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THE MECHANICS OF DAILY LIFE

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PREFACE.

Some apology seems necessary for the production of another treatise on a subject so well-worn as Mechanics.

The present work, however, makes no attempt at the mathematical treatment generally adopted. It aims rather at using the subject as a means of scientific training, and as an illustration of the method of examining Nature by reasoning and experiment.

It appeals to that large class of people in all stations of life who have not the training necessary for the enjoyment of Mathematical Gymnastics, but yet take keen interest in the purely experimental side of science.

The mathematical side of the question has therefore been dispensed with, only the simplest arithmetical examples being admitted where reference to figures was unavoidable.

The book is in the main the substance of a course of Oxford University Extension Lectures, delivered in various small towns in Devonshire in the Spring of 1891. The course was one of several, given under the auspices of the County Council, in their pioneer experiment of providing University Extension Teaching for rural districts, in connection with the Government grant towards Technical Instruction.

The experience gained in the lectures has been of great service in the compilation of the work, and the lecture method has been to a great extent retained, as specially suited to the end in view.

The book does not pretend to do more than touch on the various mechanical actions of daily life, and many are necessarily omitted, the difficulty having been to choose, out of the mass of material, points of special interest or utility.

To pursue the study further, Mathematics must be used, but not to any great extent. Perhaps as good a sequel as any would be Magnus' Elementary Mechanics, that only requiring a very slight knowledge of Algebra, with sometimes a little Geometry.

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MECHANICS OF DAILY LIFE.

CHAPTER I.

REST AND MOTION.

THE more we examine into the actions of our daily lives the more we are struck by the numerous cases which meet us of the employment, in one way or another, of mechanical facts and principles. Not to speak of what are generally called machines, we cannot move a finger or lift an eyelid without bringing into play machines and forces of more or less complexity, so that the very number of instances plunges us into a difficulty—that, namely, of choosing what points to discuss and with what examples to illustrate them. At the very outset, however, we are met by two conditions with which we have first to become familiar, these being—Rest and Motion. Too familiar already they seem perhaps, but still something may and must be said about them. They are practically opposite states of matter. We say a body is in motion when it changes its position from time to time, and at rest when it has no motion—that is, does not change its position; and rest may be described as want of motion. But position is of course relative, it must be stated, with reference to some other body; and here comes in the question, What shall that second body be?

A ball thrown from the hand of a person walking on the deck of a moving steamer is not at rest, we admit; neither is it if held in the hand under the same circumstances. There is still motion relatively to the ship. If the person stops in his walk, the ship still moves. If that stops, we get, indeed, fixity of position in the ball as far as the earth itself is concerned; but then we find the globe itself, not only spinning on its axis with a rate (at the equator) of 1000 miles an hour, but rushing round the sun at 18 miles a second. And further still, we ascertain beyond the possibility of a doubt that our great ruling sun is itself only a drifting speck in space, hurrying on at some dizzy speed we know not whither.

Absolute rest, then, absolute want of motion, we do not and cannot know, and we have consequently to narrow down our definition till we say that a body is at rest if it remains in the same position relatively to the earth itself. Often, in fact, we speak of things at rest when they are merely so in reference to ourselves or our surroundings, as, for instance, in a ship or railway carriage.

We have spoken of Rest and Motion as opposites, but they are continually changing one into the other, and we have now to examine the conditions of this change. We find one property characteristic of all bodies as regards rest and motion—that is, permanency or conservatism. We find a disinclination to change, a tendency to preserve the *status quo*, whether that *status* be one of rest or motion.

Is a body at rest towards another?—it tends to remain so; is it moving away?—it will tend to increase its distance indefinitely. At first sight this seems contrary to experience, at all events on the one side. We are willing to allow that a football will remain at rest till moved, but we are not so clear as to its continued activity if propelled by a single kick. It seems, we feel, to have a tendency to rest, that requires a continual supply of exertion from without to counteract it. But, replace the rough ground by a smooth level table, and the football by a billiard ball, turned and polished with the utmost care, and with the same blow the ball will move much farther, and for a longer time.

We have removed obstructions and found the tendency to keep in motion prolonged. If we go further in the same direction, we get still better results; but for ease of observation it is necessary to substitute for the onward motion of the ball such a body as a top or a pendulum, which, *as a whole*, is at rest inasmuch as it stays in the same place, though its particles are in rapid motion. In such a body we can examine the matter more carefully, and we then find that, given a certain impulse to start with, the more polished the points of support are the longer the motion will be continued. If, now, the instrument be placed beneath the receiver of an air-pump, and the air removed as far as possible, the period of motion will be still further prolonged. In this way, by gradually removing one hindrance after another, we have succeeded in greatly increasing the time of motion. But as we can never succeed in getting pivots or edges entirely without friction, or a space absolutely void of air, the top or pendulum will ultimately stop. It is not, however, any stretch of reasoning to conclude that if we could abolish the impeding actions we should have that motion continuing for ever. We arrive, then, at the conclusion that the state of rest or of motion is a permanent one if nothing from without interferes. In the same way, when a body is moving, the motion will be in a straight line unless diverted. Here common experience will again come to our aid, and remind us that the more freely a body can move the greater its chance of keeping in a straight course. The difference between a ploughed field, a croquet lawn, and a billiard table is merely a question of the completeness with which obstacles have been removed.

We may sum up the whole matter thus, "That a body tends to preserve its state; whether that state be one of rest or of uniform motion in a straight line." This tendency, one of the invariable properties of matter, we call Inertia, a property of great practical value.

It is the Inertia of a moving hammer that enables it to drive a nail into a plank, or to beat iron bars into any desired shape. A jumper runs before he springs, so as to add the inertia of motion, so-gained, to his effort. The inertia of a fly wheel enables it to store up the superabundant energy of an engine, and give it out again in time of need, so acting as an invaluable regulator. On the other hand, it is the inertia of a moving train that produces the disastrous results of a collision. A man on horseback tends to fall backwards as the horse starts, and forward as it stops; and in alighting from train or tram in motion, the inertia of the body carries it forward, while the feet are suddenly brought to rest by the friction of the ground, resulting, unless care be taken, in a serious fall.

Inertia, then, is the resistance to change of state, either of motion or of rest. It has been said that the characters of the English and American nations might be well described by a difference in their definition of inertia; the Englishman being supposed to call it "resistance to starting," and the American "resistance to stopping." A body, then, tends to preserve its state, and indeed will preserve it, unless under compulsion it changes it. Whatever exercises this compulsion we call, for want of a better name, Force. Here we have the introduction of the idea of *Force* as something that will change motion, whether in the direction of increasing it, as when a body at rest is moved, or of diminishing it, as in stopping an already moving body, or, again, of merely altering its direction. We are surrounded by illustrations of this principle, but will here consider one only.

