *crests* and those below it *troughs*. The vertical distance between the top of a crest and the level of the water when at rest, or between the bottom of a trough and that level, is called the *amplitude* of the wave. The distance from crest to crest or from trough to trough is called the *wave length*.



FIG. 118 SHAPE OF A SIMPLE WAVE

224. Mechanism of Wave Motion. If we throw a chip on the surface of the water, well out from the shore, and observe its motion while a wave is passing, we find that the chip is not carried along in the direction in which the wave is

moving, but that it merely rises and falls as each wave passes beneath it. Since the chip indicates the motion of the water on which it rests, we see that the water does not move forward horizontally with the wave. Its particles merely vibrate up and down as the waves pass them. Since at one instant a given particle is at the crest of the wave, and at the next it is at the bottom of the trough, each particle moves through a vertical distance equal to twice the amplitude of the wave (Art. 223).

The way in which a wave of this sort travels may be illustrated as follows. Let us consider a row of particles which are held together by some elastic force.

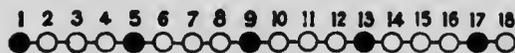


FIG. 119 THE PARTICLES AT REST

These particles may be represented by large buttons strung on a rubber cord, so they may be moved to various positions as in Fig. 119. For convenience let us suppose that the particles are numbered from left to right, beginning with 1 and ending with 18. If the particle 1 is given a vibratory motion in a direction perpendicular to the row, the elastic force that is supposed to hold 1 and 2 together will compel 2 to follow 1; but since the connection is elastic, not rigid, 2 will lag a little behind 1. Hence when 1 has reached the end of its trip, 2 will not have traveled quite so far; 3 will lag a little behind 2; and so on. Therefore, the condition of

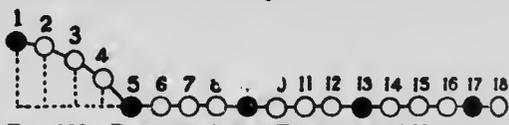
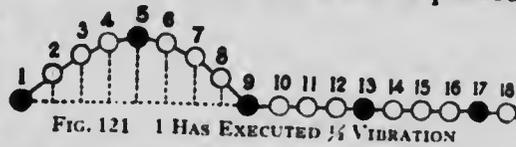


FIG. 120 PARTICLE 1 HAS EXECUTED $\frac{1}{4}$ VIBRATION

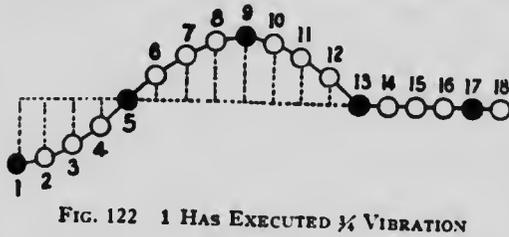
the row of particles when 1 has reached its position of greatest displacement will be that shown in Fig. 120.

When particle 1 has reached its position of greatest displacement, it pauses there for an instant, then begins to retrace its path. While 1 is stationary, 2 catches up and reaches its position of greatest displacement as 1 starts back. Particle 3 follows 2 in the same way, and so on. The successive particles reach their positions of greatest displacement one after another. We may say that this position of greatest displacement is passed along from one particle to the next.

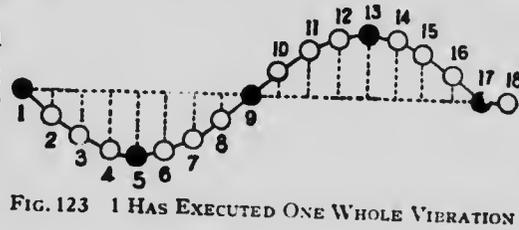
But the position of greatest upward displacement constitutes the crest of the wave; and so the crest of the wave is passed along a row of particles that are held together by cohesion, or any other elastic force. The positions of the particles when number 1 has returned to the starting point are shown in Fig. 121.



When particle 1 reaches the position from which it started, i. e., when it has completed half a vibration, it is moving with considerable velocity. Therefore, because of its inertia, it will move past its original position and make an excursion on the opposite side. It will now move downward, dragging the adjacent particle after it, will reach a position of greatest downward displacement (Fig. 122),



and return again to the starting point. The positions of the particles, when this has been done, are shown in Fig. 123. Particle 1 is now in the same condition in which it was when it began to move. If nothing interferes with it, it will repeat the operation just described and continue to do so until its energy is expended.



Since in this case the particles move in directions at right angles to that in which the wave travels, a wave of this kind is called a *transverse wave*.

Waves are formed when a periodic motion is passed along from particle to particle in an elastic medium.

The particles of the elastic medium do not travel with the wave, but each one merely vibrates over a small space on either side of its position of rest.

225. Speed of Propagation. From the discussion in Art. 224 we may learn how the speed with which the wave travels is related to the wave length and vibration frequency. Referring to Fig. 123, we note that while particle 1 has been executing one complete vibration, the disturbance has traveled from 1 to 17. But this distance is exactly the length of a wave. In other words *the disturbance travels just one wave length while a particle at the source makes one complete vibration.*

If particle 1 makes 100 vibrations in 1 second, the disturbance will travel 100 wave lengths in that second. If the wave length is 10 feet, the length of 100 waves is $10 \times 100 = 1000$ feet. This is the distance traversed by the disturbance in one second. But since the distance traversed in one second measures the speed,

The speed of a wave motion may be found by multiplying the wave length by the frequency.

226. Relation of Speed to the Properties of the Medium. If a medium is not elastic, there will be no force tending to restore the displaced particles to their normal positions; and the motion of one particle will not be passed along to the next. Also, if the particles of the medium have no inertia, they will not fly beyond their normal positions and continue to vibrate. *Waves will not travel in a medium unless the medium has both elasticity and inertia.*

Referring to Fig. 120, we can see that if the elastic force with which particle 2 is pulled by particle 1 is increased, particle 2 will follow 1 more quickly in its vibrations; and the wave will travel faster along the row of particles.

On the other hand, if the inertia of each particle is increased, it will be slower than before in taking up the vibratory motion. Consequently, the disturbance will travel more slowly along the row of particles. But greater inertia means greater mass (Art. 10) for each particle; and greater mass per particle means greater density for the medium. Hence the conclusion:

The greater the elasticity, the faster the speed; and the greater the density, the slower the speed.

227. How Sound Travels in Air. In Arts. 226 and 217 we learned that a medium must have elasticity in order to transmit waves, and also that sound travels in air. If the particles in Fig. 119 are particles of air, a motion of 1 at right angles to the row has no effect on 2. The particles of air do not cling together with sufficient force to drag one another along so as to propagate a transverse wave. So sound cannot travel in air in transverse waves like those on the surface of water.

Air does, however, resist compression. As Boyle showed (Art. 77), it has considerable "spring" in it. So when a small volume of air is suddenly compressed, as is the air between your hands when you clap them together, the compressed air at once springs back to its original volume. This expansion of the compressed volume of air sets the air particles into motion; and so, because of their inertia, they are carried a little way beyond their original positions, and produce a rarefaction in the air behind them and a condensation in the layer of air in front of them. The original volume of air is thus slightly rarefied, and is surrounded with a layer of slightly condensed air.

This layer of condensed air then expands, becomes itself rarefied, and produces a condensation in the next surrounding layer of air. So each condensation is passed along, from one layer of air to the next; while the air particles merely vibrate back and forth in the direction in which the condensation (the wave) travels.

We may now see why a sudden motion is necessary for the production of sound. Air is so mobile that when a body moves slowly through it, it slips around the moving body and is not condensed appreciably. When it is struck suddenly, as by the prong of a vibrating tuning fork, or by a board when struck with a hammer, it does not move quickly enough to get out of the way before it is condensed, and a sound wave is started.

228. How to Convert Sound Into Visible Vibrations.

If sound waves consist of a series of compressions and rarefactions in air, their presence might be shown if we could catch them in a sufficiently delicate pressure gauge and observe the changes in pressure which they produce. This can be done in the following way.

A thin rubber membrane AB (Fig. 124) is stretched between two rings of wood or metal. A flexible tube C leads the sound waves up so that they can act on one side of this membrane.

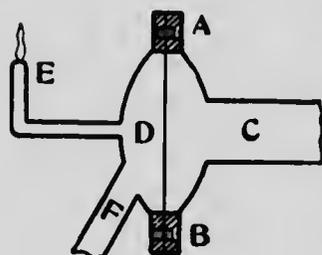


FIG. 124

When the air in C is slightly compressed, the membrane will bulge out toward D ; and when the air in C is rarefied, the membrane will bulge the other way. On the other side of the membrane is a small gas chamber D . Illuminating gas flows into this chamber at F and burns at the jet E .

Whenever the membrane AB vibrates, the gas in D will vibrate also; and this will cause the flame to vibrate, the tip of the

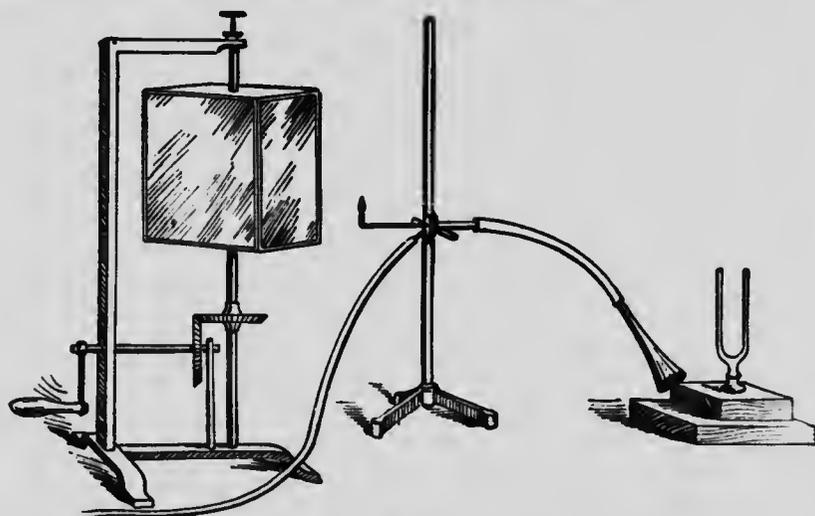


FIG. 125 WHEN THE TUNING FORK SOUNDS THE FLAME VIBRATES

flame following roughly the vibrations of the membrane. Since the vibrations of sound are too rapid to be observed by

the unaided eye, we have to observe the flame in a mirror which is kept in rotation. The apparatus ready for use is shown in Fig. 125.

When it is thus observed in the rotating mirror and no sound is acting, the image of the small flame appears to be drawn out into a straight band of light; but when sound waves are sent into the tube *C*, the band is no longer straight. Its upper edge has a wave-like form as shown in Fig. 126. The upper band in the figure shows the appearance of the flame in the rotating mirror when the sound from a rather high-pitched tuning fork is sent into the tube *C*. When a tuning fork with a frequency half as great as that of the first is used, the appearance of the flame is that shown in the second

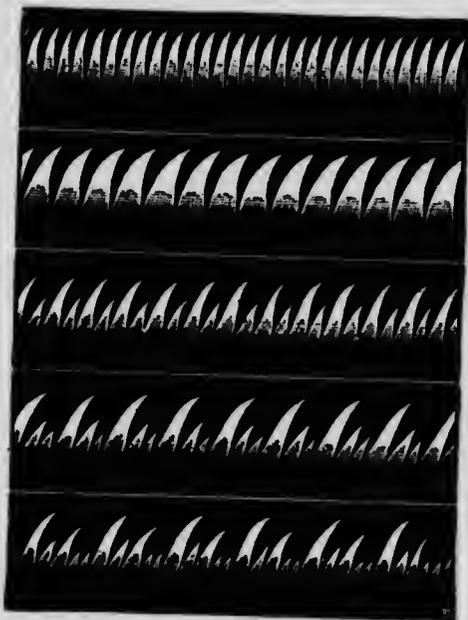


FIG. 126

band in the figure. If we send in the sound from both these forks at the same time, we get the result shown in the third band in the figure. Singing the vowels *a* and *o* into the tube gives effects similar to those shown in the last two bands in the figure.

Since the vibrations of the flame indicate changes in the pressure of the air in the tube *C*, this experiment proves that sound waves in air consist of a series of periodic compressions and rarefactions. Waves of this type are called *longitudinal waves*, because the changes in the air pressure cause the air particles to swing back and forth in the direction in which the wave is traveling. These longitudinal waves are different from the transverse waves, in which the motion of the par-

ticles and the motion of the wave are at right angles to each other (Art. 224).

Sound is transmitted by longitudinal waves in air.

229. How We Hear. When sound passes into the opening of the ear, it produces periodic changes in the pressure of the air in front of the ear drum. The drum is thus set into vibration, and its vibrations are passed along by a very delicate mechanism, till they excite the extremities of the auditory nerve, producing the sensation of hearing.

The ear is extraordinarily sensitive. The "ear power," i. e., the rate at which energy is supplied to the ear when a faint sound is just audible, has been measured completely, and it is found to be something like $\frac{1}{100,000,000}$ gram-centimeter a second. If energy flowed continuously at this rate into a cubic centimeter of water, and if all of it were converted into heat, and retained in the water, it would take roughly 100,000 years to heat the water 1°C.

DEFINITIONS AND PRINCIPLES

1. When vibrating freely, every body vibrates in its natural period.
2. The greater the frequency of a tone, the higher its pitch.
3. The speed of sound in air at 0°C. is 1088 feet per second.
4. The speed of sound in air increases 2 feet per second for every degree C. rise in temperature.
5. In order that a body be set into vibration by resonance, the period of the impulses given it must be the same as its own natural period of vibration.
6. Waves transmit energy from one place to another.
7. The particles of the elastic medium in which waves travel do not move forward with the waves; but each one merely vibrates over a small space on either side of its position of rest.

8. The speed with which a wave travels is found by multiplying the wave length by the frequency.

9. Waves will not travel in a medium unless it has both elasticity and inertia.

10. Waves are transverse when the particles of the medium vibrate at right angles to the direction in which the wave travels, and longitudinal when the particles vibrate in the same direction in which the wave travels.

11. Sound is transmitted by longitudinal waves in air.

QUESTIONS AND PROBLEMS

1. Why must the impulses be given to a swing at regular intervals in order to make it swing?
2. Does a rocking chair rock more slowly when some one is sitting in it than it does when empty? Why?
3. Why is it difficult for a tall person to walk comfortably with a short person?
4. When a circular saw starts through a board the pitch of the buzzing tone is high. Why does the pitch fall soon after the saw enters the board?
5. If you know the number of teeth on the saw in question 4, can you determine how many revolutions per second it is making from the tone that you hear? How?
6. Can a fog-horn on a steamer be heard astern? Why?
7. If the moon were inhabited, could we ever make enough noise to be heard by the inhabitants? Why?
8. When a tree falls in a lonely forest, and no animal is near by to hear it, does it make a sound? Why?
9. If someone scratches one end of a table with a pin, can you hear it when your ear is close to the other end? Why?
10. When you tap with a key on a steam-pipe in the basement, can the sound be heard upstairs? Why?
11. Why do processions always "break step" while marching across a bridge?
12. Do you get a higher note when you blow across the mouth of a large bottle than when you blow across the mouth of a small one? Why?

13. How does the energy from a passing steamer do the work of rocking a small boat a considerable distance away?
14. A toy boat is adrift 20 feet from the shore. Can its owner get it back by throwing stones into the water on the far side of it so as to make waves that travel toward the shore? Why?
15. Why does clapping your hands make a noise, while waving them does not?
16. Why does burning loose gunpowder make practically no noise, while shooting it in a cannon makes a loud noise?
17. If you fill a paper bag with air, hold the mouth shut, and strike it, it explodes with a bang. What happens if you strike it without holding the mouth shut? Explain.
18. Sound spreads in every direction from the source. Why does it become fainter as you get farther away from the source?
19. How does a megaphone or a speaking tube act so as to make sounds louder at a distance from the source?
20. Which travel faster, high or low notes? Why do you think so?
21. The speaking tone of the average man's voice has a frequency of about 160. How long are the waves that he emits at 16° C?
22. The average length of the waves that transmit the sound of a woman's voice is $3\frac{1}{2}$ feet at 16° C. What is the period of the corresponding tone?
23. Do women talk faster than men? Why?
24. A thunder clap is heard 7 seconds after the lightning flash is seen. How far off was the flash?
25. If a sunset gun was fired at exactly 6:30 P. M. at a fort, what time was it when the report was heard 20 miles away, the temperature of the air being 25° C?
26. If you remain still in a row boat, the waves come in and strike the boat at regular intervals. If you row out towards the approaching waves, do they strike the boat more frequently or less frequently?
27. If (question 26) you turn round and row in toward the shore how about the frequency with which the waves now strike the boat?
28. Can you explain why the pitch of a tone from a locomotive whistle rises as you rapidly approach it and falls as you recede from it?

CHAPTER XII

MUSIC

230. The Piano. The most familiar of all devices for the production of music is the piano. On its keyboard there are usually 88 keys. Each key, when struck, produces a note of definite pitch. When certain of these keys are struck successively, we hear a pleasing succession of tones called a melody; and when several keys are struck together, we hear chords which may be either pleasing and harmonious or discordant, depending on which particular keys are struck. The piano cannot give tones of all possible pitches, but only those tones to which its strings have been tuned.

When we open the piano case, we find a large number of wires of various lengths and thicknesses. We also find that each key is connected by a very ingenious system of levers with a little felt hammer, which, when the key is pressed, strikes a wire and sets it into vibration, thus producing the note that corresponds to that particular key. *The longer and thicker the wire, the lower the pitch of the tone it produces.*

One end of each wire is wound around and fastened to a pin, which can be turned with a wrench so as to loosen or tighten the wire. By this means the strings are tuned, since *tightening the string raises the pitch of its tone, while loosening the string lowers its pitch.*

231. Sounding Board. Directly beneath the strings, with its edges fastened to the frame over which the strings are stretched, is a large, thin board called a sounding board. The vibrations of a string are transmitted through the frame to the sounding board, forcing it to vibrate in the same period with the string. Since the sounding board has a much larger

area than the string, it is able to set into vibration a larger mass of air than the string alone can. Consequently, a much louder tone is produced with the aid of the sounding board than could be produced without it.

232. Other Stringed Instruments. Like the piano, the violin, the violoncello, the mandolin, and the guitar consist of sets of strings tuned to give certain notes, and wooden bodies which serve as sounding boards, to make the tones from the strings louder. These instruments differ from the piano in that they have but few strings, and that these are set into vibration by picking or by bowing them instead of by striking them with hammers.

In instruments of the violin type, each string is made to furnish a large variety of different notes, by pressing a finger on it at various places, thereby changing its length. Since the finger may be placed on a string at any point, an instrument of this kind can give not only all those tones given by piano strings whose pitches are higher than that of its lowest string, but also notes of any intermediate pitches. Yet the notes actually used in playing stringed instruments are practically the same as those given by the strings of a piano. Thus, although the piano is tuned to give notes of only 88 different pitches, while the instruments like the violin can easily be made to give a far greater number than this, yet practically all musical instruments use only those few notes found in the piano scale. There must be some peculiar charm about this particular series of notes,—else why should we use these and no others? To answer this question, we must find out how strings vibrate.

233. How Strings Vibrate. Stationary Waves. The jump-rope is a vibrating string familiar to all children. Most of us know that when the rope is turned at a moderate rate, it swings in a single loop as shown in Fig. 127. It is not necessary to have two to turn the rope; one end may be tied to a tree, and so remain fixed while the rest of the rope vibrates.

With practice it is possible to make the rope vibrate in two loops (Fig. 128). When it is vibrating in this way, not only is the end *T* at the tree fixed; but also the middle point *N* remains nearly stationary. When the rope is up, as at *A*, on one side of the stationary point in the middle, it is down, as at *B*, on the other side. When the rope starts down at *A*, it starts up at *B*. Both parts of the rope pass through the straight line *TH* at the same instant.

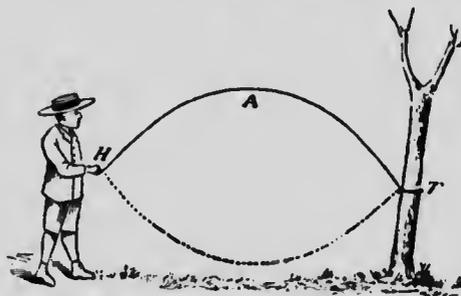


FIG. 127 IT SWINGS IN ONE LOOP

Waves of this kind may be seen when the vibrations from the electric vibrator of a door bell, or from one of the prongs of a tuning fork, are sent along a thin string (Fig. 129). In this case, because of the regularity of the vibration, the stationary points are much more clearly defined. When a string vibrates in this way it has the appearance of a wave; but the wave does not seem to move along the string in either direction. For this reason this kind of vibratory motion is called a *stationary wave*.

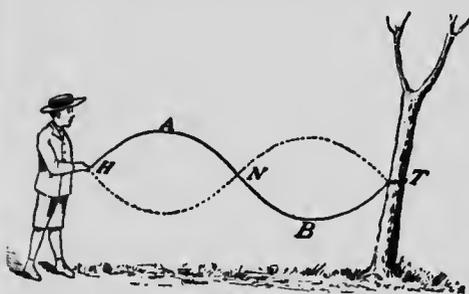


FIG. 128 THE MIDDLE POINT STAYS STILL

The points where the string remains still are called the *nodes*; and the parts of the wave between the nodes are called *loops*.

234. Loops on a Vibrating String. Because the strings of musical instruments are fastened at both ends, they vibrate in stationary waves. The points where a string is supported must be nodes in the stationary wave. Because the ends must be nodes, a string can vibrate in one whole loop (*a*, Fig. 130),

in two whole loops (*b*, Fig. 130), in three whole loops (*c*, Fig. 130); and so on; i. e.,

A string of a musical instrument vibrates only in some whole number of loops.

235. Relation Between Number of Loops and Frequency.

Violin players know that if they touch the tip of one finger

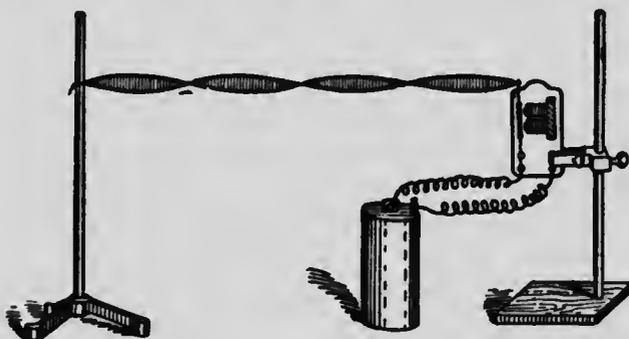


FIG. 129 STATIONARY WAVES ON A STRING

gently to the middle of a violin string when it is vibrating, the note that is produced is an *octave* higher than the note given by the whole string.

Touching the string in the middle forces a node on it at that place, and makes it vibrate in two loops instead of in one; i. e., the wave is half as long as before (Fig. 130, *b*).

The relative frequencies of these two notes an octave apart may be found with the siren (Art. 214). The siren is tuned first to one note and then to the other, and the frequencies of the two notes are determined as described in Art. 214. In this case we find that the octave vibrates twice as fast as the lower note—i. e.,

The frequencies of two notes an octave apart are related as 2 to 1.

When the finger is placed lightly on the string at a point $\frac{1}{3}$ of the length of the string from one end, a node is forced on it there and it then vibrates in 3 loops (Fig. 130, *c*). When the frequency of the corresponding tone is determined with the siren, we find it to be three times as great as that given by the string when vibrating as a whole. So the frequency of the vibration is twice as great when there are two loops as it is when there is one; three times as great when there

are three loops, as when there is one; and so on. But each of the two loops is half as long as the single loop (i. e., it is half of the length of the string); and each of the three loops is $\frac{1}{3}$ as long as the length of the string. Therefore, other things being equal,

The frequency of a note from a vibrating string is inversely proportional to the length of the string.

A note given when a string vibrates as a single loop is called the

fundamental. Those given when it vibrates in two or more loops are called *harmonics* or *overtones*. *The frequencies of the harmonics are related to the frequency of the fundamental by the ratios of the whole numbers 1: 2: 3: 4: 5: etc.*

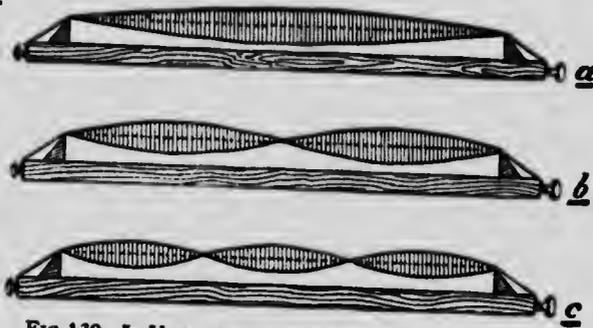


FIG 130 IT VIBRATES IN A WHOLE NUMBER OF LOOPS

236. Major Triad. When the three notes called *C, E, G* (do, mi, sol) are sounded at the same time on the piano, they give a chord that is pleasing. The combination of these three tones is called a *major triad*.

We can find the relative frequency of these three tones by playing them in succession on a violin or other stretched string, and measuring the length of string required for each note. The frequencies are inversely proportional to the corresponding lengths (Art. 235). When we do this we find that if the whole string gives the note *do*, $\frac{2}{3}$ of it gives the note *mi*, and $\frac{3}{4}$ of it gives the note *sol*. But $\frac{2}{3}$ of it has $\frac{3}{2}$ the frequency of the whole, and $\frac{3}{4}$ of it has $\frac{4}{3}$ the frequency of the whole. Therefore, the frequencies of the tones of the major chord, *do mi sol*, are related to one another as 1 to $\frac{3}{2}$ to $\frac{4}{3}$. These ratios are more simply expressed by the whole numbers 4 to 5 to 6. Hence,

The frequencies of the notes of a major triad are related by the ratios 4: 5: 6.

237. The Musical Scale. A major triad can be sounded on the piano with any desired note as *do*. In any one of these triads, the three tones have frequencies that are related to one another by the same simple ratios. Nevertheless, when we play several of these triads in succession, some successions are pleasing and others are not. If the three triads *C-E-G*, *G-B-D*, and *C-E-G* are played in succession, the result is pleasing and leaves the hearer with a sense of finality and repose. So these triads must be related to one another.

In like manner, the triads *C-E-G*, *F-A-C*, *C-E-G* produce a pleasing succession, and are therefore related in some way. Finally, the succession *C-E-G*, *F-A-C*, *G-B-D*, *C-E-G* produces a pleasing effect when played in this order. In playing this series of triads, all the white keys on the piano are used, and no additional keys are needed. When these same white keys are played in the order *C, D, E, F, G, A, B, C*, we hear the well-known musical scale *do, re, mi, fa, sol, la, si, do*; i. e., *the musical scale is made up of the particular notes that are needed to produce chords which sound well when played in succession.*

The scale composed of the notes *C, D, E, F, G, A, B, C*, is called the scale of *C*, because *C* is its lowest note (*do*). If we try to play a similar scale beginning on *D* as *do*, we find that it cannot be done if we use only the white keys that make up the scale of *C*. In order to render the musical scale, the notes must be those needed to form the three triads that sound well when played in succession; and the triad *D-F-A* does not have the same sort of harmonious sound as the triad *C-E-G*. The note *F* does not harmonize. So an extra key has been added to the piano—the black key between *F* and *G*. The note that is produced by this key is called *F sharp*, because its pitch is a half step higher than

that of Γ . The triad *D-Fsharp-A* has the same sort of harmonious sound as the triad *C-E-G*.

In like manner the second triad needed for the scale beginning on *D*, namely *A-C-E*, does not sound correct unless *C sharp* is played instead of *C*. Thus it is not possible to form a triad on every note of the piano if only the white keys are used. The black keys have been added so that a triad of tones whose frequencies are related by the ratios 4 to 5 to 6 may be formed on any one of the notes of the piano as its lowest tone. The addition of the black keys thus makes it possible to play the musical scale beginning with any of the notes of the piano as *do*.

238. Standard Pitch. In working out the relative frequencies of the tones of the triads in the major scales, nothing was said as to the actual frequencies of the tones. The frequencies of the notes of the triad beginning on any note have the same ratios to one another as do those of the triad beginning on *C*. In order to define the actual frequencies of the notes in the scale, we must select some particular number as the frequency for some one note. The frequencies of the other notes are then defined by the ratios. Musicians have agreed that middle *a* (the *a* of the violin) shall have a frequency of 435 vibrations per second. Instruments tuned so that the note *a* has this frequency are said to be tuned to the *International Standard Pitch*.

Since *A* is the middle note of the triad *F-A-C*, the actual number of vibrations of *F* is $\frac{2}{3} \times 435 = 348$; and that of *C* is $\frac{4}{3} \times 435 = 522$. Since middle *C* on the piano is the octave below this *C*, its number of vibrations is $\frac{1}{2} \times 522 = 261$. The frequencies of the other notes on the piano may be found in a similar manner.

239. Discord and Beats. In Art. 237 we learned that the notes of the musical scale have been selected because they may be played in chords and in successions of chords that are pleasing to us. When a piano is out of tune, its chords

are no longer pleasing; they are discords. The reasons why some combinations of tones are pleasing and others displeasing were first discovered by Hermann von Helmholtz, the great German physicist (1821-1894), in 1871.

If the notes given by any two sources of sound, two organ pipes for example, are accurately in tune, the tone given when both pipes are sounded together is a steady tone like that given by either pipe alone, only louder. But if the two pipes are not accurately in tune, the tone given when both are played together is not a steady tone; it is first loud, then soft, then loud again, and so on. In other words, it "throbs." These throbs of sound, produced when two tones of slightly different pitch are sounded together, are called *beats*.

240. How Beats Are Produced. Let the two upper curves of Fig. 131 represent two water waves that have slightly different wave lengths. They start at the left of the page with the crest of one under the trough of the other. At *a*, however, the two crests are in line; at *b* crest and trough are in line; at *c* the two crests are in line again; and so on. This must be so because one wave is shorter than the other. When a crest falls on a trough, each wave destroys the other's effects; no motion results. But when two crests fall together, the effects of the two waves are added together,

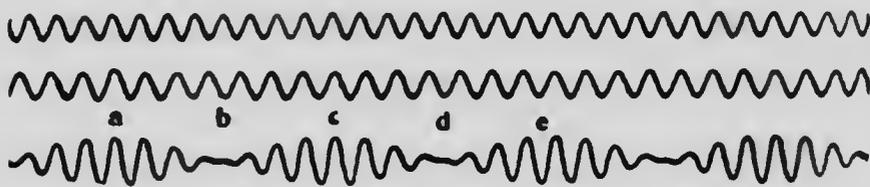


FIG. 131 WHEN CREST FALLS ON TROUGH NO MOTION RESULTS

producing a larger motion than is produced by either one alone. The result obtained when the two waves are combined is shown in the third curve in the figure, which shows how the surface of a pond would appear when both waves were traveling over it at the same time.

When two organ pipes that have slightly different frequencies are sounded together, the sound waves that they send out have slightly different lengths. They will therefore resemble the two waves shown in Fig. 131, in that there will be certain positions in which the condensations of one wave coincide with the rarefactions of the other, and other intermediate positions in which the condensations of the two coincide. When the condensation of one wave coincides with the rarefaction of the other, the two annul each other's effects and silence results. But when two condensations coincide, their effects are added together and a loud tone is heard.

Suppose one pipe sends out 100 waves and the other 101 waves in a second. Both trains of waves will extend the same distance from the source, because the waves travel at the same rate. In this distance there will be 100 of the longer waves, and 101, i. e., one more, of the shorter ones. Hence in this distance the shorter wave gains one wave length on the longer, and there must be one position in which the condensation of one falls on the rarefaction of the other. If one sends out two waves more than the other each second, there will be two positions in which a condensation of one falls on a rarefaction of the other; i. e., two periods of silence and two of louder sound each second, or two beats. Hence the conclusion:

The number of beats per second produced by two tones is equal to the difference in their frequencies.

241. Reason for Discord. Helmholtz showed that whenever two tones are combined so that discord results, beats can be detected either between the two fundamentals or between some of the overtones. When the beats are slow, they are not disagreeable; but when they are faster,—more than five or six a second, they become very annoying. When the beats become still more rapid, they merge into a tone. They are disagreeable only when there are more than five and less than thirty a second. These facts have been shown to

be true by all subsequent work on this subject. So we now know that

Discord is due to beats produced either by the fundamentals or by the overtones.

To avoid discord, we must play together only notes whose frequencies are such that no disagreeable beats are produced.

This is the case when the frequencies of the fundamentals are related by the simple ratios $\frac{1}{2}$, $\frac{2}{3}$, $\frac{3}{4}$, $\frac{4}{5}$. Hence,

The particular notes used in the musical scale have been selected so as to avoid disagreeable beats when the notes are played in chords.

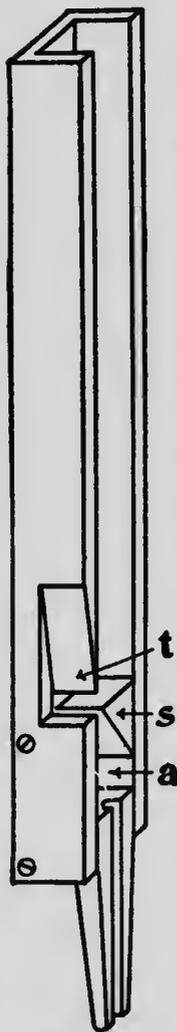


FIG. 132 SECTION OF ORGAN PIPE

242. Musical Air Columns. Not all of our music is produced by the stringed instruments we have been studying. Much of it comes from such instruments as the pipe organ, the flute, and the various horns. They are called *wind instruments*. Fig. 132 represents an organ pipe split open lengthwise, so that its construction can be understood. Air under pressure is admitted to the small chamber *a*, whence it is blown through the slot *s* in such a way as to strike the tongue *t*. This stream of air blowing across the tongue makes the air in the pipe vibrate in its natural period, which depends only on the dimensions of the pipe. When an organ pipe is blown gently, it sounds its fundamental tone. It is then vibrating longitudinally in stationary waves. Since the air is free to move at both ends of the pipe, each of these ends will become the middle of a loop in the stationary wave. When the pipe is giving its fundamental tone, it vibrates with a node at the middle and the middle of a loop at each end, as indicated at *a*, Fig. 133. Since the two

half loops are equal to one whole loop, the length of the

pipe is the same as that of one loop; and since the length of one loop is half that of the wave, *the length of the wave of the fundamental tone of an open pipe is twice the length of the pipe.*

When the pipe is blown a little more strongly, it gives out the first overtone, which is the octave of the fundamental. Since the octave vibrates twice as fast as the fundamental, the wave it sends forth is half as long; i. e., it is equal to the length of the pipe. As both ends of the pipe must be loops, the stationary wave is placed as shown at *b*, Fig. 133. The second overtone, which is five notes above the octave, is made by blowing still harder.

When it is sounding this tone

the stationary wave in the pipe is placed as shown at *c*, Fig. 133.

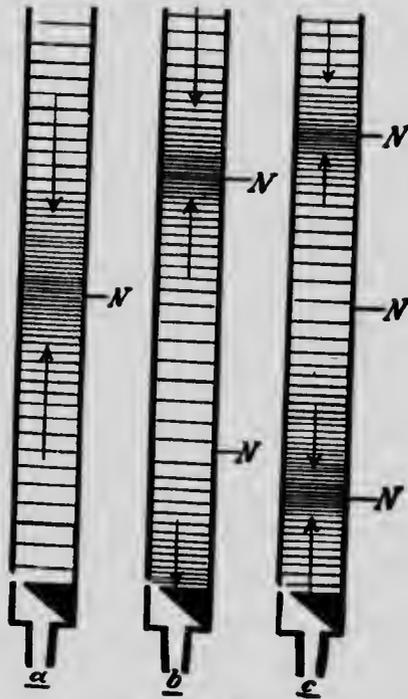


FIG. 133 WAVES IN ORGAN PIPES

DEFINITIONS AND PRINCIPLES

1. A stretched string vibrates as a stationary wave in some whole number of loops, with nodes at the ends.
2. The frequency of a note from a string vibrating in a single loop is inversely proportional to the length of the string.
3. The frequencies of the overtones of a string are related to that of the fundamental by the ratios 1:2:3:4:5: etc.
4. The frequencies of the three notes of a major triad are related by the ratios 4:5:6.
5. International Standard Pitch is violin $a = 435$ vibrations per second.

6. The number of beats produced by two tones is equal to the difference in their frequencies.

7. Discord is avoided by relating the frequencies of two tones so that there are no disagreeable beats when the tones are sounded together.

8. Beats among fundamentals and overtones are avoided when the frequencies of the fundamentals are related by the simple ratios $\frac{1}{2}$, $\frac{2}{3}$, $\frac{3}{4}$, $\frac{4}{5}$, $\frac{5}{6}$.

9. The frequencies of the overtones of an open organ pipe are related to that of the fundamental by the ratios 1:2:3:4:5: etc.

QUESTIONS AND PROBLEMS

1. Which wires in the piano give the notes of highest pitch? Why?
2. If the pitch of a violin string is too high, how does the violinist lower it?
3. How can a violinist play a tune on a single string?
4. What is the effect on a piano string of winding a soft copper wire in a close coil around it?
5. When giving the pitch to the class, why does the music teacher hold the end of the vibrating tuning fork against the table top?
6. In the violin or the guitar, what takes the place of the sounding board in the piano?
7. When a violinist touches a string lightly in the middle, how does the string vibrate when bowed near one end?
8. When the middle of one loop of the violin string of question 7 is going in one direction, in what direction is the middle of the other loop going?
9. How often do the middle points of all the loops of a stationary wave come into the same straight line?
10. If a string when vibrating in 1 loop makes 256 vibrations per second, how many vibrations will it make when vibrating in 2 loops?
11. How does the pitch of the tone of a string vibrating in 2 loops compare with that of its fundamental tone?
12. If the frequency of a string when vibrating in 1 loop is 256, what is its frequency when vibrating in 3 loops? In 4 loops?
13. A banjo string 24 inches long gives 240 vibrations per second. How many vibrations does it give when its length is reduced to 18 inches by pressing it against a fret with the finger?

14. If the first note given by the string in the preceding question is *do* of the musical scale, what is the name of the second?
15. What are the frequencies of the first 5 overtones of a string whose fundamental tone has a frequency of 128 vibrations per second?
16. Find the frequencies of the notes of the major triad that begins with $C=240$ vibrations per second.
17. Find the frequencies of the major triad that ends with $C=480$ vibrations per second.
18. Why is it necessary to have a standard pitch?
19. Is the music of a band just as harmonious when heard at a distance of 1000 feet as when heard at a distance of 100 feet? Why?
20. What happens to two water waves when a crest meets a crest and a trough meets a trough?
21. What happens when two sound waves meet so that a condensation coincides with a condensation and a rarefaction coincides with a rarefaction?
22. One person takes 120 steps per minute and another 125. How many times a minute will the two walkers be in step? How many times a minute will one be advancing the left foot just as the other is advancing the right?
23. Describe and explain what is heard when two organ pipes, one making 512 vibrations per second and the other 510, are sounded together.
24. How many beats per second will occur when two tuning forks whose frequencies are 435 and 441 respectively, are sounded together?
25. Will the tones of the two tuning forks of question 24 harmonize?
26. What determines the pitch of the note given by a toy whistle?
27. What is the approximate length of an open organ pipe that sends out waves four feet long?
28. How many vibrations per second does the air in the organ pipe of question 27 make at the temperature of $16^{\circ}C$?
29. How is the air in an open organ pipe vibrating when the pipe is sounding its fundamental tone?
30. How are the frequencies of the overtones of an open organ pipe related to the frequency of the fundamental?
31. An open organ pipe when sounding its fundamental tone makes 64 vibrations per second. What are the frequencies of its first and second overtones?
32. A bugle is like an open organ pipe. What are the notes that can be played on it?
33. Can you find out how the valves on a cornet operate to change the pitch of the tone?