A stone in a sling is travelling in a circle, but the tendency is to travel in a straight line, this being overcome only by the resistance of the hand and arm at the other end of the string. Release the string, or one end of it, and the stone flies forward at a tangent to the circle just described. The effect is often said to be due to centrifugal force, which is a convenient term if properly understood, but may give a wrong impression. Strictly speaking, the force acting on the body is not *from* but *to* the centre. The stone tends to keep in a straight line, but is continually pulled out of that line by the hand acting along the string. If the force at the centre ceases to act, or if the tendency to keep straight on is too great for the strength of the string, the stone flies off.

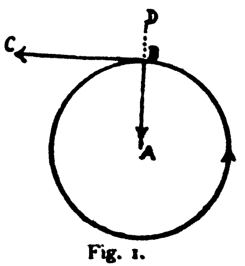


Fig. 1.

But the motion is not really from the *centre*, as may be shown very simply. If in Fig. 1 the circle represent the path of the stone, A the hand at the end of the string, and B the stone, then, in the position shown, the latter is moving in the direction BC, which is the direction it will go off in if the string be loosed or cut at this moment, instead of in the direction BD, as we should expect from the term "centrifugal force." The experiment can easily be made by tying a ball, by a thread, to a wheel that can be quickly spun round. Then, by holding a sharp knife so as to cut the string at any given point, the path of the ball may be studied, and will be found to be as stated.

The *force* in this case is really exerted *towards* the centre, in order to pull the body round into its circular path, and we speak of it as a centripetal (centre-seeking) force. Thus, in Fig. 2, if we have a body moving round the centre A, when it gets to E it is really moving towards F, and would go forward in that direction if it were not pulled towards A by some force, either the cohesion of a string, as in the sling, or the attraction of gravity, as in such an instance as that of the earth revolving round the sun, or the moon round the earth. By this continually acting force it is pulled aside to B, and then is momentarily moving towards C. But the attraction to A still continues, and curves its path as before. But, though a force directed towards the centre is needed to give the curved motion, this force is exhausted in the effort, and violent and striking effects are only seen when this centripetal force suddenly ceases or is overcome, and the bodies before held by it are allowed to rush forward with their full inertia. It is then no wonder that the centrifugal effects are the ones of most account in the mechanics of revolution, though in all that follows regard must be had to the principles here laid down.

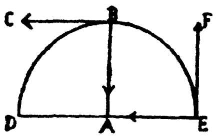


Fig. 2.

The chief characteristic, we may say, then, of a revolving body, is the tendency of every part of it to fly off, at a tangent to its circle of revolution, with a force depending on the speed with which it moves.

The sling is apparently the oldest application of this principle; the object of the circular path being, of course, to keep the stone under control sufficiently long to give it a high velocity, far above that obtained by the hand and arm alone. In the centrifugal drying machine, the same idea is used. The wet substances are placed in a cage of perforated metal which can be revolved at a high speed. Each separate particle in the cage is acted on in the same way, but the water alone can take the opportunity afforded by the holes in the metal to escape, which it accordingly does, leaving the rest all but dry. The great advantage of the process is that each particle of water acts for itself, and there is no pressure between hard substances, which is attended with such damage to buttons in the ordinary laundry wringer. The same freedom from injurious pressure is the great recommendation for the use of this means of drying for such delicate things as sugar crystals, which otherwise would have to be dried by the slow process of exposure to the air, which would be unsuitable for other reasons.

Another curious example is the cream-separator. To understand this, we must recollect that in all cases of precedence, the individuals of greatest weight, whether socially or physically, get their own way. If two inclined tubes containing water be placed on a rapidly revolving table, one having a cork ball floating on the top, and the other a marble at the bottom (the ends of the tubes being closed to prevent the whole flying out), there will be a struggle between water and cork and water and marble, which shall get farthest from the axis of revolution. The marble, being heavier bulk for bulk than the water, will rise up the tube to get to the outside of the circle, the place of greatest velocity; but the cork being lighter, will be overcome, and we shall have the strange spectacle of a cork sinking by the water trying to get above it, instead of as usual below.

Fig. 3 gives an idea of the apparatus mentioned.

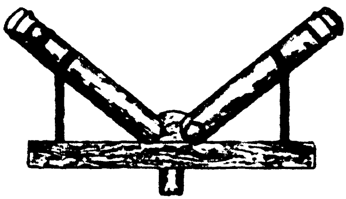


Fig. 3.

Now, the cream is really present in the milk in minute globules of fat, which are lighter than the watery part, and if allowed to stand, rise to the top. The separator consists of a hollow vessel narrowing at the top, so that the greatest speed occurs at the central bulge A (Fig. 4). The milk is fed in through the opening in a continuous stream, and falls into a sort of cup at the bottom, with cross partitions intended to force the milk to take up the rotary motion as quickly as possible. The whole having been put into rapid motion, the milk is turned on, and falling into the cup, at once flies into the bulging sides; the watery parts, however, get there first and the

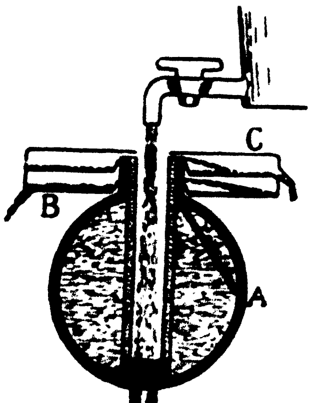


Fig. 4.

cream is left in the centre, as a lining to the liquid tube which forms. The skim milk is driven off continuously by a pipe leading from the point A up to the neck, and so out into a circular tin B, arranged to catch it. The cream at the same time escapes along a narrow groove cut in the edge of the top, and is received in another circular tin C. Things are so managed that the separator is never completely full, thus giving the hollow cylindrical space just mentioned.

The same centrifugal tendency is the cause of serious accidents in large grindstones and fly wheels, a slight increase above the normal speed being often sufficient to overcome the cohesion of the particles, when fragments are scattered in all directions with the violence of an explosion.

Action and Reaction.—There is another point in connection with the sling that it is important to notice, and that is, with regard to the nature of force. We say the hand pulls down the stone out of its straight course, but, at the same time, the stone certainly pulls the hand. We are too apt to think of a force as something by itself, but we find that really we can have no conception of a force without matter for it to act on, and still more, that there must be at least two bodies between which it acts. Take a stretched spring for instance, and fasten it at one end to a small weight, and at the other to a fixed body, such as a wall or a table. On releasing the spring, it pulls the weight towards the wall. In such a case we *see* only one action, and are apt to forget that the spring is also pulling the wall. That it is so doing is evident if we fix the free end of the stretched spring to another wall. The spring will then remain stretched, and is evidently pulling both walls, and with an equal force. If the spring were compressed instead of stretched, it would act in a similar way, though in the opposite direction. In fact, we may class the effects of all forces as being in the nature of a pull or push ("strain" or "thrust") between two or more bodies, the *amount* of pull or push being equal at each end of its line of action, but in opposite directions.

To take a few common instances, a horse pulling a cart is as surely pulled back by the cart. This is almost self-evident, as the horse would be able to go much farther and faster if the cart were not attached. A pair of nut-crackers with one arm removed would be quite useless for its purpose, as would a steam hammer without its ponderous anvil. A rubber band cannot be stretched unless force can be brought to bear on both ends of it.

Perhaps, however, the best illustrations of the fact come from the use of explosives such as gunpowder, because here we have a force chemically supplied, and which has nothing to do with the means by which the explosion is produced. What is the effect? That an impulse is given to both the gun and the projectile, but in opposite directions. And more than that, that this impulse, though opposite in direction, is equal in amount in the two cases. The first fact is sufficiently proved by the well-known "kick" of an ordinary shot gun or rifle, still more in the case of a large cannon. For testing purposes at Woolwich, the guns are mounted on trucks, running on a railway of considerable inclination, and it is a striking sight to see a gun weighing some thirty or forty tons running backwards up hill for some distance when fired. So much is this recoil recognised as being an essential part of the work done by the gunpowder, that means are now taken to utilise it, and it can be made either to replace the gun in its firing position, as in the Moncrief system of disappearing guns, or actually to load and fire it again without further exertion on the part of the gunner, as in the Maxim quick-firing gun.

As regards the second point, there is a little more difficulty. We are accustomed to think of the shot as the destructive or active part of the combination, and unless a gun actually bursts, and so shows the force exerted on it, we are apt to think of its motion as something quite insignificant, if worthy of notice at all. The explanation is, however, quite simple. We are having constant experience of how a light body with great velocity will do the work of a heavy one of small velocity. Before the rapidly moving cannon shot, came the heavy and cumbrous battering ram, seeking to make up by weight what it lacked in speed. If our hammer is light, it must be wielded more vigorously. If we take, then, the weight of gun and shot into account, as well as their speed, we find an exact proportionality. To put it quite simply, multiply the weight of the gun and its speed together, and do the same with the shot, using the same units, and we get an identical result in the two cases.

Momentum.—To put this idea into a tangible form, we want another term to express the total *quantity of motion* in a body, as distinguished from the *rate of motion.* This is given us in the word Momentum, which is used exactly in this sense.

If we express the velocity and the weight (or more strictly the mass) of a body in ordinary standard units, as feet-per-second and pounds, then the expression representing the momentum is found by multiplying these together. This enables us often to find the velocity or weight of a body in given circumstances. For instance, if a gun weigh 2000 lbs. and its shot 20 lbs., the latter having a velocity of 1500 feet per second, the momentum of the shot will be 1500 × 20, or 30,000. As the cannon has the same, its velocity evidently will be given by dividing 30,000 by 2000—*i.e.*, 15 feet per second. Of course this velocity would only be obtained if the gun were perfectly free to move when fired; in practice it would be greatly reduced by the friction of the carriage and the resistance of the various fastenings. In fact the gun might be so fastened that it would have no appreciable recoil, and what has then become of our theory? A moment's consideration shows us that in fastening the gun to the earth we have lessened the visible recoil simply by increasing the weight to be moved. It is now the whole earth that has to take part, and the weight being practically infinite in proportion to the shot, it is naturally difficult to detect any motion, to say nothing of the fact that we ourselves are now part of the moving mass, and in that way would be unable to perceive it. There is, however, no doubt whatever that the earth does move in this way, though to an absolutely inappreciable extent; but of course the various motions upon it practically counteract one another. When we get bodies concerned, whose size is comparable to that of the earth, we have no difficulty in discovering this motion. The earth, for instance, by the attraction of gravity pulls the moon round her in a curve, and at the same time is pulled by the moon, and made to follow a different path, and to point her axis in a different direction than she would if the moon were non-existent.

We are now able to sum up our ideas of Force. Motion we know, and rest we can realise in part, and know that these are constantly changing one into the other, and the cause of this change, whether from one side or the other, we call Force. We may therefore define Force as whatever causes alteration of motion in a body, in respect either of increase or decrease, or change of direction, and can moreover measure it by the amount of motion (the Momentum) given or destroyed in a unit of time.

Again, we only know Force as it acts between two (or more) material bodies, either pulling them apart or pushing them together, the momentum generated in each body being the same in amount but opposite in direction.

The last result is summed up in Newton's third law of Motion, "To every action there is an equal and opposite reaction," or more shortly still, "Action and reaction are equal and opposite."

CHAPTER II.

FORCE: A CRICKET BALL.

HAVING thus become familiar with the idea of Force, it will be useful to speak of it more at length, and the first thing to notice about it is the effect produced by a continuous force, because, from the nature of things round us, this is apt to be obscured, and so overlooked. Force, we say will produce motion in a body; but further, as long as it acts it will *continue* to produce motion, adding to it every second exactly as much as it added in the first second of its application. If a given force produce a velocity of one foot per second during the first second of its action on a body, then as long as it acts it will continue to increase the velocity at the same rate every second—*i.e.*, after three seconds the velocity will be 3 feet per second, after 5 seconds, 5 feet, and so on. This continual increase has a characteristic name given it, that of "acceleration," and if only one force acts on a body, this acceleration is well marked. Perhaps the best instance of such a continuously acting force is presented to us in the attraction of gravity, the force that brings a stone to the ground, and at the same time rules the motions of earth and planets, and even of the distant suns that we know as stars.

It is not rigidly true that gravity is the same at all places on the earth, as it is slightly more active at the poles than at the equator, nor is it true that it is the same at the top of a tower and at its base, as the top is a little farther from the centre of the earth, and the force of gravity diminishes as the distance increases. In the latter case, however, the difference is inappreciable, and we can thus get a force acting continuously for a considerable distance. This particular case has great historical interest, as the first experiments on record on falling bodies were performed by Galileo on the leaning tower of Pisa. His experiments were really undertaken to answer the disputed question whether a heavy body falls more quickly than a light one. The philosophers of that time, relying mainly on Aristotle, whom they seem to have considered omniscient as well as infallible, answered the question in the affirmative; but Galileo, on putting it to the test, proved the reverse, light bodies falling in the same time (within certain limits) as heavy ones. The reason for this is, of course, the fact that, though the larger body would be more strongly acted on by gravity, its inertia would be correspondingly greater; the two effects exactly counterbalancing one another.