34. Try to find out how a trombone is constructed so that notes of different pitches can be played on it.
35. Why does opening the holes on a flute or a piccolo change the pitch of the note that is being played?
36. Will the tone given by an organ pipe be the same if the pipe is blown with cold air as when it is blown with hot air?
37. How is the vibration started when a tin horn is blown?
38. Organ pipes are often made with their tops closed. The air is then not free to move at the top, and so there must be a node there. How do the wave lengths sent out by an open and a closed pipe of the same length compare?
39. The lowest note on the organ has a wave length of about 64 feet. What must be the length of a closed pipe that gives this tone?

CHAPTER XIII

OPTICS

243. Apparent Size of Objects. If a number of people are asked how large the moon looks, each will give a different answer. One may say that it looks as large as a dime, another that it seems as large as a saucer, while a third may say that it appears as big as a cart wheel. Then too, the moon looks larger to every one when it is near the horizon than when it is high in the sky.

Infants reach for the moon and cry because they can not get it. Landsmen find it very difficult to estimate the distance between two boats at sea. On the other hand, when we look at a man climbing a distant hill, he appears as but a small speck on the landscape, yet we estimate his size correctly. We even use our knowledge of the man's size to estimate the distance or actual size of the hill or the height of the trees there. Ability to estimate distances and sizes from the way things look is obtained from long practice. Let us see if we can find the reasons for these things.

244. How Light Indicates Direction. When sunlight streams through a window, it traces an outline of the window on the floor. If you hold your open hand so that the sunlight falls vertically upon it, the outline of the shadow cast on the floor resembles the outline of the hand. Most of us have amused ourselves making shadow pictures, by so placing the hands between a lamp and the wall that the shadow on the wall resembled a rabbit, a goose, a clown, or any other creature. We might draw the same outline by pivoting one end of a long straight pencil at the source of light, and moving it around the edges of the object, while the other end marked on a paper suitably placed. We can think of such a pencil as

if it were the beam from a tiny searchlight moving about the edges of the object and tracing the outline.

When a sunbeam is allowed to enter a darkened room through a small opening, its path, as revealed by the dust particles in the air, is seen to be a straight line. Where it falls on some object, it makes a bright spot. The sun, the opening, and the bright spot all lie on the same straight line; so from inside the darkened room we can determine the direction of the sun with reference to objects in the room, by means of the line drawn from the center of the bright spot through the center of the opening. Because light travels in straight lines, *we judge the direction of an object by observing the direction in which light from the object travels.*

245. How Relative Directions are Judged. If we have two sources of light outside the darkened room, instead of one, each sends its own beam of light through the opening. A model of this arrangement may be made by setting two candles at *A* and *B* (Fig. 134) respectively and placing near by an

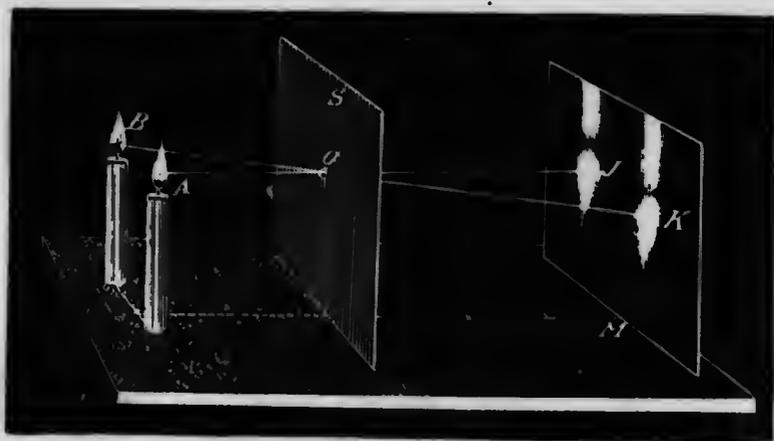


FIG. 134 THE DIRECTION IS JUDGED BY THE ANGLE

opaque screen *S*, having in it a small opening *O*. When a white screen is placed anywhere behind the first, as at *M*, two bright patches *J* and *K* are seen on it, one corresponding to each candle.

An observer behind the screen S judges the direction of the source A by the straight line JO ; and that of the source B , by KO . The difference in direction between the two candles A and B is judged by the angle JOK included between these two intersecting lines. But since the light travels in straight lines, the angles AOB and JOK are equal. So the relative directions of the two sources of light are judged by the angle AOB ($= JOK$) included by the two beams at the opening through which they reach the observer.

246. Image Through a Small Opening. The patches JK on the screen (Fig. 134) are not shapeless spots. They resemble the candle flames. If one candle be replaced by an incandescent lamp or any other source of light, the corresponding spot changes accordingly and resembles the new source in shape. Because of this, the patch of light that resembles the source of light in shape is called an *image* of the source. If the lens of an ordinary camera be replaced by a card perforated with a pin-hole, the instrument may still be used for taking pictures: because an image will be formed in this "pin-hole camera" in the manner shown in figure 134. Such an image is always upside down.

If we remove the screen S , or if the opening at O is made large, no image of the source is seen. When the opening O is small, the image of A may be found anywhere behind S along the line AOJ . In all positions of the screen, however, the image is blurred or fuzzy,—it does not look clear and sharply defined as does the source itself. So long as the opening is large enough to let through sufficient light to form a visible image, *the smaller the opening, the clearer the image.*

The reason for this lies in the fact that the candle flame consists of a very large number of luminous particles, each one of which is sending out light in all directions. Some of the light from the particle at a (Fig. 135) passes through the opening O in the screen S , and falls on the screen I at j . But since the light starts from a point, and passes through an opening of appreciable size, the beam that forms the spot at j

is shaped like a cone. It spreads over a larger and larger area the farther it goes. So the point a on the source is represented by the relatively large spot j in the image. In like

manner each other point on the source produces a spot in the image. So the object itself is composed of luminous points, but the image is composed of luminous spots; and therefore its outlines are vague and fuzzy.



FIG. 135 THE IMAGE IS INVERTED AND FUZZY

The cone of light from the point b (Fig. 135), after passing through the opening O , makes its corresponding spot at k . Since b is above a in the source, and since the two beams cross each other at O , the spot k , corresponding to b , will be below j in the image. So the image is inverted, because the beams of light travel in straight lines and cross each other at the opening.

The straight line drawn from any point in the source a or b through the middle of the opening O is called the *axis of the beam*. The axis is the path followed by the light in the middle of the beam.

247. Size and Distance of the Image. As the screen I (Fig. 136) is moved farther away from the screen



FIG. 136 GREATER DISTANCE, LARGER IMAGE

S , the image mn of the flame grows larger. So long as the candle and the screen S are not moved, the angle aOb , between the axes of the two beams remains fixed; hence the

angle jOk ($= aOb$) between the axes of the two beams jO and kO remains unchanged, because these axes are the straight lines aj and bk . When the distance between the image and the opening is doubled, the size of the image mn is doubled; when this distance is three times as great as at first, the image is three times as great; and so on. Other things remaining unchanged,

The length of the image is proportional to its distance from the opening through which the light shines.

If the distance between the opening O and the image remains fixed, and the candle flame is moved farther away from O (Fig. 136), the image becomes smaller. In this case, the angle aOb , included at O by the axes of the beams from the two points a and b , becomes smaller. Hence the angle jOk becomes smaller, and the size of the image is reduced. The size of these equal angles aOb and jOk does not change when the image screen I is moved; it changes only when the distance between the object and the opening is changed.

When the two points are at the extremities of the object, the angle included at the opening by the axes of the beams from them is the *angle subtended at the opening* by the object. Thus a and b (Fig. 136), are at the extremities of the object, and aOb is the angle subtended by the object at O .

The nearer the object is to the opening, the larger the angle subtended by it at the opening.

248. The Eye. Although the image of the candle flame (Fig. 135) is not as sharply defined as the flame itself, it enables an observer behind the screen S to determine the directions of the various points on the flame with reference to the opening and the screen I . An examination of the structure of the eye shows that it resembles the apparatus described in Art. 245, in that it consists of a dark chamber E (Fig. 137) into which light is admitted through a small opening P , called the *pupil*. Because of this fact, an inverted image of an object is formed

on the back of the eye. The inner surface R of the back of the eye is called the *retina*. It is covered with nerves, which are affected by the light, causing us to see.

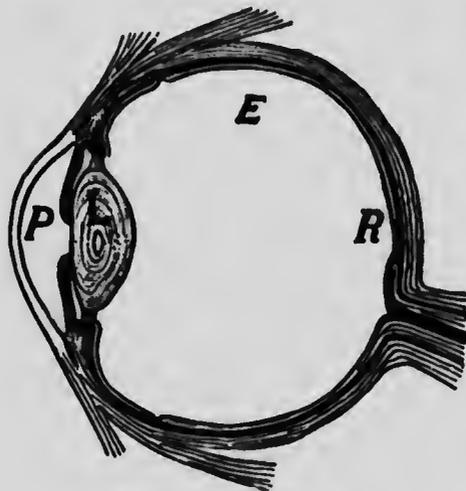


FIG. 137 THE EYE

This image on the retina, however, differs from that of the candle (Fig. 135), in that it is not fuzzy, but distinct. The eye differs from the apparatus used in Art. 245, in that directly behind the pupil P there is a small transparent object called the *crystalline lens* (L , Fig. 137). This lens is round like a button; its front and back surfaces are

curved outward (convex), so that it is thicker in the middle than at the edges.

249. What a Lens Does. In order to find out what the crystalline lens in the eye does, place a glass lens L (Fig. 138), which is thicker in the middle than it is at the edges, behind the opening in the screen S as shown in the figure. When the screen I is moved back and forth, one position only can be found where the image of the flame is clear and distinct.

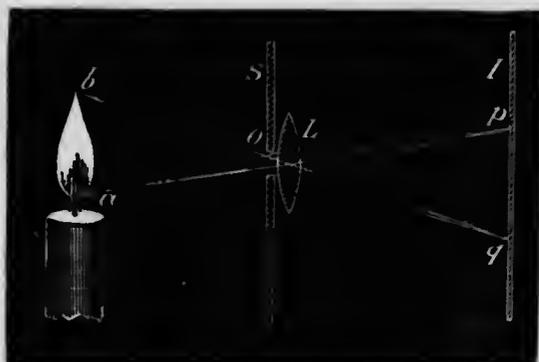


FIG. 138 THE LENS MAKES THE IMAGE CLEAR

The light that was diverging from a to form the spot J (Fig. 135) is brought together by the lens at a point p (Fig.

138); so that the image of the flame is no longer made up of a series of spots, but of a series of points. The point p lies on the axis of the beam, showing that *the axis of a beam of light is not bent by the lens.*

If sunlight is passed through the lens in a direction perpendicular to its surfaces, we can see that the lens does act in this way. Before striking the lens, the sides of the sunbeam are parallel to the axis of the beam; but after passing the lens, the light converges to the point F , (1, Fig. 139) which lies on the axis of the beam. If a screen is placed at F we find a small image of the sun there.

250. Principal Focal Length. When the beam of sunlight is passed through a lens different from the one just used (Art. 249), the distance from this lens to the place where the light converges is not the same as it was before. If several lenses of different shapes are tried in succession, the distance at which the image of the sun is formed distinctly will be different for each. Thus the 3 lenses in Fig. 139 all have the same diameter, but lens 1 is much thicker in the middle (more convex) than the others; and the light comes together at a point near the lens. Lens 2 is not so thick in the middle (not so convex) as lens 1; and the light comes together farther away from it. Lens 3 is still less convex than 2; and the light converges still farther away from the lens.

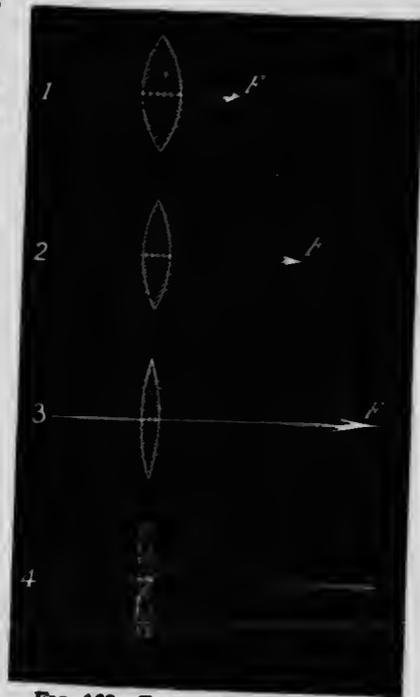


FIG. 139 THINNER LENS, LONGER FOCAL LENGTH

Number 4 is a piece of ordinary window glass with parallel sides and it does not converge the light at all.

The lenses shown in Figure 139 are all placed so that the planes of their rims are perpendicular to the direction in which the sunlight is moving. The line drawn through the middle of a lens perpendicular to the plane of its rim is called the *axis of the lens*. A beam of sunlight is called a *parallel beam*, because it neither converges nor diverges, but has the same diameter at every cross-section. When a parallel beam falls on a lens in the direction of the axis of the lens, the point at which the light converges is called the *principal focus* of the lens. The distance from the lens to the principal focus is called the *principal focal length* of the lens.

A lens that is thicker in the middle than it is at the rim makes a parallel beam converge to a focus, and is called a convex or converging lens.

The more convex the lens, the shorter its principal focal length.

251. Lens Angle Not Changed by a Lens. Place the first of the lenses just used (Art. 250) behind the small opening in the screen *S* (Fig. 138), and move the screen *I* until a sharp image of the candle flame is formed. Then remove the

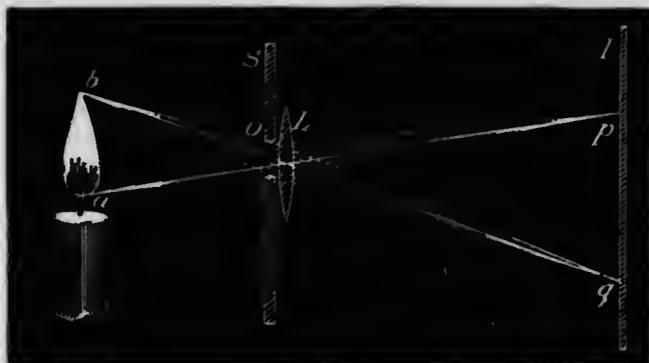


FIG. 140 THINNER LENS, LARGER IMAGE

lens. The image becomes fuzzy, but *its size is not changed*. The angle POq included between the axes of the two beams is the same, whether the lens is present or not.

The angle pOq is the angle included at the center of the lens between the axes of the two beams that make the extreme points p and q in the image. This angle is called the *lens angle of the image*. The angle aOb is called the *lens angle of the object*; and it is equal to the angle pOq . That is,

The lens angle of the object is equal to the lens angle of the image.

252. Size of Image and Focal Length. If the second of the lenses used in Art. 250 be placed behind the small opening in the screen S (Fig. 138) the image on the screen I will not be clear, i. e. it will not be *in focus*. We shall have to move I farther away to find the focus. When the focus for lens 2 is found (Fig. 140), the image is larger than it was when lens 1 was used. Since the lens angle of the object is the same in both cases, the lens angles of the images pOq (Figs. 138; 140), are the same. But the image from lens 2 is larger because it is farther away from the lens. It is farther away from the lens, because lens 2 does not converge the light as strongly as lens 1 does; i. e., its focal length is greater. When different lenses are placed at the same distance from the same object, the lens angles of the different images are all of the same size; but the images are of different sizes, because they are focused at different distances from the lenses.

With a given lens angle, the greater the focal length of a lens, the larger the image formed by it.

253. Conjugate Foci. If the distance between the candle and the lens (Fig. 141) be changed, the image will no longer be in focus. As the candle approaches the lens, the screen I must be moved farther away to focus the image on it. As the object goes farther away, the image comes nearer the lens. Photographers know that the nearer the object comes to the lens, the farther back the plate must be placed in order to be in focus.

A given lens produces only a certain amount of convergence in a beam. If the beam is parallel, it is converged at

the principal focus. If the beam is divergent (Fig. 141), it has first to be rendered parallel and then converged; so it does

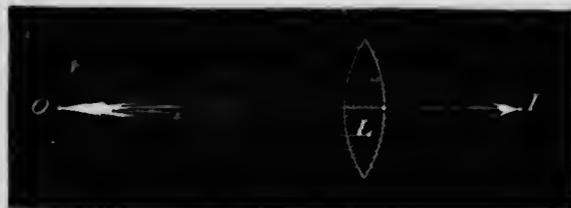


FIG. 141 FARTHER OBJECT, NEARER IMAGE

not converge as rapidly as a parallel beam and the focus is farther away. Part of the converging power of the lens is used in making the

divergent beam parallel, so only part of it remains to make the beam converge.

As an object O approaches a lens, the beam from each point on the object becomes more divergent in front of the lens, and on this account, the beam behind the lens becomes less convergent; so the focus I moves away from the lens (Fig. 142).

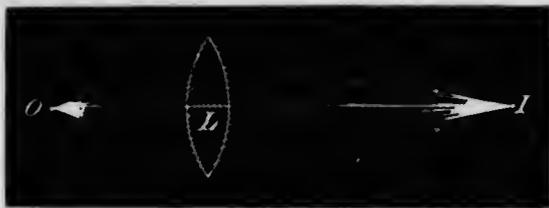


FIG. 142 NEARER OBJECT, FARTHER IMAGE

When the distance between the object and the lens becomes equal to the principal focal length of the lens, the lens can only render the beam from each



FIG. 143 SOURCE AT THE PRINCIPAL FOCUS; BEAM BECOMES PARALLEL

point parallel (Fig. 143), and then there is no real focus. When the distance between the object and the lens becomes less than the principal focal length, the beam behind the lens remains divergent.

The points where the object and image are when the image is in focus are called *conjugate foci*. The distances from the lens to the conjugate foci are called *conjugate focal lengths*. For a given lens, when forming a real image,

The smaller the distance from the lens to the object, the greater the distance from the lens to the image.

254. How the Lens Forms a Real Image. Let OP (Fig. 144) represent an object, ALB a lens, and JK the image. From the point O , light spreads out in all directions; but only that part of it which falls on the lens is brought to a focus in the image. The axis of this divergent beam of light from O is the line OL . The lens changes this divergent beam into a

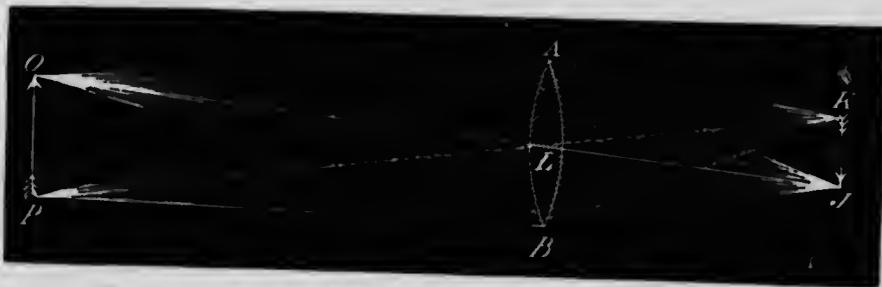


FIG. 144 THE LIGHT FROM EACH POINT COMES TO ITS OWN FOCUS

convergent beam, but the direction of the axis of the beam is not changed. So the convergent beam comes to a focus at some point on the line OLJ . The distance of this point from the lens depends on the converging power of the lens.

In like manner the axis of the diverging cone of light from P (Fig. 144) is the line PL drawn from P through the center of the lens. The image of the point P will be formed somewhere on the line PIK ; because PLK is the axis of the beam. Similarly, every other point of the object sends its cone of light to the lens, and each of these cones is focused by the lens at a point in the image which corresponds to the point of the object from which that particular beam diverged.

If a screen be placed at KJ , the image of OP may be seen on the screen. An image that may be thus received on a screen is called a *real image*.

255. How the Eye is Focused. In the eye (Fig. 137), the distance from the lens to the retina is fixed; therefore, the eye

cannot be focused by moving the retina backward and forward as the screen *I* was moved in Art. 253. Yet we can bring objects that are near by, or those at a distance, into clear focus at will.

To do this there is a set of tiny muscles surrounding the lens of the eye. When an object is brought near the eye, these muscles act on the lens in such a way that it bulges out and becomes thicker in the middle. This thickening of the lens increases its converging power, and so shortens its focal length (Art. 250) enough to bring the image on the retina.

Conversely, when an object is far away from the eye, the muscles about the lens allow it to relax, so that it becomes thinner than usual in the middle. Its focal length is thereby increased enough to bring the image of the distant object into focus on the retina. This act of the eye in changing its focal length is called *accommodation*.

256. Near-Sighted and Far-Sighted Eyes. Some eyes cannot be focused on distant objects, but see things clearly only when they are close by. Such eyes are called *near-sighted*.



FIG. 145 NEAR-SIGHTED EYE

The lens in such an eye is too thick in the middle. When the focusing muscles have relaxed until the lens is as thin as possible, it is still too

thick to focus distant objects clearly on the retina. Its focal length is too short, and the focus falls in front of the retina (Fig. 145). Since the lens in a near-sighted eye is too thick in the middle, this defect may be corrected by placing in front of the eye a lens *cd* that is thinner in the middle than it is at the edges. The eye lens and this added lens combine to make up a lens of correct focal length.

The far-sighted eye cannot focus objects that are near by. The lens has too long a focal length, and the focusing muscles cannot make it thick enough to bring the image into focus on

the retina (Fig. 146). The lens is too thin in the middle, but its fault may be corrected by combining it with a glass lens ab

that is thicker in the middle than at the edges. This added lens must be so selected that, when placed before the



FIG. 146 FAR-SIGHTED EYE

eye lens, the two act as a single lens of correct focal length.

257. Visual Angle and Apparent Size. We can now answer the question about the size of the moon. (Art. 243) The moon can be hidden behind a dime, when the dime is held less than 6 feet from one eye and the other eye is shut. At a distance of about 6 feet, the dime just covers the moon's disk, i. e., it has the same apparent size. A saucer five inches in diameter just covers the moon, if held at a distance of about 42 feet from the eye. A cart wheel 35 inches in diameter must be placed at a distance of about 300 feet in order to have the same apparent size as the moon.

A cat 12 inches long climbing a small tree 15 feet away has the same apparent size as a panther 3 feet long climbing a large tree 45 feet away. The angles subtended at the eye by the cat and the panther would be the same; and if we did not make allowance for its nearness, we might easily mistake the cat for a panther. When an artist draws a picture he holds his pencil at arm's length and sights across it to measure the angles that various objects subtend at the eye, by noting how great a length of pencil covers the same angle as each object does. The angle which an object subtends at the eye is called the *visual angle*.

Two objects have the same apparent size when they subtend equal visual angles at the eye.

When you look along a railroad track, the rails seem to come nearer together as their distance from you increases. The width between the rails is the same, but that width

when far away forms a smaller visual angle at the eye than it does when it is near by.

By long experience we have learned to estimate roughly the actual size of an object from its visual angle; yet few people are expert at this. A well-known parlor game consists in setting a hat on a table and asking those present to indicate with their hands the height of the hat. Nearly every one will overestimate it. The moon looks bigger when near the horizon because we can then compare it with objects whose actual sizes we know. We are apt to judge such objects larger than their visual angles indicate; and so, when the moon appears among them, we "enlarge" it too.

258. Limit of Distinct Vision. When trying to read very fine print, we bring it close to the eye. The visual angle of each letter is thereby enlarged, making the letters appear larger, so that it is easier to distinguish the details in them. When a merchant wishes to observe the quality of a piece of cloth, he holds it near his eye in order to be able to see more of the details of the weave. We are all familiar, however, with the fact that when an object is brought too near the eye, it cannot be clearly focused. The shortest distance at which an object can be clearly focused by the eye is called the *limit of distinct vision*.

In normal eyes the limit of distinct vision is reached when objects are about 10 inches from the eye. When an object is at that distance from the eye, the lens in the eye has bulged out as far as it will go; so if the object is brought nearer, its image becomes blurred. The focal length of the lens is too great to focus the image on the retina.

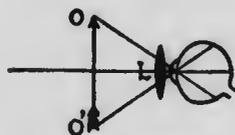


FIG. 147 SIMPLE MICROSCOPE

259. The Simple Microscope. The limit of distinct vision may be reduced very materially by introducing in front of the eye a converging lens L (Fig. 147).

This lens and the lens of the eye together form a com-

pond lens which has greater converging power than either alone. When the eye lens has been thus strengthened, objects close to the eye may be focused clearly. Because a lens, when used in this way, enables us to see details in small objects better, it is called a *simple microscope*.

The action of the simple microscope is the same as that of a lens for a far-sighted eye (Art. 256). If some small object is held within 2 or 3 inches of the eye, and a simple microscope introduced close to the eye, it becomes evident that the visual angle of the object is not changed by the microscope. The increase in apparent size is not produced by the microscope, but by the increase in the visual angle due to bringing the object nearer to the eye. *The microscope helps the eye lens to focus clearly objects that are closer to the eye than the limit of distinct vision.*

260. The Astronomical Telescope. If a lens L (Fig. 148) of long focal length (say 40 inches) be placed upright in an open window, an image of the landscape outside will be formed at a distance of about 40 inches from the lens. This image

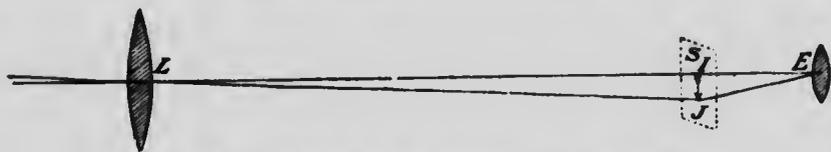


FIG. 148 DIAGRAM OF THE ASTRONOMICAL TELESCOPE

may be received on a screen S and so observed; or it may be seen directly if the screen is removed and the eye placed somewhere near the axis of the lens and far enough away.

If the eye is far away, say 10 feet, this image appears very small indeed. But as the eye is brought nearer, the visual angle of this image becomes larger, and the apparent size of the image increases. When the eye reaches the point E , 10 inches from the image, the limit of distinct vision is reached (Art. 258); and any nearer approach makes the image indistinct.

When the eye is at E , the visual angle of this image is IEJ . The lens angle of the image is JLI , and this angle is equal to the lens angle at L of the distant object. Since the object is distant, its lens angle at L is practically equal to its visual angle at E . The image IJ is common to both the triangles ILJ and IEJ ; and since IL is 40 inches and IE 10, the angle IEJ is larger than the angle ILJ . Thus *the image subtends a larger visual angle at the eye than the object itself does.*

The visual angle of the image may be further increased by bringing the eye still nearer. Then the eye will not be able to focus it clearly, so a simple microscope will be needed (Art. 259). This combination of a lens of long focal length with a simple microscope is called the *astronomical telescope*. The telescope makes distant objects look larger by placing an image of the distant object close to the eye. Although the image is much smaller than the object, yet because it may be brought very near to the eye, its visual angle may be made much larger than the visual angle of the distant object itself.

261. The Looking Glass. Presumably every one makes daily use of the looking glass and so knows that the images of objects in front of it appear to be behind it. When you stand before the glass, your image appears to be as far behind the glass as you are in front of it. As you approach the glass, your image approaches you; it appears to be a duplicate of yourself in size, in color, and in expression. The image is, however, reversed. When you raise your right hand, it raises its left hand. If you part your hair on the left, it parts its hair on the right.

Some mirrors give distorted images. A sheet of ordinary tin for example, acts as a mirror; but the image is not a true likeness of the object because the tin is not perfectly plane. Good mirrors must be made of plane surfaces like plate glass, because accurate images are reflected only when the surface is a perfect plane.

The back of the plate glass is coated with a thin layer of silver or mercury. An image may be seen in a piece of glass

without the metallic coating, but such an image is faint. The metal back makes the image much brighter, because it reflects more light from the luminous object to the eye.

262. Reflection from a Plane Surface. Every child has amused himself reflecting a sunbeam from a mirror into his playmates' faces. By turning the mirror, the beam is sent in the desired direction. Let a sunbeam fall on the mirror M (Fig. 149), and note how the reflected beam changes its direction as the mirror is moved.

When the beam falls perpendicularly on the mirror, it is reflected directly back toward the sun. When the beam IM falls on the mirror at an angle of 45° measured from a line MN perpendicular to the mirror (Fig. 149), the reflected beam MR

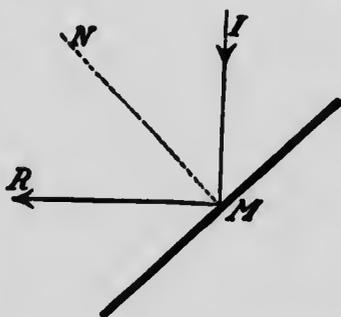


FIG. 149 REGULAR REFLECTION

leaves the mirror at an angle of 45° with the perpendicular. As the mirror is turned so that the angle IMN between the perpendicular MN and the incident beam IM changes, the angle NMR between the perpendicular and the reflected beam MR changes by the same amount.

The angle between the incident beam and a line perpendicular to the mirror at the point where the light strikes it is called the *angle of incidence*. The angle between the reflected beam and the same perpendicular is called the *angle of reflection*. As the result of many measurements on light reflected from various mirrors, the following fact has been found to be true. This fact is generally called the *law of reflection*.

The angle of incidence is always equal to the angle of reflection.

263. How the Image is Formed by a Mirror. Let S (Fig. 150), be one point of an object placed before the mirror MM . To an observer's eye at C , light from S will appear to come

from the mirror in the direction of BC , the point B being so placed that the angle NBS is equal to the angle NBC (Art.

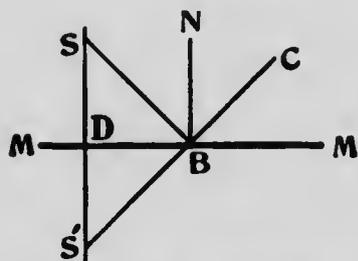


FIG. 150 THE PLANE MIRROR

262). Hence to the observer at C the point will appear to lie in the direction CBS' .

But the source S sends out light in all directions. Some of the light will strike the mirror perpendicularly along the path SD , and be reflected back on itself in the direction DS . To an observer along this line the

reflected light will appear to come from behind the mirror from some point along the line SDS' . In order that the light may seem to come from behind the mirror along both the paths $S'D$ and $S'B$, the image of S must appear to lie at S' , the intersection of these two lines.

The two triangles SBD and $S'BD$ are equal. Therefore the distance $SD = S'D$. The point S is only one point of the object. The same fact is true for every other point; so that the conclusion is just as true for the whole object as it is for the point S ; i. e.,

The image appears as far behind the mirror as the object is in front of it.

Since the light does not really come from the point S' , but only appears to come from that point, the image S' of the point S is called an unreal or *virtual image*.

264. Diffuse Reflection. Walls, floors, carpets, plaster, clothing, grass, and trees cannot be used as looking glasses. They do not reflect light as a mirror does. Yet unless they either reflected some, or were themselves luminous, we could not see them. If a piece of white paper, a bit of cloth, a block of unvarnished wood, a book, or any unglazed and unpolished substance be held in the sunlight, there is no reflected beam as there is with the looking glass, yet there

must be some kind of a reflection, as we have seen above. Reflection of this kind is called *diffuse reflection*.

A surface that is reflecting diffusely appears as if it were itself the source of the light. Such a surface is rough, not polished, and may be thought of as consisting of a vast number of tiny mirrors, facing in every possible direction. When light falls on these millions of tiny mirrors, each reflects its minute beam in its own way, the total result being that the reflected light is distributed in every direction.

265. Intensity of Illumination. A hundred years ago candles were the chief means of lighting houses at night. Most of us would feel abused now, if we were obliged to study at night by "yellow candle light." We turn on the electric light, or light a brilliant Welsbach and read in comfort at some distance from the lamp. We are apt to forget that even one candle, when near by, illuminates a printed page as brightly as a "50-candle-power" Welsbach at a distance.

In order to find out how the intensity of illumination of a printed page changes as it is moved away from the source of light, let the page *P* (Fig. 151) be held 1 foot from the candle *C*. In this position, it intercepts a definite amount of light



FIG. 151 THE ILLUMINATION IS LESS AT THE GREATER DISTANCE

from the candle, and is thereby illuminated with a certain brightness. Now move the page *P* to *Q*, 2 feet from the candle. The light that was intercepted by the page when it was at *P* is spread out at *Q* over four times the area of the page, because the diameter of the cross section of the beam has

been increased to twice its former length both horizontally and vertically. Since the same amount of light is spread over four times the area at Q , the printed page when at Q receives only one-quarter as much light as it does when at P .

When the printed page is placed 3 feet from the candle, the light that reached it when at a distance of 1 foot is spread over an area 9 times as great as it was then. Its area is, therefore, only $\frac{1}{9}$ of the area over which the light now spreads. So the brightness of the light on the page at a distance of 3 feet is only $\frac{1}{9}$ as great as it is at a distance of 1 foot. At a distance of 4 feet from the source, the page receives only $\frac{1}{16}$ as much light as it receives at a distance of 1 foot; and so on.

This fact is often called the *law of inverse squares for light*, and is stated as follows:

The intensity of illumination of a given surface is inversely proportional to the square of its distance from the source of light.

From this principle it follows that the brightness of a printed page at a distance of 1 foot from a single candle is as great as its brightness at a distance of about 7 feet from a Welsbach burner which sends out as much light as 50 candles.

266. Photometry. As with machines and steam engines, the important thing about a lamp is its efficiency. In order to determine the efficiency of a lamp, we must measure the brightness of its light, and the cost of maintaining it. The law of inverse squares (Art. 265) enables us to measure the brightness of a lamp in the following way.

Suppose we wish to compare a candle with an electric lamp. In front of a screen (Fig. 152), is an opaque rod B . The candle C and lamp L to be tested are placed so that the shadows of B cast on the screen by C and L respectively fall side by side. At D , where the shadow cast by C falls, the screen is illuminated only by light from L ; while at M , where the shadow cast by L falls, it is illuminated only by light from C . L is then moved farther away from the screen, until the brightness of the light over the two shadows is the same. If, when the two shadows are equally illuminated, L

is four times as far from the screen as C is, the brightness of L must be $4^2 = 16$ times that of C . Since L shines as brightly as 16 candles, it is said to be a *16-candle-power lamp*.



FIG. 152 THE TWO SHADOWS ARE EQUALLY ILLUMINATED

This method of comparing the brightness of lamps was devised by Count Rumford (1753-1814). The instrument is called a *Rumford photometer*. There are several other kinds of photometers, but they all depend on the same principle, namely,

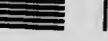
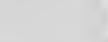
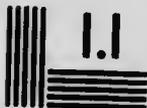
When two lamps illuminate an object with the same brightness, the candle-powers of the two lamps are proportional to the squares of their distances from the object.

267. Cost of Illumination. In Art. 207 we learned that an ordinary incandescent lamp consumes energy at the rate of 55 watts. If it actually sends out as much light as 16 candles do, the light takes $\frac{55 \text{ (watts)}}{16 \text{ (candle-power)}} = 3.5$ (nearly) watts per candle-power. A certain arc lamp takes 10 amperes of current at 110 volts. Its candle power is 2200. Therefore,



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its rating is $\frac{1100 \text{ (watts)}}{2200 \text{ (candle-power)}} = 0.5$ watts per candle-power.

When electricity costs 10 cents per kilowatt-hour (Art. 209), 55 watt-hours costs $\frac{55}{1000}$ of 10 cents, or 0.55 cents. So the ordinary incandescent lamp costs but little more than half a cent an hour. Since it has a candle-power of 16, its cost per candle-power-hour is $\frac{0.55}{16} = 0.035$ cents. The cost of the arc lamp is 0.005 cents per candle-power-hour.

An ordinary gas jet consumes 5 cubic feet of gas an hour, and its candle-power is about 25. If gas costs 85 cents per thousand cubic feet, such a burner costs $\frac{85}{1000} \times 5 = 0.42$ cents per hour. Since its candle-power is about 25, such a light costs about $\frac{0.42}{25} = 0.016$ cents per candle-power-hour.

DEFINITIONS AND PRINCIPLES

1. Light generally travels in straight lines.
2. Relative directions of objects are determined by the visual angle.
3. The size of the visual angle depends only on the size of the object and its distance from the eye.
4. A lens that is thicker in the middle than at the rim converges light.
5. The principal focal length of a lens is the distance from the lens to the point where a parallel beam comes to a focus.
6. The lens angle of the object is equal to the lens angle of the image.
7. With a given lens angle, the greater the focal length of a lens, the larger the image formed by it.
8. The smaller the distance of the object from the lens, the greater the distance of the image from the lens.

9. Two objects have the same apparent size when they form equal visual angles at the eye.

10. The simple microscope enables the eye to focus objects closer to the eye than the limit of distinct vision.

11. The telescope makes an object look larger by placing an image of the object close to the eye.

12. The image in a plane mirror seems as far behind the mirror as the object is in front of it.

13. The angle of incidence is always equal to the angle of reflection.

14. A surface that reflects diffusely appears as if it were self-luminous.

15. The intensity of illumination is inversely proportional to the square of the distance from the source of light.

16. The candle-powers of two lamps are proportional to the squares of their distances from a screen on which they produce equal illumination.

QUESTIONS AND PROBLEMS

1. When you reach for an object that you see, or when you search for a distant object with a field glass, upon what fact do you rely as to the path of the light from the object to your eye?
2. Why should windows in a school room all be on one side?
3. What is the method of sighting a gun? Would this method be effective if light followed a curved path?
4. Why should school room windows reach to the ceiling?
5. How do you judge the difference in direction between two electric lights?
6. If you bore a 1 inch hole in an opaque shutter that covers a window in the school room, can an image of the scene out of doors be shown on the opposite wall? How?
7. Why must the room be dark in order to see the image of question 6?
8. Explain why the image made with a hole in a shutter or with a "pin-hole camera" is inverted.
9. What is the relation between the size of an image and its distance from the hole? Can you prove this relation by geometry?
10. Given a small bright light that may be considered a "point source," a small square card, and a white screen, what will be the shape of the shadow of the card on the screen? Why?

11. What are silhouettes and how are they made?
12. Why is the image of a candle, formed through a hole, not sharply defined?
13. Why is the shadow that an object casts in light from a "point source," like an arc lamp, sharp, while that cast in light from a source of large area, such as a gas flame, is not clearly defined? (The black portion of the shadow is known as the *umbra* and the gray margin as the *penumbra*.)
14. Would the image of a candle flame be formed on the retina of the eye if the eye had no lens? How?
15. If the eye lens could be removed without injury to the remainder of the eye could the owner of the eye see a candle? How would it look to him?
16. A candle placed at a certain distance from the pupil of the eye makes on the retina an image of a certain size. How does the image change when the candle is moved nearer? Farther away?
17. On what does the size of an image depend when the distance from the hole to the "screen" remains constant as it does in the eye?
18. If a tree subtends an angle of 10° at the pupil of your eye, what angle does its image subtend?
19. What does the lens of the eye do to the light beams in order to form on the retina a distinct image of an object?
20. All other conditions remaining the same, how will the size of an image formed by a pin-hole camera compare with that formed when the hole is provided with a lens?
21. How can you find the principal focal length of a lens?
22. How does a "wide angle" or "short focus" lens differ from a long focus lens?
23. Why is a long focus lens better than a short focus lens for taking a picture of a distant boat?
24. Why is a wide angle lens better for taking a picture of the interior of a room?
25. When a photographer takes your picture and moves you nearer the camera, must he move the ground glass screen nearer to the lens, or farther away, in order to focus the picture?
26. For a given sized picture on the screen why must the projecting lens of a "magic lantern" (stereopticon) have a greater focal length if it is to be used at the back of a large auditorium than if it is to be placed close to the screen?
27. In a stereopticon the illuminated transparent slide is the object. The image on the screen is focused by moving the lens toward or from the slide. If the slide is moved toward the screen, which way must the lens be moved in order to focus the image?

28. After focusing the image of the slide on the screen, if the stereopticon be moved farther back, which way must the lens be moved in order to focus again?
29. A lens is used to project on a screen an enlarged image of a candle. Is the candle or the image the farther away from the lens?
30. If the candle were placed where the image was (question 29) where should the screen be placed to catch the image?
31. In the last question, how large a candle, relatively, would make an image of the same size as the original candle?
32. How is the eye accommodated (i. e., focused) as an object gradually approaches it?
33. How is near-sightedness caused, and how is it corrected? Illustrate by a diagram?
34. What is the shortest distance from the eye an object can be placed that focuses clearly on the retina of the eye when the accommodating muscles are relaxed?
35. Why do streets and railway tracks appear to converge when you look down them?
36. Why does the moon "look bigger" when near the horizon?
37. Why does a student when sketching sometimes hold his pencil at arms length to take the measure of an object that he wishes to draw?
38. In reading fine print why is the book brought to within about ten inches from the eye? Why is it not brought nearer?
39. Explain why a simple microscope helps in looking at the parts of an insect or a flower.
40. How does a telescope make distant objects look bigger?
41. What purpose does the eye piece of a telescope serve?
42. Photographers sometimes examine the image on the ground glass plate of the camera by means of a magnifying glass. When so used, how does the magnifier compare with the eye piece of the telescope?
43. Where must a person stand with reference to a narrow vertical mirror in order to see his own image?
44. Where must a person stand with reference to a narrow vertical mirror to see the image of another who stands 6 feet in front of the mirror and 3 feet to the right of it?
45. How far behind the mirror does your image appear?
46. When you see your reflection in a pool of water is it upside down?
47. With a mirror having a silvered back you see two images of yourself, one fainter than the other. Why?
48. With reference to your own height, what is the length of the shortest mirror in which you can see your entire figure?
49. Why does transparent, colorless glass or ice become white and opaque when it is broken into tiny bits?

50. Why are shiny gilt wall papers poorly adapted to the purposes of decorating a room?

51. Why are wall paints with soft tones and no gloss or rough gray plaster better for the walls of school rooms than smooth white plaster or "glossy" paints?

52. If one can read comfortably at a distance of 2 feet from a candle, how many times as intense must the light be if he can read with equal comfort 6 feet from it?

53. A standard candle and a lamp, give equal illuminations to a screen that is one foot from the candle and 6 feet from the lamp. What is the candle-power of the lamp?

54. A 16 candle-power incandescent lamp takes 55 watts. A 40 candle-power tantalum lamp on the same circuit consumes 40 watts. What is the relative efficiency of the two lamps?

55. An ordinary arc lamp requires a current of 10 amperes at a P. D. of 50 volts, and its candle power is about 50. How does its efficiency compare with that of the incandescent lamp (problem 54)?

56. The carbons of a "flaming arc" lamp have cores made of magnesia, lime and, silica. These lamps require about .3 watts per candle power. How much more efficient are they than the ordinary arc lamp?

57. Which gives the brighter light for reading, an ordinary arc lamp (problem 55) at a distance of 10 feet from the book, or five candles at a distance of 1 foot?

58. A lantern slide 3 inches square is projected on a screen so as to make a picture 12 feet square. How much more intense is the light at the slide than at the screen?

59. Have you ever examined a moving picture machine? If so, tell how it works.

CHAPTER XIV

COLOR

268. Matching Colors. Women know well that it is not safe to match colors of dress goods and trimmings by gas light if they want to have them match by daylight. A ribbon that looks red by gas light may be of a purple tint in daylight. Ghost stories are sometimes told around a "spirit lamp" made by burning in a saucer alcohol in which common table salt has been dissolved. The faces of the company look ghastly in this light, because no red is reflected from them. A piece of red paper when seen in this light looks to be either orange or black.

Those who have worked in a photographic dark room know that the white plates appear red in the ruby light there. The light from those long, greenish tubes—the Cooper-Hewitt mercury lamps—now so much used in government offices, makes men look ghastly, and changes the color of postage stamps so that one not accustomed to it would hardly recognize even the familiar red 2-cent stamp. *The apparent color of an object depends both on the nature of the object and on the kind of light in which it is observed.*

269. The Rainbow. From time immemorial the rainbow has held the admiration of all men. Men have long known that the rainbow could be seen only when the sun shone on a mist or a shower of rain; but it was not until 1675, when Sir Isaac Newton explained it, that even scientists learned how the rainbow is formed.

A small model of the rainbow can be produced by sending a broad beam of sunlight, or a beam from a lantern, into a spherical flask *F* full of water, as shown in Fig. 153. The



FIG. 153 EACH DROP FORMS A CIRCLE OF COLORS

flask represents a raindrop. The sunlight passes through the hole O in a white screen, enters the flask, is reflected at its rear surface, and comes back again to the screen, where it forms a ring of colors VR .

The rainbow in the sky is formed by a similar action of a multitude of raindrops, each of which is in a suitable position for sending a single color to the observer's eye.

270. The Spectrum. In 1675, Newton showed how to produce a band of colors similar to those of the rainbow but very much more brilliant. He admitted a beam of sunlight through a small hole H (Fig. 154) in a shutter of a darkened

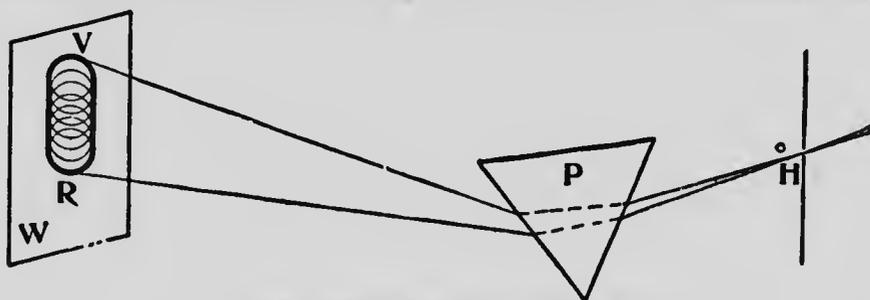


FIG 154 NEWTON'S SPECTRUM EXPERIMENT

room. The beam then passed through a glass prism P , to a white screen W . The light is not only bent from its straight path, but is also spread out into a band RV of various colors from red to violet. The names usually given to these colors are as follows: Violet, indigo, blue, green, yellow, orange, red. The initial letters of these names spell "vibgyor"—a combination of letters which looks like a word though it means nothing, but which may help the student to remember the

colors. A band of colors formed in this way is called a *spectrum*.

Newton found also that when a second prism, similar to the first, is introduced behind the first and in a reversed position, as shown in Fig. 155, the variously colored beams that come from the first prism are bent back again into a single white beam. This beam makes a white spot on the screen instead of a colored band.

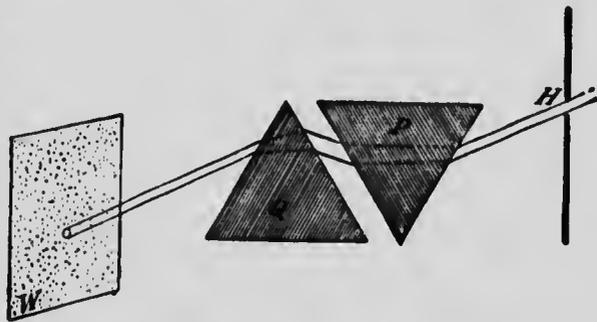


FIG. 155 WHITE LIGHT IS A MIXTURE OF LIGHTS OF THE RAINBOW COLORS

Since these experiments show that all the colors of the rainbow may be obtained from white light, and that these colors may be put together again so as to make white light, Newton concluded that

White light is a mixture of lights of all the rainbow colors.

271. Colors of Transparent Bodies. Selective Absorption. When a piece of blue glass is placed anywhere between the source *H* of white light and the screen *W* (Fig. 154), the resulting spectrum consists of violet and blue, with some yellow and green. If a red glass, such as photographers use for their ruby light, is substituted for the blue, the spectrum is reduced to a band of red. If the red and blue glasses are overlapped, so that the white light must pass through one after the other, the spectrum disappears from the screen. None of the colored light of which the white light is composed passes through both red and blue glasses. The red glass absorbs the green, blue, and violet from the white light; and the blue glass absorbs the red, orange, and yellow; i. e., each of the two glasses absorbs those colors which the other transmits.

The colors shown when light is transmitted by such things as the stained glass in church windows, precious stones, colored inks, bluing, and many chemical solutions, are due to the fact that these things contain substances called *dyes* or *pigments*, which absorb some of the colors from the white light. The different colors of different dyes and pigments are due to the fact that each pigment absorbs only certain particular colors from the white light, and sends to the eye only those colors which it does not absorb; so the process is called *selective absorption*.

It is interesting to note that the colors do not belong to the colored objects, but to the colored lights of which white light is composed. When pigments absorb all the different colors from the white light, we call them black.

272. Colors of Opaque Objects. When white light passes through red ink in a bottle, the dye in the ink absorbs from the white light all the colors except the red (Art. 271); so the light that has passed through it looks red. A spot made by red ink on white paper appears red. The light that falls on the paper penetrates through the layer of ink and is reflected from the paper beneath; but only the red light comes back. The spot appears red because the dye in the ink has absorbed the lights of other colors from the white light and allows only the red light to reach the eye.

Opaque paints, such as are used for painting houses, and opaque objects generally, appear colored for the same reason. *A paint or dye contains a pigment that absorbs some of the colors and reflects others. A white body reflects all of the colors and absorbs none; a black body absorbs them all, and so reflects none.*

273. Colored Objects in Colored Light. If a group of brightly colored objects like ribbons or flowers be illuminated with a beam of white light, and if a piece of ruby glass be then introduced in the path of the beam before it reaches the objects, a great change in their colors results. Red objects

remain red, yellow objects become orange, green and blue objects become purple or black. Changing the red glass for a blue or a green one produces other changes in the colors observed.

The way in which the color of an object changes as the color of the light in which it is seen changes, may be studied best with the help of the spectrum (Art 270). If we hold a red object like a piece of red ribbon, or a strip of red paper, in the red light of the spectrum, it appears bright red, just as it does in white light. In the yellow light it appears a very dark yellow; in the green light it is still darker—a greenish black; and in the blue and violet it is as black as soot. The pigment in the red ribbon or paper is capable of strongly reflecting only red light; it absorbs light of all other colors. Similarly a violet colored object, when placed in the violet light, appears as it does in white light, but it grows darker as the light in which it is seen approaches the red region of the spectrum; and in the red it looks perfectly black. It absorbs all the colors except blue and violet. Hence blue and violet are the only ones it reflects.

We can now understand why people appear ghastly when seen in the light of the alcohol flame colored with salt. If we look at such a flame through a prism, we see nothing but yellow. The flame radiates only yellow light. The blood and the red pigment of the skin reflect red light but if no red light shines on our faces, none can be reflected by them. So in the yellow light of the salt flame, the red color is missing from faces ordinarily ruddy. If the mercury light is examined with a prism, it is found to radiate only yellow, green, and violet. Since it radiates no red light, objects which seem red in white light look black when observed in the mercury light.

274. Color Mixtures. Primary Hues. In Art. 271 we learned that the blue light transmitted by a piece of blue glass is not a simple color consisting of blue only. The spectrum of this blue light shows that it is really a mixture of blue,

green, and yellow. On the other hand the light from the salt flame was found to be a simple yellow (Art. 273).

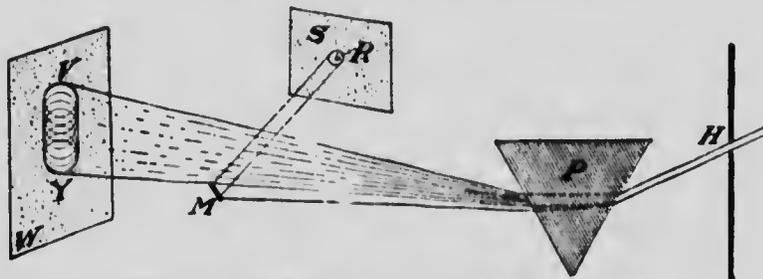


FIG. 156 THE SPECTRUM COLORS ARE NEARLY PURE

If a small strip of looking glass *M* (Fig. 156) be placed in the path of the colored light from the prism *P*, one of the colors may be reflected to the screen *S*. When this reflected beam of colored light *MR*, is sent through a second prism it is bent from its path, and made somewhat wider, but no other colors appear. In other words,

The spectrum colors are pure colors.

For this reason we can study the effects of mixing pure colors by reflecting different portions of a spectrum to the same spot. If two colors are to be mixed in this way, we place two strips of looking glass in the path of the colored light, one to reflect each of the colors to be mixed, and turn these mirrors until they reflect their respective beams to the same spot on a white screen. When we want to mix three colors we use three mirrors instead of two.

When orange-red, yellowish-green, and violet-blue are thus mixed, the spot on the screen where these three colors overlap appears white; just as it does when all the colors of the spectrum are brought together by means of a second prism (Art. 270). The three spectrum colors—red, green, and violet—are called *primary hues*; because, when mixed in the right proportions, they form white.

275. The Color Top. One of the standard toys in every toy store is the color top. It consists of a wooden or metal

top *T* (Fig. 157), accompanied by a set of colored paper disks, each having a hole in the center and a slit from the hole to the rim. Two or more of these disks may be interlocked, as



FIG. 157 THE TOP MIXES THE COLORED LIGHTS

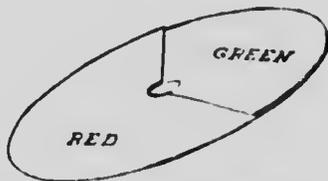


FIG. 158 RED AND GREEN MAKE YELLOW

indicated in Fig. 158, and placed on the top so as to expose sectors of various sizes and colors. When the top is spun rapidly, the colors of these sectors are blended in the eye of the observer.

The red, green, and blue disks, when combined so as to expose sectors of about equal size, appear gray when the top is spinning in a strong light. Gray is a dull white, i. e., a white of low intensity. These colors do not give pure white, because the colors of the disks are produced by pigments, and such colors are not perfectly pure (Art. 271).

276. Color Photographs. Ever since the process of making black and white pictures by photography was invented, efforts have been made to discover a method of taking pictures that would show objects in their true colors. Most of the processes of color photography are based on the idea that red, green, and blue are the three primary colors, and that therefore the other colors can be produced by suitable combinations of these three. One method of taking color photographs is the following:

Three exactly similar transparent "negatives" of the same scene are taken, one through red glass, one through green glass, and the other through blue glass. From each of these negatives a transparent "positive" is printed. Each of these positives has the high lights clear and the shadows black, just like an ordinary, uncolored lantern slide; but the first

shows only the proper intensities or "values" of red, not only where the red was pure in the original scene, but also where it was mixed with other colors; because the red color-screen, through which the negative was taken, absorbed from the light sent out by the scene all the colors except the red. In like manner the second positive shows only the proper values of green, and the third only the proper values of blue. When the first (red) positive picture is placed behind a piece of red glass or other red color-screen in a projecting lantern, and thrown on the screen, we see a red picture in which all the red portions of the original scene are properly reproduced, but which contains none of the other two primary colors, and none of the mixed colors. If we project the second (green) positive through a green color-screen with another lantern, it will show only the green portions of the original scene. Likewise the third (blue) picture, projected by a third lantern with a blue color-screen, will show only the blue portions of the scene. Finally, if we adjust the three lanterns so as to place the three pictures accurately one upon another, the original picture appears in its natural colors on the screen.

Since the method with three photographs and three lanterns is expensive and troublesome, several methods have been devised for reproducing color pictures with one exposure on a single plate. To do this the picture is taken, and also shown when completed, through a single color-screen, so made that the three primary colors are uniformly distributed all over it in very small strips or patches. Each part of the picture behind a red strip or patch shows red, each portion that is behind a green strip or patch shows green; and each portion that is behind a blue strip or patch shows blue. Such a picture, when magnified, shows that it is made up of narrow strips or small patches of red, green, and blue. When unmagnified, however, the colored patches are so small and so near together that they cannot be distinguished separately, but are blended in the eye.

One of the most successful methods of making the color

spots as small as possible, is that used in the Lumière plates. In these, the color-screen is made up of transparent starch grains, colored red, green, and blue. Equal amounts of grains of the three colors are thoroughly mixed and sifted over the glass plate, then pressed out flat, and fixed to the plate by a suitable transparent adhesive. This color-screen is then covered with the sensitive film, which is so made that it is equally sensitive to all three primary colors. When the picture is taken on this plate, the glass side is turned toward the object, so the picture is taken by light which has passed through the glass and the color-screen. The process of developing the picture is such that the exposed plate comes out not a negative but a positive. This colored positive, when viewed in white light by transmission, is so nearly perfect that only a skilled artist could detect the errors in it.

277. Three-Color Printing Process. Colored souvenir calendars and colored pictures in the magazines are now so common that we have ceased to wonder at them. When examined through a microscope such a print is seen to be made up of fine lines and dots of the three pigments red, yellow, and blue, with the addition in some cases of black. The various colors in the picture are produced by the mixtures of these three colors and the white of the paper. The greens result mainly from the overlapping and mixing of the blue and yellow pigments, while the purples result from red and blue spots or lines that are close together but do not overlap. The process by which these colored pictures are made is as follows:

Three negatives are taken of the original scene or picture that is to be reproduced. Each negative is taken through a transparent color screen of one of the three primary colors, red, green, and blue. Each of these color screens is crossed by fine opaque lines or rows of dots. From each of these negatives there is made—by photographic processes and etching with acid—a zinc or copper plate; and each of these plates is inked for printing with an ink of such color that, when mixed

with the color of the screen through which the negative was taken, the resulting color is white. The plate made from the negative that was taken through the red screen has to be printed with greenish-blue ink. The plates made from the negatives that were taken through the green and the violet screens are printed with crimson red and with yellow inks respectively; for the green and crimson red give white, as do the violet and yellow. The impression taken through the violet screen is shown printed in yellow at *A* (Plate III). At *B* the plates taken through the green and violet screens, but printed in yellow and red, are superposed. At *C* all three color plates are superposed, reproducing the original picture with a very fair degree of faithfulness.

278. Theory of Color Vision. The fact that it has been found possible to reproduce color pictures with the use of only the three primary colors, leads us to think that the tiny nerve ends or "cones," which are distributed all over the retina of the eye, are of three sorts or sets. When the nerves of one set are stimulated, they give the sensation of red. Likewise the other two sets give the sensations of green and blue respectively. Each of the sets of nerves is stimulated to a greater or less extent by lights of all colors; but each is stimulated most strongly by light of that primary color which corresponds to it. The red sensitive cones give a very faint sensation of red when stimulated by blue light, a stronger sensation of red when stimulated by green light, and the strongest sensation of red when stimulated by red light. When all three sets of nerves are stimulated equally, the resulting sensation is interpreted as white. This occurs when lights of all the colors enter the eye in the proportions found in the spectrum of sunlight. It also occurs when red, green, and blue lights of approximately equal intensities enter at the same time. By varying the intensities of these three colors in a picture, the three sets of color nerves are stimulated with various intensities; and we

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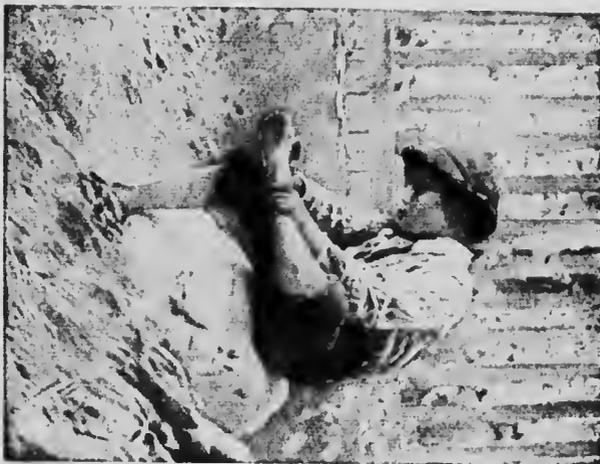
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A. THE YELLOW PLATE

B. THE YELLOW AND RED PLATES

C. THE YELLOW, RED AND
BLUE PLATES

PLATE III





interpret the sensations to mean the various hues, tints, and shades seen in the picture.

279. After-Images. If you place a disk of red paper on a black surface and look steadily at it for about 30 seconds, then suddenly slip a white paper over the red disk, you seem to see on the white paper a bluish-green disk of the same size as the red one. If you immediately look at a white wall you seem to see the bluish-green disk there also. This image of the same form as the colored object looked at, but of different color, is called an *after-image*. If a bright picture containing colors is looked at intently in the same manner, and the gaze is then directed to a white surface, an after-image of the picture appears; but each color in the after-image differs from the corresponding color in the picture.

When we gaze steadily for some time at an object of given color, the eye nerves that are most sensitive to that color become fatigued, so when the eye turns to a white wall, these nerves fail to respond fully *to the light of that particular color* in the white light. But the other colors in the white light stimulate the other two sets of nerves, because they have not been fatigued. Therefore, the resulting sensation is that of a color different from the one looked at. The color of the object looked at first and the color seen later on the white wall are called *complementary colors*, because either one is what is left of white light when the other is absorbed or removed from it. *Two colors are complementary if they produce white when they are mixed.*

DEFINITIONS AND PRINCIPLES

1. White light is a mixture of lights of all colors.
2. Every dye or pigment absorbs certain of the colored lights from white light (selective absorption).
3. The colors of objects are due to selective absorption.
4. The three primary hues are red, green, and blue.
5. Spectrum colors are pure colors.
6. The mixture of two complementary colors produces white.

QUESTIONS AND PROBLEMS

1. Why should colors that are to be worn in art be selected by the same kind of light?
2. What did Newton's spectrum experiments prove?
3. How does a white flower look when viewed through red glass? Through blue glass and red glass?
4. Why does a red ribbon appear black when seen through blue glass? Why does a red ribbon appear red when seen by red light?
5. Why does purple velvet appear black in the alcohol flame?
6. A white rose seen through a red glass, looks red. That is "naturally" red. Give the reasons for the redness.
7. Why is a yellow light "trying" to the complexion?
8. Why is a yellow gas flame less trying to the complexion if it is surrounded by a globe of red glass?
9. A narrow strip of purple velvet when illuminated and looked at through a prism looks red on one side and blue on the other. What does this show about purple light?
10. What is the result of mixing on a screen equal parts of green, and violet-blue lights? What are these hues called?
11. Blue paint when examined with a prism is found to contain green. Likewise yellow paint is found to contain blue. Can you explain why a mixture of equal parts of blue and yellow appears neither blue nor yellow, but green?
12. A mixture of green and red lights gives the sensation of yellow. Can you suggest why a mixture of blue and yellow light gives the sensation of white?
13. How are photographs in natural colors made?
14. With a magnifying glass examine a colorizing card made by the three color printing process. What following colors formed:—red, orange, yellow, green, blue, purple.
15. Describe the after images of a red circle, a blue triangle, a purple square, a yellow star.
16. If you can get purple by mixing red and blue lights, can you not get purple by mixing red and blue paints?

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CHAPTER XV

RADIATION

280. Where Light Comes From. Those of us who can see, find it difficult to realize how unfortunate those are who cannot see. If we could not see, we would not only be unable to go about easily, but reading would be impossible, beautiful scenery would fail to impress us, and the sun, moon, and stars would be utterly unknown. Light and the power of vision are among the most precious of Nature's gifts to man.

In Art. 149 it was shown that the ultimate source of heat is the sun. A similar search for the ultimate source of light leads to the conclusion that it, too, is derived directly or indirectly from the sun. Since there are some 93,000,000 miles of space between us and the sun, it would be fatal to have the base of supplies so far away, if we had to rely on railroads to do the carrying. Fortunately, this is not necessary, because the solar energy is delivered to us daily by a much more efficient and rapid system of transportation. Let us inquire into this system and its operation.

281. Amount of Energy from the Sun. The amount of energy received per minute from the sun on each square centimeter of the earth's surface has been measured in the following way: Sunlight is allowed to fall perpendicularly on one end of a metal can *C* (Fig. 159), containing a known quantity of water and a thermometer. The surface *B* on

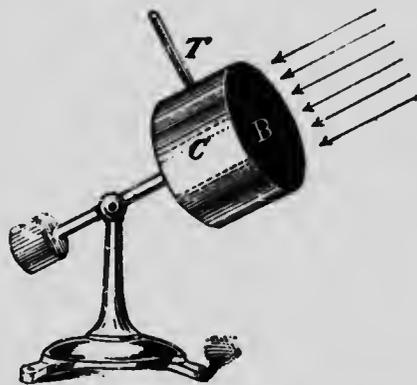


FIG. 159 THE SUN'S ENERGY ABSORBED AND MEASURED IN HEAT UNITS

which the sunlight falls is coated with soot, because the black soot absorbs all the light that falls on it (Art. 271). Since all the energy of the sunshine that falls on the soot is absorbed and converted into heat and since this heat is conducted into the water, the energy received on the sooty surface may be measured in heat units by the product of the weight of the water and its rise in temperature. The number of heat units received on the whole surface divided by the area gives the number of heat units per unit of surface; and this number divided by the time during which the sunshine was received gives the number of heat units received on a unit of surface each minute.

After making due allowance for the disturbances produced by the atmosphere, it is found that each square centimeter perpendicular to the sunlight receives energy at the rate of 2.84 gram-calories per minute. From this the rate at which energy is being received by the earth has been calculated. The result shows that the earth receives from the sun, energy at the rate of about 342 million million horsepower. This would be about 230,000 horsepower for each inhabitant of the earth. Imagine what it would cost to feed so many horses! Yet the earth receives only one two thousand million millionth part of the energy radiated by the sun.

282. Speed of Light. Not only does this rapid-transit system handle such an enormous amount of power, but it also operates with great dispatch. Light travels so fast that for many centuries it was supposed to take no time in transit. For two points within sight of each other on the earth's surface, this is very nearly true.

Nevertheless it is possible, by most refined and delicate measurements, to catch the light in transit and find out how fast it really goes. Many measurements of the speed of light have been made, among the best of which are those made by the American physicist Michelson, and the results tell us that light travels at the rate of 186,000 miles a second. If a railway train could travel at this rate, it could run com-

pletely around the earth about $7\frac{1}{2}$ times in one second. We think the Twentieth Century Limited travels rapidly, when it goes from New York to Chicago in 18 hours; but light can cover that distance in one two-hundredth of a second.

While the speed of light seems tremendous when compared with speeds with which we are familiar, we must remember that it has enormous distances to traverse. It takes light about 8 minutes to come from the sun to us. The nearest of the fixed stars is so far away that light requires three and a half years to travel from it to the earth. If this star should explode now, we should not see the explosion for three and a half years. The most distant stars that we can see are so far away that it takes light some 5000 years to traverse the distance between us and them. If there were people near those stars, and if they could see what was happening on the earth, they would now see what took place here 5000 years ago.

283. How Energy Travels from Sun to Earth. We have seen how energy may be transported from one place to another by waves (Art. 222). We find that enormous amounts of energy are constantly being received by the earth from the sun (Art. 281). Let us therefore make the hypothesis that the transfer of energy from the sun to us is accomplished by waves of some sort, and then see if other facts support or disprove this hypothesis.

In Art. 217 we found that sound waves would not travel across a space from which the air had been pumped. In other words, a suitable medium is necessary for the existence of waves. So if this solar energy is carried by waves, the waves must have a medium in which to travel.

The common incandescent electric lamp consists of a carbon filament contained in a glass bulb from which the air has been pumped. Yet when the filament is sufficiently heated by the electric current, light comes to us through the vacuum in the bulb. Although we are sure that the earth's atmosphere does not extend to the sun, yet light from the sun and stars reaches us. So air is not the medium through

which light travels. But since a medium is necessary for the transmission of waves, the hypothesis that light is a wave motion carries with it the further hypothesis that space is filled with a medium through which light can travel. This hypothetical medium is called the *ether*. The hypothesis concerning the transmission of light is therefore stated in the form:

Light is transmitted by waves in the ether.

284. Bending of a Beam of Light. Although light usually travels in straight lines (Art. 244), a glass prism bends it from its straight path (Art. 270). A straight stick appears bent when part of it is dipped into a pool of water. A straight straw in a glass of lemonade seems to be bent at the surface of the liquid. Light travels in straight lines only so long as the substance through which it is passing remains the same. When a beam of light which is traveling through air falls obliquely on a surface of water, the beam is

bent downward (Fig. 160). This bending of the light at the surface where two different substances meet is called *refraction*.

In order to see how refraction may be described on the theory that light is transmitted by waves, let us imagine that we have a beam of light of



FIG. 160 LIGHT IS REFRACTED IN PASSING FROM ONE MEDIUM INTO ANOTHER

width ab (Fig. 161), traveling in air, and approaching a surface of water ac . Let the direction in which the light is traveling be represented by bc . The fronts of the advancing waves are represented by the lines parallel to ab , which is perpendicular to bc . When the light has entered the water, we find that it is traveling in the direction ce ; so

that the wave fronts, which in the water are perpendicular to ce , the new direction of travel, have been turned from the direction ab to that of cd . This result would be accomplished if that portion of the wave near b traveled the distance bc through air in the same time that was taken by the portion of the wave near a to travel the distance ad through water. But ad is less than bc —i. e., *light-waves travel more slowly through water than through air.*

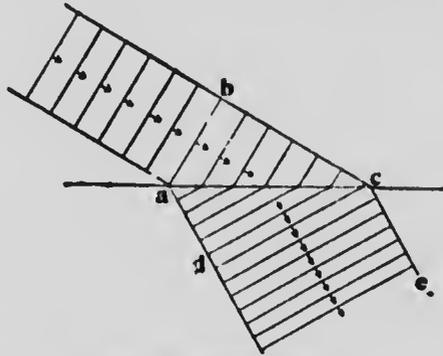


FIG. 161 REFRACTION

The speed with which light travels through water has been directly measured, and it is found to be less than its speed through air in the same proportion as the distance ad is less than bc . This fact strengthens our belief that the wave theory of light is correct.

285. Refraction by Lenses. If the surface ac (Fig. 161), is the dividing surface between air and a plate of glass, the beam bc is found to be bent in the glass in the same manner as in the water.

Therefore, *light travels more slowly through glass than through air.*

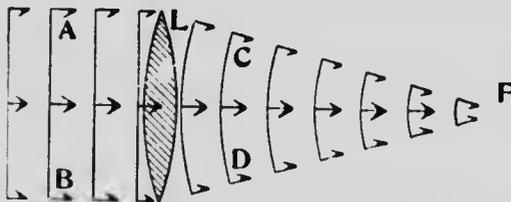


FIG. 162 THE STRAIGHT WAVES ARE CURVED BY THE LENS

If the lines parallel to AB (Fig. 162) represent a series of parallel wave fronts approaching the converging lens L , then since the lens is thicker in the middle than it is at the rim, that portion of each wave which passes through the middle of the lens has to travel through more glass than the portions of the wave near the rim do.

But since light travels more slowly in glass than in air, the center of the wave will be retarded more than the edges; so that the wave fronts will be bent into concave curves parallel to CD when they come out of the lens. Such curved waves come to a focus at F , just as we know light does (Art. 249). Thus the action of lenses helps confirm the belief that light is propagated by wave motion.

286. Colors of Soap Bubbles. Every one has noticed the beautiful colors on the surface of large soap bubbles. On the bubbles themselves, it is difficult to study these colors. But if the top of an ordinary round tumbler (Fig. 163) is dipped in the soapsuds used for blowing bubbles, and then placed horizontally on the table, as shown in the figure, the



FIG. 163 COLORED BANDS ON A SOAP FILM

film of soapy water over its open end will soon become covered with bands of colors.

If this soap film is observed in the light from burning alcohol in which salt has been dissolved (Art. 273), it will appear to be crossed by a series of bright yellow bands separated by dark bands. If observed in light transmitted by a red glass, a series of wider red and black bands appears.

The theory that light is a wave motion enables us to see how these black bands are produced. The soap film is really a very thin wedge of soapy water RPO (Fig. 164). When light falls on it in the direction ab , some of the light is reflected at a in the direction ad , and some more of it penetrates the film and is reflected at the second surface at b in the direction ce . The vibratory disturbance produced at a by the incident light



FIG. 164 SOAP FILM DIAGRAM

thus sends one train of waves to the eye along the path ad , and another along the path $abce$. But because the train of waves that comes to the eye along the path ce has had to travel the distance abc more than the waves that come along the path ad , and since they started together at a , the waves that come along ce will be a number of waves behind the waves along ad . If the distance abc is such that the former is half a wave behind the latter, the crest of each wave along ad will fall in the trough of a wave along ce . Then the two waves will neutralize each other, and the strip ac on the film will appear dark.

Since the thickness of the film gradually increases from top to bottom, the length of the extra path abc of the light reflected from the rear surface gradually increases. When the thickness is such that this extra path amounts to a whole wave, the waves in the two reflected trains come from the film crest on crest and trough on trough. These waves re-enforce each other, and the film appears bright. When the extra path of the second train of waves amounts to $1\frac{1}{2}$ waves, a dark band appears; and so on.

The fact that two beams of light may be so united as to destroy each other's effects is further evidence that light is a wave motion.

287. Color and Wave Length. The dark and bright bands in the soap film furnish a means of measuring the length of the light-waves. If we can measure the thickness of the film at a place where a dark band occurs, and find out how many light-waves one train of waves is behind the other, we have the data for calculating the length of a light-wave. It is difficult to do this with a soap film; but the same phenomena may be obtained in other ways, in which the measurements may be made without serious difficulty.

As a result of such measurements it is found that the waves of red light are about $\frac{1}{30,000}$ inch long. The waves of blue light are only $\frac{1}{50,000}$ inch long. The other colors have waves

between these limits, the wave lengths of the colors becoming shorter as we go along the spectrum from red to blue.

Lights of different colors are due to waves of different lengths.

When we consider how fast light travels, the shortness of the waves is very astonishing. In Art. 225 it was proved that the speed with which a wave travels is equal to the product of the frequency and the wave length. Hence the frequency of the blue waves may be found by dividing the speed (i.e., 186,000 miles per second, reduced to inches) by the wave length (i.e., $\frac{1}{50,000}$ inch). The result for the blue waves is 600,000,000,000,000 vibrations per second. The vibrating particles that start these waves must be extremely minute to be able to vibrate as fast as this.

288. Invisible Radiations. Heat Waves. The visible spectrum extends only from red to violet (Art. 270). But if a sensitive thermometer, with its bulb blackened to make it absorb better, be held just beyond the red end of the solar spectrum, the temperature indicated by the thermometer will rise, although no light is visible there. With sensitive instruments for detecting heat, a heat effect can be traced far out from the red end of the visible spectrum. Because this ultra-red spectrum cannot be seen, and can be detected only by instruments that are sensitive to heat, it is called the *heat spectrum*.

Whenever you stand near an open fire you feel the warmth from the fire, just as you feel the warmth from the sun when you stand in the sunshine. Under these circumstances the heat is not carried by conduction (Art. 107) or convection (Art. 106). It is transmitted by radiation, just as light is. Heat transmitted by radiation is called *radiant heat*.

Since red light consists of longer waves than blue light, and since the heat spectrum always accompanies the visible spectrum but lies beyond its red end, we conclude that

Radiant heat is transmitted by waves just as light is.

Heat waves are longer than light waves.

289. The Complete Spectrum. Photographs of the spectrum have been taken, and these show that it extends far beyond the violet end of the visible spectrum. Although invisible to the eye, these ultra-violet radiations act even more strongly than visible light on photographic plates. With their aid we can photograph things that we cannot see. Besides affecting photographic plates, the ultra-violet beams cause other chemical changes. They fade artificial coloring matters, cause tan and sunburn, assist in the growth of plants, and kill many kinds of deadly disease germs. Since the ultra-violet, as its name implies, lies beyond the blue of the visible spectrum, this *ultra-violet radiation is of the same nature as light, but its wave lengths are shorter.*

The complete spectrum is thus very much longer than the visible spectrum. It is made up of three parts; namely, the ultra-red or heat spectrum, the visible spectrum, and the ultra-violet spectrum.

290. Eye Power. Although the amount of energy carried each day from the sun to the earth by the ether waves is tremendous (Art. 28¹), yet the eye which receives the light is an organ of extraordinary sensitiveness. When the eye is placed at a distance of 3 feet from a candle, the light seems bright. Yet under these conditions the light energy received each second by the eye is equivalent to only $\frac{1}{1000}$ of a gram-centimeter. At this rate it would take the light over a year to heat one gram of water 1° C.

With the naked eye we can see faint stars by light that is so feeble that its energy is too small to be measured exactly by any method yet known. The rate at which the eye receives energy from such stars has been carefully estimated, and it is found that it would take the light energy received at that rate about 100,000,000 years to heat 1 gram of water 1° C. Yet the eye perceives it without effort.

The greater part of the energy in sunlight is carried by heat waves, only about 3% of it being in the form of light. Thus heat and light travel together from the sun to warm and

illuminate the earth; but though radiant heat and light are of the same nature, the energy they carry is so distributed between them that each is fully adapted to accomplish its own special mission, either here on our earth, or millions upon millions of miles away among the suns and stars of other parts of the universe.