One has, however, to notice one condition which may modify the effects—that is, the surface of the body in proportion to its weight. A feather for instance will fall far more slowly than a leaden bullet, simply because the resistance of the air is proportionately so much greater. Take away the air, as in an air-pump, and the feather will fall as quickly as the bullet. Even without an air-pump, this may be shown by substituting for the feather a disc of thin paper, slightly smaller than a penny piece If this and a penny be dropped at the same time, the penny will fall first; but if the paper be put on the top of the penny, and this then be let go, the paper will accompany it to the bottom. In this case, the penny does the work of clearing the air out of the way of the paper, which is consequently not obstructed and falls freely. Under ordinary circumstances, and with ordinary velocities, this air resistance may be neglected if the body is above a certain weight for a given size, and in this sense we are able to say that all bodies fall at the same rate.

To return to our special line of argument. If we take bodies falling freely under certain general conditions, we have a good example of the action of a continuous force. Actual experiments have shown that at the end of the first second of its fall, a body has acquired a velocity of (roughly speaking) 32 feet per second; at the end of the next second twice 32, or 64 feet; at the end of the third, three times 32, or 96 feet per second; and so on, an additional velocity of 32 feet per second being added every second, whatever the velocity already attained, neglecting, of course, the resistance of the air. Knowing this, we can at once find the total space passed through in any given time. Supposing we wish to find the depth of a well or the height of a cliff. We drop a stone and watch for the moment of its striking the bottom, either by hearing or sight, though in the first case, a slight error arises from the small velocity of sound. If the time taken to descend is three seconds, then the velocity at the end of that time is three times 32 or 96 feet per second, and as it started at a velocity of 0, the average for the whole time is $\frac{96}{2}$ or 48. But this is the average for three seconds, so that to get the total space traversed, we must multiply by 3, thus getting 144 feet as the depth we were to measure.

Gravity as Standard.—Gravity thus being of universal application, it is no wonder that from it was obtained the first unit of force. The weight of a body is really simply a measure of the force with which it is attracted towards the earth, and a pound weight seems at once a natural unit of force. It is, of course, a unit extremely easy of application and comparison, and probably for all practical purposes will always hold its own. But it would be foreign to the purpose of this treatise not to point out its unsuitableness for an absolute scientific standard. The first and gravest fault is, that the value of a pound weight is not the same in different parts of the world, the pull being greater at the poles, as already mentioned, than at the equator. The difference is not much, being only one in 190 (so that a man, weighing 190 lbs. at the equator, would weigh 191 at the pole), but that is, of course, too great to be endurable with modern refinement of measurement. The second objection is, that the particular value of the pound weight depends on the pull of the earth as a whole, and therefore, is not an absolute independent measure. This objection would, of course, have more practical influence if we were able to visit the neighbouring planets in our solar system, or even communicate with them by some telegraphic system, when it would naturally be better to meet on a neutral scientific ground.

To meet, however, both these objections, it is usual to define the English unit of force as that force which, in acting for one second on a mass of one pound, gives it a velocity of 1 foot per second. As gravity, roughly speaking, gives a velocity of 32 feet in the same time, this is evidently $\frac{1}{32}$ of the force of gravity acting on a pound weight—that is, about half an ounce. This unit is for convenience styled the poundal, and must be carefully distinguished from the pound. The decimal French measures of centimetre and gramme are, however, generally used in scientific work.

Mass.—The word Mass in the above needs a little further explanation. It is used to signify the quantity of matter in a body. In practice it is of course measured by the weight of a body, but a moment's consideration will show that while a body's mass remains the same, its weight may be varied by putting it under different conditions, as for instance, if that were possible, by carrying it to the moon, when its weight would be reduced to $\frac{1}{6}$, or to the sun, when it would be increased 27 times.

As a rule, it is quantity of matter we want in a body, though weight gives us a convenient measure of that quantity. Many a market woman returning with her purchases would be glad to have the actual weight lessened if that could conveniently be done without sacrifice of the mass. The quantity of sugar that here weighs a pound would in the moon (using a spring balance in each case) weigh only one-sixth of a lb., though it would be just as sweetening and just as large in bulk. On the other hand, in the sun it would weigh 27 lbs., a heavy penalty to pay for its sweetening power.

Not being able to put this to a practical test by a journey from our earth, we can still show the difference between mass and weight in the case of a body suspended so as to move without interference from gravity,—for instance, a gate, or an easily running truck. Assuming friction to be the same whether the body be heavy or light, the heavy gate or truck will offer much more resistance to motion than the light one, simply because it contains more matter to be acted on—that is, has greater Mass. From this consideration it is evident why we must, in defining the unit of force, assume it to act on the unit of mass.

We are now ready to examine the case where two or more forces act on the same body.

Hitherto we have been considering Force and Motion in their simplest aspects, as acting along one definite line, but in daily life we see continual instances of forces acting at all sorts of angles to one another, and we have now to examine some of these cases.

Perhaps the most familiar, as well as one that shows the principle best, is afforded by the path of a cricket ball. The bowling gives it one definite direction, the bat gives it another. This second may of course be exactly in the line of the first, but opposite in direction, and if then the momentum given by the bat is equal to what the ball already has, the two mutually destroy each other, and the ball drops dead or is "blocked." If the force of the bat is much greater, the ball will return along its previous course. Supposing, though, that instead of hitting in the line of the ball's path, the bat makes an angle with it, as in Fig. 5, where A shows the direction of bowling and B of batting. If the two directions are at right angles, and the two forces are exactly equal, then the ball will travel eventually neither in one direction or the other, but midway between the two, as shown by the arrow C. If the batting is stronger, the final direction will be more as E; if the bowling, more as D.

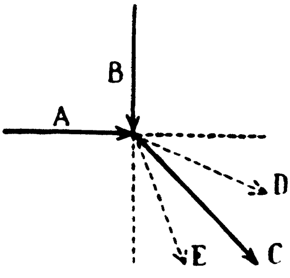


Fig. 5.

To make the representation complete, we want some way of showing not only the direction but the magnitude of these forces, and we get this by using lines of definite length to represent definite amounts of force. The units may be chosen entirely to suit our own convenience, but of course must be used consistently in each figure or set of figures. For example, let us take a length of $\frac{1}{4}$-inch to represent a force of 1 lb., and assume that the bowling force is 3 lbs., and the batting 4 lbs., and at right angles to one another. We may thus represent the action as in Fig. 6, by two lines at right angles, one, the bowling line AB, $\frac{3}{4}$-inch, the other, the batting line, AC, 1 inch long. The ball will then travel in a direction more along the batting than the bowling line, but the question of course occurs, What will its exact direction be, and what its force?

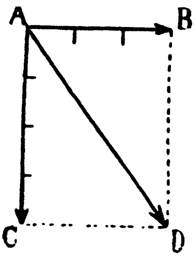


Fig. 6.

Its direction can be obtained easily by following out the principle that each force acts independently of the other. Thus, supposing the bowling would carry it from A to B in a given time, and in the same time the batting carry it from A to C, we can follow it first to B, and then in the same direction as AC for the same distance to D.

We should get to the same point if we went first to C, and then along the direction of AB to D. A glance at the figure will show it to be a parallelogram, and it is natural to suppose a body to travel, not round the outside as we have supposed, but along the diagonal AD, which, as a matter of fact, it does. Moreover, the line AD represents not only the direction in which the ball travels, but the magnitude of the force acting on it, if the other two lines are considered as representing in length the magnitudes of the forces along them. The length of this diagonal may be found either by calculation or measurement, to be $1\frac{1}{4}$ or $\frac{5}{4}$ inch, corresponding to a force of 5 lbs. in this case.

Here we have evidently two forces replaced by a single one, to which is given the name of the "Resultant," and if this one is exactly counteracted, both the others are neutralised.

This method, however, is by no means confined to the case when the forces are at right angles; whatever the angle may be the resultant is found in the same way, as in Figs. 7 and 8, where the arrows show the direction of the forces, as well as their magnitude, and R is the resultant.

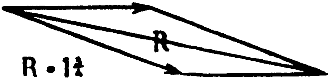


Fig. 7.

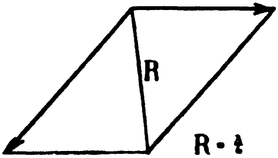


Fig. 8.

A glance at the figures will make it evident that the smaller the angle between the forces the greater will be the resultant. This follows naturally from the following considerations, which, at the same time, afford a good experimental method of investigation. If we take two pulleys, and place them edge to edge (Fig. 9), so that the two strings shall be practically in the same line, and fasten both together to a weight of 5 lbs., we find that to support this we must hang other weights to the two outer ends. These outer weights may have any proportions whatever relatively to each other, as long as the total comes to 5 lbs. Thus 2 lbs. and 3 lbs., or 1 lb. and 4 lbs., would serve, or 1 oz. and 4 lbs. 15 ozs.

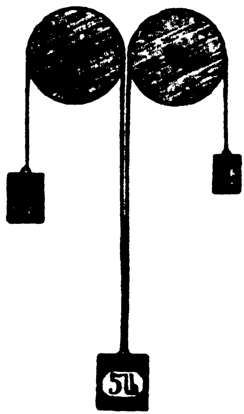


Fig. 9.

We have here a proof of the fact that if two forces act along the same line, their resultant is equal to the sum of the two. This can be shown, if the pulleys move freely, and the strings are so light that we may neglect them, by moving the 5 lbs. weight up and down, when it will be found to continue moving if started, or to stay in any position in which it is stopped.

If now, instead of leaving the strings in the same line, we separate the pulleys, so as to make an angle between them, we find the two outer weights are no longer able to balance the middle one of 5 lbs., which accordingly sinks as far as the strings will allow, or until it has gone so far that the strings are again practically in the same line. This destruction of balance is evidently due to the partial opposition of the two forces to each other, and their consequent inability to exert the same force on a third body as they did before. To restore the balance we shall have to add to one of the outer weights, and we then find the whole system takes up one definite position, in which it will rest and to which it will return if displaced (Fig. 10). Supposing that our outer weights were originally 4 lbs. and 1 lb., balancing the 5 lbs. in the centre, and we add 2 lbs. more to the 1 lb., we have now 4 lbs. and 3 lbs. counteracting the downward pull of the 5 lbs., or, to put it in the barest form, in this case 4 and 3 seem to equal 5. The apparent difficulty is at once seen to be due to the partially

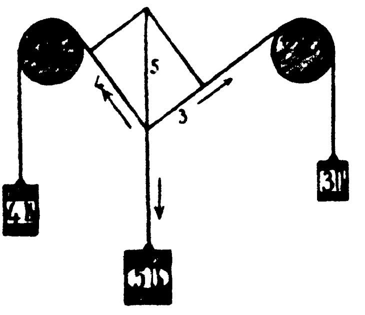


Fig. 10.

opposing pulls of the 4 lbs. and 3 lbs. With these weights the whole system assumes a definite position, and a black-board or sheet of cardboard may be held against it and the position of the lines marked off, with at the same time a vertical line through the angle (best got by a small plumb-line) which shows the direction in which the 5 lbs. act.

We also mark off on each line a length (in any units suitable) corresponding to the weight at the end of that string; here 4 and 3 respectively. We find that the angle between the strings is a right angle, and, on completing the parallelogram, the vertical line will correspond to its diagonal, and will be found to measure 5 on the scale on which the others were 4 and 3; bringing us to the same result as the former more abstract line of argument. The resultant is of course equal to 5 lbs., as it just supports that weight and acts along the same vertical line. It may be as well to point out that it is not the whole length of string, from the angle to the pulley, that represents the force, but only a definite length measured along it; in fact, the longer string is that of the smaller force. This should be clearly grasped, as it is a frequent cause of misconception.

It is evident too from the diagram, which represents an actual experiment, that the resultant is nearer to the greater force, or, in other words, makes a smaller angle with it than with the other.

Parallelogram of Forces.—The whole result is commonly known as the doctrine of the Parallelogram of Forces, and may be summarised thus, "If two forces acting on a body can be represented, in magnitude and direction, by two straight lines meeting at a point, and if the parallelogram be completed, then the resultant will be represented, in the same way, by the diagonal drawn through that point."