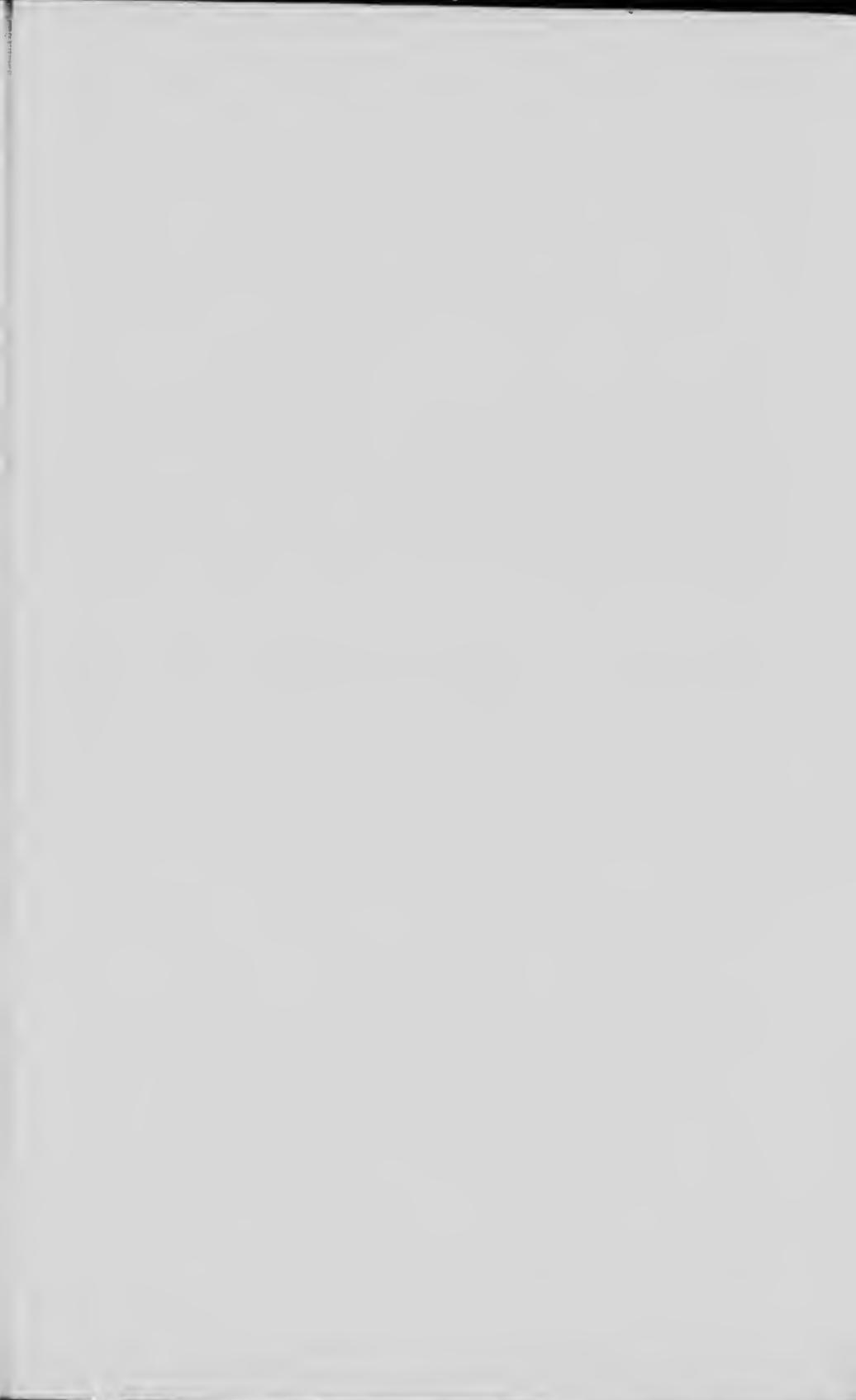
DEFINITIONS AND PRINCIPLES

1. The sun is our ultimate source of light and heat.
2. Light travels at the rate of 186,000 miles per second.
3. Light travels more slowly in water or in glass than it does in a vacuum or in air.
4. Refraction is caused by the change in speed, when light passes obliquely from one medium into another.
5. Lenses bring the light to a focus by causing the wave fronts to become curved.
6. Two beams of light from the same source may be made to meet so as to destroy each other's effects and produce dark bands called "interference fringes."
7. The refraction of light and the "interference experiments" lead to the supposition that light is a wave motion in the ether. All other light phenomena are satisfactorily explained by this supposition. It is therefore accepted as an established theory.
8. By means of interference experiments light waves have been measured; and their lengths are found to vary from $\frac{1}{30,000}$ inch (red) to $\frac{1}{50,000}$ inch (blue).
9. The ultra-red invisible heat spectrum is caused by ether waves that are much longer than the red waves.
10. The ultra-violet invisible spectrum is caused by chemically active ether waves that are shorter than the violet waves.

QUESTIONS AND PROBLEMS

1. How long does it take light to travel across the earth's orbit, if the diameter is 186,000,000 miles?

2. One of the planet Jupiter's moons is "eclipsed" by passing behind it every $1\frac{3}{4}$ days. Does the answer to the preceding question explain why the eclipse is seen "behind time" instead of "on time" when the earth is on the opposite of the sun from Jupiter?
3. The Danish astronomer Römer found that the eclipse of Jupiter's moons were seen 16.3 minutes later when the earth was at the opposite point from Jupiter in its orbit than when it was at the point nearest to Jupiter. Römer was the first to attribute the delay in seeing the eclipse to the time required by the light to travel across the earth's orbit, a distance of 186,000,000 miles. From these data he calculated the speed of light. What is the speed?
4. Show by a diagram how refraction makes a cent in the bottom of a pan of water appear higher up than it really is.
5. If an Indian shoots an arrow at a fish down in the water must he aim at the fish or above or below it? Show by a diagram?
6. With a simple diagram explain how refraction takes place.
7. Show by diagram how a lens focuses a beam of light that has plane wave fronts.
8. Suggest a simple method of measuring the principal focal length of a lens.
9. What relations must exist between two trains of waves from the same source if they are to destroy each other's effects? If they are to intensify each other's effects?
10. Give a simple explanation of the interference fringes (i. e., the bright yellow and black bands) seen in a soap film by yellow light.
11. How long are the waves that cause our color sensations?
12. What proof does an ordinary electric glow lamp furnish that light waves are not air waves.
13. No one has ever seen or weighed ether, why do we believe that there is such a medium?
14. What is the difference between light and "radiant heat"?
15. What is the difference between visible light and ultra-violet light?
16. Why does paper burn when an image of the sun is focussed on it with a lens?
17. Can you account for the twilight after sunset by the refractive power of the atmosphere? How?
18. Can you account for red sunsets by refraction of the atmosphere? How?
19. Thin smoke and other fine particles floating in the air reflect short waves of light more than the long ones. Does this help to explain why the sky is blue, and why the sun looks red after forest fires?
20. Many petroleum oils look bluish green when the light falls on them from behind the observer, and yellowish red when held between the eye and the sun. Explain.



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PART TWO

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CHAPTER XVI

COMPOSITE MACHINES

291. Mechanical Advantage. In Art. 18, it was found that when a heavy body is raised through a vertical height by pushing it upward along an inclined plane of a certain length,

$$\text{Resistance} \times \text{Height} = \text{Effort} \times \text{Length}.$$

If we divide both members of this equation by the height of the plane, the result is

$$\text{Resistance} = \text{Effort} \times \frac{\text{Length}}{\text{Height}}.$$

Supposing the length of the plane to be 12 feet and the height

3 feet, the quantity, $\frac{\text{Length}}{\text{Height}} = \frac{12}{3} = 4$. For this particular

plane, then, $\text{Resistance} = \text{Effort} \times 4$; or the greatest resistance that can be overcome with this plane is equal to 4 times the effort applied. If then we wish to know the resistance that may be overcome with this plane when an effort of 100 pounds is applied, we have only to make the mental calculation, $\text{Resistance} = 100 \times 4 = 400$ pounds. Conversely if we are to raise a weight of 600 pounds with this plane, the effort = $\frac{600}{4} = 150$ pounds.

This number, which tells relatively how great a resistance can be overcome with a machine when a given effort is applied to it, is called the *mechanical advantage* of the machine. *The mechanical advantage of a machine is the number by which the effort must be multiplied to get the resistance.*

From this definition it follows that

$$\text{Effort} \times \text{Mechanical Advantage} = \text{Resistance}.$$

292. Mechanical Advantage of the Simple Machines. By carefully considering the discussions of the simple ma-

chines in Arts. 18-28 and the work equation (Art. 291 in connection with the discussion of Art. 291, the following statements may be clearly understood.

(a) The mechanical advantage of the inclined plane when the effort acts along the plane is equal to $\frac{\text{Length}}{\text{Height}}$

(b) The mechanical advantage of the wheel and axle is equal to $\frac{\text{circumference of wheel}}{\text{circumference of axle}}$, or to $\frac{\text{diameter of wheel}}{\text{diameter of axle}}$ or to $\frac{\text{radius of wheel}}{\text{radius of axle}}$.

(c) For any machine whatever

$$\frac{\text{Resistance}}{\text{Effort}} = \frac{\text{Displacement of Effort}}{\text{Displacement of Resistance}} = \text{Mechanical Advantage.}$$

293. Compound Lever. Nearly all composite machines can readily be seen to be made up of parts that act in accordance with the principles of the simple machines. Thus the compound lever (Fig. 165) illustrates a principle which is applied in the hardware merchant's platform scales.

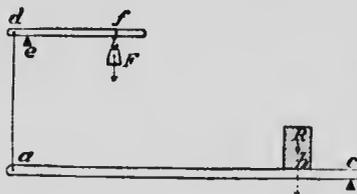


FIG. 165 COMPOUND LEVER

It consists of a lever def of the first kind, which turns about a fulcrum at e , and acts at a on another lever abc of the second kind so as to turn it about the fulcrum a and make it balance the weight of R at b . For the first lever the effort arm $ef = 12$ inches and the resistance arm $de = 2$ inches, so its mechanical advantage is $\frac{12}{2} = 6$, i. e., the force exerted at a by d is 6 times the force F . But for the second lever the effort arm $ac = 48$ inches and the resistance arm $bc = 4$ inches, therefore its mechanical advantage is $\frac{48}{4} = 12$. Hence, since the pull by F at $a = F \times 6$, and since the resistance that can be lifted at R by any force at a is 12 times that force, the resistance $R = F \times 6 \times 12$, or $R = F \times 72$.

The mechanical advantage of the combination (i. e. $\frac{R}{F} = 72$) is thus found to be the product of the mechanical advantages of the two simple machines that compose it. Similar reasoning with any composite machine will be found to give a similar result; so we may say that *the mechanical advantage of a composite machine is the product of the mechanical advantages of its component parts.*

294. Geared Windlass. This combination (Fig. 166) consists of a windlass AB and a wheel and an axle CD .

AB drives CD by means of teeth or cogs which fit smoothly into the teeth of C . The resistance W is thus overcome by winding the rope on the axle D .

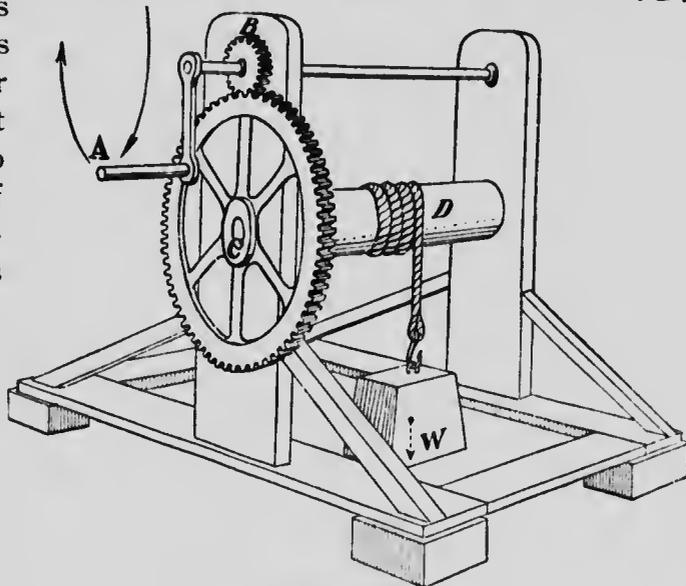


FIG. 166 GEARED WINDLASS

Suppose the circumference of the circle in which the crank handle A moves is 36 inches, and that the circumferences of the wheels B and C and of the axle D are 9, 48, and 12 inches respectively. Then for one revolution of the crank, the displacements of A and B are 36 inches and 9 inches respectively; so the mechanical advantage of AB is $\frac{36}{9} = 4$. In like manner the mechanical advantage of $CD = \frac{48}{12} = 4$. Hence the mechanical advantage of the combination $= 4 \times 4 = 16$, i. e. a force of 100 pounds at A would balance a pull of 1600 pounds at D .

Such a machine is often combined with a pulley in the *derrick* and in the *crane*, which are used for hoisting heavy stones and steel girders in the construction of buildings and bridges.

295. Train of Cog Wheels. Instead of only two cog wheels we may have several, geared one into another as in Fig 167. The mechanical advantage for a combination of any number of wheels is found by the same principle as for two (Arts. 293 and 294). If a, b, c represent the circumferences of the larger wheels, and a', b', c' those of the corresponding smaller wheels as in the diagram, the mechanical advantage = $\frac{a \times b \times c}{a' \times b' \times c'}$. Since the numbers of teeth in the

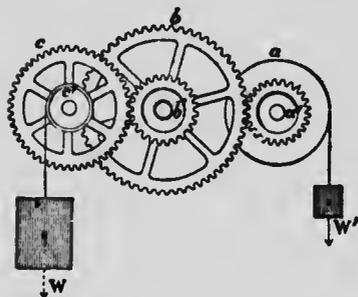


FIG. 167 TRAIN OF COG WHEELS

wheels are proportional to their circumferences, we may let the letters a', b, b', c represent the numbers of teeth in the wheels instead of the numbers of inches in their circumferences; and the calculation for the mechanical advantage will give the same result. It is sometimes more convenient to count the teeth than to measure the circumferences. Such trains of cog wheels are used in the running gears of trolley cars, elevators, and turning-lathes to increase the speed and reduce the necessary force, or vice versa.

Gear wheels are also used in clocks. The minute hand and the hour hand are attached to cog wheels that are so geared to the driving wheel that the former goes around once an hour while the latter goes around once in 12 hours, or $\frac{1}{12}$ as fast. The speed of the driving wheel is controlled by the regular swings of the pendulum, which in its turn is kept going by little pushes communicated to it at each swing by a toothed wheel that is properly geared to the driving wheel. The driving wheel is kept going either by a weight (as at

Wc' Fig. 167), or by a spring, which is wound up by the familiar clock key.

296. Friction. In our studies of simple machines, of steam engines and of motors and dynamos, we found that whenever a machine runs and does work, some of the energy is used in overcoming friction. This energy is converted into heat, which is wasted by being radiated and conducted out into space. *By friction we generally mean the resistance that must be overcome in moving one surface over another.*

The *sliding friction* between rough solid surfaces is caused in most part by the fact that the minute hills and valleys, so to speak, of the two rough surfaces fit into each other to a greater or less extent (Fig. 168), so that when one object is pulled along over the other, work is done in dragging the hills of one up out of the valleys of the other, or else in breaking off the hills of both and smoothing them down.

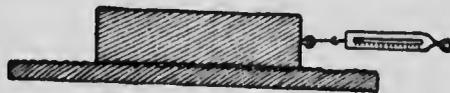


FIG. 168 SLIDING FRICTION

297. Rolling Friction. When a wheel rolls over a smooth track, as in Fig. 169, its weight and the weight of its load not only flatten it a very little, but also cause it to make a slight depression in the track. So, as it rolls along, it is always slightly flattened, and always forced to climb up out of the depression. Although it is not so easy to detect this depression in the case of a car wheel on a steel track as in the case of a heavily loaded wagon on a soft road, it is there, nevertheless, and gives rise to what is called *rolling friction*.

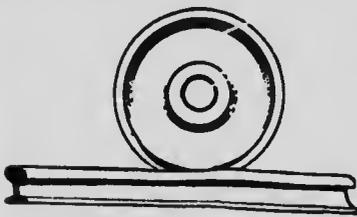


FIG. 169 ROLLING FRICTION

298. How Friction is Reduced. The various methods of reducing friction are very familiar. The runners of skates and sleds are faced with hard, smooth steel. Roads over

which wagons are to be driven are made hard and smooth. The axles of car wheels and the spindles of lathes revolve in bearings provided with "bushings" (i. e., rings) of brass or babbitt metal, and are lubricated with graphite or oil. If the oil gives out, the result is a "hot box" and the bearings wear "out of true."

The bearings of lawn mowers, sewing machines, bicycles, and automobiles are provided with hard steel balls which roll around the axle (Fig. 170) as it turns. It is becoming quite common nowadays to fit the bearings of very heavy machinery with rollers, which act like the balls in ball bearings.

Two other well known facts about friction are illustrated by the action of a loaded sled. We find that the force

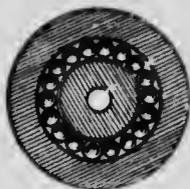


FIG. 170
BALL BEARINGS

necessary to get the sled started is greater than that necessary to keep it going. When it is once started, however, the frictional resistance is approximately the same for all speeds. We find also that the more heavily the sled is loaded, the harder it presses against the road; and the greater the force with which the sled is pressed against the

road, the greater the resistance of friction. All these facts about friction may be briefly summed up in the following statements, which are sometimes called the *laws of friction*.

1. *The harder and smoother the surfaces the less the friction.*
2. *Friction may be reduced by making the two surfaces of different materials and by using a suitable lubricant.*
3. *Rolling friction is less than sliding friction.*
4. *Friction is greatest at starting, but after starting it is approximately the same for all speeds.*
5. *Other things being equal, the total force of friction between two surfaces is proportional to the force that presses them together.*

299. Coefficient of Friction. If the block (Fig. 168) is pulled along the board with uniform motion, the reading of

the spring balance measures the friction. If the board is horizontal, the weight of the block is the force by which the block and board are pressed together. Suppose the force of friction is found to be 2 pounds. Suppose also the pressing force (i. e., the force that is pressing the two surfaces together, the weight of the block in this case) is 8 pounds. If we divide the friction by the pressing force, the quotient, i. e., $\frac{2}{8} = \frac{1}{4}$, or 25%, tells us that the friction between the two surfaces is $\frac{1}{4}$ (or 25%) of the force that is pressing the surfaces together.

The fraction, $\frac{\text{Friction}}{\text{Pressing force}}$ is called the *coefficient of sliding friction* for the two materials. The coefficient of friction is *the number by which the pressing force must be multiplied in order to find the amount of the friction.*

If several experiments be made with the same block and board, loading the block each time with a different weight, so as to have different pressing forces, it will be found that the coefficients of friction thus obtained have approximately the same value; i. e., *for any two given materials the coefficient of friction is approximately constant.* This is only another way of stating law 5, Art. 298.

300. Resistance of a Fluid. Besides friction of solids, another kind of resistance to motion has to be considered, namely, the resistance of the air. When boats or fishes move through water, a similar but greater resistance is offered to their motion by the water. The resistance offered by fluids, such as water or air, to bodies that are moving through them may be included under the general term *fluid resistance.*

The greater part of fluid resistance arises from the fact that the moving body must do the work of pushing away those portions of the fluid that are directly in front of it, just as a snow plow pushes away the snow from a road, or as a farmer's plow pushes away the soil and piles it up beside the furrow. This suggests why the bodies of swiftly swimming fishes and of swiftly flying birds are tapered

toward a point in front, and when they also have a more gradual taper toward the rear

The short sharp prow and the slender tapering stern of the racing boat or the airship are made in imitation of the shape of the fish and the bird, in order to reduce the fluid

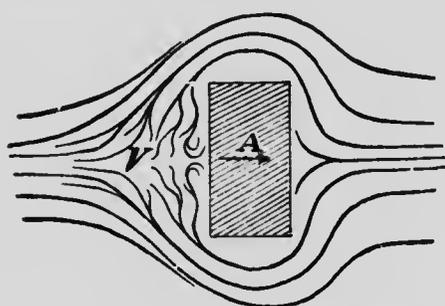


FIG. 171 FLUID RESISTANCE

resistance as much as possible. The advantage of the fish shaped model may be understood in a general way by considering Fig. 171. When the rectangular body A is rapidly pushed through a fluid in the direction of the arrow, the fluid is piled up or crowded together in front, as at C , and opposes the motion. A corresponding depression or partial vacuum at V behind results from the motion. Into this triangular area of low pressure V , the fluid is continually whirling in eddies, trying to fill it up. So the motion is opposed by a resultant resistance equal to the difference between the high pressure at C and the low pressure at V . Fig. 172 shows how the sharp prow p and the long tapering stern s reduce both the piling up at C and the depression or vacuum effect at V , and so diminish the fluid resistance by making the difference $C - V$ smaller.

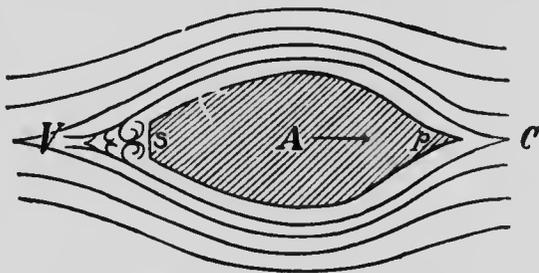


FIG. 172 REDUCTION OF FLUID RESISTANCE

It is found by experiment that when the speed is doubled the fluid resistance becomes 4 times as great, when the speed is tripled it becomes 9 times as great, and so on; i. e., other things being equal, *the resistance of a fluid to the motion of a body through it is proportional to the square of the speed.* This is true only approximately and for moderate speeds.

If the speed becomes very high, the resistance increases much faster than this.

Fluid resistance is a serious hindrance to the attainment of high speeds with boats, railway trains, automobiles, and dirigible balloons. At high speeds the greatest part of the fuel that is consumed in driving the machine is used in furnishing energy to overcome the resistance of the water or of the air. On the other hand, without fluid resistance no boat could propel itself, and neither bird nor aeroplane could fly.

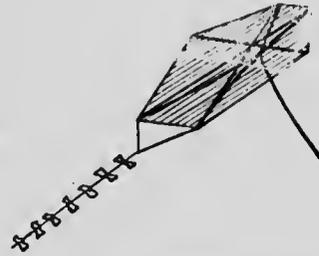


FIG. 173 THE COMMON KITE

301. Kite Flying. The kite (Fig. 173) is composed of a light rigid frame, covered with paper or cloth, which exposes a large surface to the air. When the kite is "standing," it is in equilibrium under the action of three forces. Let the thick line AB (Fig. 174) represent the cloth surface of the kite seen edgewise. Two forces are acting on the kite trying to pull it downward: 1, its weight, represented by the

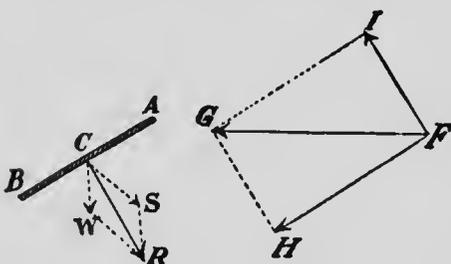


FIG. 174 FORCES ACTING ON KITE

line CW ; 2, the pull of the string, represented by CS . By the principle of the parallelogram of forces (Art. 41) we find that these two forces are equivalent to the single force represented by CR . Thus in order to keep the kite

in equilibrium, there must exist a third force equal and opposite to CR . This third force is due to the wind, and is represented by FG . When this force FG acts on the surface AB , it is resolved into two components. The first component, FH turns the air and causes it to blow along the surface of the kite, i. e., nearly in the direction AB . The other, FI causes a push perpendicular to AB . This

latter component, then, is the force that balances the combined effect of the weight CW and the pull of the cord CS . It must therefore be equal and opposite to their resultant CR .

If the kite is made heavier, CW becomes greater; and a stronger wind is required to make the kite "stand." So also if the kite has risen higher, more cord is unwound and its weight makes the pull CS greater, so the wind must be stronger to balance this extra pull also. On the other hand if the wind increases when the kite is "standing," FI becomes greater than CR , and the kite rises to a position wherein the resultant of its weight and the increased pull of the cord is just sufficient to balance the new force of the wind against it.

302. Stability of a Kite. Boys know that a kite of ordinary form will "dart" and turn somersaults if the bridle by which the string is attached to the frame happens to slip up or down or sidewise, so that the pull is not properly centered. The center of the pull of the cord must coincide with the center of the wind pressure and with the center of gravity of the kite, otherwise the plane of the kite will tend to revolve in one direction or another and the kite will not "stand." The air currents are extremely variable near the earth, because its surface is so irregular and so unevenly heated. Also a very slight change in the direction of the air currents about the kite will cause a difference in the position of the center of pressure (i. e., the point where the resultant effect of the wind acts), and will quickly turn the kite. It therefore becomes necessary to have some means of adding to its stability. In the ordinary form of kite this means is the tail, which, by its inertia and the resistance of the air on it, opposes rapid turning of the kite in any direction.

The more modern box kite (Fig. 175) consists of a rectangular frame around the front and rear ends of which are stretched two strips of cloth, so as to make equal short rectangular-sided tubes, like a pair of open boxes with their

bottoms knocked out. The upper and lower surfaces of each box act just like the surface of an ordinary kite, or like two kites with their surfaces parallel. In the combination, the front box may be regarded as a double kite, and the rear box as a double tail. Since the rear box is separated by some distance from the front box, it acts like the long tail

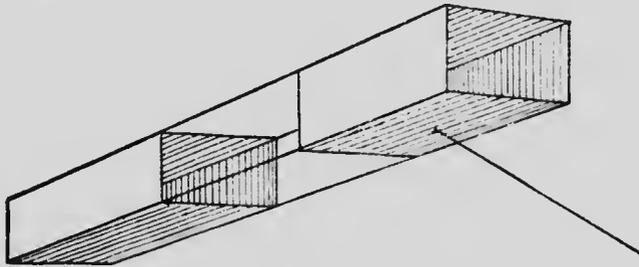


FIG. 175 BOX KITE

of the ordinary kite in opposing sudden changes of direction. The horizontal surfaces of the rear box oppose any sudden turning in the up and down direction, while the vertical surfaces of both boxes oppose any sudden turning to one side or the other. The "box" kite is therefore very steady.

303. Aeroplanes. We are now in a position to understand the principles on which the aeroplane or heavier-than-air flying machine is built and operated. If a boy wants to fly his box kite when there is no wind at the surface of the earth, he runs rapidly and pulls the kite along by the string. The plane surface of the kite then encounters the resistance of the air, which acts on it just like a wind having a speed the same as that with which the boy pulls the kite. The kite then rises into the upper air, where it may find a wind that will make it stand.

If instead of pulling the kite forward with a string, the boy placed on the floor of the front box a very light but powerful motor with a light propeller shaped like an electric fan, then by means of this rapidly revolving propeller, he

could push the kite forward just as fast as, before, he pulled it forward by the string; and it would fly in just the same way. He would then be the owner of a "biplane" type of aeroplane, like those used by the Wright brothers, Curtiss and Hamilton in this country and Henri Farman in France.

Fig. 176 shows how the forces act on the plane. Let f represent the amount and direction of the force with which

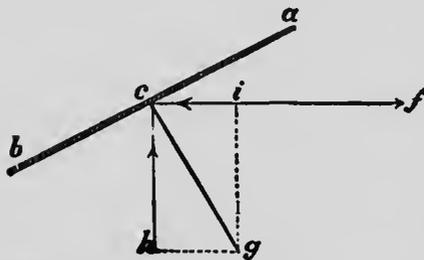


FIG. 176 FORCES ACTING ON AEROPLANE

the propeller drives the aeroplane ab forward. The motion in the direction ab pushes the plane against the air and develops a resistance of the air that acts perpendicularly against the plane. This resistance is represented in direction and magnitude by gc . This force gc is in its turn resolved into two components; one ic , which tends to resist the forward motion of the aeroplane, and the other hc , which tends to support its weight.

Since the air resistance is proportional to the number of square feet of the aeroplane surface, and to the square of the speed, it is evident that if the surface of the aeroplane is large enough and the speed fast enough, this component hc will support the aeroplane and its load.

304. Stability of an Aeroplane. Fore and aft stability is maintained by another plane or pair of planes far out to rear, which acts like the rear cell of the box kite. Side to side stability is maintained by some form of small horizontal wings at the sides of the aeroplane, which can be slanted up or down. If the aeroplane tilts down on one side, the wing on that side is inclined upward; so the air rushes under it and lifts it up. At the same time the one on the opposite side is slanted down, so the air rushes over it and pushes it down. In this way any tendency to tip sideways is counteracted.

305. Steering the Aeroplane. In order to turn to one side or the other, the aeroplane must have a rudder, like that of a boat. This consists of a vertical plane or pair of planes which can swing to the right or left like a door on hinges. It is controlled by a steering wheel or a lever, just as the boat rudder is; and when it is turned to the right, it tends to push the rear end of the aeroplane toward the left; so that the front end swings toward the right. The rudder, then, makes the aeroplane go in the direction toward which it slants. In front of the machine is a similar horizontal rudder which makes the front end rise when it is slanted upward, and dip down when it is slanted downward.

306. Monoplanes and Biplanes. Aeroplanes of the type just described resemble most closely the box kites, and belong to the type called biplanes, because the supporting surfaces consist of two planes, one above the other. In another type of aeroplanes, the monoplanes, the supporting surface consists of one plane only, which must therefore have a proportionally greater area. It is modeled after the bird, with its broad wings and long tail, rather than after the box kite. Otherwise the principles of construction and operation are substantially similar for the two types of machine.

The long delay in the perfection of the aeroplane was due to the difficulty in learning to build engines that are very light in proportion to their horsepower. A good aeroplane gasoline engine weighs only a little over 2 pounds per horsepower. As a man is physically constructed, in order to put forth one horsepower he would have to weigh $\frac{1}{2}$ ton. A domestic goose weighs about 12 pounds, and develops about $\frac{1}{12}$ horsepower when flying. It weighs, therefore, about 144 pounds per horsepower. It is very easy to see that a man would never be able to fly with his own muscular power. A goose can fly but cannot carry much more than its own weight; while an aeroplane equipped with a gasoline motor can carry its own weight, together with

that of a man and enough fuel in the shape of gasoline supply its needs for several hours.

DEFINITIONS AND PRINCIPLES

1. The mechanical advantage of a machine is the number by which the effort must be multiplied to get the resistance.
2. The mechanical advantage of a composite machine is the product of the mechanical advantages of its parts.
3. Other things being equal, the total force of friction between two surfaces is proportional to the force that presses them together.
4. The coefficient of friction is the number by which the pressing force must be multiplied in order to find the amount of the friction.
5. For two given materials, the coefficient of friction is approximately constant.
6. The resistance of a fluid to the motion of a body passing through it is proportional to the square of the speed.

QUESTIONS AND PROBLEMS

1. What is the mechanical advantage of an inclined plane on which a wagon load of coal that weighs all told 8000 pounds can be pulled up by a force of 800 pounds?
2. If the plane (question 1) has a length of 20 feet, what is its height?
3. How heavy a load can be dragged up an inclined plane having a mechanical advantage of 6 by a horse that can pull with a force of 300 pounds?
4. If an inclined plane has a mechanical advantage of 100, what is the weight of the heaviest train that can be pulled up the incline by an engine pulling with a force of 2000 pounds?
5. A capstan consists of a vertical cylinder which has a diameter of 9 inches, and is turned by a horizontal lever or handspike that measures $4\frac{1}{2}$ feet from the center of the cylinder to its handle. What is the mechanical advantage of the capstan?
6. If the capstan (question 5) has 6 handspikes instead of one, is its mechanical advantage increased?
7. In what respect is the capstan with 6 handspikes (question 6) better than the same capstan with one handspike?

8. The capstan (question 7) is mounted on the deck of a ship and is winding up a rope that is attached to a wharf. If the resistance of the ship to motion toward the wharf is 1800 pounds, with what force must each of the six men push on his handspike?
9. If a bucket full of water weighs 45 pounds, and it is to be raised from a well by a force of 15 pounds, what would be the dimensions of a windlass adapted to the purpose?
10. What is the mechanical advantage of a letter press if the screw thread has 6 turns to the inch and the wheel a circumference of 3 feet?
11. With the letter press (question 10) what force would be exerted on the letter book if a 10-pound force were applied to the wheel?
12. If the saw of a foot-power jig saw moves 4 times as fast as the treadle, what is the mechanical advantage?
13. In the jig saw (question 12) is the resistance that may be overcome by the saw teeth greater or less than the force that is applied by the foot at the treadle?
14. In a compound lever like that in Fig. 165 the first lever has an effort arm of 12 inches and a resistance arm of 3 inches. The end of this resistance arm acts on the effort arm of the second lever, which is 20 inches long. The resistance arm of the second lever is 2 inches long. What force must be applied at the end of the first effort arm to lift with the second lever a weight of 80 pounds?
15. In a geared windlass (Fig. 166) the crank arm is 16 inches long and the cog wheel *B* to which it is attached has 8 teeth. If the cog wheel *C* attached to the winding axle *D* has 72 teeth and the radius of *D* is 6 inches, what force must a man apply to the crank handle to lift a safe weighing 1200 pounds that is suspended on a rope wound around *D*?
16. A wheel *A* having 48 teeth is geared into a wheel *B* having 12, and *B* is rigidly attached to the same axle as a wheel *C* having 120 teeth. *C* is geared into another wheel *D* having 8 teeth. If *A* makes one revolution in an hour how many will *D* make?
17. The driving pulley of a motor in a shop has a diameter of 4 inches and makes 1200 revolutions per minute. It is belted to a pulley 24 inches in diameter which is rigidly fastened to a long shaft. How many revolutions per minute does the shaft make?
18. If a belt (problem 17) keeps slipping when it is driving machinery, in what ways may the trouble be remedied?
19. What use do you make of friction when you walk or run?
20. What use is made of friction in the case of automobiles? In the case of nails and screws? Of corks in bottles?
21. Why do boys put rosin on their hands when performing on a turning bar?
22. Why does a locomotive engineer sometimes put sand on the track?

23. Why do baseball players wear spikes on their shoes?
24. Why is it difficult to walk on ice?
25. Why does an automobile "skid" in going around a corner on a wet pavement?
26. Why are roller skates fitted with ball bearings?
27. What is the advantage of rubbing soap into the grooves between windows and their frames? Of waxing dancing floors?
28. Why will a wagon wheel turn better if the diameter of the axle is as small as the requirements of strength will admit?
29. Why are the ends of the axle of a grindstone often set on little rollers?
30. What force is required to draw a sled along a road if the coefficient of friction is 10% and the sled and load weigh 150 pounds?
31. Of what use is fluid resistance in making a boat go by means of a paddle wheel or propeller?
32. If the water resistance acts against the motion of the boat as well as against that of the propeller, why does the boat go at all?
33. In a fish what takes the place of the propeller? Of the rudder?
34. What means has a fish of maintaining fore and aft stability? Side to side stability?
35. Why is the general form of the fish imitated in airships and boats?
36. How do the propeller, the rudder, and the stability apparatus of a modern airship compare with the fins and tail of a goldfish?
37. What three forces act on a standing kite? Why does the kite sometimes rise higher and sometimes sink lower?
38. Would a kite fly well if a piece of lead were attached to it in place of the tail? Why?
39. On rare occasions a kite has been known to rise vertically over the point on the earth where the string is being held. Can this action be explained by supposing that it has gotten into a vertically ascending current of air?
40. Why does not a box kite need a tail?
41. How does the forward push of an aeroplane propeller cause the air to act on the surface of the plane?
42. Into what two forces is the resistance of the air on an aeroplane resolved?
43. In the case of the aeroplane, against what forces do the two components of the resistance of the air act?
44. If the weight to be carried by an aeroplane is to be increased, how must the aeroplane be altered?
45. How is an aeroplane turned from left to right?
46. How is an aeroplane turned upward or downward?

CHAPTER XVII

HEAT ENGINES

307. Expansion of Heated Air. In Art. 100 we learned that when a mass of air confined in a flask is heated, it expands and does work in pushing the drop of liquid up the tube against the atmospheric pressure (Art. 131). We can find out how much work is done when the flask of air is heated through a number of degrees if we know how much the air expands per degree.

Place a thermometer in the flask (Art. 100); and suppose that the flask contains 273 cubic centimeters of air, and that the temperature of the air is 0°C . Suppose also that the cross section of the upright tube is 0.1 cm^2 (i. e., square centimeter). Then when the air is warmed 1°C . the drop a (Fig. 64) will move 10 cm (i. e., centimeters) up the tube. The increase in the volume of the air is $0.1 \times 10 = 1\text{ cm}^3$ (i. e., cubic centimeter). When the temperature of the air rises to 2°C . the drop a is 20 cm above the starting point. The increase in volume is thus 2 cm^3 for 2°C . rise in temperature. For every rise in temperature of 1°C . the drop moves 10 cm higher.

Since the pressure of the atmosphere remains constant during the experiment, and since the original volume of air was 273 cm^3 , we see that *when a given mass of air is heated at constant pressure, its volume (V_t) increases $\frac{t}{273}$ of its volume at 0°C . (V_o) for every rise of 1°C . in temperature, i. e., when heated to the temperature t ,*

$$V_t = V_o + \frac{t}{273} V_o.$$

By reducing the right-hand member of this equation to the common denominator 273 and factoring out $\frac{V_o}{273}$, it may be reduced to the form

$$V_t = \frac{V_o}{273} (273 + t). \quad (1)$$

Since the fraction $\frac{1}{273}$ tells the ratio of the change in volume produced by a rise of $1^\circ\text{C}.$ in temperature to the volume at $0^\circ\text{C}.$, it is called the *coefficient of expansion of air*. All gases, like hydrogen, oxygen, and nitrogen, have the same coefficient of expansion. The measurements by which these facts were established were first made by two Frenchmen named Charles and Gay Lussac, so this relation is known as the *Law of Charles and Gay Lussac*.

308. Work Done by Expanding Air. When the air in the flask (Art. 100) has expanded 1 cm^3 against atmospheric pressure, the work done is measured by the product of this pressure and the change in volume (Art. 92). In this case the pressure against which the air expands is that of the atmosphere, which is $1033\text{ grams weight per cm}^2$ (Art. 80) and the change in volume is 1 cm^3 , therefore,

$$\text{Work} = 1033 \frac{\text{grams weight}}{\text{cm}^2} \times 1 (\text{cm}^3) = 1033 \text{ g. cm}$$

(i. e., gram-centimeters).

The energy that did this work was supplied by the heat. Therefore the amount of heat required to do this work was (Art. 145)

$$\frac{1033 (\text{gm-cm})}{42700 (\text{gm-cm per calorie})} = 0.024 \text{ gram-calorie (nearly).}$$

Since this amount of heat depends only on the normal atmospheric pressure and on the fact that the volume of air has changed by 1 cm^3 , but does not depend on the original volume of the air or on its original pressure, it follows that: *When any volume of air at any pressure expands 1 cm^3 against normal atmospheric pressure, $0.024\text{ gram-calorie}$ of heat is converted into work.*

When a cubic meter of warm moist air is carried from sea level up the side of a mountain, the atmospheric pressure grows less as the air rises; so the air expands and does work as it moves upward. In order that it may expand and do this work, heat must be supplied. There being no other

source of heat at hand, the air gives up some of its own heat, and its temperature falls. When its temperature falls below the dew point of the water vapor that is mixed with it, the vapor condenses, forming clouds.

309. Heating Air at Constant Volume. The 0.024 gram-calorie of heat that was required to do the work of expansion in the preceding article is not all the heat needed to raise the temperature of air. If we replace the open tube on the flask (Fig. 64) by a tube *ab* bent as shown in Fig. 177 and containing mercury in the bend, and then heat the air, the mercury falls at *a* and rises at *b*. But if, as the heating progresses, we keep pouring more mercury into the tube at *c* we can keep the mercury at *a* at the same level, thereby keeping the volume of the enclosed air constant.

Because mercury has to be poured into *bc* to keep the column at the same level *a*, the pressure of the air in the flask must increase as the air is heated. But since the air is not allowed to expand, it does no external work. The added heat is required merely to warm the air. By measuring the difference in level between the ends of the mercury column at *a* and *b*, we can determine how much the pressure of the air in the flask increases when it is warmed 1°C . Suppose the air was originally at 0°C . and the barometer stood at 76 cm, indicating normal atmospheric pressure. Then the end *b* of the column of mercury rises about 0.3 cm (more accurately, 0.278) for every rise of 1°C . in temperature. Accurate measurements show that *when a mass of air is heated at constant volume, its pressure (P) increases $\frac{1}{273}$ of its pressure at 0°C . (P_0) for every rise of 1°C . in temperature; i. e., when heated to a temperature t ,*

$$P_t = P_0 + \frac{t}{273} P_0.$$

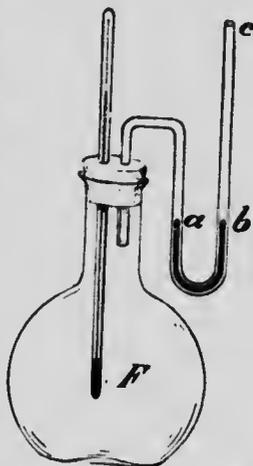


FIG. 177 HEATING AIR AT CONSTANT VOLUME

On reducing to a common denominator and factoring out

$$\frac{P_0}{273} \text{ we get } P_t = \frac{P_0}{273} (273 + t). \quad (2)$$

310. Absolute Temperature Scale. When the air in the flask has been heated at constant volume it can expand and do work, because its pressure has been increased. If, however, the flask is placed in a freezing mixture of ice and salt, and cooled below 0°C ., the pressure (P_t) becomes less than its pressure at 0°C . (P_0); also t in equation (2) becomes negative. If we could cool the air to a temperature 273° below the Centigrade zero, its temperature would be -273°C . Then the value of the factor $(273 + t)$ would be $273 - 273 = 0$. Therefore the pressure P_t at that temperature would also be zero; and if the gas exerted no pressure it could do no work.

We have not yet been able to cool any gas down to -273°C .; and most gases become liquid before reaching that temperature. Nevertheless we believe that if we could cool it that far it would be unable to do any work. So -273°C . has come to be regarded as an "absolute zero," and temperatures are often measured on a scale which begins with this zero. The temperature of melting ice on this "absolute scale" is 273° ; so the magnitude of the degree is the same as that on the Centigrade scale. *Any temperature T on the absolute scale is equal to 273 plus the temperature t on the Centigrade scale; i. e.,*

$$T = 273 + t.$$

Equations (1) and (2), when reduced to absolute temperature become,

$$V_T = \frac{V_{273}}{273} T.$$

$$P_T = \frac{P_{273}}{273} T.$$

The volume of a gas heated at constant pressure is proportional to its absolute temperature.

The pressure of a gas heated at constant volume is proportional to its absolute temperature.

From these principles it follows that when both the pressure and the volume of a given mass of gas change as the temperature changes, the product of the pressure P and the volume V is proportional to the absolute temperature T , i. e.,

$$PV = \text{Constant} \times T.$$

The value of the constant depends on the density of the gas and the units used. For a given gas and given units, it has a fixed value. So when the same gas is heated to some other temperature T' , and its pressure becomes P' and its volume V' , we have

$$P'V' = \text{Constant} \times T'.$$

$$\text{Hence } \frac{PV}{P'V'} = \frac{T}{T'} \text{ or } \frac{PV}{T} = \frac{P'V'}{T'}. \quad (3)$$

Equation (3) is a combination of Boyle's law (Art. 77) and that of Charles and Gay Lussac (Art. 307). It enables us, if we know the pressure, volume, and temperature of a gas, to calculate its pressure at some other volume and temperature, or its volume at some other pressure and temperature.

311. The Air Thermometer. Since the pressure of a given mass of air, when heated at constant volume, increases $\frac{1}{273}$ of its pressure at 0°C . when the temperature rises 1°C ., measurements of the pressure of a given mass of air give a ready means of measuring temperatures. The instrument used for these measurements is called an *air thermometer*.

Fig. 177 is a crude form of air thermometer. Since pouring in the mercury is difficult, the instrument may be improved by cutting the glass tube in two between a and b , and connecting the two ends with a piece of rubber tubing. The mercury may then be kept at the same level at a by raising or lowering the end b .

The form of instrument generally used is shown in Fig. 178. The tube R is connected to the tube R' by the rubber tube K . As the air in the bulb is heated, the mercury in R is kept constantly at the same level d by raising or lowering the tube R' . The pressure due to the difference in level h , when added to the pressure of the barometer, gives the

pressure of the constant volume of air in the bulb. The bulb is packed in melted ice and the pressure P_0 determined. The temperature of the air in the bulb at any other measured pressure P_t is found by equation 2 (Art. 309).

Since the coefficient of expansion of air is large and very constant over a large range of temperature, the air thermometer is the standard thermometer for accurate scientific work.

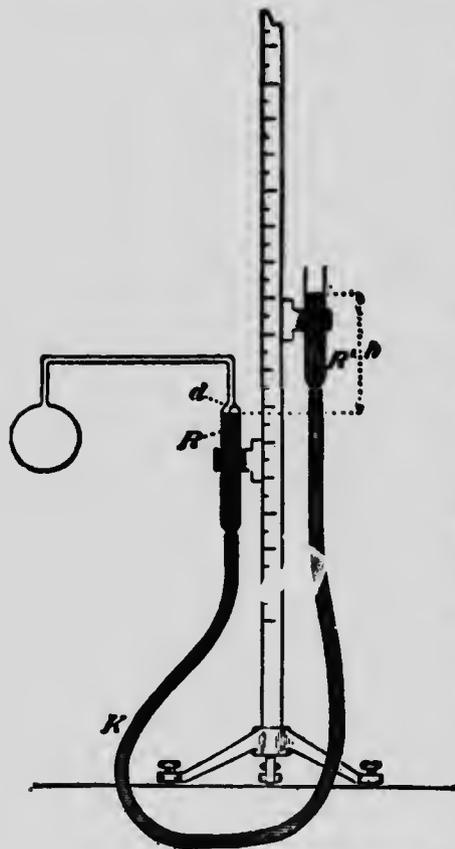


FIG. 178 THE AIR THERMOMETER

312. Energy and Temperature. When a gas expands 1 cm' against atmospheric pressure, 0.024 gram-calorie of heat is converted into work (Art. 308). In order that the gas may expand, its pressure must be greater than that of the atmosphere. So in heat engines some gas or vapor is heated at constant volume until its pressure is raised. The gas or vapor is then allowed to expand in a cylinder and do work. For every 1033 gm-cm of work done 0.024 gram-calorie of heat disappears. If there is no other source of heat at hand, the heat

has to be supplied by the gas itself, and its temperature falls. *The greater the amount of work done by an expanding gas, the greater the fall in its temperature.*

The amount of heat that can be supplied by a gas at a temperature T depends on the mass of the gas and the temperature T . So, *for a given mass of gas, the higher the temperature T , the greater the available amount of heat.*

Therefore, the conditions most favorable for getting work

from heat are: 1. *Have the gas as hot as possible at the start.*
2. *Allow it to cool through the greatest possible range of temperature.*

313. What the Condenser Does. If we have a locomotive boiler with a pressure of 225 pounds to the square inch, the temperature of the steam there is 200°C . (Art. 124). The locomotive exhausts into the air at atmospheric pressure. In order to do this, the steam at exhaust must exert a pressure as great as that of the atmosphere; and hence its temperature must be at least 100°C . (Art. 124). The range in temperature in this locomotive is, therefore, $225 - 100 = 125^{\circ}\text{C}$.; and its efficiency is less than 6% (Art. 146).

If the locomotive were supplied with a condenser which was kept at a temperature of 40°C ., the range of temperature for the steam would be $225 - 40 = 185^{\circ}\text{C}$. A given mass of steam evidently gives up more heat in cooling to 40°C . than in cooling only to 100°C . Therefore, *the condenser increases the range of temperature and so increases the amount of heat available for doing work.*

314. Advantage of a Flash Boiler. The range in temperature in the locomotive might be increased by increasing the temperature of the boiler. As the temperature is increased, the pressure increases also (Art. 123). Since it is not safe to have a high pressure in a large boiler, a limit is placed on the temperature of the boiler at about 225°C .

A thick-walled tube can withstand a much higher pressure than a large boiler. So a "flash boiler," made of a coil of thick-walled steel tubing, can be heated to a much higher temperature than an ordinary boiler—say to 500°C . Boilers of this kind are used in some automobiles and motor boats.

The advantage of the "flash boiler," therefore, lies in the fact that *it enables us to increase the range in temperature, and so to increase the amount of heat available for useful work in a given quantity of steam.*

315. Compound Engines. Suppose we have a condensing engine working between the temperatures of 225°C . and 40°C . The range in temperature is then 185°C . If the engine has but one cylinder, the steam enters it at a temperature of 225°C ., expands, and cools nearly to 40°C . This great range in temperature produces the same trouble that Watt found in the early engines (Art. 137). When the hot steam enters the cylinder that was filled a few seconds before by steam at about 50°C . some of it is condensed in reheating the cooler cylinder. On the other hand, the expanded steam cannot cool to 40°C ., because the hot cylinder tends to keep it warm. So, if the total change of temperature is too great in one cylinder, we are not able to take full advantage of it.

Efforts to get around this difficulty have led to the "compound engine." In this engine the total range of temperature is divided between two or more cylinders. For example, in a triple-expansion engine, working between the temperatures 225°C . and 40°C ., the steam enters the first cylinder at a temperature of 225° and expands, thereby cooling to about 175° . It then enters the second cylinder at about 175° and expands some more, thereby cooling down to about 120° . In the third cylinder it expands until it has cooled down to 40° . The first cylinder has to be smaller than the others, because the hot steam is at a higher pressure. The middle cylinder has a greater diameter than the first; and the last cylinder has a still greater diameter. This is because the pressure of the steam decreases as it cools, and since it is desirable to have each cylinder do one-third of the work, the volume of each cylinder is made larger in the same ratio that the pressure becomes smaller. Thus the product PV (i. e., the work) is the same for each of the cylinders.

By thus dividing the total range of temperature into three steps the loss of heat by condensation in the cylinder is diminished. Another advantage of the compound engine is that it has a piston and a crank for each cylinder, and so gives

two or more thrusts to the shaft each revolution, thereby lessening the jars and strains on the shaft and cranks.

A good triple-expansion condensing engine burns about 1 pound of coal per horsepower hour. Its efficiency is, therefore, about 17% (Art. 146).

316. Steam Turbines. In the engines thus far considered the rotary motion of the drivers or of the flywheel was produced by a translatory motion of the piston to and fro. Engines of this type are therefore called *reciprocating engines*. In all such engines, useless work has to be done in starting and stopping the piston at each stroke; and this action always produces a jarring which is harmful both to the engine and to the building or boat in which it is placed.

Many attempts have been made to construct an engine in which a wheel would be set into rotation by blowing steam against blades or paddles on it after the manner of the water turbine (Art. 91). It is only within the last few years that engineers have learned how to apply this principle so as to make a steam turbine equal in efficiency to the best reciprocating engines.

Fig. 179 is a picture of one of these modern steam turbines. The cover has been removed so that we can see how it is made. Instead of a few large blades, like the water wheel, it has one or more rows of small blades fastened to a steel cylinder called a rotor. High pressure steam is blown through nozzles at high speed against the blades, thereby setting the rotor into rapid rotation. In larger machines the movable blades pass between rows of stationary blades fastened to the case of the machine.

Turbines have now been so far perfected that their efficiencies are somewhat greater than those of reciprocating

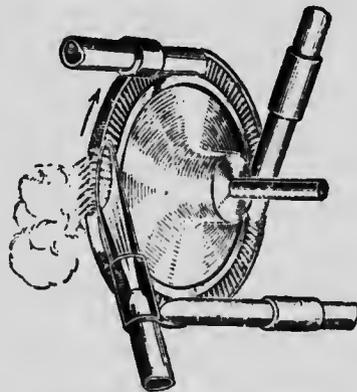


FIG. 179 A STEAM TURBINE

engines. On account of their freedom from jarring, their high efficiency, and their compactness, they are now coming into general use. It is interesting to note that the principle of the steam turbine was known to Hero of Alexandria (B. C. 120). The technical difficulties involved in the practical construction of a steam turbine of high efficiency delayed its perfection for 2000 years.

317. The Gas Engine. In the ordinary steam engine much heat is lost between the fire and the boiler, and the

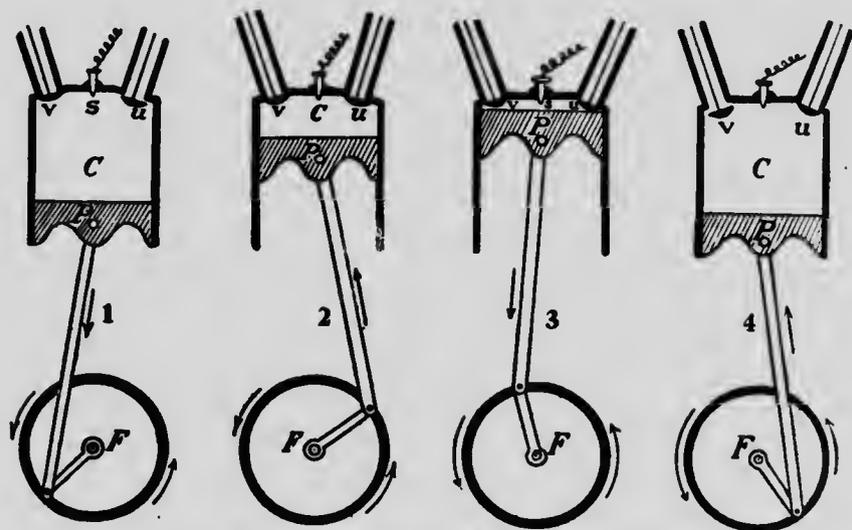


FIG. 180 DIAGRAM OF A FOUR CYCLE GAS ENGINE

possible range of temperature is relatively small. These defects are to a certain extent remedied in the gas engine.

There are four steps or cycles in the operation of the ordinary single cylinder gas engine. These are shown at 1, 2, 3, 4, in Fig. 180. The fly wheel is first turned by hand, until the piston *P* has sucked a mixture of gas and air through the valve *u* into the cylinder *C*, (Cycle 1). The piston *P* is then pushed back by the fly wheel, compressing the mixture in the cylinder (Cycle 2). An electric spark *S* explodes the mixture just as the piston *P* starts forward; and the pressure developed by this explosion pushes the

piston P outward (Cycle 3). It is then pushed back by the rapidly rotating fly wheel F , and the products of combustion are driven from the cylinder through the valve v (Cycle 4).

In the gas engine the fuel is burned in the cylinder, so waste in the furnace and boiler is avoided. Also the temperature of the gases in the cylinder after explosion is very high — 800 to 1000°C. — so the range in temperature is large. We may therefore expect that the efficiency of a gas engine will be high.

A good gas engine consumes about 16 cubic feet of gas from the city mains for every horsepower that it supplies for 1 hour. The heat of combustion of illuminating gas in New York has been found to be 720 B. T. U. per cubic foot. Hence the heat supplied by 16 cubic feet of gas is 11,520 British thermal units. This heat energy is equal to $11,520 \times 778 =$ about 9,000,000 foot-pounds. The number of foot-pounds in one horsepower-hour is about 2,000,000. Therefore the efficiency of a good gas engine is roughly $\frac{2}{3} = 2\frac{2}{3}\%$.

DEFINITIONS AND PRINCIPLES

1. When a mass of air is heated at constant pressure, its volume increases $\frac{1}{273}$ of its volume at 0°C. for every rise of 1°C. in temperature.
2. The coefficient of expansion of air is the ratio of the increase in volume produced by 1°C. rise in temperature to the original volume. Its numerical value is $\frac{1}{273}$.
3. When a volume of gas at any pressure expands 1 cm³ against normal atmospheric pressure, 0.024 gram-calorie of heat is converted into work.
4. When a mass of air is heated at constant volume, its pressure increases $\frac{1}{273}$ of its pressure at 0°C. for every rise of 1°C. in temperature.
5. Less heat is required to raise the temperature of a gas 1°C. at constant volume than to raise it 1°C. at constant pressure; because when the volume remains unchanged no external work is done.

6. The absolute zero is 273°C . below the Centigrade zero.
7. The temperature on the absolute scale is equal to 273 plus the temperature on the Centigrade scale.
8. The volume of a gas heated at constant pressure is proportional to its absolute temperature.
9. The pressure of a gas heated at constant volume is proportional to its absolute temperature.
10. When a gas expands and does work its temperature falls unless it is heated from without.
11. The amount of work that can be done by an expanding gas is proportional to the range in temperature through which it cools.

QUESTIONS

1. When a cubic meter of air at normal barometer pressure and at 0°C . is cooled 1°C ., what happens to it?
2. If a cubic meter of air at normal barometer pressure were cooled to 273°C . below zero, would its volume become zero? Why?
3. When the air is being pumped out of the receiver of an air pump, what is the source of the energy used in expanding the air against atmospheric pressure?
4. If the air in the receiver of the air pump (question 3) were allowed to expand into a steam engine condenser against a pressure of 5 pounds to the square inch, would it cool more than when pumped by an air pump to the same lower pressure? Why?
5. Why does a mass of air when carried by a wind up the side of a mountain become cooler as it is pushed up?
6. Is the gas in a balloon likely to become cooler when the balloon rises rapidly? Why?
7. When a steam whistle is blown we see a white cloud escaping from it. The cloud consists of fine particles of water. Why does the steam condense into these water particles as soon as it has escaped from the whistle?
8. Does it require more heat to raise the temperature of a given mass of air 10°C . at constant volume than at constant pressure? Why?
9. What advantage is gained by using a flash boiler for an automobile or a motor boat engine?
10. If gas engines have higher efficiencies than steam engines, why are they not used more in large power plants?

11. Are gasoline engines better than steam engines for automobiles and motor boats? Why?

12. Can you tell how many revolutions per minute the fly wheel of a single-cylinder gas engine is making by counting the puffs of the exhaust? How?

13. How could the toy water turbine (Fig. 60) be converted into a steam turbine?

14. How could you improve the toy turbine so as to increase its efficiency?

15. Why do we need a number of stationary blades as well as a number of moving blades in a steam turbine, although one set of blades is enough for a water turbine?

PROBLEMS

1. If a cubic meter of air at 0°C . is heated to 273°C . at normal barometer pressure, what will be its final volume?

2. How many gram-centimeters of work were done by the expanding air of problem 1?

3. How many gram-calories of heat were converted into work by the expanding air of problem 1?

4. A gram of air at 0°C . has a volume of 778 cm^3 . How many cm^3 does it occupy when it has been heated to 20°C .?

5. How much work was done by the expanding air in problem 4?

6. How many gram-calories of heat were required to do the work of problem 5?

7. The specific heat of air at constant volume is 0.17 gram-calorie per gram. How many gram-calories of heat must be supplied to heat 778 cm^3 of air at 0°C . and normal barometer pressure to 20°C .?

8. What will be the pressure of the air in problem 7 at the temperature 20°C .?

9. How many more gram-calories were required to heat the air in problem 6 where external work was done than to heat it in problem 8 where no external work was done?

10. Since it requires 0.17 gram-calories to heat a gram of air 1°C . at constant volume, how many gram-calories are required to heat the gram of air 1°C . when it is allowed to expand at normal barometer pressure?

11. What is the specific heat of air at constant pressure?

12. One cubic inch of water makes about 1 cubic foot of steam at normal barometer pressure. How many foot-pounds of external work are done when the water evaporates into the steam?

13. An empty oiled silk balloon lying collapsed on the ground, when filled with illuminating gas occupies a volume of 300 cubic meters. If

the atmospheric pressure is normal, how many gram-calories of heat converted into work in the process of filling the balloon?

14. The coefficient of linear expansion of a bar of metal is the ratio of the increase in length produced by a rise of $1^{\circ}\text{C}.$ in temperature to the original length. An iron steam pipe 996 cm long expands 1 cm when steam is turned on so that it is heated from $17^{\circ}\text{C}.$ to $100^{\circ}\text{C}.$ What is the coefficient of linear expansion of iron?

15. The coefficient of linear expansion of brass is 0.000018. If the steam pipe of problem 14 were made of brass instead of iron, how much would it expand when heated in the same way?

CHAPTER XVIII
ELECTRICITY

318. Electric Sparks by Friction. Most children know that in winter, in a house heated by a furnace, electric sparks accompanied by crackling noises can be obtained by stroking the fur of a cat with the dry hand. A frequent parlor amusement consists of sliding along the carpet in a warm dry room and lighting the gas with the electric spark that jumps from the finger to the burner. Crackling sparks are often seen and heard when the hair is combed with a rubber comb, and the hair is seen to stand up and follow the comb. The ancient Greeks were familiar with a similar phenomenon. When amber ornaments had happened to rub against woolen material they were found to attract threads and other light bodies. Hence the Greeks called amber "electron" which means "clutcher." Later on, when more phenomena of this sort had become known, they were called electrical phenomena, and the "substance" which was thought to be the cause of them was called *electricity*.

319. Electrified Bodies. When a glass rod is rubbed with silk, light bodies of any sort are attracted to it; and after they have come in contact with it are rapidly repelled from it. They are similarly affected by any resinous substance such as sealing wax or shellac. A body that has been rubbed with another body, and in consequence is able to attract other bodies and repel them, is said to be *electrified, or charged with electricity*.

320. Discharge. When the electrified rod of glass or resin comes in contact with any substance that is not charged, it loses a part of its charge of electricity by transferring it to

the uncharged body. The transfer often takes place by means of a spark, with the usual crackling noise. If the charged body be connected with the earth by means of any substance such as the moist hand or a metallic wire, which is an electrical conductor (Art. 158), it loses its charge entirely. It is then said to be *discharged*.

The electricity tends to flow to the earth from a body that is electrically charged, even though the electrical resistance of the body along which it flows is very large (Art. 168). It will often times break through dry air as a spark. Since this is true, we know that there must be a very great difference of potential between a charged body and the earth. Hence a charged body is said to have a *high potential* with reference to the earth. The P. D. necessary to produce a spark 1 inch long is some 75,000 volts. (Arts. 200 and 201)

321. All Substances Electrified by Contact. Electricity developed by rubbing two substances together has been commonly called frictional electricity, but the *contact*, the mere touching rather than the friction, is the necessary condition. Rubbing serves merely to bring the two substances more closely into contact. The early experimenters with electricity, before the invention of the voltaic cell (Art. 152), were unable to get metals electrically charged, and thought that it was impossible to do so. Their failure was due to the fact that the difference between conductors and insulators was not then known. When they tried to electrify a piece of metal that was held in the hand, the metal became electrified; but the charge was not discovered because it immediately traveled through the experimenter's body to the earth. After the discovery of conduction by Stephen Gray of Warwick, England, about the year 1727, it was found that if a piece of any kind of metal be fastened to a rubber or glass handle, and rubbed with flannel or fur, it becomes electrically charged. Various experiments with all sorts of substances have shown that whenever two different substances are brought into contact with each other and

then separated, both substances become charged. Since the electricity on bodies thus charged is not flowing in currents along conductors, but remains at rest until it is discharged, it is often called static electricity, and the charges are called *electrostatic charges*. Any substance may be electrostatically charged by rubbing it with any other substance.

322. Two Kinds of Electric Charges. When two pith balls are suspended by silk threads from an insulating support (A, Fig. 181) and are touched by a glass rod that has been rubbed with silk, they are repelled by the rod. In accordance with Newton's third law of motion (Art. 49) they repel the rod; and they also

repel each other. They also attract and are attracted by a rod of sealing wax that has been rubbed with flannel. Two other suspended pith balls

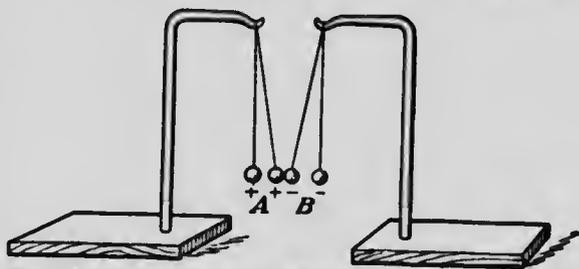


FIG. 181 LIKE CHARGES REPEL: UNLIKE ATTRACT

B likewise repel each other when they have been charged by contact with a rod of sealing wax that has been rubbed with flannel. Now if the charged pair *A* be brought near to the charged pair *B*, the balls *A* still repel each other and the balls *B* still repel each other; but either ball of the pair *A* attracts and is attracted by either ball of the pair *B*. It appears, therefore, that we have on the balls *B* two like charges that repel each other but attract the charges on *A*, and vice versa. So there must be two different kinds or states of electrification; and each kind repels the kind that is like it and attracts the other kind.

The electrification that is developed on glass when rubbed with silk is called *vitreous* or + (i. e., *positive*); and that which develops on sealing wax when rubbed with wool is called *resinous* or - (i. e., *negative*).

Like electrostatic charges repel each other, and unlike attract.

323. The Electroscope. A suspended and insulated pith ball serves as an *electroscope*, by means of which we may detect a charge, and determine its sign. A more sensitive instrument is shown in Fig. 182. It is called a *metal-leaf electroscope*. Instead of a pair of pith balls it has two strips of gold or aluminum leaf, attached to a metal rod. The rod



FIG. 182
THE ELECTROSCOPE

passes through the cork of a flask, and is surmounted by a metal ball or plate. The rod is insulated from the cork by passing it through a glass tube and pouring melted sulphur around it. The flask serves as an insulating support, as well as to keep all moisture and to protect the light and fragile leaves from any disturbing currents of air. A very small charge communicated to the metallic ball or plate at the top is conducted to the leaves, and causes them to repel each other. Also, the greater the charge, the greater the divergence of the leaves. When the ball or plate is touched by the hand, the leaves collapse, showing that the electroscope is discharged.

To test a charge by means of the electroscope, give the leaves a known charge sufficient to cause a moderate divergence.

If a charge of the same sign is brought near, the divergence of the leaves is seen to increase; but if a charge of the opposite sign is brought near, their divergence is seen to diminish. The *proof plane* (Fig. 183) is a disk of metal with an insulating handle. It is used to carry a small charge from a charged body to the electroscope in order to test the body's electrical condition.



FIG. 183 PROOF PLANE

324. The Substances Charged Oppositely. If we rub a glass rod and silk together, the silk when tested with the elec-

roscope, will prove to be negatively electrified. But if we rub sealing wax and flannel together, the flannel will prove to be positively electrified. In this experiment, the silk and the flannel must be tied to insulating handles of glass or rubber, as they themselves are not sufficiently good insulators to retain their charges when held in the hand. In this way it has been shown that *whenever two dissimilar substances are rubbed together one of them gets a positive charge and the other a negative charge.*

325. The Two Charges are Equal. We may find out whether the two charges are equal by taking two brass disks *A* and *B* (Fig. 184), fastened to insulating handles, covering one of them, *A*, with flannel or fur, and rubbing them together. When *A* is held two or three centimeters from an uncharged electroscope the leaves diverge by a certain amount. Withdraw *A* and put *B* as nearly as possible in its place. The leaves are again seen to diverge; and the divergence is the same in amount as before. Without having allowed the disks *A* and *B* to touch anything, fit their surfaces closely together and bring them near the electroscope. While they are together there is no effect on the leaves of the electroscope — i. e., *the two opposite charges exactly neutralize each other's effects, and are therefore equal in amount.*

These matters have been thoroughly and accurately tested by many experiments, all of which go to prove the following general statement.

Any two dissimilar substances when brought into intimate contact and then separated, acquire equal electrostatic charges of opposite signs.



FIG. 184 TWO OPPOSITE CHARGES ARE EQUAL

326. Electrostatic Polarization. If two insulated conductors A and B (Fig. 185), made by mounting on sticks of sealing wax a pair of brass balls such as are used on the ends of a curtain pole, are placed in contact with each other, they form practically a single conductor AB . When a positively electrified glass rod R is held near them (but not near enough for a spark to pass), and they are tested with the electroscope (Fig. 182) it is found that A has a $-$ charge and B a $+$ charge. If the rod R is now removed and the conductors AB again tested, they are found to show no signs of electrification at all. These facts are most simply

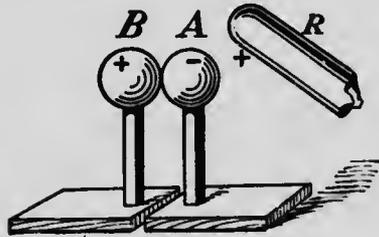


FIG. 185 ELECTRIC POLARIZATION

accounted for by supposing that when no electrified body is near them, the conductors AB have an indefinite quantity of $+$ and $-$ electricity combined in equal amounts so that they neutralize each other. When the body R is brought near the neutral conductors AB , its $+$ charge attracts an equal $-$ charge to the side of AB that is nearer to it, and repels an equal $+$ charge to the side that is farther away. When R is removed, the two charges that were thus separated reunite; and AB become again uncharged. When R is negatively charged, A gets a $+$ charge and B a $-$ charge.

When an insulated conductor becomes charged positively at one end and negatively at the other, because of the presence near it of a charged conductor, it is said to be *electrostatically polarized*.

327. Charging by Influence. If the conductors AB (Fig. 185) are polarized by the influence of the charged body R , and B is then separated from A , both the $+$ charge on B and the $-$ charge on A will remain on them until discharged in some way. This will be true even though R is removed. Again, if instead of separating A and B we simply touch one of them with the hand, the positive charge will go to

the earth instead of remaining on AB . This repelled charge is then said to be *grounded*. If the influencing charge R be removed while the conductors AB are still grounded, AB will again become neutral; but if the hand be removed so as to break the earth connection before R is taken away, the $-$ charge remains on AB . If R be charged negatively instead of positively, the charge remaining on AB will be positive. The simplest way to account for the phenomenon is to suppose that when a conductor becomes polarized by an influencing charge and is then grounded, a charge of the same kind and amount as the influencing charge is repelled to the earth; so that if

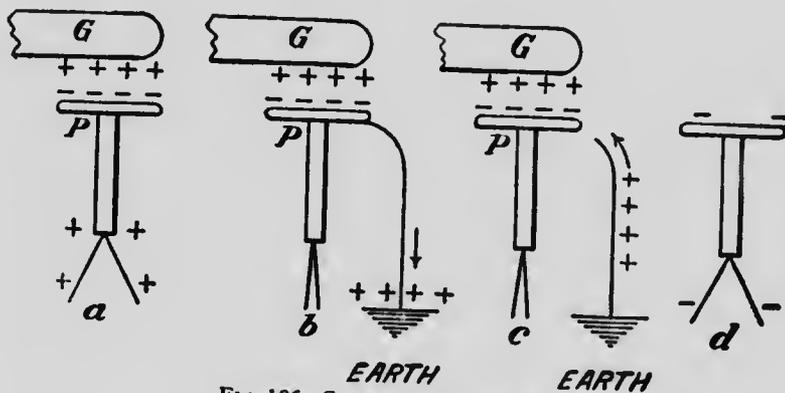


FIG. 186 CHARGING BY INFLUENCE

the earth connection is broken before the influencing charge is removed, the repelled charge cannot get back. Hence an equal charge of the kind opposite to that of the influencing body remains. The body is then said to be *charged by influence* and its charge is called an *induced electrostatic charge*.

The electroscope (Fig. 182) may be most conveniently charged by influence so as to give any desired degree of divergence to the leaves. The four stages of the operation are represented at a , b , c , and d (Fig. 186). If we wish to give the leaves a $-$ charge, we (a) bring a positively charged body G near enough to give the leaves the desired

divergence, (b) touch the electroscope with the hand so as to ground the repelled charge, (c) remove the earth connection, so the repelled charge cannot return, (d) remove the influencing body.

328. Condensers. In the experiment (Fig. 186), the negative electricity of the electroscope-plate P acts as if it were attracted as near as possible to the $+$ charge on G , and held or "bound" there by the mutual attraction between unlike charges (Art. 322). It is found by experiment that whenever two conductors are separated by a non-conductor, and one of them is connected with the earth, a very much larger charge can be imparted to the other than would otherwise

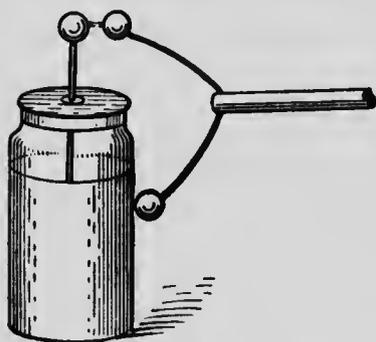


FIG. 187 LEYDEN JAR

be possible. In other words the capacity of a body for holding a large charge is much greater when it is placed near a grounded conductor from which it is separated by a thin layer of non-conducting material. The non-conducting material, such as air, glass, resin, or rubber, is called a *dielectric*, because the electric attraction acts freely through it.

This fact is taken advantage of in the construction of condensers. *A condenser in its simplest form consists of two sheets of metal with a thin layer of a dielectric between them. It is useful because it has a large capacity and so can hold a large amount of electricity.*

One well-known form of condenser is called the *Leyden jar* (Fig. 187), because the principle of the condenser was first discovered in 1745 at Leyden in Holland. It consists of a wide mouthed glass jar, the lower half of which is coated inside and out with tinfoil. The inner coating is connected with a metal rod that passes through the insulating cover and ends in a metal ball. It may be charged by connecting one coating with the earth and the other with a source of

high potential electricity, such as an electrostatic machine, an induction coil, or a battery of many cells in series. Condensers are extensively used in induction coils (Art. 191), and many other kinds of apparatus used in telephone and wireless telegraph work.

329. Discharge of a Condenser. If one end of a conducting wire be touched to one coating of a condenser and the other end be brought near the other coating, a spark passes. The spark is more energetic the larger the amount of the charge and the greater the difference of potential between the two coatings. If an insulated wire through which a Leyden jar is discharging be coiled around an unmagnetized steel needle, the needle will be magnetized. If wires from the two coatings of a charged condenser be placed in a solution of a salt under suitable conditions, it may be shown that the discharge produces electrolysis (Art. 194). It has also been proved that an electrostatic charge on a conductor that was rotated at great speed would deflect a magnetic needle. When the terminals of a voltaic battery are examined with the aid of a sensitive electroscope, the copper or carbon terminal is found to be positively charged and the zinc terminal to be negatively charged. All these facts go to prove that *static electricity is not different in its nature from electricity obtained from batteries and dynamos.*

The discharge of a condenser, however, differs considerably from the current of a battery in the way it acts. It is much more sudden and violent,—more powerful because its energy is expended in so short a time, and hence at such a high rate.

Joseph Henry, who discovered that the electrostatic discharge will magnetize a needle, found that the needle was magnetized sometimes in one direction and sometimes in the other; and since this result is what would be expected if the current through the magnetizing coil were alternating instead of direct, he was led to believe that the discharge of a condenser does not go in one direction only, like that of

a battery, but that it oscillates rapidly back and forth. The idea of an oscillating or alternating discharge may be understood by comparing electricity with water, as we have so often done.

If the level of the water in *A* were considerably higher than that in *B* (Fig. 188), the water would tend to flow with great pressure through the opening at *C* from the higher level to the lower. Now if the valve at *C* were opened very gradually the water would flow in a continuous stream from *A* to *B* until the pressures were equalized; but if the valve were opened suddenly the water on

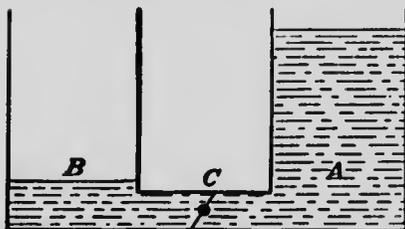


FIG. 188 THE WATER MAY OSCILLATE

account of its inertia would rise in *B* to a level almost as high as that at *A* from which it had descended. It would then flow back into *A*, then into *B*, and so on, until its oscillations were gradually stopped by friction.

That similar oscillations of electricity back and forth take place when a condenser is discharged, has been directly proved by viewing the spark in a rapidly rotating mirror



FIG. 189 THE SPARK OSCILLATES

in the manner described for the vibrating flame in Art. 228. Fig. 189 is a copy of a photograph made by reflecting the spark into a camera by means of a rotating mirror. The spark which was vibrating vertically up and down was drawn out into a horizontal band by the rotating mirror, and so made the zigzag trace here shown. The oscillations have an exceedingly short period—i. e., from one-thousandth to

one ten-millionth of a second, and are therefore rapid enough to start waves in the ether (Art. 283). These waves are similar to light waves and radiant heat waves but of much lower frequency. It is these waves that carry the messages in wireless telegraphy. Their existence was inferred from theory by Maxwell (England, 1831-1879) and experimentally proved by Hertz (Germany, 1857-1894). *The discharge of a condenser consists in a very rapid vibration of electricity, back and forth between two conductors; and such vibrations start the waves that are utilized in wireless telegraphy.*

330. Lightning. It was long suspected that lightning and thunder are electric spark discharges with their accompanying "crackle" on a huge scale. In order to test the matter the famous philosopher and statesman Benjamin Franklin, made a silk kite and placed at the top of it a pointed wire which he connected with the string. He then flew this kite in a thunderstorm, and found, as he expected, that he could charge a Leyden jar with the electricity which was conducted from the clouds to the jar along the pointed wire and the wet string. This famous experiment of Franklin's proved that *a lightning discharge is the discharge of a condenser, of which a cloud is one coating, and the earth the other coating; and the air between them is the dielectric.*

331. Capacity and Self-Induction. When a Leyden jar of given size is discharged, the period of oscillation of its discharge depends on its capacity, which in turn is determined by the areas of the coatings, and the kind and thickness of the glass or other dielectric that separates the coatings. Besides depending on the capacity of the jar, the period of oscillation of the discharge depends on the circuit of wire by which the electricity travels from one coating to the other. If the wire in this circuit is wound into coils of many turns close together the alternating current in each turn induces alternating currents in every neighboring turn.

These induced currents in the neighboring turns oppose the changes in the original current (Art. 183), and introduce what may be called an electrical inertia (Art. 11), which makes the alternating discharge oscillate more slowly. This property of a circuit which retards the electrical oscillations because of induced currents, is called the *self-induction* of the circuit.

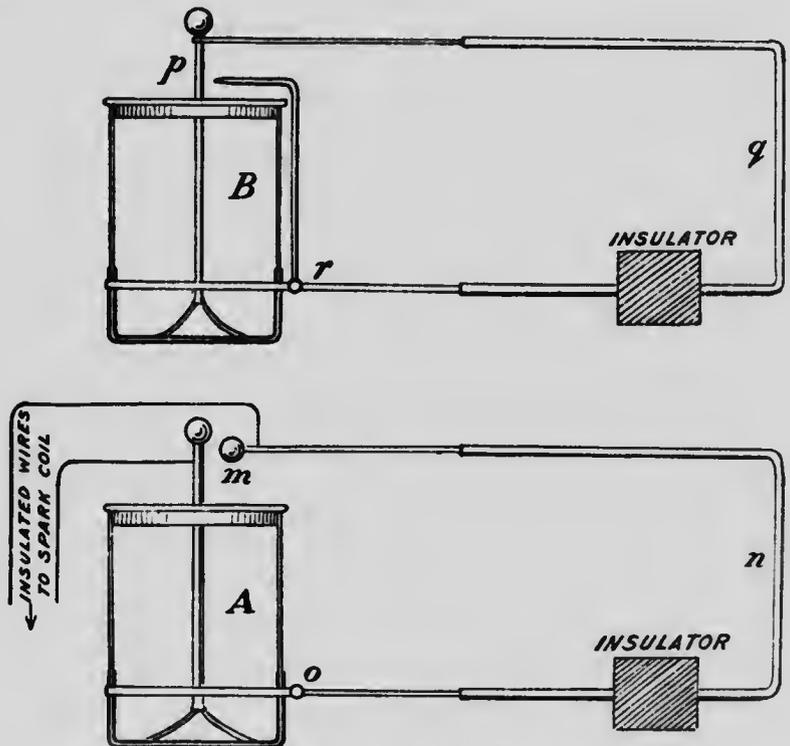


FIG. 190 ELECTRIC RESONANCE

We can get an idea of the effect of capacity and self-induction on the period of oscillation of the spark by considering the analogous case of the vibrating meter stick (Art. 220). The longer the vibrating end of the stick, the more slowly it vibrates; so the larger the Leyden jar, the greater its capacity, and the slower the oscillations of the discharge. If a block be fastened to the end of the meter stick, its inertia is increased and it vibrates more slowly.