If we take half the parallelogram, as cut off by this diagonal, we have a triangle whose sides show the same magnitudes and directions, so that we have here again a way of getting the resultant, though in this case the second force must be drawn from the far end (so to speak) of the line representing the first and not from the point of action. Thus, if we have two forces represented by arrows as in (*a*) Fig. 11, we may make the triangle by taking either A first

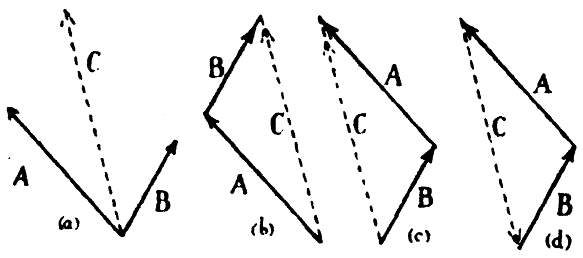


Fig. 11.

or B first, the figure in the two cases being differently placed, as (*b*) and (*c*), but giving the same length and direction for the finishing line C, which represents the resultant, the two figures forming the two halves of the usual parallelogram. The lines have of course, wherever they start, to be drawn parallel and equal in length to the original force-line they stand for. If, instead of asking for the resultant, we inquire what force will balance the two, we have only to take the same line C, and imagine it acting the opposite way, as at (*d*). This result may be summed up thus, "If three forces acting at a point can be represented, in magnitude and direction, by the sides of a triangle taken in order, the forces will be in equilibrium;" that is, will exactly balance each other. The *direction* in the above must of course be continuous round the triangle, either right-handed or left-handed.

This again can be extended to more sides than 3: thus the five forces represented in Fig. 12 are in equilibrium, or any one of them reversed is the resultant of the other four. The results are known respectively as the Triangle and Polygon of Forces. These methods of finding the combined effects of any number of forces are of great value, especially perhaps to the builder or engineer, who has to take into account the various shocks and strains to which his work may be exposed.

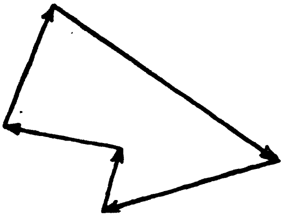


Fig. 12.

The chief practical point to notice here is the way in which the magnitude of the resultant diminishes as the angle between the forces increases, and the consequent advantage of getting any different powers exerted into one and the same line. Thus, in hauling timber, it is more advantageous to put the horses in line than side by side, and in a "tug of war," the straighter the rope can be kept on either side the more power can be usefully exerted against the opposing pull. Some very curious results follow from this same fact. We have only to make the *angle* large enough and we can reduce the *resultant* as much as we like, however large the two original forces may be. Now, if the resultant of the forces is very small, the force to balance them (which is equal, and opposite to the resultant) is also very small. In other words, if we wish to balance two large forces by a small one, we can manage to do so by sufficiently increasing the angle between the first two. We may thus make a very small force balance, or even overcome two large ones. The simplest illustration of this is found in a stretched string. However tightly this may be pulled at each end, a very slight pressure, sideways, will deflect it, as in harp and piano strings. The same thing is seen in tying up a box or parcel; however straight the first turn of cord may be, it can be tightened by another turn, pulling it at right angles. If a string of any moderate length is stretched horizontally its own weight will bend it, and it can never be pulled quite straight. If we try to do this the string will part before it reaches the horizontal position. The effect is, of course, increased by hanging a moderate weight on the string, this weight seeming to break the string, though it would be unable to do so by itself. The experiment may be tried, by hanging a weight of a pound or two on a thread, one end of the thread being held in each hand. If the weight is not too great, it is easily raised when the hands are kept together, but breaks the thread and falls as they are separated. In the same way, a stout cord, *if stretched tightly enough*, can be broken by pulling it aside by a thread or hair. We have only to reverse the arrangement of things, by replacing the strings by rigid bars, and push the joint towards (instead of pulling from) the straight line, and we get the well-known toggle joint. This is used for giving great pressure through a short distance, as in some printing presses.

Resolution of Forces.—It must here be pointed out that just as two or more forces may be practically replaced by one, so one may be split up or "resolved" into any number. Perhaps the simplest example of such resolution of force is presented by the towing of a barge. If only the horse could walk directly in front of the boat all its force could be utilised in propulsion; as this is not the case, its force has to be exerted at an angle to the course of the boat.

In Fig. 13, if AB represent the force of the horse, and the boat moves along Ac, then only part of AB is actually useful along Ac, the rest tending to pull the boat to the bank along Ad.

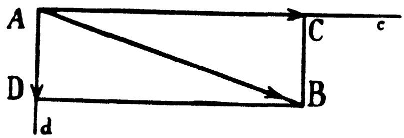


Fig. 13.

If Ac and Ad are at right angles to each other, as for convenience we may consider them to be, then by drawing lines from B at right angles to Ac and Ad we get the parallelogram ACBD, in which evidently AB is the resultant of AC and AD. Putting it another way, the force exerted by the horse, AB, can be looked on as acting in two directions, one a pull equal to AC, propelling the boat, the other equal to AD, merely pulling it sideways. This last is counteracted by the resistance of the water acting on the boat's sides and on the rudder.

The length AC is called the component of AB along Ac, and AD the component along Ad. This idea of resolving any force into two others, in such a way that one of these two is entirely balanced and need not be further considered, is extremely useful in the consideration of many of the problems of every-day mechanics. We have a certain force, for instance, pulling at a lever handle (Fig. 14), but which cannot be got to act exactly at right angles to it. If the arrow AB in the figure represent the pull, then by drawing a line BC at right angles

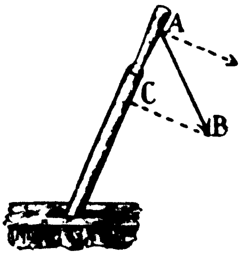


Fig. 14.

to the lever as shown, CB is the force effective to pull the lever, though its point of application is still at A as before, and AC represents force wasted in pressing the lever on to its axis or pivot, and so making it actually more difficult to turn.

The case of a sailing boat is another common though more complicated case. In the three Figs. 15, 16, 17, the same lettters stand for the same points.

If AB represents a boat, A being the bow, C the mast,

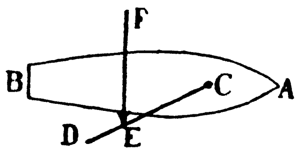


Fig. 15.

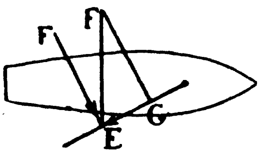


Fig. 16.

and CD the sail; and if the force of the wind is represented by FE, this FE is first resolved into two forces, one GE, which is along the sail, and consequently produces no effect, the other FG (or F'E) at right angles to it. But FG, acting by itself, would tend to push the sail, and with it the boat, in its own direction. But as from the shape of the boat, it travels more easily forward than sideways, we again resolve this force along the length of the boat HG. Draw from F a line FH at right angles to HG, we get HG cut off as the component available for propelling the boat, FH being used up in pressing it against the water on its lee. We get consequently but a small proportion of the original force actually serviceable, but quite enough to drive even the largest ship through a fluid mass like water.

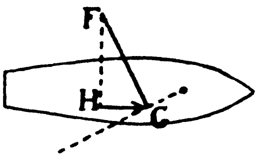


Fig. 17.

CHAPTER III.

LEVERS.

THE case of forces acting at an angle having been fully considered, we return to the perhaps less common case where the forces act in the same direction. If they are in the same straight line, the case requires no further consideration. It is sufficient to simply add all the forces in one direction and all those in the opposite one, and subtract one quantity from the other to find the resulting force. The same kind of reasoning, however, holds good if, instead of being in one and the same straight line, the forces act in *parallel* lines, as long as the body on which they act is sufficiently rigid under the conditions.

If, in the example given above of the parallelogram of forces, we flatten out the weight so as to reach from one pulley to the other, or preferably fasten the strings to a bar of metal or wood, and hang the weight from a suitable point in that, we find that (allowing of course for the weight of this bar) we have restored our balance with the original weights of 1 and 4. This question of parallel forces is worth further attention, which we can give it in the consideration of levers. It is enough to notice here that carriage and waggon builders have long recognised the use of this principle. In tramcars it is especially used, as in this case the horses have only to exert a straightforward pull, the guiding being done by the rails. Here, then, we see the traces at the side of each horse, fastened to the ends of a rigid bar or link, these two links again being attached at their centres to the ends of another, the centre of which is attached to the car itself (Fig. 18). In this way we get rid of any opposing pull of one horse against the other, as would be the case if the traces were fastened to the central point. The same idea is illustrated by the shoulder yoke used in carrying two pails.

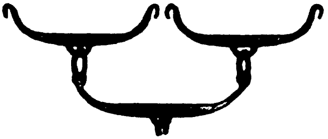


Fig. 18.

Here, if the pails are about the same weight, the resultant acts downwards through the body, and has no tendency to pull it one way or another. The muscles thus act in the most natural way and to the best advantage. If the same weight were put on one side, the pull would have to be sideways as well as upwards, and much greater in amount altogether. Even with the same two weights, one on each side, if they are of any bulk, there is an appreciable difference between supporting them by the hands directly, and attaching them to the ends of a rigid bar, which is then

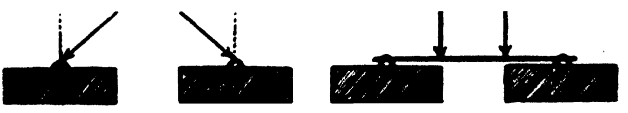


Fig. 19.

grasped by the hands. The two cases are shown in Fig. 19, the arrows representing the pull on the shoulders.

In the first case the pull is much larger than the weight (which is shown by the dotted arrow); in the second case it is exactly the same. In the same way, for a given load it is often easier to carry it on a stick between two persons than for each to take half of it. But if we replace the stick by a rope, we get the task made harder instead of easier, and the more so the longer the rope. In this case, each person is exerting force to pull the weight, and so the other person, sideways, all which is wasted as far as raising the weight goes.

A good example of parallel forces is found in an ordinary pair of scales or balances. Here we have the weights in the two pans exerting force vertically downwards under the action of gravity. If they are equal, the balance will remain horizontal and at rest. The pull of the weights must evidently be counteracted in some way, and is so by the resistance to compression of the pivot and support on which the beam rests. This resistance acts vertically upwards, as we may prove by suspending the beam on a string or wire instead of resting it on a rigid support, when the wire will hang perfectly vertical. We can see then that here to produce equilibrium the forces are not acting at an angle at all, but are parallel to each other, and the pressure on the support, neglecting for the moment the weight of the beam, is exactly equal to the weight of both pans together. Here, as regards the magnitude of the resultant, we have the same case as if the forces were in one line, and this is true in all cases where the forces are parallel to each other in direction. The resultant is equal to the sum of the forces if they are in the same direction, and their difference if opposite. That the resultant is always parallel to the forces may be shown by suspending the beam by a string or wire, and then pulling the pans on one side, taking care to still keep them pulling parallel. The beam will at once alter its position till the string by which it is hung is parallel to the pull on the pans.

We now return to the ordinary construction of the balance, which we may describe as a body moveable round a line or axis, and with parallel forces acting on it at different points. This serves to introduce us to a very important class of machines called levers, which we can now examine in detail. The pivot or line about which the movement takes place is called the Fulcrum, and it is usual, as well, to speak of two forces acting on the lever, one as the Power, the other as the Weight, this latter being the resistance to be overcome, whether an actual weight or not.

In the balance we have a lever with equal arms, but the more usual case is for the arms to be unequal, as it is in this way that the special value of levers is seen. Experimental investigations into the action of a lever can be easily performed with an ordinary flat boxwood rule, holes being bored in the centre of its breadth and at every half inch along its length. If then it be suspended at the six inch mark by a pin passed through the hole into an upright support, as the weight is equally distributed about the point of suspension, it should stay indifferently in any position it may be put in, and its own weight is thus neutralised and may be neglected. If, however, it will rest in a horizontal position only, it will do for the purpose. The weights for attaching to different parts of the bar should be of two kinds, as in Fig. 20, one with a fairly long wire hook to fit into the holes of the rule, the other either bars bent into horse-shoe form, or discs with a slot running to the centre, so as to allow them to pass on to the hook weights while hanging,

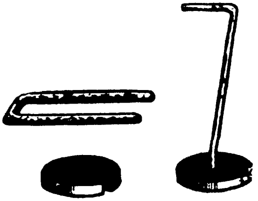


Fig. 20.

for the purpose of increasing the weight to any given extent. All these may conveniently be of equal weight.

Taking now our rule or lever, we suspend it as said by its centre point, and may therefore neglect its weight. If, then, a weight of 1 (ounce, dram, or any unit we like) is hung at one end of the rule, say at 12 inches,* and a weight of 2 at 3 inches, they will be found to balance each other. Here the first is 6 inches from the fulcrum, and the second 3, or just half the distance, and it is evident at once that there is a simple relation between the two weights and their respective distances. In other positions the relation will be found equally simple, in fact, in every case, if the lever is in equilibrium, then the weights acting (if the weight of the lever itself has no influence on the result) are inversely proportional to their distances from the fulcrum. Another way of putting it is, that either of the weights multiplied by the length of its arm (*i.e.*, its distance from the fulcrum), is equal to the other weight multiplied by *its* arm.