So with the Leyden jar circuit, the greater the self-induction of the circuit, the greater the electrical inertia, and the slower the period of the electric oscillations. Thus, *the period of an electric oscillation depends on the capacity and the self-induction of the circuit.*

332. Resonance. In Art. 220 we found that one meter stick will respond by resonance to the vibrations of another if both have the same period of vibration. In like manner we may arrange two Leyden jar circuits so that they have the same capacity and the same self-induction, and therefore the same period of oscillation. Thus let the two jars *A* and *B* (Fig. 190) be just alike, with exactly similar circuits *mno* and *pqr*; then the electricity in the one circuit will be capable of surging back and forth in exactly the same period as that in the other. When we connect the jar *A* with an induction coil as shown, and send a spark across the gap *m*, a spark also jumps across the gap *p*; i. e., some of the energy of the spark at *m* has been transmitted to the jar *B*, and causes the spark there. Since there is no conducting connection between the jars, we conclude that the energy was transmitted by electric waves (Art. 222), which were started by the electric oscillations at *m*. Thus *an electric spark sends out electric waves of definite period.*

An electric circuit tuned to the same period as that of the spark, may be set into electric vibration by resonance.

333. Wireless Telegraphy. The fact that electric sparks send out electric waves whose effects can be detected at a distance suggests the idea of using them to send signals. Since no wires are needed to carry the waves, this form of signaling is called *wireless telegraphy.*

The sparks for starting the waves are produced by a powerful induction coil. The sparking of the coil is controlled by the operator by means of an ordinary telegraph key which opens and closes the circuit of the primary coil (Fig. 191). One side of the spark gap is connected by a single wire

to a "grid" of parallel wires (Fig. 191), which is suspended on insulating supports from a tall mast or tower. The grid and single wire make up the aerial system or *antenna*. The other side of the spark gap (i. e., the one that is not connected with the antenna) is connected with the earth.

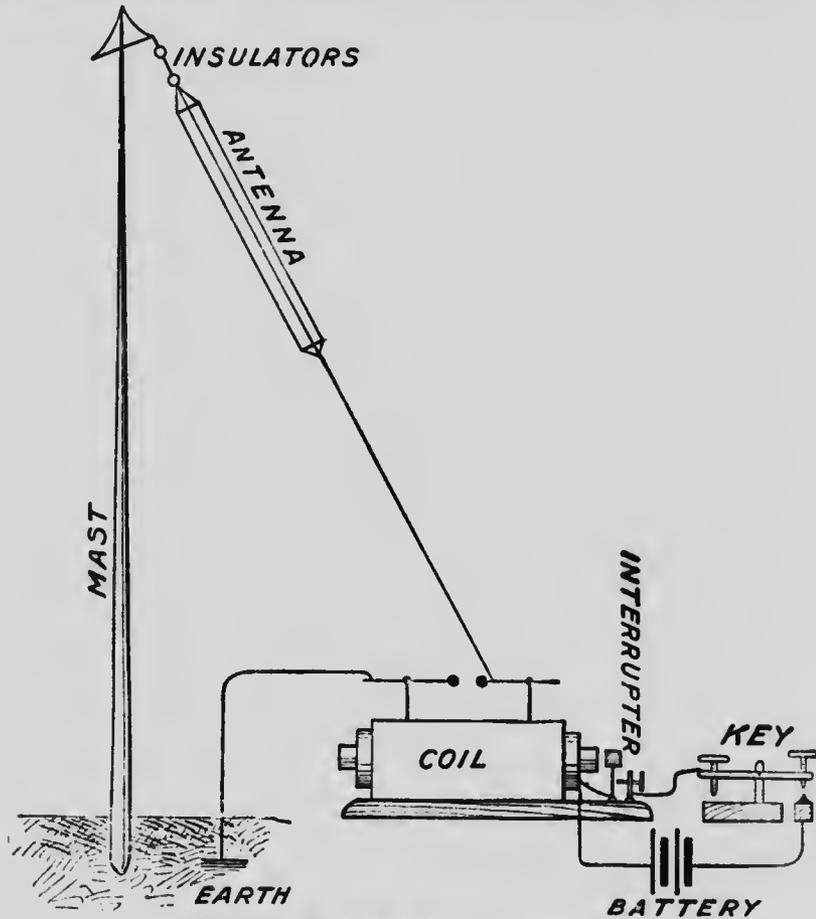


FIG. 191 WIRELESS SENDING APPARATUS

so the antenna and the earth act something like the two coatings of a condenser of which the air between forms the dielectric.

When the key is pressed down, the coil begins to work as described in Art. 191, and sparks occur between the terminals. The electric surges thus started flow up and down the an-

tenna, which extends well up above the earth and gives them a chance to make a large disturbance in the surrounding ether. The electric wave vibrates on the antenna, in much the same manner as the stationary air wave in an organ pipe that is closed at one end. The latter is a stationary air wave in a pipe, the former a stationary electric wave on a wire. In the organ pipe there is a node at the closed end and a loop at the open end; on the antenna there is a node at the upper

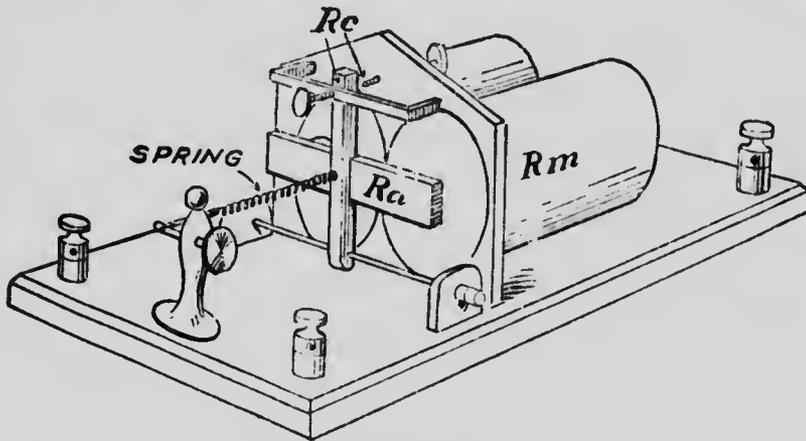


FIG. 192. TELEGRAPH RELAY

end and a loop at the spark gap. The air wave from the organ pipe is four times as long as the pipe; and the electric wave from the antenna is four times as long as the antenna.

334. The Coherer. The sensitive portion of the receiving apparatus of the wireless telegraph consists of a small tube (*XY*, Fig. 194) containing a pair of slender metal rods whose ends almost meet but are separated by a small quantity of a mixture of nickel and silver filings. In the best form of coherer the air is pumped from the tube, which is then sealed up so as to be air tight. The mass of loose metal filings conducts electricity very poorly, so that a battery can send almost no current through it but when an electric wave has passed through the tube, the loose filings seem to get welded together at the points where they touch each other; for they

then constitute a very good conductor. When in this condition, the metal filings in the tube are said to "cohere" and the tube of filings is called a *coherer*. After the filings have been caused to cohere by an electric wave, they may be separated by jarring the tube; and the mass of filings is then changed back from a good conductor into a very poor conductor. The device used for automatically jarring or "tapping back" the filings so as to "decohere" them is called a *decoherer*.

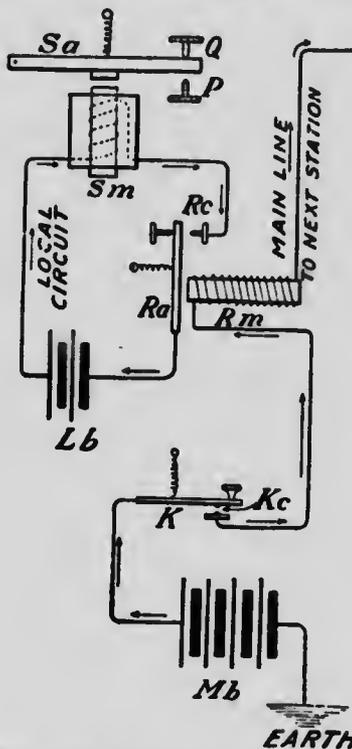


FIG. 193 STATION ON LONG DISTANCE TELEGRAPH LINE

335. The Relay. Another important part of the receiving apparatus is the *relay* (Figs. 192 and 193). The relay consists of an electromagnet *Rm* (Fig. 192) wound with many turns of fine wire, and a small, light, soft iron armature *Ra*. When even a very weak current is passed through the coils of such a magnet, it attracts the delicately mounted armature. The armature is connected with one terminal of a "local circuit" containing a "local battery" *Lb* (Fig. 193) and the magnet *Sm* of a sounder or an electric bell (*Bm*, Fig. 194). The

contact screw *Rc*, against which the relay armature strikes when it is attracted by the magnet *Rm* is connected with the other terminal of the local circuit.

In ordinary telegraphy over long distances, a relay is always placed at each station in circuit with a main battery and a key in the main line that leads from station to station. At each station (Fig. 193) there is a local circuit whose terminals are connected with the relay armature and its contact screw, and which contains only a local

battery and a sounder in series with it. When the main line circuit is alternately opened and closed, the relay armature at each station is alternately attracted to its contact screw and released. It thus alternately opens and closes the local circuit through the local battery and the sounder, and causes the sounder lever to be alternately attracted and released. The necessity for the relay on an ordinary long distance telegraph arises from the fact that the current on the line is very weak because of the great resistance of the long line wire. Although the relay cannot itself make enough noise to be distinctly heard, it can open and close the short

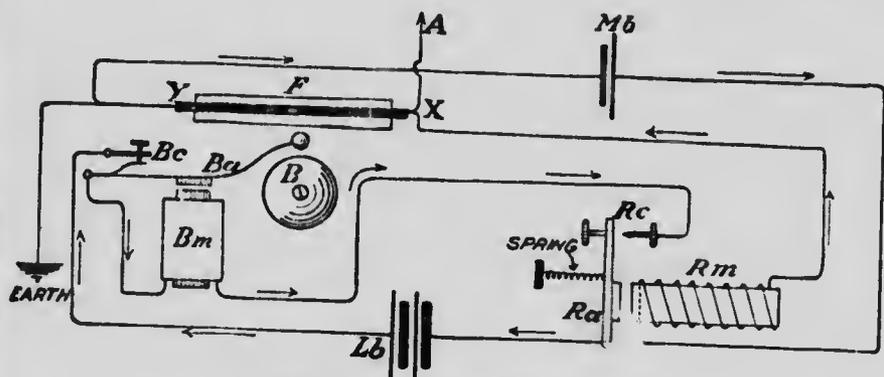


FIG. 194 WIRELESS RECEIVING APPARATUS

local circuit, and so operate a sounder which is placed in the local circuit. Since the sounder has a large armature and is driven by a strong current from the local battery, it reproduces the signals received by the relay and gives them with sufficient loudness so that they may be heard. For the same reasons the relay is a necessary part of a wireless telegraph outfit.

336. How the Wireless Message is Received. At the receiving station, one end *X* of the coherer (Fig. 194) is connected at *A* with an antenna, just like that of the sending station. The other end *Y* is connected with the ground. The two ends *X* and *Y* of the coherer are also connected to

the relay circuit, which contains the main battery Mb and the relay magnet Rm . When the operator at the sending station closes his key, the coil there begins to spark and sends out electric waves from its antenna through the ether to the receiving station. When these waves arrive, they vibrate up and down the receiving antenna, and pass through the coherer, causing the filings at F to cohere. Their resistance is thus reduced, so that the current from the main battery Mb increases enough to make the relay magnet Rm attract the relay armature Ra and close the local circuit. The current from the local battery Lb then flows through the local circuit, and makes the armature Ba of the bell vibrate back and forth, making the clapper strike the bell B and the coherer tube alternately. The clapper thus alternately rings the bell and decoheres the filings.

When the operator at the sending station opens his key, the coil ceases to spark, and the electric waves stop coming to the receiving station. Then, since the filings are decohered by the last tap from the clapper of the bell, the current ceases to flow through the relay magnet Rm , the relay armature Ra is drawn away from the contact screw Rc , the local circuit is broken, and the bell ceases to ring.

Since the bell jingles whenever the operator at the sending station depresses his key, and ceases to jingle whenever he releases his key, he is able to send any desired combinations of long and short jingles corresponding to the letters of the telegraph alphabet.

An ordinary sounder may be used instead of a bell, or if one of the types of coherer is used which does not require tapping back, a telephone may be used as a receiving instrument.

In this case the operator hears the familiar crackling noise that one hears in the telephone when the circuit is alternately made and broken. There is always both a sending and a receiving apparatus at each station, either of which can be connected to the antenna or disconnected from it as the operator may wish.

337. Tuning for Resonance. For long distance and commercial work the terminals of the two sides of the spark gap of the sending coil are always connected with the two terminals of an oscillating circuit much like those described in Art. 332. This oscillating circuit consists of Leyden jars and a coil of variable self-induction. Since more or fewer of the turns of wire of the self-induction coil may be included in the oscillating circuit, the circuits at the sending and receiving station may be tuned to the same period. Then instruments of the receiving station will be more sensitive to the waves from the sending station; and if two or more stations are sending messages at the same time, the receiving station will respond more readily to the station that is in tune. Unless the receiving instruments are tuned, they pick up all the messages that are being sent at a given time.

DEFINITIONS AND PRINCIPLES

1. A substance may be charged with electricity by rubbing it with another substance. Its electrical potential is then higher than that of the earth.
2. There are two kinds of electrostatic charges, positive and negative.
3. Like electrostatic charges repel each other and unlike attract.
4. Any two dissimilar substances, when brought into intimate contact and then separated, acquire equal charges of opposite signs.
5. A conductor may be polarized by the influence of a neighboring charged body.
6. If the repelled charge of a polarized conductor be grounded, and if first the ground connection and then the influencing body be removed, the conductor remains charged with an amount of electricity equal and opposite to that of the influencing body.

7. A condenser consists of two plates of metal with a thin layer of dielectric between them. It has a very large capacity for holding electric charges.

8. The spark discharge of a condenser oscillates very rapidly and is capable of starting the ether waves used in wireless telegraphy.

QUESTIONS AND PROBLEMS

1. How could you tell by means of a suspended pith ball whether a piece of paper becomes electrified by rubbing it with an eraser?

2. Would your experiment be more likely to succeed if you handled the paper (question 1) by sticking it to a pane of dry glass? Why?

3. Will the eraser (question 1) become electrified also?

4. What can you say of the kinds and amounts of the electric charges developed by rubbing together two insulated disks, one of fur and the other of metal?

5. Could you electrify one of your classmates if you placed him on a board supported by 4 battery jars and stroked him with a fur cap?

6. In the experiment (question 5) why would it be better to have the jars hotter than the air in the room?

7. Why will an electrostatic charge escape along moist wood or glass when the electricity from a battery will not send a perceptible current through it?

8. If you test the inside of an electrified tin fruit can by means of a proof plane and electroscope you get no charge from the inside. Can you explain this by the law of electrostatic repulsion?

9. If an electroscope be completely surrounded by wire gauze the gauze may be highly charged and the electroscope will not be affected at all. Explain.

10. Does the self-repulsive tendency of an electrostatic charge help to explain why it collects more densely at the corners or edges of a cubical conductor than on its flat surfaces?

11. If a tack be dropped point up on the plate of an electroscope, the leaves quickly collapse. What effect have sharp points on charged conductors? Why?

12. If a pointed wire be attached to either terminal of a good electrostatic machine and the machine is rapidly worked, a current of air streams off the point swiftly enough to blow out a small candle. Can you explain this air stream by electrical attraction and repulsion?

13. Why do well grounded lightning rods help to discharge quietly an overhanging cloud, and so diminish the probability of a violent discharge?
14. Would a lightning discharge affect a wireless receiver?
15. How do "wireless" waves differ from ultra red, and visible waves?
16. Make a diagram of a two-station long-distance telegraph line, with a battery, key, and relay on the main line at each station.
17. On the diagram (problem 16) add at each station a local circuit, with local battery and sounder; and connect its terminals with the armature and contact screw of the relay, just as the local battery and sounder are connected at *Rc* (Fig. 193).
18. Trace the main line current through the main circuit in your diagram (problem 17) and tell what happens when the key on the main line is opened and closed.
19. Tell what happens in the local circuit (problem 17) when the relay contact (as at *Rc*, Fig. 193) is made and broken.

CHAPTER XIX

OPTICAL INSTRUMENTS

338. Convex Lens. Rule for Construction of Image. In Chapter XIII, the image formed when the light from a luminous or illuminated object passes through a small hole in an opaque screen, with and without a lens, was described, and its general relations were set forth. It may help the student to get more definite notions concerning the characteristics of an image and their relations to the corresponding characteristics of the object, if a general rule is given for constructing the image when the conditions with respect to the object are known. The following construction (Fig. 195) will illustrate a rule which is very simple and very general in its application.

Let OO' be an object placed on the axis of a convex lens LL' whose principal foci are F and F' . Since all the rays in a beam of light that spreads out from the point O and passes through the lens are brought by it to a conjugate focal point I somewhere on the opposite side of the lens (Art. 253), all the rays in the beam must intersect one another at this point. Hence if we know definitely the paths of two of these rays we can then draw them and extend them till they meet in a point; and this point in which the two known rays meet must be the point of meeting of all the other rays that come to the lens from O ; i. e., it must be the conjugate focus of the point O .

Now there are two rays whose paths we do know. The first one is that which passes through the center c of the lens. This one Oc is not changed when it passes through the lens, but continues on in the same straight line Ocz in which it was going before it reached the lens. The second ray whose path is known is the one OL that is parallel to the principal

axis FF' . Since all rays that are parallel to its principal axis are deviated by the lens so that they meet at its principal focus (Art. 250), we know that this one OL must

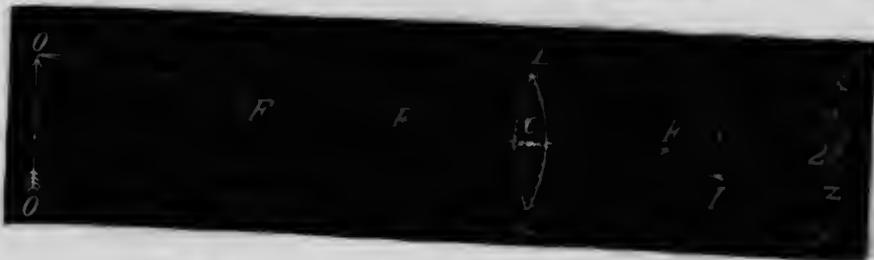


FIG. 195 CONVEX LENS. CONSTRUCTION FOR THE IMAGE

pass through this point F' . The path of the ray then must be OLy . Since the two known rays Ocz and OLy intersect after passing through the lens at a point I , and since all the rays from O meet at the same point, this point I must be the one where they all meet; i. e., it is the conjugate focus of the point O . The two characteristic rays $O'cw$ and $O'L'x$ from O' , another point of the object, are drawn in a similar manner; and the conjugate focus of the point O' is found to be their intersection I' . $I'I$ is therefore the image of OO' . We may state this process concisely in the following rule:

To draw the image of an object placed before a convex lens—(1) Choose a characteristic point of the object (say one end). (2) From this point draw the ray that passes through the center of the lens. It continues on in a straight line. (3) From the same point draw the ray that is parallel to the principal axis of the lens. After leaving the lens, it passes through the principal focus. (4) The intersection of these two rays that came from the same point of the object is the conjugate focus of that point. (5) Locate similarly as many such characteristic points as may be necessary to determine the size and position of the object.

339. Effect of Object-Distance on Image. Case I. In Fig. 195 the object was at a considerable distance from the

lens; and the image was found to be nearer to the lens than the object was. It was also smaller than the object.

Fig. 195 represents the relative positions of the object and its image as they are in the eye, the view camera, and the object glass of the telescope.

From the diagram (Fig. 195) it will be seen that IcI' , the lens angle of the image, is always equal to OcO' , the lens angle of the object (Art. 251). Hence if OO' be moved nearer to the lens, the rays Ocz and $O'cw$ open out like a pair of scissors, and the lens angle OcO' of the object becomes larger; so the lens angle IcI' of the image becomes larger also; and the image must increase in size. But this is not all. Since the object does not change its size, the parallel rays OLy and $O'L'x$ do not change their positions at all. Therefore when the rays cz and cw open out as the lens angle IcI' increases, their intersections I and I' with Ly and $L'x$ respectively, will be farther away from c . From this construction therefore we reach the same conclusion that was reached by other reasoning in Art. 253; i. e.,

The nearer the object is to the lens, the larger and more distant the image is from the lens.

Case II. If we use the same construction as in Fig. 195, and keep moving the object nearer to the lens, we soon reach a point where the image has the exact size of the object, and also is at exactly the same distance from the lens



FIG. 196 OBJECT AND IMAGE EQUAL

lens is twice the focal length of the lens, and therefore that the distance between the image and the object is four times the focal length of the lens.

(Fig. 196). When this is true, it is found by measurement that the distance of either the object or the image from the

The knowledge of this fact leads to a convenient way of measuring focal length; for if we keep moving the object toward the lens, and the screen away from the lens, until the clearly focused image has the same size as the object, and then divide the measured distance between the object and its image by 4, the result is the focal length of the lens.

Another important way in which this case is applied is in making a photographic copy of a drawing, when the copy is to be exactly the same size as the object. The object must then be placed at twice the focal distance from the lens; and the image will then be at twice the focal distance on the other side.

Case III. If we wish to make an enlarged copy of a picture by photography, we move the object still nearer the lens. If this case be drawn according to the same rule that was used to get Figs. 195 and 196, a similar analysis of the resulting figure will show that the nearer we bring the object to the camera the larger the image and the more distant it is from the lens. Hence, if making enlarged photographs of an object, a camera with a long bellows is necessary. Other applications of this case are the projection lantern and the object glass of the compound microscope. These will be described in later paragraphs.

Case IV. In the case of the "spotlight" used on the stage it is desired to throw on the performers, not an image of the flame, but a flood of parallel beams. For this purpose the light is placed in a box behind a lens and just at its principal focus. By the same rule for construction it is found (Fig. 197) that when the object is placed at the principal focus, the rays from each point, as O or O' , of the object, are parallel after passing through the lens, and no image is formed. This principle is also applied in bull's-eye lanterns, automobile lamps, and in lighthouses.

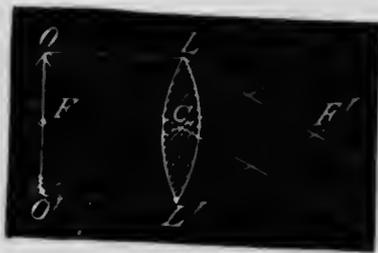


FIG. 197 OBJECT AT F: NO IMAGE

If the object be moved nearer to the lens than the principal focus, the same construction shows that no image can be formed, since the rays from every point will remain divergent, although less so than before passing the lens.

340. Projecting Lantern. Fig. 198 shows the arrangement of the light and lenses in an ordinary projecting lantern.

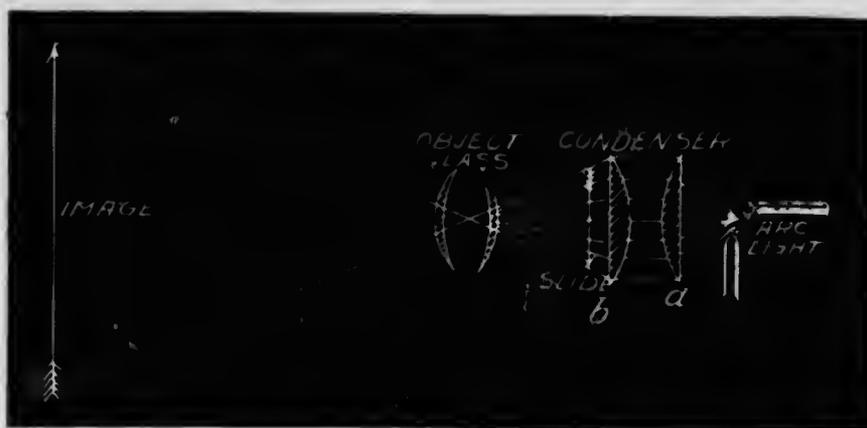


FIG. 198. PROJECTING LANTERN

The light is placed in a metal box just at the principal focus of a large thick convex lens a of short focal length, which causes the rays to become parallel. It then passes through a second lens b of somewhat greater focal length, which bends it into a rather short cone. This pair of lenses ab constitutes the *condenser*; and its purpose is to gather as much of the light as possible from the lamp and concentrate it on the "slide" or transparent picture. After the light has passed through the slide, a beam from each point of the slide goes on through the central part of the object glass and is focused on the screen. In the diagram only two such beams are shown. The object glass is made up of two lenses. It is placed at a little more than its focal distance from the slide; and the image is formed at more than twice the focal distance from it.

341. Compound Microscope. The compound microscope (Fig. 199) differs from the telescope (Art. 260) in that it is used in examining very small objects that are near at hand. The object glass, or objective LL' has a very short focal length, and the object is placed near the principal focus, like the slide in the projecting lantern. The image is formed in the tube of the microscope farther away from the objective than twice its principal focal length. Unlike the image of the moon in the telescope tube, the image of the small object is much larger than the object itself. This image is further enlarged by the aid of the eyepiece EE' , which is so placed that the image II' in the microscope tube is very nearly at its principal focus. Therefore the rays that diverge from the image are parallel after passing the eyepiece and are focused on the retina RR' by lens YY' of the eye. As in the case of the telescope (Art. 260), the eyepiece forms with the lens of the eye a combination of lenses whose focal length is short enough to focus the image on the retina when the object is nearer to the eye than the limit of distinct vision. The angle RcR' is the lens angle of the image at c . Since the lens angles of the image and object are equal, the object seems to subtend the visual angle EcE' . The magnification is caused by the fact that the *visual angle EcE' is very much greater than the visual angle of the object:*

- (1) because the image itself II' is larger than the object; and
- (2) because the image II' is brought very near to the eye.

Thus the object is magnified by two different means. Since the object is so much magnified, the light from it is spread over a large area, and would become very faint unless it were



FIG. 199
COMPOUND MICROSCOPE

intense to start with. In order to avoid this difficulty the microscope is provided with a mirror to reflect light on the object from the sky or a lamp. The beam from the mirror is condensed into a cone by a condensing lens which acts exactly like the condenser of the projecting lantern (Fig. 198).

342. Index of Refraction. In Art. 284 it was shown that when a parallel beam of light strikes a plane surface of water obliquely it is bent, or refracted, because its speed is less in the water than in the air. The same is true for glass and other transparent substances.

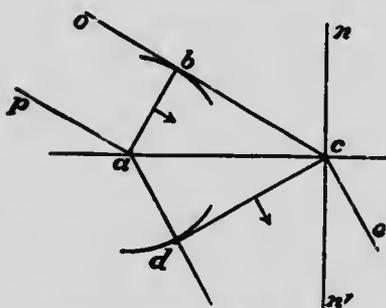


FIG. 200 INDEX OF REFRACTION=
RATIO OF BC TO AD

Let ab (Fig. 200) represent a section of one of the plane wave fronts of a beam of light included between the two rays ob and pa . The perpendicular nn' to the common surface ac of the two media (i. e., in this case, air and glass) is called the *normal*. The angle bcn which the direction bc of the incident beam makes with the normal is called the *angle of incidence*; and the angle $n'ce$ that the direction ce of the refracted beam makes with the normal is called the *angle of refraction*. The wave front is always perpendicular to the direction in which the wave is going, hence cd , perpendicular to ce represents the wave front in the glass. If bc represents the actual distance traveled by the beam in air in a certain time, ad represents the distance traveled by it in the glass in the same time. Hence the ratio of bc to cd is the same as the ratio of the speed of light in air to its speed in the glass. Since this ratio measures the amount of the bending for any two media when light passes from the one medium (air) into another (glass) it is called the *index of refraction* of the second with respect to the first—i. e.,

Speed of light in air

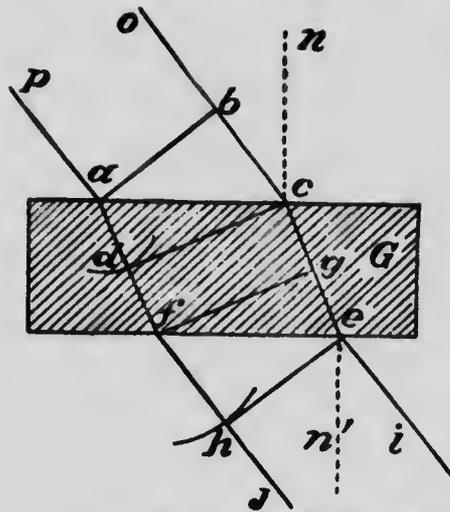
$\frac{\text{Speed of light in the second medium}}{\text{Speed of light in the first medium}} = \text{Index of refraction}$
of the second medium with respect to air.

343. Laws of Refraction. Since other things being equal, the speed of the light in any medium is independent of the angle at which it enters or leaves that medium, this ratio is found to be constant for any angle of incidence provided the light be of one color.

Also, as the speed of ab in the glass is slower than its speed in the air, the diagram shows that the angle of refraction $n'ce$ is smaller than the angle of incidence bcn , and so the light is bent toward the normal when it passes from air into glass. Conversely if the direction of the light wave were reversed so that it was coming out of the glass into the air, its speed in the second medium (air) would then be greater than its speed in the first (glass); and the angle of refraction (now ncb) would be greater than the angle of incidence (now ecn'); so that the light would be bent away from the perpendicular when it passed from glass into air. These facts may be summarized in the following statements, which are often called the *laws of refraction*.

1. *The index of refraction is constant for any two media and for light of a given color.*
2. *When the light passes from one medium into another in which its speed is slower, it is bent toward the normal; and when it passes into a medium in which its speed is faster, it is bent away from the normal.*

344. Light Traced Through a Plane Parallel Plate. The principles explained in the preceding paragraph enable us to trace the path of a beam of light through a piece of plate glass G , whose index of refraction is known. That of plate glass is 1.5 or $\frac{3}{2}$; i. e., the speeds in air and glass are related as 3 to 2. Hence if we draw oc , pa , and ab (Fig. 201) just as we drew them in Fig. 200, and if with a as a center and a radius equal to $\frac{2}{3}$ of bc we describe an arc, then the line cd which passes through c and just touches this arc will repre-



F. 201 PLANE PARALLEL PLATE

sent the position of the new wave front at the instant when the wave has passed entirely out of the air into the glass. Hence ce and adf perpendicular to the wave front cd represent the direction in which the beam is traveling in the glass.

When the beam comes out of the glass its speed in the air is $\frac{3}{2}$ of what it was in the glass; so, proceeding exactly as before ex-

cept that we take the radius fh equal to $\frac{2}{3}$ of ge , we find that eh is the direction of the new wave front at the instant when the wave has passed entirely out of the glass into the air; and therefore ei and fhj , perpendicular to eh , represent the direction of the beam after emerging from the glass.

It will be seen from the figure that the angle of refraction $n'ei$ on coming out of the glass is equal to the angle of incidence ocn in going in; so the deviation or bending toward the normal nc in going in is exactly offset by the deviation from the normal en' in coming out. This is found to be true no matter what the plate is made of, so long as its two faces are plane and parallel to each other; i. e.,

After passing through a plane parallel plate a beam of light passes on in the same direction that it had when it entered.

345. Deviation by a Prism. When a beam of light passes through a prism (Fig. 202) its path in and out may be found just as it was in the case of the plane parallel plate. Since

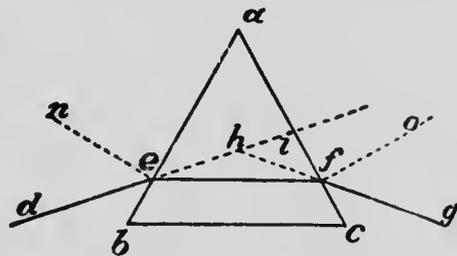


FIG. 202 DEVIATION BY A PRISM

the light is bent toward the normal ne on entering and away from the normal of on leaving, and since in the case of the prism the two normals are not parallel to each other, a beam on entering obliquely at one side ab of the prism is bent twice toward the next adjacent side bc , and takes the path $defg$. The angle ghi is called the *angle of deviation*, because it measures the amount by which the beam de is turned out of its path by passing through the prism.

346. Explanation of the Spectrum. For two media, such as glass and air, it is found by measurement that the index of refraction of orange light is greater than that of red, that of yellow greater than that of orange, and so on for green, blue, indigo, and violet; i. e., the latter colors are deviated more than the former. This enables us to understand why the white light is separated into various colors in Newton's experiment (Art. 270). White light is a mixture of all the colors, therefore *since the prism bends some colors more than it bends others, the mixed beam is spread out like a fan and makes on the screen the succession of colored bands which we call the spectrum.*

347. Total Internal Reflection. Critical Angle. On tracing a beam from glass into air by the construction explained in Art. 344 it will be seen (Fig. 203) that if the angle of incidence be made larger the corresponding angle of refraction will increase much faster.

Hence there will be found a certain value of the angle of incidence ocn for which the corresponding angle of refraction $n'ci$ will be a right angle and the direction of the

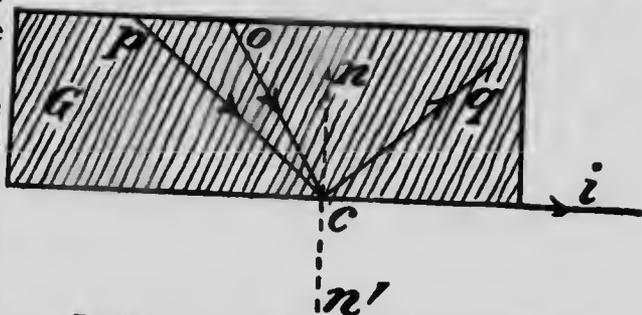
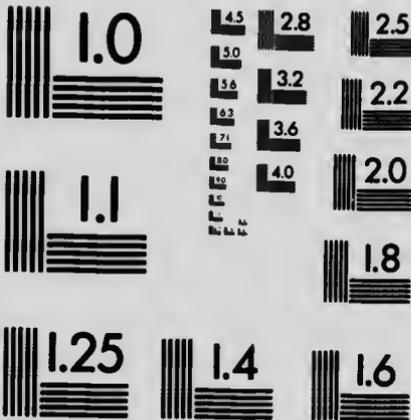


FIG. 203 TOTAL REFLECTION: CRITICAL ANGLE



MICROCOPY RESOLUTION TEST CHART

(ANSI and ISO TEST CHART No. 2)



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refracted beam will coincide with the surface. But the angle of refraction can never exceed a right angle; and so if the angle of incidence be further increased as pcn the beam does not emerge from the glass at all, but is turned back into it, so that its path is pcq . This phenomenon is called *total internal reflection*. Hence when a beam of light is passing from a denser medium like glass into a less dense medium like air, the angle of incidence cannot exceed a certain value without causing total internal reflection. This particular angle of incidence is called the *critical angle*.

The great brilliancy of diamonds is due to total internal reflection. These gems are cut with their faces at such angles that nearly all the incident light that is not reflected by the front faces is totally reflected from the rear faces and so is flashed back through the diamond into the room.

348. The Rainbow. When the sun shines through a rift in the clouds while rain is falling, we may see a rainbow if we stand with our backs to the sun. If sb (Fig. 204) represents a beam of light from the sun, then since thousands of raindrops are falling all the time, this beam will strike some one drop b at such an angle of incidence that after entering and being refracted downward it will strike the back of the drop at an angle that is greater than the critical angle. Therefore it will be totally reflected and will pass out of the drop, bending slightly upward as it goes, and will be perceived by an observer whose eye happens to be at e . Since the violet of the white light is bent more than the red, the emergent violet beam will be higher than the red, as indicated. So an observer at e would see only the red from the drop b . He would, however, see the violet that came from a drop a , that was lower down than b , and the other colors from drops that happened to be in the right positions between the two. Furthermore, since a raindrop b is so situated that its direction from the observer's eye, eb makes a certain angle beo with the horizontal line eo drawn forward from this observer's eye, and is therefore capable of sending only red

light into that eye, it follows that all other drops whose directions make an equal angle with eo at e will also send only red light to that eye. Such drops will all be situated

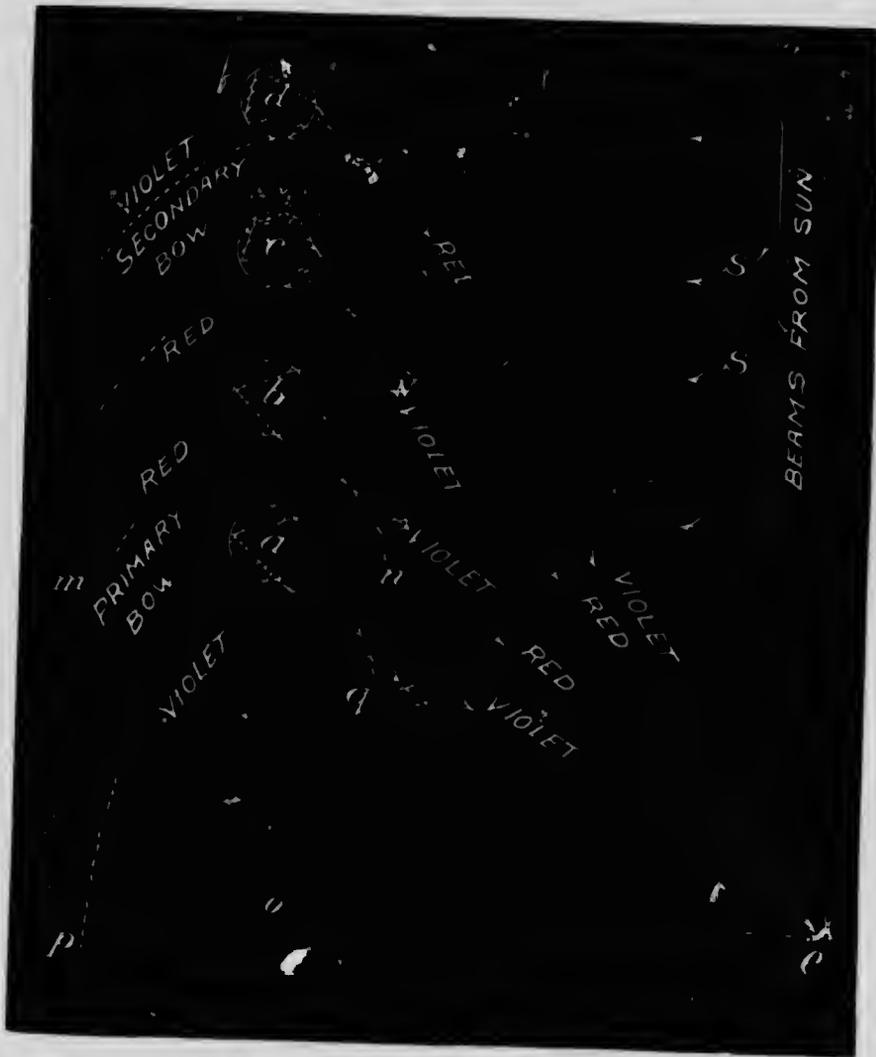


FIG. 204 FORMATION OF THE RAINBOW

on the circular arc mbn , whose center is o and whose radius is ob ; and the red light from them makes up the red band in the bow.

The violet band is made by other drops like a , whose

directions make a little smaller angle oea with eo ; and so on for the other colors, which would lie between the red and violet in the order of the spectrum. The rainbow seen by another observer would be caused by other drops that happened at each instant to be similarly situated with reference to his eye. The experiment described in Art. 26 illustrates the action of a single raindrop. Sometimes a second bow is seen above the first, with the colors reversed, i. e., violet above and red beneath. This second bow is caused by light that has been twice totally reflected from the inside of the drop, as represented at c and d Fig. 204.

349. Concave Lens. Sometimes a concave lens whose cross section is shaped like LL' in Fig. 205 is used to look



FIG. 205 THE CONCAVE LENS SPREADS THE BEAM

at a drawing in order to see how it will look when copied photographically and reduced in size. When any object is looked at through such a lens it seems to come nearer and become smaller, but remains right side up. In other words an erect and diminished image is formed between the object and the lens. Such an image cannot be caught on a screen because the light rays do not really come from it as they seem to do. A slight modification of the construction employed in Art. 338 shows what happens.

The ray from O to c passes on in a straight line Ocz just as it did with the convex lens; but the ray OL , parallel to the principal axis, is bent toward the thicker part of the lens (which is now at the rim, not at the center). Its path ay on leaving the lens is that which it would have had if it had come straight from the principal focus F in the direction Fy . Since the rays ay and cz are divergent, they cannot meet and make a real image after passing the lens, but they appear to diverge from the point I where they would inter-

sect if they were extended backward. This point I is the image of O , and the point I' (found by the same rule) is the image of O' . It will be noted that the lens angle of the object OcO' is equal to the lens angle of the image IcI' , as is the case with the convex lens. The use of concave lenses in spectacles for near-sighted persons was mentioned in Art. 256. They are also used for the eyepieces of opera glasses. In both cases their utility is due to the fact that by causing parallel rays to diverge, or by causing convergent rays to become parallel, they assist the eye lens in focusing on the retina a beam of light that would otherwise converge to a focus before it reached the retina.

350. Opera Glass. In this familiar instrument the paths of the rays from the object through the object glass may be traced by the same construction (Art. 338) already so often



FIG. 206 OPERA GLASS

used. In so far as the action of the object glass is concerned the opera glass is exactly like the telescope; but as to the action of their eyepieces the two instruments are quite different.

Let LL' (Fig. 206) represent the object glass of an opera glass and EE' the concave lens used as the eyepiece. The beam from the point O of the object OO' , if left to itself, would converge to a conjugate focus at a point near E' . It is not, however, allowed to do so, but is made to pass through the concave eyepiece, which overcomes its convergence and renders it parallel. It then enters the pupil of the eye and passes through the lens of the eye, which renders it convergent, and focuses it on the retina.

The eyepiece just neutralizes the converging power of the lens of the eye. Hence the image that otherwise would be formed near E' is really formed on the retina of the eye.

The lens angle of this image at q is IqI' , so the object appears to subtend the angle sgs' . Since this angle is larger than the visual angle OqO' of the object when the glass

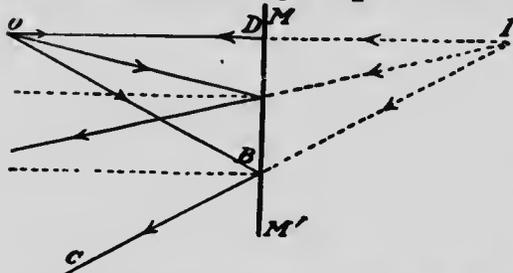


FIG. 207 PLAIN MIRROR DIVERGENT BEAMS

not used, objects appear larger when seen through the optical glass than when observed by the unaided eye. They all look right side up since their images are inverted on the retina

just as those of all right-side-up objects are.

351. Concave Mirrors. In Art. 262 we learned that a plane mirror reflects the light so that the angle of reflection equals the angle of incidence. A beam of light from a point

O of an object near a plane mirror MM' (Fig. 207) is always divergent when it strikes the mirror, and has the same divergence when it leaves the mirror. The divergences before and after reflection are measured by the angles DOB and DIB respectively. If the surface of the mirror is curved so as to be concave, as in Fig. 208, the angles of incidence and of reflection are still equal, but the rays of the reflected part

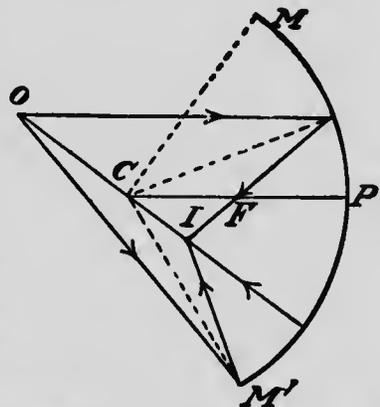


FIG. 208 A CONCAVE MIRROR FOCUSES THE BEAM

of the beam from O are brought nearer together, so that if they are very divergent they are made less so, and if they are not so very divergent they become parallel or even con-

verge to a real focus and form a real image I in front of the mirror instead of a virtual image (as I , Fig. 207) behind it.

The point c , which is the center of the sphere of whose surface the mirror is a portion, is called the *center of curvature* of the mirror. The straight line from the center P of the mirror through its center of curvature c is called the *principal axis*. The angle McM' is called the *aperture* of the mirror.

Provided that the aperture of the mirror is small, it may be shown that since the rays are so reflected at each point that the angle of reflection equals the angle of incidence, *all the rays that are parallel to the principal axis converge at a point on that axis half way between the mirror and the center of curvature*. This point is therefore called the *principal focus*.

352. Construction for Image With Concave Mirror.

Of the many rays in a beam that starts from a point O of an object and reaches the mirror MM' , (Fig. 209), the one that is parallel to the principal axis cP will, after reflection pass through the principal focus F . Its path, therefore is $OaFx$. Another, which passes from O through the center of curvature c , strikes the surface of the mirror perpendicularly at a point y , and is reflected directly back along its former path. Its path after reflection is ycO . The point I in which these two reflected rays intersect is therefore the point where all the rays of the beam from O to the mirror meet after reflection. It is therefore the conjugate focus of the point O . The

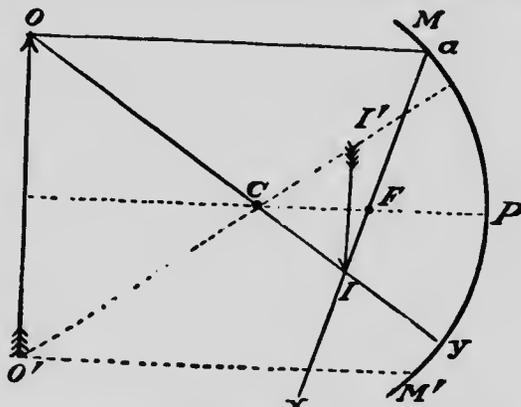


FIG. 209
CONCAVE MIRROR CONSTRUCTION FOR THE IMAGE

conjugate focus of the point O' may be found by the same rule; and the image of OO' is therefore II' . The rule for finding the image with a concave mirror is therefore very similar to that for the convex lens:

(1). From a characteristic point of the object draw the ray through the center of curvature. After reflection it passes back along the path by which it came. (2). From the same point draw the ray that is parallel to the principal axis of the mirror. After reflection it passes through the principal focus. (3). The intersection of these two reflected rays from the same point is the conjugate focus of that point. (4). In exactly the same way, locate the conjugate foci of as many other characteristic points as may be necessary.

353. Characteristics of the Image. By constructing different cases, such as were described for the convex lens, and noting the characteristics of the image, the following facts may be noted. They all may be verified in any dark room with a candle for an object, a white paper on the wall for a screen, and an ordinary concave lamp reflector for a mirror.

Case I. When the object is beyond the center of curvature, the image is near the principal focus, smaller than the object, inverted, and real.

This case is sometimes applied in making a reflecting telescope, the image being viewed through a convex eyepiece placed at its own focal distance from the image. The magnification results from the fact that the visual angle of the image is larger than that of the object just as with the refracting telescope (Art. 260).

Case II. When the object is at the center of curvature the image is there also, is the same size as the object, inverted, and real. This suggests a common method of finding the focal distance of the mirror. The object is moved gradually up toward the mirror until the image coincides with it in position and size, and its distance from the mirror is then

measured. This distance is the radius of curvature of the mirror, and one-half of it is the principal focal length.

Case III. When the object is between the center of curvature and the principal focus, the image is out in front of the center of curvature, is larger than the object, inverted, and real.

Case IV. When the object is at the principal focus the rays from each of its points are too divergent to be converged by the mirror, and are found to be parallel; hence no image is formed. Concave mirrors are thus used as reflectors for carriage lamps and bicycle lanterns, the source of light being placed at the principal focus.

Case V. When the object is between the principal focus and the mirror, as in Fig. 210, the rays from each point of the object are still more divergent. They do not meet in

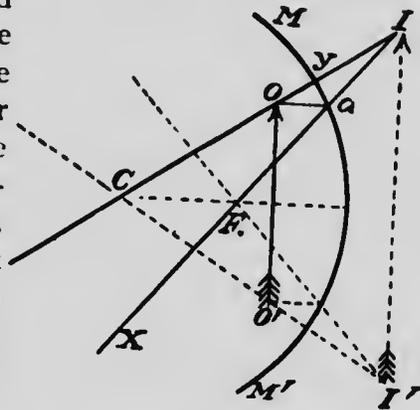


FIG. 210
CONCAVE MIRROR. VIRTUAL IMAGE

front of the mirror, but if they are extended behind the mirror they will meet at a point. This point is the point from which they seem to diverge, and is therefore a virtual image of the point from which they really come. The image is found to be behind the mirror, and to be larger than the object, right side up, and virtual. The image of himself that a man sees in a

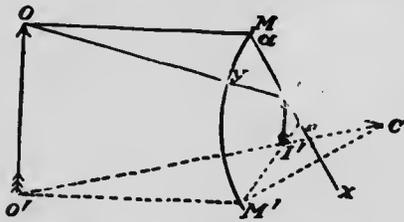


FIG. 211
CONVEX MIRROR. VIRTUAL IMAGE

concave shaving mirror, and the image of a tooth that a dentist sees in his little mouth-mirror are formed in just this way.

354. Convex Mirror. When parallel rays fall on a convex mirror they are made to diverge as in Fig. 211, and they

seem to diverge from a point behind the mirror which is its principal focus. The image may be constructed in accordance with the same rule as for the concave mirror except that the center of curvature and the principal focus are behind the mirror, and the reflected rays have to be extended behind the mirror in order to determine their directions by drawing them through these points. The image is found to be always behind the mirror, smaller than the object, right side up, and virtual. There are no important practical applications of the convex mirror.

355. Distorted Images. In places of amusement, mirrors are sometimes found which furnish very grotesque and ludicrous virtual images of the spectators. Their surfaces are more like cylindrical, than spherical, surfaces. Some are convex, others concave, and still others have the upper half concave and the lower half convex or vice versa. Usually their surfaces are shaped something like the shell of an egg, i. e., having one radius of curvature for the up and down direction of the surface and another for the sidewise direction. Such a mirror if concave would give an inverted real image of a person at a distance, but an enlarged, virtual, erect one of a person standing close to it. The convex surfaces would always give a virtual image smaller than the person. The image in each case would be distorted as to breadth and height. If the long curvature were up and down it would make the person look very slim, and if it were sidewise it would make him look very fat. If the surface were curved like a letter S the image would be part too large and part too small.

DEFINITIONS AND PRINCIPLES

1. When an image is formed by a convex lens the ratio of the size of the object to the size of the image is the same as the ratio of the distance of the object from the lens to the distance of the image from the lens.

2. When an object and its real image are of equal size,

the distance between them is four times the principal focal length of the lens.

$$3. \text{ Index of refraction} = \frac{\text{Speed of light in air}}{\text{Speed of light in second medium}}$$

4. The index for refraction of light of a given color is constant for any two given media.

5. When the index of refraction is greater than 1 the angle of refraction is less than the angle of incidence.

6. Lights of different colors travel at different speeds in transparent media.

7. Real images may be formed by reflection with concave mirrors.

8. The images formed by convex mirrors are always virtual.

QUESTIONS AND PROBLEMS

1. What are the different cases as to the location of an object whose image is formed by a convex lens?
2. By the rule for construction (Art. 338) find the location and size of the image for each case of an object placed in front of a convex lens as given in your answer to question 1.
3. In each case (problem 2) describe the characteristics of the image—i. e., position, size, position, and character (real or virtual).
4. Name as many practical applications as you can for each case.
5. In general, how do your diagrams (problem 2) show the effect on the size and distance of the image caused by moving the object nearer the lens or farther away from it?
6. The focal length of a camera lens is 24 inches. Where must the face of a sitter be placed in order to get a picture just as large as the face? How far from the lens must the ground glass screen be moved in order to focus the image?
7. Given a candle, an ordinary magnifying glass, and a white wall. Tell how you could prove experimentally all the statements as to the formation of images included under Art. 338.
8. Mention two methods by which you can determine the focal length of the lens of a photographic camera.
9. An opaque object such as an engraving or a picture post card may be projected on a screen by concentrating on it a strong light from a con-

condensing lens and placing a projecting lens at the proper distance between it and the screen. Make a diagram to show the direction of the condenser beam and the direction of the beams from the picture through the lens to the screen.

10. Just how must a lantern slide be placed in order that the picture on the screen shall not be upside down, and left-hand to right?

11. In projecting opaque objects, why is a large condenser necessary? Why is a projecting lens of large diameter necessary?

12. In projecting opaque objects, why is it necessary to use a very strong light and not try to magnify the picture very much?

13. In projecting a picture post card with light, condenser, and projecting lens, the picture is reversed from right to left. What addition to the apparatus is necessary to get a correct picture instead of a reversed one?

14. To get the best results with a compound microscope, why must the condenser used with an object glass of very short focal length have a shorter focal length than one that is to be used with a long focus object lens?

15. Show how two prisms may be so arranged as to produce double the deviation that is produced by one.

16. Which has the greater index of refraction from air to glass, red light or violet light?

17. With an ordinary glass lens will the principal focus for red light be exactly the same as that for violet light? If not the same, which focus will be nearer to the lens?

18. How can you prove your answer to question 17 with an ordinary lens, a beam of white light, and a white card? The phenomenon is known as *chromatic aberration*.

19. Draw a right triangle abc with the sides ab and cb about the right angle equal. Let this right isosceles triangle represent a section of a flint glass prism. The critical angle of the flint glass is about 38° . Show that if a parallel beam enters perpendicular to the face ab it will leave perpendicular to cb .

20. Show that if a parallel beam enters the prism abc (problem 19) near a , and perpendicular to the face ac , it will emerge near c and perpendicular to the same face.

21. If a projecting lantern whose object glass has a certain focal length cannot be moved farther away from the screen without making the picture too large for the screen, suggest a way in which a long focus concave lens may be used so as to enable this to be done.

22. The critical angle for water is $48\frac{1}{2}^\circ$. Show by a diagram how much of the sky you would be able to see if you were to dive down under clear water, open your eyes, and look up.

23. If the bottom (problem 22) were covered with grass and stones, what would the border of the sky patch that you saw look like?
24. In what part of the sky must you look to see a rainbow in the morning? In the afternoon?
25. How could you make a rainbow with a lawn spray?
26. How do the rules for constructing an image with a concave lens, with a concave mirror, and with a convex mirror compare with the construction for a convex lens?

CHAPTER XX

ENERGY OF MOTION

356. Bodies in Motion Possess Energy. In Chapter II we learned how to measure the work done in lifting heavy bodies and in pushing or pulling them against resistances of various kinds. Nothing was said, however, about the work that must be done in putting a body into motion or about that done in bringing a body to a state of rest. Yet every one knows that when a baseball is thrown, work has to be done in overcoming the inertia of the ball and giving it a velocity; and also that the energy thus put into the ball remains with it during its flight and is expended on the catcher who stops it.

In like manner, if you invert a bicycle and start the front wheel to spinning on its axle, you have to push on the tire or spokes to accomplish this, thereby doing work. When once spinning rapidly, the wheel continues to spin for a long time unless you apply some force to stop it. The energy put into it in giving it a rotary motion stays in the wheel, and does work on anything that acts to stop it. Thus *energy is required to set bodies into motion, and is given up by bodies in motion when they are stopped; i. e.,*

Moving bodies possess energy because of their motion.

Since bodies in motion possess energy, an accurate treatment of such problems as that of finding how much work must be done in hauling a train from one station to the next makes it necessary to take account both of the work done against friction and of that done in overcoming inertia when getting up speed.

357. Potential and Kinetic Energy. When a child is pushed in a swing, work has to be done in starting the swing,

because the center of gravity of the child and swing has to be lifted to a higher level. When the swing has been lifted to a higher level, it is stored with the energy that was expended in lifting it; it is therefore in a position to descend and do work. The energy which a body possesses because of its position is called *potential energy*. Since in this case the potential energy is measured by the product of the weight of the child and swing and the difference in level, and since the weight of the child and swing does not change, and since the same relations exist for all other cases like this, we conclude that *the greater the difference in level through which the center of gravity of a body is lifted, the greater is its potential energy*.

When the swing has been lifted and let go, its center of gravity descends to the level from which it was lifted, and theoretically rises on the other side to the level from which it fell. Its potential energy is then as great as it was at the beginning, showing that no energy has been lost. Therefore at the middle of the swing it still possesses all the energy that was put into it at the beginning. Since it then has no energy of position, but is in rapid motion, its energy at the middle of the swing, must be energy of motion. Energy of motion is called *kinetic energy*. *When a body falls, potential energy is transformed into kinetic energy; ignoring friction, the gain in kinetic energy is equal to the loss in potential energy.*

358. Factors on Which Kinetic Energy Depends. With a given child and swing, the greater the difference in level through which the center of gravity has been lifted, the greater the potential energy at the beginning, and the greater the difference in level through which the center of gravity may fall. But the greater the distance through which it falls, the greater the velocity which it acquires in falling and with which it passes the lowest point of its path. Thus when a body falls, kinetic energy increases at the expense of potential energy, and velocity is acquired at the expense of difference in level; and since difference in level is one of the factors by

which potential energy is measured. *velocity is one of the factors by which kinetic energy is measured.*

If we put two children into the swing, more work must be done in lifting their common center of gravity through a given difference in level than was done before in lifting one child through the same difference in level. Hence the potential energy of the two at the higher level is greater than that of one at the same level. Therefore, the kinetic energy of the two at the middle of the swing is greater also.

But at the middle of the swing the center of gravity of the children and swing is directly beneath the point of support; therefore their weight is counterbalanced by the ropes of the swing; so weight cannot be one of the factors of kinetic energy. The children continue to move past the middle of the swing and rise to the higher level on the other side, because of their inertia or mass; i. e., *mass is one of the factors by which kinetic energy is measured.*

Potential energy is measured by force and distance, kinetic energy is measured by mass and velocity.

In order to find out more definitely how kinetic energy is measured by mass and velocity, we must study more closely the way in which forces and distances vary when various velocities are imparted to different masses.

359. Force and Mass. An ounce of powder will give a small steel bullet a high velocity, but it takes several hundred pounds of powder to give a large steel shell the same velocity as the bullet. An empty sled can be set into motion quickly by a small pull; but when the sled is loaded, a much greater pull is required to give it the same velocity in the same time. An empty freight train gets up speed much more easily and quickly than a loaded one. In all of these cases *greater force is required to give the larger body the required speed in the required time because the larger body has the greater inertia or mass.*

A large cannon ball can do more damaging work than a small bullet, when both are traveling at the same speed.

Railway spikes are not driven home with a carpenter's hammer, but with the more bulky sledge, which strikes the spikes with more force. So, conversely, *when a body is moving with a given speed, the greater the mass of the body, the greater the force required to bring it to rest in a given time.*

The impressions derived from everyday experience in setting bodies into motion have been tested by careful measurements in the laboratory. For example, we find that twice as much force is required to give two cubic feet of water a velocity of 1 foot per second, as is required to give one cubic foot of water the same velocity in the same time; three times as much force is required to give three cubic feet of water a given velocity as is required to give one cubic foot of water the same velocity in the same time; and so on—i. e., *the force required to produce a certain change in velocity in a certain time is proportional to the mass of the body moved.*

360. Force and Change in Velocity. When you are riding in a train that is moving with a uniform velocity, you sit as comfortably in your seat as when the train is at rest. But when the train suddenly begins to slow down, you have to brace your feet against the floor and push backward in order to decrease your own velocity as that of the train decreases. The greater the change in velocity in a given time, the harder you have to push. When the train starts quickly, you feel a forward push, which increases your velocity as that of the train increases. The greater the change in velocity in a given time, the greater the force with which you are pushed. When a body that is free to move is either at rest or moving uniformly, i. e., when there is no change in its velocity, we infer that no force is acting; but when the velocity changes, we infer that a force is acting. *So change in velocity indicates that force is acting, and the greater the change in velocity in a given time, the greater the force.*

In like manner, when you jump from the porch step to the ground you are in no danger of being hurt by the shock.

Your velocity is not large, and a relatively small force is sufficient to reduce it to zero in a short time. But when you jump from the porch railing, the shock of landing is much greater. No one can jump from a fourth story window without serious results. In falling through the greater height, the velocity acquired is so great that the force that can reduce the velocity to zero in the brief time in which it is done, is large enough to break your bones. Similarly a man may jump from a slowly moving train without hurting himself. A relatively small force is sufficient to reduce his velocity to zero in a brief time. Any one who jumps from a train running at a velocity of 50 or 60 miles an hour is almost sure to be seriously injured. If he stops quickly, the force required to reduce to zero the greater velocity which he has when he lands is great enough to cause disaster. Careful measurements show that *the force required to produce in a given mass and in a given time a change in velocity is proportional to the degree of the change in velocity.*

361. Force and Time. Firemen carry with them to fires strong nets, which may be stretched near the ground to catch people who may jump from the windows of a burning building. Acrobats at the circus often jump from a great height into a stretched net without injury. We say the net "breaks the fall"; and this means that the velocity acquired by the acrobat in falling is not reduced to zero as quickly as it is when he lands on the ground. A less force acting for a longer time brings him safely to rest.

A sick man does not jump quickly out of bed, but rises slowly. Less force is required to put his body into motion slowly than to do it quickly. When a man starts for a ride on a bicycle he may break the bicycle chain if he tries to get up speed too quickly. The driving wheels of a locomotive slip on the track when the train is starting from rest if the engineer tries to get up speed too quickly. Measurements confirm these general conclusions and show that *the force required to produce a given change in the velocity*

of a body is inversely proportional to the time in which the change in velocity is accomplished.

362. Force, Momentum, and Time. In the three preceding articles we have learned that when the velocity of a body is changed, the force (f) that produces the change is proportional to the mass (m), proportional to the change in velocity (v), and inversely proportional to the time (t); i. e., force (f) \propto $\frac{\text{mass } (m) \times \text{change in velocity } (v)}{\text{time } (t)}$, or

$$f \propto \frac{m v}{t}. \quad (4)$$

The product mass \times velocity is called the *momentum* of a body. Therefore, for a given body when m is constant, the mass \times change in velocity ($m v$) is the *change in momentum*. So when the velocity of a body is changed, *the force is proportional to the change in momentum.*

363. Action and Reaction. The conclusion just reached enables us to verify Newton's Third Law of Motion (Arts. 9 and 49). The compressed spring (Fig. 14) pushes with equal force on each of the blocks. When allowed to act, it imparts momentum to each. Since the force that acts on each is of the same magnitude, and since it necessarily acts for the same time, the momenta imparted to the blocks must be equal. By measuring the masses of the blocks and the velocities imparted to them, we can thus verify Newton's Law. This has been done with great care in many cases, and the law has been verified with a great degree of accuracy.

The fact that in every case of action and reaction the momenta are equal enables us to understand why it is difficult to dive from a canoe. The mass of the diver gets a velocity in one direction, and the mass of the canoe a velocity in the opposite direction. Since the two momenta are equal, if the mass of the canoe is less than that of the man, the canoe acquires the greater velocity. When a man dives from a large steamer, or from a pier, the mass of the man is

much less than that of the other body, and so the velocity of the man is proportionally greater. In most cases of action and reaction the earth is one of the bodies concerned, and since the mass of the earth is very great, the velocity it acquires when objects on its surface act on it is extremely small. Whenever there is action and reaction,

The momenta are equal and opposite in direction.

364. Velocity at a Point. While considering force and momentum in the preceding articles, frequent mention has been made of change in velocity. Before we can accurately measure momenta, we must find out how change in velocity is measured.

When a stone is dropped, its velocity increases as it falls. When dropped from a third story window, it has, at the instant when it passes the top of the second story window, a smaller velocity than that which it has when it passes the top of the first story window.

The way in which the speed of a falling body increases as the body descends may be studied if we drop a vibrating tuning fork (Fig. 212) and allow it to trace a wavy line showing its vibrations on a plate of smoked glass. Since each vibration of the fork takes place in the same time—namely, the period of the fork—the length of the wave traced by each vibration indicates the distance traversed by the fork in that time. At the top of the glass, where the fork was moving slowly, the waves

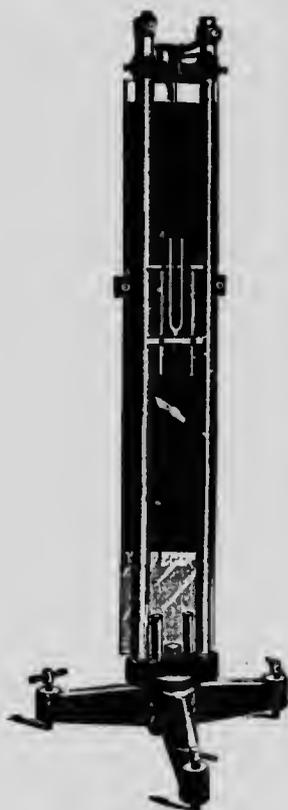


FIG. 212
FALLING TUNING FORK

traced on the glass are short. They grow longer the farther they are from the starting point, showing that the farther the fork falls, the greater the distance passed over in the time of one vibration of the fork.

Since the velocity is not uniform, but is changing at every instant, we cannot measure the velocity with which it passes a point directly. If we assume that the fork traveled with uniform velocity while it was tracing one particular wave, then the velocity with which it was traveling at that time is obtained by dividing the length of the wave by the period of the fork. This quotient gives the value of the uniform velocity that would take it over the same distance in the same time. This uniform velocity is a little greater than the velocity of the fork at the beginning of the small time interval, and a little smaller than the velocity of the fork at the end of the small time interval. If the time interval is small, we make no serious error if we say *the value of the velocity at the middle of the time interval is found by dividing the distance passed over in the time interval by the time interval.*

In order to find the velocity with which the falling fork passed any point, say one *a* that is 10 centimeters below the starting point, we measure 10 centimeters along the trace of the waves and mark a line across the trace at *a* (Fig. 213). Then mark off half a wave on each side of this mark, as at *b* and *c*, measure the length *bc* of the wave thus marked off, and divide by the period of the fork. The result will be the velocity with which the fork was traveling at the middle of the time interval when it passed the point *a*. If the period of the fork is small, it will be better to lay off two whole waves on each side of the point, as at *d* and *e*, and to measure the greater distance *de* and divide by the corresponding time interval (four vibrations of the fork).



FIG. 213
TRACE OF THE FALLING FORK

365. Rate at Which Velocity Changes. Acceleration. Suppose the falling tuning fork has a period of $\frac{1}{140}$ second.

On measuring off on the trace two wave lengths on each side of the point 10 centimeters distant from the starting point we find the distance *de* (Fig. 213) between the end marks to be 4 centimeters. The velocity at the point 10 centimeters

from starting point is then $\frac{4 \text{ (centimeters)}}{\frac{1}{140} \text{ (second)}} = 140 \frac{\text{cm}}{\text{sec}}$

(i. e., centimeters per second). In falling 10 centimeters the velocity of the fork increased from 0 to 140 $\frac{\text{cm}}{\text{sec}}$

By counting the number of wave lengths from the starting point down to the 10-centimeter mark, we find the time in which this increase in velocity took place. Suppose there are 20 waves in this distance. The time is then $\frac{20}{140} = \frac{1}{7}$ second.

Since the velocity thus increased $140 \frac{\text{cm}}{\text{sec}}$ in $\frac{1}{7}$ second,

in 1 second it would have increased $\frac{140}{\frac{1}{7}} = 980 \frac{\text{cm}}{\text{sec}}$. The

velocity was therefore increasing at the rate of 980 centimeters per second each second.

Rate of change of velocity is called acceleration.

If we mark off two wave lengths on each side of another point on the trace 40 centimeters from the starting point we find the distance between the outside marks to be 8 centimeters. The velocity of the fork at this point was therefore

$$\frac{8 \text{ (cm)}}{\frac{1}{280} \text{ (sec)}} = 280 \frac{\text{cm}}{\text{sec}}$$

The velocity has changed between the 10 and the 40 centimeter marks $280 - 140 = 140 \frac{\text{cm}}{\text{sec}}$. Between these two marks

there are again 20 waves, showing that the time in which this change in velocity took place is $\frac{1}{7}$ second as before. So the rate of change of velocity—i. e., the acceleration—of the falling fork is $\frac{140 \left(\frac{\text{cm}}{\text{sec}}\right)}{\frac{1}{7} \text{ (sec)}} = 980 \frac{\text{cm}}{\text{sec}^2}$ (i. e., centimeters per second per second).

$$\text{Acceleration } (a) = \frac{\text{Change in velocity } (v)}{\text{Time required for change } (t)} \text{ or}$$

$$a = \frac{v}{t}. \quad (5)$$

366. Force, Mass, Acceleration. In Art. 362 we found that

$$f \propto \frac{m v}{t}.$$

We now find that $\frac{v}{t}$ is called the acceleration a . Therefore, substituting a for $\frac{v}{t}$, we get

$$f \propto m a.$$

In our discussions thus far we have used as units of force the gram-weight and the pound-weight. These units are convenient for ordinary use, but they are not perfectly satisfactory for accurate scientific work, because they are not absolutely constant. If the standard pound avoirdupois (Art. 15) is carried down to the equator, it weighs less on a spring balance than it does in London, because the earth is not a sphere, and points on the equator are farther from the center of gravity of the earth than the city of London.

The relation of $f \propto ma$ enables us to frame a more satisfactory definition of a unit force. The mass of a cubic centimeter of water is the same the world over. We therefore take the mass of a cubic centimeter of water as the unit of mass, the centimeter per second per second as the unit of acceleration, and define *the unit of force as that force which will give to unit mass unit acceleration* ($\frac{\text{cm}}{\text{sec}^2}$). This unit of force is called the *dyne*. Because of this definition, the relation $f \propto ma$ becomes f (dynes) = m (grams) \times a (centimeters per second per second); i. e.,

$$f = ma. \quad (6)$$

The acceleration of a freely falling body is $980 \frac{\text{cm}}{\text{sec}^2}$.

Therefore the weight in dynes of a cubic centimeter of water (gram mass) is

$$f \text{ (dynes)} = 1 \text{ (gm)} \times 980 \frac{\text{cm}}{\text{sec}^2} = 980 \text{ dynes.}$$

So the relation between the old unit of force (gram-weight) and the new unit (dyne) is

$$1 \text{ gram-weight} = 980 \text{ dynes.}$$

367. Distance and Velocity. Having thus found the relations between force on the one hand and mass and velocity on the other, we must next find the relation between distance and velocity (Art. 358). In Art. 365 we found that the falling tuning fork acquired a velocity of $140 \frac{\text{cm}}{\text{sec}}$ in falling a distance of 10 cm. While passing over the 10 cm, the velocity changed from 0 to $140 \frac{\text{cm}}{\text{sec}}$. This change in velocity was accomplished in $\frac{1}{4}$ second; so the distance traversed (10 cm) in this time was the same as if the fork had moved with a uniform speed of $70 \frac{\text{cm}}{\text{sec}}$. But $70 \frac{\text{cm}}{\text{sec}}$ is the average of the initial velocity (0) and the final velocity (140); i. e., $\frac{0 + 140}{2} = 70 \frac{\text{cm}}{\text{sec}}$. Hence the conclusion: When a body starts from rest and moves with uniformly accelerated motion, the distance traversed (s) is equal to the product of the average velocity ($\frac{0+v}{2}$) and the time (t); i. e.,

$$s = \frac{v}{2} t.$$

The definition of acceleration was $a = \frac{v}{t}$, from which $t = \frac{v}{a}$.

If we substitute this value of t in the preceding equation we get

$$s = \frac{v^2}{2a}. \quad (7)$$

A study of the results of the experiment with the falling fork gives the same result. The velocity at a distance of 10 cm from the start was $140 \frac{\text{cm}}{\text{sec}}$. At a distance 4 times as great (40 cm) it was $280 \frac{\text{cm}}{\text{sec}}$. If the velocity is measured at a distance of 90 cm from the starting point, it will be found to be $420 \frac{\text{cm}}{\text{sec}}$, and so on; i. e., *the distance passed over by a freely falling body is proportional to the square of the velocity acquired.*

368. Kinetic Energy. We can now apply the results of Arts. 366 and 367 to solve the problem of measuring energy of motion. Suppose the bob of a Galileo pendulum (Art. 32) weighs f dynes and is lifted vertically a distance of s cm; the work done is $f \times s$ (dyne \times cm). The bob is now let fall. When it reaches its original position it has acquired a velocity (v) and retains all the energy that was put into it when it was lifted. Since $f = ma$, and $s = \frac{v^2}{2a}$,

$$f s = ma \times \frac{v^2}{2a} = \frac{m v^2}{2}$$

Its energy when it swings through the lowest point of the swing is measured by half the product of the mass and the square of the velocity acquired by falling; i. e.,

$$\text{Kinetic energy} = \frac{m v^2}{2}. \quad (8)$$

369. Laws of Uniformly Accelerated Motion. Much importance is sometimes attached to the "laws of accelerated motion," which are here briefly stated together, for the convenience of those who may wish to use them.

By definition (Art. 365), $a = \frac{v}{t}$; hence, clearing of fractions we get

$$v = at; \text{ i. e.,}$$

Law I. For a body starting from rest with a unifo.

acceleration, the velocity acquired in a given time is numerically equal to the product of the acceleration and the time.

$$\text{From Art. 367, } s = \frac{v^2}{2a}; \text{ i. e.,}$$

Law II. For a body starting from rest with uniform acceleration, the distance traversed while the velocity changes a given amount is numerically equal to the square of the change in velocity divided by twice the acceleration.

By clearing this equation of fractions and extracting the square root of both members, Law II may be reduced to the following alternative form:

$$v = \sqrt{2as}; \text{ i. e.,}$$

For a body starting from rest with uniform acceleration, the change in velocity in a given distance is numerically equal to the square root of twice the product of the acceleration and the distance.

From Art. 367 we have $s = \frac{v}{2} t$. By substituting for v its equal at (Law I), this equation becomes $s = \frac{at}{2} t$, or

$$s = \frac{at^2}{2}; \text{ i. e.,}$$

Law III. For a body starting from rest with uniform acceleration, the distance traversed in a given time is numerically equal to half the product of the acceleration and the square of the time.

Since freely falling bodies move with uniformly accelerated motion, these laws are often called the *laws of freely falling bodies*.

370. Absolute Units. I. Art. 366 a new unit of force, the dyne, has been defined. Since the magnitude of this unit does not depend on the position on the surface of the earth where it is used, *the dyne is called the absolute unit of force.*

When a force of 1 dyne acts through a distance of 1 centimeter, 1 absolute unit of work is done. This absolute unit of work is called the erg.

Since 1 gram-weight = 980 dynes,

1 gram-centimeter = 980 ergs.

The erg is a very small amount of work. A larger unit called the *joule* is, therefore, often used.

1 joule = 10,000,000 ergs.

In this system the unit of power is the *erg per second*. Since this also is a very small unit, the *joule per second* is generally used. This unit is called the *watt*. It is the same unit used for electric power (Art. 265); i. e.,

1 watt = 1 joule per second = 10,000,000 ergs per second.

371. Measurement of Mass. When we wish to compare the mass of 1 cm³ of any substance, for example brass, with that of 1000 cm³ of the same substance, we may do so by comparing the respective volumes. Evidently 1000 cm³ of brass contains 1000 times as much brass as 1 cm³. *When bodies are made of the same substance, their masses are proportional to their volumes.*

When we wish to compare two masses of different substances, for example, a mass of sugar with a mass of iron, the process is not so simple. We then use equation (6). Since force (dynes) = mass (grams) × acceleration ($\frac{\text{cm}}{\text{sec}^2}$).

$$\text{mass (grams)} = \frac{\text{force (dynes)}}{\text{acceleration}(\frac{\text{cm}}{\text{sec}^2})}; \text{ i. e.,}$$

Mass may be measured by dividing a measured force by the acceleration produced by it.

The process of comparing two masses may be simplified if we can measure the forces that give the two masses the same acceleration. Thus if m and m' represent the two masses, and f and f' the two forces required to give m and m' respectively the same acceleration a , then, for the first, $f = ma$. Similarly for the second $f' = m'a$. Hence

$$\frac{f}{f'} = \frac{ma}{m'a} = \frac{m}{m'}; \text{ i. e.,}$$

The masses are proportional to the forces that give the same acceleration. Therefore *we may compare masses by comparing the forces that give the masses the same acceleration.*

This method of comparing masses makes it necessary to find some convenient means of giving different bodies the same acceleration. From time immemorial masses have been compared by means of the ordinary equal arm balance; but it was reserved for Galileo and Newton to find the complete justification of this method.

372. Galileo's Experiment. Mass and Weight. By his celebrated experiment of dropping at the same instant a small bullet and a large bombshell from the top of the leaning tower of Pisa, Galileo was the first to show that two heavy bodies, when dropped at the same instant from the same height and allowed to fall freely, reach the ground at the same time.

Galileo attributed the fact that a body of large size in proportion to its mass, like a feather, falls more slowly than a small heavy body, like a penny, to the resistance of the air. After the invention of the air pump, it was shown that a coin and a feather, when dropped at the same instant from the top of a long glass tube from which the air has been pumped, fall side by side and reach the bottom at the same instant. This experiment has been repeated carefully in many different ways, so that we now know that

At a given place all freely falling bodies have the same acceleration.

So, because weight gives all bodies the same acceleration, *we may compare the masses of bodies by comparing their weights; i. e.,*

Mass is proportional to weight.

373. Variations of the Acceleration Due to Gravity. In Art. 366 it was stated that the acceleration of a freely falling body is $980 \frac{\text{cm}}{\text{sec}^2}$. This is not strictly true for all places

on the earth's surface. At places near the equator, bodies weigh less (Art. 366) than they do at places farther north. A given mass weighs most at the pole. Since the force of gravity (weight) of a given mass varies, the acceleration due to that force varies. The variation is not very large—between about 984 at the pole and 977 at the equator. In all calculations where great accuracy is not required, the value 980 may be used. The acceleration due to gravity is one of the important constants of Nature. It is usually denoted by g . For all ordinary calculations,

$$g = 980 \text{ centimeters per second per second, or}$$

$$g = 32.2 \text{ feet per second per second.}$$

374. Mass in the British System of Units. In the British system of units, forces are measured in pounds-weight, and work in foot-pounds. Since the weight of a body = mass $\times g$, the mass = $\frac{\text{weight}}{g}$; i. e., *the mass of a body is found by dividing the weight in pounds by the value of g in feet per second per second.*

Thus the kinetic energy of a wagon that weighs 644 pounds and is moving with a velocity of 10 feet per second is

$$\frac{\text{mass} \times \text{velocity}^2}{2}$$

$$\frac{644 \text{ (pounds-weight)}}{32.2 \text{ (ft. per sec. per sec.)}} \times \frac{100 \text{ (ft. per sec.)}^2}{2} = 1000 \text{ foot-pounds.}$$

375. Energy of Rotation. Fly Wheels. Gas, steam, and gasoline engines generally have heavy wheels called *fly wheels* mounted on their shafts. The rim of a fly wheel is usually made thick and broad, so that it contains a large portion of the iron in the wheel. When such a wheel is rotating rapidly, it has kinetic energy, just as it would have if moving in a straight path. So work must be done in starting it when it is at rest, and in stopping it when it is in motion; there-

fore, it acts to prevent sudden jerks or changes in the motion of the engine.

When the wheel is rotating those points of the wheel that are on the axis have no velocity; while points on the wheel but not in the axis are moving with velocities which are greater in proportion as the distance of the point from the axis is greater. Thus when a wheel makes 1 revolution per second, a point 10 cm from the axis travels over a circumference of 10 cm radius in 1 second. A point 20 cm from the axis travels over a circumference of 20 cm radius in a second; it goes twice as far in the same time and therefore has twice the linear speed—i. e., when the wheel is turning,

The velocity of a point on a rotating wheel is proportional to the distance of the point from the axis of rotation.

The kinetic energy of a mass m moving with a velocity v is measured by the product $\frac{mv^2}{2}$. If this mass m is a small

part of a rotating wheel, and if it lies near the axis, its velocity v is relatively small; and so its kinetic energy is small. But if the small mass m is twice as far from the axis of the rotating wheel, its velocity is twice as great, because the velocity increases in proportion to the distance r from the axis. Since the velocity of the mass m is proportional to r , *the kinetic energy of a small mass m rotating about an axis is proportional to the square of its distance r from the axis.*

This fact explains why fly wheels have such massive rims. A given mass when placed at a distance from the axis has much more kinetic energy than the same mass when placed near the axis and rotating at the same speed.

376. Centrifugal Force. Since the kinetic energy of a small mass m on the rim of a wheel is greater the greater its distance r from the center, we can increase the rotary energy of a fly wheel of given mass by making it of larger diameter. There is a limit, however, beyond which we cannot go, as the following considerations will show.

When a wet grindstone is rotating, the water flies off from the rim. Mud flies off from the wheels of bicycles and automobiles when they are running fast on a muddy road. Drops of water may be shaken out of bottles by swinging them quickly in a circle at arms length. A pail of water can be swung around in a vertical circle without spilling any water, notwithstanding the fact that the pail is upside down at the top of the circle. In a loop-the-loop, the car does not fall from the track when it is inverted at the top of the loop. Wet clothes are dried by placing them in a large metal cylinder with perforated sides, and rotating the cylinder rapidly.

All of these experiences are illustrations of the fact that every body has inertia and tends to move in a straight line; therefore, when a body is compelled to move in a curved path it appears to be pulling away from the center about which it is turning. This pull away from the center of rotation is called *centrifugal force*.

When a wheel is making a certain number of revolutions per second, the centrifugal force of a small mass m on the rim of the wheel is twice as great as the centrifugal force of an equal mass m that is located in a spoke halfway between the rim and the axle. In other words, *for a given number of revolutions per second, the centrifugal force is directly proportional to the distance from the axis of rotation*. Every fly wheel is designed to make a certain number of revolutions per second. If the radius of the wheel is too large, the centrifugal force may cause the rim to burst when the wheel is making the required number of revolutions per second.

For a wheel of given size, the centrifugal force increases as the speed of rotation increases, being four times as great when the number of revolutions per second is doubled; i. e., it is proportional to the square of the number of revolutions per second. Hence fly wheels that have to rotate rapidly must have small diameters or they are liable to burst.

The cream separator makes use of centrifugal force in skimming milk. Since skimmed milk is denser than cream, it has greater mass per cm^3 ; and so, when rapidly rotated in

a suitable vessel, the centrifugal force causes the milk to gather at the circumference of the vessel, thereby pushing the less dense cream toward the center, very much as colder air settles down and pushes hot air up a chimney (Art. 101).

DEFINITIONS AND PRINCIPLES

1. Moving bodies possess energy because of their motion.
2. The force required to give a mass m a velocity v in t seconds is proportional to the mass and to the velocity and inversely proportional to the time; i. e., $f = \frac{mv}{t}$.
3. Momentum is measured by the product of the mass and the velocity, i. e., momentum = mv .
4. In every case of action and reaction, the momenta are equal and opposite in direction; i. e., $mv = m'v'$.
5. When a body is moving with uniform velocity, the velocity at every instant is the same.
6. When a body is moving with varying velocity the change in its velocity is the difference between its velocity at one instant and its velocity at some other instant.
7. By dividing the distance traversed in a small time interval by the time interval, we find the value of the velocity of a body at the middle instant of the time interval.
8. Acceleration is the rate at which the velocity changes.
9. Acceleration a is measured by dividing the change in velocity v by the time t in which the change took place; i. e., $a = \frac{v}{t}$.
10. A body has uniformly accelerated motion when its acceleration is constant.
11. Force (f) = mass (m) \times acceleration (a); i. e., $f = ma$.
12. The dyne is the force that gives a gram-mass an acceleration of 1 centimeter per second per second.

13. A constant force imparts to a given mass a uniformly accelerated motion.

14. The numerical value of the acceleration of gravity is 980 centimeters per second per second.

15. 1 gram-weight = 980 dynes.

16. Masses are compared by comparing their weights.

17. The distance passed over by a body moving with uniformly accelerated motion is found by dividing the square of the change in velocity by twice the acceleration; i. e.,

$$s = \frac{v^2}{2a}.$$

18. Kinetic energy is measured by half the product of the mass and the square of the velocity; i. e., kinetic

$$\text{energy} = \frac{mv^2}{2}.$$

19. When a force f acts through a distance s and produces in a mass m a change in velocity v , $fs = \frac{mv^2}{2}$.

20. All bodies falling freely at the same place have the same acceleration.

21. The kinetic energy of a mass m rotating about an axis is greater the greater its distance from the axis.

22. When a body is rotating about an axis its inertia gives rise to centrifugal force.

23. Centrifugal force is greater the greater the mass, the greater the distance from the axis, and the greater the number of revolutions per second.

QUESTIONS

1. Why is the wind able to do the work of turning a windmill?
2. Why is it hard work to swim through the breakers?
3. Will the water motor (Fig. 57) be able to do more work if the water from the nozzle stops when it strikes the buckets, or if the buckets move with the same velocity as the water so that the water strikes the opposite side of the motor case?
4. Why is the efficiency of a water motor reduced if it is running too fast?

5. A heavy man is usually preferable to a light-weight for a football team. Is this because of his greater mass or his greater weight?
6. Why does the fuse blow on a trolley car if the motorman tries to get up speed too suddenly?
7. Why do automobiles have different sets of gears between the engine and the driving wheel?
8. Which set of gears does a chauffeur use when getting up speed in a large auto?
9. Does the weight of the auto of question 8 make it necessary to start it gradually?
10. Why does the catcher of a baseball team wear a padded glove when playing?
11. Which stings your hand the more, a swift baseball or a equally swift tennis ball? Why?
12. Is it possible to catch a swift baseball without a glove and not get stung? How?
13. When a man chops wood why does he swing the ax high when he is trying to chop a knotty piece?
14. Why is it that you can drive an ax-head on by striking on the other end of the handle?
15. If there were no air resistance, would a bullet fired vertically upward return to the earth with the same velocity with which it left the muzzle of the gun?
16. Raindrops often fall from a great height. Why is not their velocity when they strike the earth great enough to make them dangerous?
17. Why do they put heavy springs on the bumpers on cars and at the ends of railroad tracks?
18. Why is it more comfortable to ride in a carriage with pneumatic tires and springs than in a farm wagon with neither?
19. Why is it easier to dive from a spring board than from a pier?
20. When you buy candy do you pay for its mass or its weight?
21. Why is it dangerous for a diver to fall flat on the water, but all right for him to strike the water head first?
22. If originally moving at the same speed, which shoots farther after the power is turned off, a 20-foot motor boat or a 200-foot steamer? Why?
23. Why do you refrain from punching brick walls but enjoy hitting a punching-bag?
24. Why do they stretch nets under acrobats when performing difficult feats at a circus?
25. Why are earthworks better than masonry walls for fortifications?

26. If sugar were always weighed on the same spring balance, would you get more sugar or less sugar when buying it in Peru than when buying it in New York? Why?
27. The mouth of the Mississippi river is some 2 miles farther from the center of the earth than its source. Do its waters flow up hill? Why?
28. Would it be advantageous to a grocer who bought goods in Chicago and sold them at the top of Pike's peak to use a spring balance in buying and selling? Why?
29. If you drop a brick and a bullet at the same instant from a third story window, which will strike the ground first? Why?
30. Is "heavy" or "massive" the better word to use in describing the rim of a fly wheel?
31. A fly wheel has a rim of a certain size; would it be better to make it of lead or of iron? Why?
32. The rims of two fly wheels have the same amount of iron in them but one has twice the diameter of the other. Which is the better as a fly wheel?
33. Which of the fly wheels of question 32 is more likely to burst when both are making the same number of revolutions per second? Why?
34. When you swing a pail of water rapidly around in a vertical circle, why doesn't the water fall out?
35. If you swing the pail of water (question 34) around slowly what happens? Why?
36. If you stand on a platform scale and swing a pail of water around in a vertical circle, do you seem to weigh more when the pail is up than when it is down? Why?
37. When you play snap the whip, why does the end man get thrown?
38. Does the cream in a cream separator go to the center or the outer surface? Why?
39. How does a centrifugal dryer succeed in drying clothes?
40. How do doctors shake down the mercury in clinical thermometers after taking the temperature of a patient?
41. Why do automobiles "skid" if they run too fast around a corner?

PROBLEMS

1. The hammer of a pile driver weighs 2500 pounds. It is lifted 15 feet and dropped on the head of a pile. How many foot-pounds of kinetic energy has it when it strikes?
2. A boy whose mass is 60 kilograms jumps from a boat with a velocity of $100 \frac{\text{cm}}{\text{sec}}$. How much momentum does the boat get?

3. A baseball that has a mass of 150 grams is thrown with a velocity of $500 \frac{\text{cm}}{\text{sec}}$. How much momentum is given to the thrower?

How much to the earth?

4. If the baseball (problem 3) is struck by a bat and sent back with a velocity of $150 \frac{\text{cm}}{\text{sec}}$ what is its change in momentum?

5. If the baseball (problem 3) strikes a house with a velocity of $150 \frac{\text{cm}}{\text{sec}}$ and bounces back with the same velocity how much momentum is given to the house?

6. What becomes of the momentum given to the house in problem 5?

7. A train starts from rest and at the end of 10 seconds has a velocity of $500 \frac{\text{cm}}{\text{sec}}$. What is its acceleration?

8. How far did the train of problem 7 go in the 10 seconds?

9. What was the velocity of the train of problem 7 at the middle of the 10 seconds?

10. A trolley car, starting from rest, acquires a velocity of $250 \frac{\text{cm}}{\text{sec}}$ in a distance of 1250 cm. What was its acceleration?

11. A box that weighs 10,000 grams is hung from a spring balance in an elevator at rest. When the elevator starts upward with an acceleration of $10 \frac{\text{cm}}{\text{sec}^2}$ how much does the spring balance read?

12. When the elevator (problem 11) is moving uniformly upward, what does the spring balance read?

13. If the cable that pulls the elevator up (problem 11) should break and the elevator should fall freely, how much would the spring balance read during the descent?

14. A man whose mass is 75 kilograms is riding in a train that is moving uniformly at the rate of $2500 \frac{\text{cm}}{\text{sec}}$. When brakes are applied so that the train slows down with a negative acceleration of $100 \frac{\text{cm}}{\text{sec}^2}$

with what force must the man push against the seat in front in order to keep his place?

15. How long must the man keep pushing (problem 14) before he comes to rest?

16. A man jumps from a height of 200 cm. With what velocity does he land?

17. If the mass of the man (problem 16) is 75 kilograms, what is his kinetic energy (ergs) when he lands?

18. A boy jumps vertically upward a distance of 2 feet. With what velocity did he leave the ground?

19. How long did it take the boy (problem 18) to reach the top of his jump?

20. If a boy when making a running broad jump is running at the rate of $800 \frac{\text{cm}}{\text{sec}}$ when he jumps, and if he rises two feet vertically during the jump, how far can he go before landing?

21. A train weighs 1000 tons and is moving at the rate of $40 \frac{\text{ft.}}{\text{sec}}$. How many foot-pounds of kinetic energy has it?

22. If the train (problem 21) strikes an incline that rises 4 feet in 100, how far up the grade would its kinetic energy carry it if there were no friction?

CHAPTER XXI

MOLECULAR PHYSICS

377. Surface Tension. If an ordinary sewing needle be laid carefully on the surface of the water in a basin, the needle will float, notwithstanding the fact that the density of steel is greater than that of water. Small insects called "skippers" move about on the surface of water as safely as other insects move on land. Small drops of mercury or water on a dusty floor are spherical in shape and roll about like solid shot. Raindrops, while freely falling in the air are nearly spherical. When a raindrop strikes against a window pane, it clings to the glass, the outer surface of the drop forming against the glass a tiny bag which holds the water. When such a drop is clinging to the window of a railway train, you may often see small cinders bouncing around inside the drop, unable to break through the surface of the drop and escape.

When a small soap bubble has been blown in a pipe, if the blowing ceases, the bubble contracts, always retaining its spherical form, until it moves back into the pipe and forms a flat film across the mouth. If a bubble is blown on the end of a small funnel, and allowed to contract, it will not only return to the funnel, but will creep up the funnel to the stem.

All of these phenomena show that the surface of a liquid acts as if it were covered with an elastic film like a thin rubber membrane, which always contracts as far as is possible. The needle floats because it is not heavy enough to break through this film. Drops become spherical because the free

surface of a liquid always tends to contract to the least possible area and the spherical form is the one which has the smallest surface area for any given volume. Because the free surface of a liquid always tends to contract to the least possible area, it is said to have *surface tension*.

378. Difference in Surface Tension. If a small piece of gum camphor be placed on the surface of water, it moves about in an irregular path. Similarly a small piece of metal sodium or of potassium, when placed on the surface of water, jumps about and often burns. A few drops of ether will cause considerable commotion on the surface of water. A drop of water, when placed on the surface of oil remains as a drop; but a drop of oil, when placed on water spreads out as far as possible, forming a layer thin enough to produce colors like those in a soap bubble (Art. 286).

These phenomena may be ascribed to differences in surface tension. The camphor, the sodium, and the ether dissolve in the water, and the surface tension is reduced. When a piece of camphor is dissolved faster on one side than on the other, the surface tension is reduced on one side more than on the other, and the camphor is pulled in the direction of the greater tension.

In like manner, the surface tension of water is greater than that of oil; so the water is held together in a spherical form on the oil, while the oil is pulled out into a thin film over the surface of the water.

379. Capillarity. If one corner of a piece of blotting paper is dipped into ink, the ink spreads upward into the paper. Water rises into a lump of sugar when one corner of the lump is dipped in the water. Lamp wicks conduct oil from the reservoir of the lamp up to the burner. The same phenomenon is seen when one end of a glass tube of fine bore is dipped into water. The water rises in the tube to a higher level than that of the surface of the water outside the tube.

On the other hand, when one end of a glass tube of fine bore is dipped into mercury, the mercury stands at a lower level inside the tube than outside. If we examine the upper surfaces of the water column and the mercury column inside the tubes, we find that the top of the water column is concave (Fig. 214), while that of the mercury column is convex (Fig. 215).

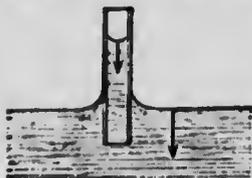


FIG. 214 WATER RISES IN THE TUBE

Because the water clings to or "wets" the glass, the edges of the surface film inside the tube are supported by the glass, and the surface tension pulls the water up the tube. The mercury, however, does not wet the glass, so the surface film on the mercury is not supported, and the mercury is pulled down by the surface tension. Since this phenomenon of surface tension is most striking in tubes of fine bore (i. e., capillary tubes) it is called *capillarity*.

The ink rises in the blotter, then, because there are many fine pores and ducts between the fibers, and when the ink wets the blotter, the surface tension pulls the ink up into these ducts. The same is true of the sugar and water, and of the lamp wick and oil. It is capillarity that causes sap to rise in trees and plants and water to spread through soils.



FIG. 215 MERCURY SINKS IN THE TUBE

380. Diffusion of Gases. If illuminating gas be allowed to escape for a few minutes from a gas fixture, in a short time the smell of gas may be detected in any part of the room. In like manner the smell of fresh paint or of a newly varnished floor soon fills the whole house.

Phenomena like these show that gases expand until they are evenly distributed throughout the space in which they are enclosed, even though this space contains other gases as well. This process by which one gas spreads through and mixes with another gas is called *diffusion*.

381. Diffusion in Liquids. If a glass jar be partly filled with water, and a layer of alcohol colored with some dye be poured carefully on the top of the water, and the whole be allowed to stand undisturbed, the water diffuse up into the alcohol, although it is denser than alcohol. After a few days, the water and the alcohol will be thoroughly mixed. Similarly, if the glass jar be partly filled with some colored solution, like one of copper sulphate, and a layer of water be poured carefully on top of the solution and the whole be allowed to stand several weeks, the blue solution will be found to have worked its way up into the clear water.

Liquids diffuse through each other just as gases do, only more slowly.

A lump of sugar dropped into hot tea soon disappears. If allowed to stand for several days, the sugar can be tasted in every part of the tea. The same is true of salt in water. These solids dissolve in the liquids and diffuse through them.

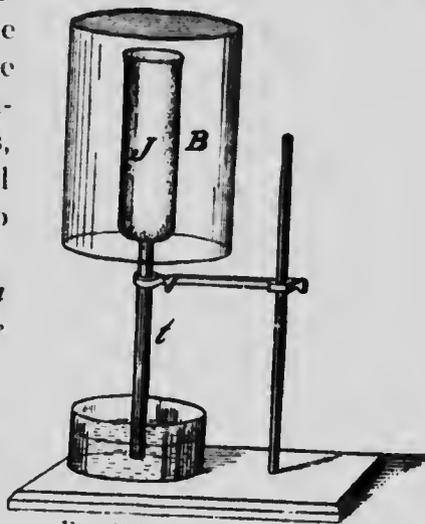


FIG. 216 DIFFUSION OF GASES

382. Diffusion Through a Porous Partition. If a porous cup of unglazed earthenware *J* (Fig. 216) be sealed with a cork through which a glass tube *t* passes, the cup will contain air at atmospheric pressure. When the cup is mounted under an inverted glass jar *B* with the end of the tube in a dish of water, and the glass jar is filled with illuminating gas, bubbles rise from the end of the tube through the water. This shows that the pressure inside the cup has increased because of the presence of the gas.

If the glass jar full of gas is removed, the water at once begins to rise in the tube *t*, showing that the pressure in the

cup J diminishes when the gas outside is removed. Because the cup is porous, both air and gas can pass slowly through it, but the gas passes through more easily and quickly than the air. When the cup is inside the glass jar full of gas, the gas diffuses through the cup into the air, and the air diffuses through the cup out into the gas. But since gas gets through porous earthenware faster than air does, more gas gets into the cup than air gets out of it. Hence the pressure in the cup rises.

When the glass jar is removed, the cup is surrounded with air only. Then the gas inside diffuses out faster than the air from the outside diffuses in; so the pressure in the cup is temporarily decreased, and the water rises in the tube t . *The gas continues to diffuse until the gas pressure inside and out is the same, and the air continues to diffuse until the air pressure inside and out is the same.*

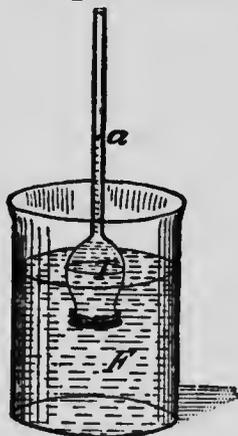


FIG. 217 OSMOSIS

383. Osmosis. If the large end of a thistle tube T (Fig. 217) is carefully fitted with a plug made from a fresh radish or carrot, filled to the point a with a solution of sugar or salt, and immersed in a jar of water, the liquid will rise in the upright tube. A suitable animal membrane, like ox-bladder or wet parchment, may be used instead of a carrot.

If the carrot is tightly fastened in the tube, the water will rise in time to a considerable height in the tube, until its weight produces a large pressure on the top of the carrot. In this experiment, the water passes through the plug at the bottom of the thistle tube, while the sugar solution does not. If the tube T is closed with a thin rubber membrane, filled with water, and immersed in alcohol, the water rises in the tube. In this case alcohol passes through the membrane and water does not.

A membrane through which one substance passes more

easily than another is called a *semi-permeable membrane*. The process by which one liquid passes through a semi-permeable membrane faster than another is called *osmosis*.

Many membranes in the bodies of human beings and animals as well as in plants and vegetables are semi-permeable membranes. Osmosis plays an important part in the circulation of the blood and other fluids that sustain plant and animal life.

384. Osmotic Pressure. The fact that the water in the thistle tube (Fig. 217) rises to a higher level in opposition to the action of gravity has led to the supposition that the sugar contained in the water in the tube acts very much like a gas confined in a balloon. It exerts a pressure on the water, and tends to expand and occupy as large a volume of water as possible. The sugar cannot pass through the semi-permeable membrane and expand into the water outside the thistle tube, but water is drawn through the membrane as if the sugar attracted it so as to have a larger volume in which to expand. Water continues to pass through the membrane and rise in the tube until the pressure due to its weight balances the pressure of the dissolved sugar. The pressure which is exerted by a substance in a solution and which tends to increase the volume of the solution is called *osmotic pressure*.

Careful studies of osmotic pressure have shown that it follows the laws of Charles and Gay Lussac (Art. 307) and Boyle (Art. 77) for gases. At constant volume it is proportional to the absolute temperature, and it increases as the volume occupied by the dissolved substance decreases. Hence we may think of a substance in a solution—like salt or sugar in water—much as we think of a gas confined in a bag.

385. Molecules and Atoms. Centuries before mankind learned to study Nature in the modern scientific way, men speculated concerning the "nature of things" and the mechan-

isms by which they conceived that physical phenomena were produced. Thus we find the Greek philosopher Democritus telling us that matter consists of atoms, an atom being the smallest conceivable particle of any substance. Democritus even insists that atoms are hard, all alike, and spherical in form;—he omits, however, to tell us how he discovered this.

The great French philosopher Descartes assures us that atoms are not solid, hard, spheres, but “vortices,” like tiny smoke rings, twirling about themselves. After Helmholtz proved mathematically that if a vortex were once started in a weightless and frictionless fluid, it would continue to rotate forever, the idea became widespread that the atom must somehow be a twirling vortex of something or other.

Notwithstanding the fact that speculations of these sorts have never been of any help at all in advancing science, hypotheses which lead to conclusions that can be verified by experiment are a very important element in scientific progress.

Without attempting to define an atom more definitely than to say it is a minute particle of matter, having mass and weight, and capable of acquiring velocity, we may suppose a molecule to be a small mass made up of several atoms. We may say *matter is made up of molecules*.

We may then try to imagine how the molecules act in order that the phenomena of diffusion, evaporation, osmosis, gas pressure, and so on, may take place in the way in which they actually do take place. In other words, we may imagine a mechanical model made in such a way that it should produce the observed phenomena. The attempt to imagine a consistent model of this sort has led to the *kinetic theory of matter*.

386. The Kinetic Theory of Matter. The fact that vapors occupy larger volumes than the solids or liquids from which they evaporate, together with the fact that vapors and gases diffuse more rapidly than liquids, makes it reasonable to suppose that *all molecules are in motion and the*

molecules of a vapor or a gas are farther apart than those of a solid or a liquid.

The facts of gas pressure may then be ascribed to the impacts of the moving molecules against the walls of the containing vessel. Since the force exerted at impact by each molecule depends on its momentum mv (Art. 362), and since heating a gas at a constant volume increases its pressure, we infer that *heating increases the velocity of the molecules.*

Since heating a gas increases the velocity of the molecules, it increases their kinetic energy $\frac{mv^2}{2}$ (Art. 368).

Therefore *heating a gas increases the kinetic energy of the molecules.*

When a gas is compressed in a cylinder, it grows warmer. We may conceive that each molecule that strikes against the moving piston bounces back with a higher velocity than that with which it approached; very much as a baseball bounces from a moving bat with an increased velocity. The increase in the velocity means an increase in the kinetic energy of the molecule. Since the gas is heated when compressed, it appears that *increasing the kinetic energy of the molecules has the same effect as adding heat.*

Conversely, when a gas is expanding, and doing the work of pushing a piston, it cools. We may conceive that each molecule that strikes the moving piston under these conditions, bounces back with a smaller velocity than that with which it struck. Since a molecule thus loses velocity when it strikes against a piston which is running away from it, it loses kinetic energy, and the loss appears as a fall in temperature; i. e., *decreasing the kinetic energy of the molecules has the same effect as cooling.* On the basis of observations and arguments like the preceding, many feel justified in concluding that *heat is kinetic energy of molecules.*

The principal postulates of the kinetic theory are:

1. Every substance consists of a great number of very small particles, each of a definite mass. These particles are called *molecules.*

2. These molecules are constantly in rapid motion.
3. Heat is kinetic energy of the molecules.

Because this theory has not only given us a simpler system for description, but has also enabled us to predict what should happen under a given set of conditions; and since such predictions have in many cases been verified, the theory is the most probable one yet advanced to describe the mechanism by which the observed phenomena of matter are produced.

387. Electrolysis Ions. In Art. 193 we learned that when an electric current is sent through a salt solution, like one of copper sulphate, the solution is decomposed and metal is deposited on the negative electrode. In Art. 322 we learned that like electric charges repel, and unlike charges attract. We also know by testing them with a suitably sensitive electroscope that the electrodes of a battery are electrically charged, the copper or carbon with a + charge, and the zinc with a - charge.

These facts make it desirable to expand the molecular hypothesis. When a current is flowing through a copper sulphate solution, the atoms of copper are taken from the solution and deposited on the negative electrode; but when no current is flowing, copper is not so deposited. Hence it seems plausible to infer that there are in the solution free atoms of copper charged with + electricity. When the copper plates in the solution are charged by connecting them with the terminals of a battery, the positively charged atoms of copper are attracted toward the plate that is charged negatively; and so they wander through the solution, give up their charges to the - electrode and are deposited there.

In like manner the remaining portion of the copper sulphate molecule, which is composed of sulphur and oxygen, is thought of as negatively charged. So it wanders toward the + electrode, takes from it a new + charged copper atom and unites with this atom to form a new neutral molecule

of copper sulphate. These electrically charged particles in a solution are called *ions*; i. e., *an ion is an electrically charged atom or group of atoms.*

388. Dissociation. Ionic Theory. In order that the process of electrolysis may begin, it is necessary that some of the copper sulphate molecules be already separated into their two component ions. Hence it seems necessary to assume that this separation has already taken place in a solution even before the electric current is sent through it. This spontaneous separation of a molecule into a + and a - charged ion is called *dissociation.*

Since the phenomena of electrolysis may be observed in a solution of any salt, we may conclude that *at least some of the molecules in every solution are dissociated into ions.*

389. Radiation. In Chapter XV we learned how the heat of the sun is brought to us by waves in the ether, and in Chapter XI the fact that waves originate at vibrating bodies was illustrated. If bodies consist of moving particles, and if heat is the kinetic energy of the molecules, we can imagine that these moving particles are really vibrating and are then in some way the source of the waves called heat waves.

For example, when a piece of iron is heated in a fire, and then held near the hand, its radiations may be felt. When the temperature reaches about 520°C , the iron begins to glow with red light. As it is heated to a higher temperature, the iron gets first yellow and then white. The red light waves of the visible spectrum have the least frequency, the yellow waves have a greater frequency, and white light includes all waves from red to violet. The white hot iron radiates more intensely to your hand than cooler iron does. So as the temperature increases, both the intensity and the frequency of the waves sent out increase. Since heating increases the velocity and the kinetic energy of the molecules (Art. 386), and also increases the frequency and the intensity

of the radiation, we may conceive that vibrating ions or molecules are directly connected with the starting of the heat and light waves.

390. Absorption. When the radiation from the iron falls on your hand, you feel the warmth. If it falls on any cold object, the temperature of the object rises. But rise in temperature means increased velocity of the molecules. So we may conceive that the energy of the waves from the hot body is used up in increasing the kinetic energy of the molecules of the cooler body. The cooler body is then said to *absorb* the radiation from the hot body, and the process is called *absorption*.



FIG. 218 THE RADIOMETER

391. Prevost's Theory of Exchanges. When the hot iron has cooled to the temperature of your hand, you no longer feel warmth from the iron. If a piece of ice is brought near the iron and the hand, you feel the chill, and some of the ice melts because of the energy radiated to it from the iron and the hand. The simplest method of accounting for these facts is to suppose that the molecules of all bodies are vibrating, so that all bodies are radiating energy in the form of long heat waves at all temperatures, and that all bodies are also absorbing these heat waves at all temperatures. *When a body absorbs faster than it radiates, its temperature rises; but when it radiates faster than it absorbs, its temperature falls.* This theory is known as *Prevost's Theory of Exchanges*.

392. The Radiometer. The radiometer (Fig. 218) consists of four light vanes fastened to the ends of the arms of a delicate cross made of aluminum wire. This system of vanes is then mounted so that it can rotate easily about a vertical axis inside a glass bulb from which most of the air has been pumped. When the instrument is set in a beam of sunlight, or when it is brought near a gas jet, the vanes revolve rapidly.

On examining the vanes, we find that one side of each is black, and the other side shiny like a mirror. The direction of the rotation when the instrument is exposed to a source of heat is always such that the black sides of the vanes move away from the source of heat. When the vanes are exposed to a source of heat, the black surfaces absorb more of the radiant heat than do the shiny sides. On this account the black sides become slightly warmer than the shiny sides. When one of the freely flying molecules inside the bulb strikes one of the warmer black sides, it takes up some heat, i. e., its kinetic energy is increased. This means that it leaves the black side of the vane with a higher velocity than it had when it struck, and in acquiring this higher velocity it must have given the black side a slightly greater push than if it rebounded with the same velocity with which it approached.

Since the shiny sides of the vanes are not warmed as much as the black sides, the velocity of the flying particles is not increased by the impact on them. The pressure on the black surfaces is therefore slightly greater than that on the shiny surfaces, and the vanes rotate in the direction of the greater pressure. If a cake of ice is placed near the radiometer the vanes may be made to rotate in the opposite direction.

393. The Velocity of Electric Waves. In Art. 329 we learned that the electric spark is not a single flash, but that it vibrates rapidly back and forth a number of times, starting the waves that are used in wireless telegraphy. We also learned that these electric waves may form stationary waves on wires, and that these are analogous to stationary sound waves in organ pipes. The number of vibrations of the spark per second can be determined by photographing it in a mirror revolving at a known speed. But the velocity with which waves travel is equal to the product of the number of vibrations per second and the wave length (Art. 225); so it has been possible to measure the velocity of

electric waves, and the result shows that *the velocity of electric waves is the same as that of light waves.*

But the spark consists of vibrating electrically charged particles. Hence *electrically charged particles in vibration start waves that travel with the velocity of light.*

This fact suggests the idea that light waves may be produced by the vibrations of electrically charged particles. Because the light waves are so very short (Art. 287), the vibrations that start them must be extraordinarily rapid—some six hundred million million vibrations per second. The molecules themselves and the ions in electrolysis are probably too large to vibrate so rapidly. Another kind of electrically charged particle—one that seems more suited to produce light waves—has recently been discovered.



FIG. 219 CATHODE RAYS CAST SHADOWS

394. Cathode Rays. An electric spark that is just able to pass between the terminals of an induction coil when they are an inch or so apart, will pass with ease through a tube several feet

long if the air be partially removed from it. In such a vacuum tube the appearance of the spark is very different from its appearance in air. The appearance changes very markedly as the amount of air in the tube changes.

When the air in the tube has a pressure of about $\frac{1}{75}$ of an atmosphere (1 cm of mercury) the tube is filled with a pinkish glow. As more air is pumped out, the glow becomes bluish, and finally disappears. When this happens, the walls of the tube begin to shine in spots with a greenish yellow light. These spots are usually opposite the negative electrode of the tube.

If some obstacle like a metal cross *b* (Fig. 219) be inserted between the negative electrode, or cathode, and the glass wall of the tube, a shadow of the cross is cast at the end of the

tube *d*. If a piece of mica with a slit in it be placed at *a* (Fig. 220) in front of the cathode, and another screen *cd* coated with a suitable mineral be placed lengthwise in the tube, a streamer appears on the screen *eb* when the tube is electrically excited. These experiments show that some sort of rays are streaming from the cathode. When these rays strike on some substance like quinine and certain kinds of glass, they cause it to shine with a soft light. Such shining of substances is called *fluorescence*, and the rays that produce fluorescence in a vacuum tube, since they proceed from the cathode, are called *cathode rays*.

395. Nature of Cathode Rays. Electrons. If a magnet *M* (Fig. 220) be brought near the tube while it is in operation, the streamer is deflected from its path, bending to one side when the north pole of the magnet is near, and to the opposite side when the south pole is near; i. e., *cathode rays are deflected by a magnet*.

Bodies on which cathode rays strike become negatively charged. Since an electrically charged particle in motion produces a magnetic field, both these properties lead to the idea that *cathode rays are negatively charged particles shot out with high speed from the cathode*.

It has been possible to measure the velocity of these particles, and it is found to be about 20,000 miles per second. It has also been possible to estimate the probable size of a cathode particle, the result showing that *the mass of a cathode particle is less than $\frac{1}{1000}$ of the mass of a hydrogen atom*.

Since the same kind of cathode rays are obtained in any tube, no matter what gas it contains, and no matter of what material the electrodes are composed, it is possible that

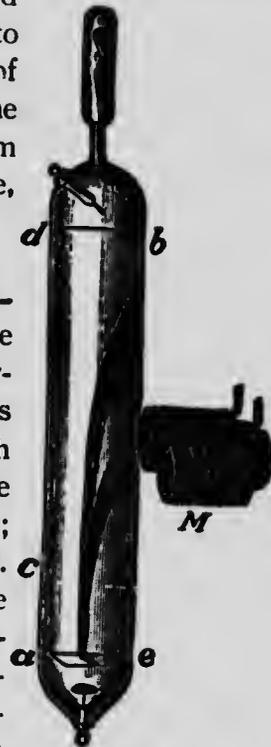


FIG. 220
A MAGNET BENDS
CATHODE RAYS

the cathode particles may be the ultimate particles of which atoms and molecules are composed.

The cathode particles have been named *electrons*.

The electron is a negatively charged particle whose mass is about a thousandth part of the mass of a hydrogen atom.

396. The Electron Theory of Atomic Structure. If in the cathode rays we have discovered a new type of particle, the electron, and if the electron is so very much smaller than the hydrogen atom, it is easy to imagine that atoms may be made up of large swarms of electrons. Sir J. J. Thomson, Professor of Physics at the University of Cambridge, has recently advanced such a hypothesis of atomic structure. According to this hypothesis, we may imagine that an atom is composed of a central nucleus which is positively charged, about which large numbers of electrons are revolving. An atom would then resemble on a very tiny scale a planetary system, with a positively charged particle as the sun and the negatively charged electrons as the planets, each revolving around the central particle in an orbit of its own.

According to this hypothesis heat and light waves are started by the revolutions of the electrons in their orbits. While electrons are surely small enough to vibrate with a rapidity sufficient to start light waves, we must not forget that however attractive the hypothesis may be, it is still in its infancy, and much further verification will be required to raise it to the rank of a theory. Since the electrons are so minute, we may never be able to verify the hypothesis by experiment.

397. X-Rays. In 1895 while experimenting with vacuum tubes, William C. Roentgen, Professor of Physics at the University of Würzburg, discovered another kind of rays, called Roentgen or X-rays. These rays originate at the surface of any obstacle on which the cathode rays strike. They produce fluorescence in certain chemicals, affect photographic plates, are not deflected by a magnet, and pene-

trate many substances that are opaque to ordinary light.

The X-rays have attracted wide attention because they penetrate flesh more easily than they do bone. Hence if a human hand is held before a screen covered with a fluorescent salt, the X-rays enable one to see on the screen a shadow of the bones of the hand. They are very valuable for surgical work, as they enable us to see something of the conditions inside the human body.

Since X-rays originate when cathode rays strike some obstacle, they are conceived to consist of irregular pulses in ether, analogous to the irregular pulses produced in air by the hammers of several men when shingling a roof.

398. Becquerel Rays. Perhaps the most wonderful of the recent discoveries in Physics is that made by Henri Becquerel in Paris in 1896. Becquerel wrapped a photographic plate in opaque paper, laid a coin on the paper, and suspended a small quantity of the mineral uranium above the coin. After the plate had remained several days under the uranium, he developed it, and found an outline of the coin on it. He concluded that the uranium must be the source of some sort of rays that affect photographic plates. The rays that are sent out by uranium are called *Becquerel rays* and the phenomenon is called *radio-activity*.

In searching for other minerals that would produce the same effect, Professor and Madam Curie, in Paris, discovered that a certain mineral called pitchblende is even more strongly radio-active than uranium. They therefore went to work to separate from the pitchblende the substance that was responsible for the action; and finally succeeded in isolating a small amount of a hitherto unknown substance, which emitted Becquerel rays more strongly than uranium. This new substance is called *radium*.

399. Radium. Since its discovery, radium has been the subject of very searching study among scientists all over the world. Its chief characteristics seem to be these:

Its atom is the heaviest atom known.

It is constantly emitting several distinct kinds of rays, called *alpha*, *beta*, and *gamma* rays.

The rays affect photographic plates, discharge a charged electroscope, cause fluorescence, are deflected by a magnetic field, (except the gamma rays,) and impart electric charges to bodies on which they fall.

The alpha rays are not as penetrating as the others, they are deflected by a magnet in the opposite direction from the beta rays, and they travel at the rate of about 20,000 miles per second.

The beta rays are much like cathode rays, but they travel at velocities that vary from 50,000 to 180,000 miles a second.

The gamma rays are not deflected by a magnet and are more penetrating than the others.

Because of these properties the alpha rays are conceived to consist of streams of positively charged particles; the beta rays of streams of negatively charged particles—i. e., electrons, and the gamma rays of irregular pulses like X-rays.

400. Subatomic Energy. The discovery of radio-activity has opened up a vast new field of exploration and speculation. Perhaps the most important phase of the discovery is that radium seems to suggest the possibility of finding a new and more powerful source of energy. The phenomena of radio-activity are interpreted to mean that the atoms of radium are composed of positively charged particles, and electrons, and that these atoms are constantly exploding and shooting out the fragments in the alpha and beta rays.

Measurements show that the energy liberated by these explosions in a gram of radium amounts to about 100 gram-calories per hour. Still no one has yet been able to detect any diminution in the weight of radium on account of its losses. Sir J. J. Thomson has estimated that if we could cause one gram of hydrogen to disintegrate, the energy liberated would be enough to raise a million tons 300 feet.

Who knows but that we may some day find out how to tap this vast store of subatomic energy? It would be convenient if we could heat a house in winter with 2 grams of hydrogen instead of 20 tons of coal. In the light of recent discoveries this does not seem to lie beyond the realm of the possible.

The scientific researches of Watt and Faraday have given to the world the knowledge that led to the perfection of the modern engines and dynamos. Other devoted explorers in the field of physical science have made the telegraph and telephone possible. These men are not always mentioned among those who have made history, yet they have done more for the real benefit of mankind than all the great conquerors. Perhaps sometime, long before our supplies of coal and other fuel are exhausted, some other great experimenter, searching diligently for the truth about Nature, will learn how to control and use the locked-up energy of atoms, and thus prepare the way for another great advance toward better conditions for all mankind.

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