Hence it follows that to get any desired power by the lever it is only necessary to have the ratio of one arm to the other sufficiently great, either by lengthening the longer arm or shortening the other. So striking is this property that Archimedes is said to have exclaimed that he could move the world itself if only he had a fulcrum for his lever.

It may be as well here to notice, what is sometimes overlooked, that the fulcrum is a very important part of the machine, that the strain on it may be very considerable,

* *N.B.*—To make the ends available, a small staple—a bent pin for instance—may be driven into the end so as to support the weight at that point.

in fact may be so great that the fulcrum and weight interchange their positions. In attempting, for instance, to lift a very large weight, the weight may remain unmoved and become a true fulcrum, the body which should have performed that office giving way or being crushed under the strain.

If a man carry a weight on a stick across his shoulder, holding the other end of the stick himself, his shoulder has to bear considerably more pressure than if the weight were resting directly on it,—double this indeed, if the weight and hand are at equal distances from the shoulder.

Connected with the fulcrum is the question of where the resultant of two parallel forces acts, or where is its point of application. This resultant must pass through the fulcrum in any case of equilibrium, or equilibrium would be impossible. Hence, if we have two parallel forces acting on a body at a given distance apart, we have only to divide this distance into two parts, so that these parts are inversely proportional to the forces, and the point of division must be where the fulcrum must be put, or in other words, where the resultant of the two forces acts. Here, as with forces at an angle, the resultant is always nearer to the larger force.

There is a special case that deserves notice—where two equal parallel forces act in opposite directions. Here no single force can possibly balance them or represent them, but they tend to cause rotation of the body on which they act. Such a pair of equal opposite forces is called a *couple*, and is of constant occurrence, though not often in such a simple state as here supposed. In winding a clock or watch the fingers press the sides of the key in opposite directions, so turning the spindle and ratchet wheel. If the key only projected on one side, one of these opposing forces would be supplied by the resistance of the bearings of the spindle, but the effect would not be so good, the tendency being then not only to turn the spindle but push it sideways as well, so wearing it and its bearing.

Resuming more directly the consideration of levers and their action, we find we may have three different cases with a simple lever, according to the relative position of the power, weight, and fulcrum. In the examples hitherto noticed the fulcrum is in the intermediate position between the power and the weight, and levers thus arranged are said to be of the First Kind.

Levers of the First Kind.—Scales and balances are perhaps the most important of the applications of this kind, and will bear further study, not only for their practical importance, but as a worked out example of the method of scientific inquiry.

Though a pair of scales is by no means a complicated instrument in principle, yet a good many small points have to be considered if we are to secure accurate weighing. The first requisite is that the arms of the balance should be equal—that is, the distances from the central main fulcrum to the fulcrum of each pan. If they are not equal, one side will have greater leverage, and instead of equal weights balancing each other, the weight on this longer side will have to be smaller than the other. This would, of course, be the case with the pans themselves in the first instance, and the balance would have to be made to hang true by adjusting the weights of these. But the truth would only be apparent, and if perfectly equal weights were put into these two pans, the one on the longer arm would at once fall and appear the heavier, and if this were the substance to be weighed, some would have to be taken off to restore equality. No doubt, in the old times, before the days of Imperial inspection, purchasers were often defrauded in this manner, though sometimes the chance might be in their favour. The defect is fortunately easily discovered by exchanging the weights in the two pans, when their inequality will at once be manifest, however well they seemed to balance before. Even with such a balance, however, it is quite possible to weigh correctly, by putting the substance to be weighed on one scale and counter-poising it by sand or shot in the other, then removing the substance and replacing it by weights till the balance is again in equilibrium.

In the very delicate balances used for chemical analysis, there is an arrangement for slightly shifting the points of support of the pans, so as to get the arms of exactly equal lengths.

But besides mere accuracy, we want the balance to turn with a small difference of weight, in other words, to be sensitive (or, as older writers used to say, "sensible"). The first step in this direction is evidently to reduce friction as much as possible at all points. Hence the beam is supported, not by a round pin, but on one edge of a piece of hard steel or agate of triangular shape, called the "knife edge," the pan supports resting on similar edges, and these knife edges work on flat polished plates. The second step is to have as long a beam as convenient, because a small difference of weight will be more effective in turning the beam the farther from the centre it acts. Of course, this soon reaches a limit in practice, because increase of length means increase of weight, which, by introducing more mass to be moved, decreases the sensitiveness.

There is another curious effect of leverage which is not so commonly recognised. Suppose the beam is supported so that the weight is equally distributed round the axis of suspension, it will then have no tendency to turn of itself, but will remain in almost any position. But in practice we have to consider the weight of the pans as well, and it is most convenient to so adjust matters that the beam tends to take a horizontal position, and will return to it if displaced. The centre of gravity is in the first case at, and in the second, below the axis of suspension or fulcrum. If we take the first case, the weight of the beam and pans is practically neutralised, and so may be neglected. If now we have the fulcrum of the pans on the same horizontal line as the fulcrum of the beam (Fig. 21), the weights in them will have the same leverage whatever the position of the beam, and will accordingly stay in any position. But with the pan fulcra lower than the beam fulcrum, there is at once a difference (Fig. 22).

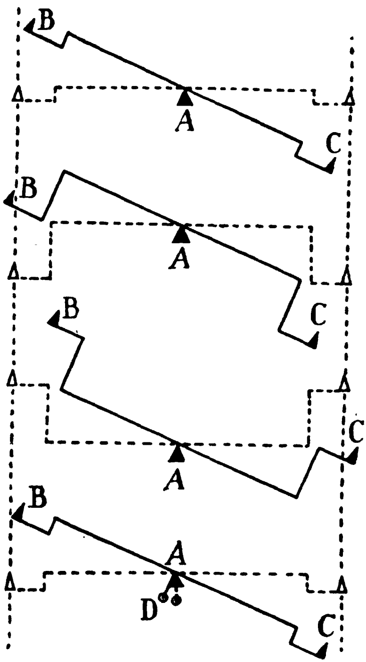


Fig. 21.

Fig. 22.

Fig. 23.

Fig. 24.

Directly the balance moves from its horizontal position, the descending weight acts at a less leverage than before, and the ascending one at a greater, and this action, of course, soon stops the further swing, and so reduces very greatly the sensitiveness of the weighing. If we go in the opposite direction, and put the pan fulcra higher than the main one, as in Fig. 23, then as the beam swings the descending weight gets more leverage, and the ascending less. Here, consequently, the effect of a minute difference between the weights is much magnified. The disadvantage of this form, however, is that the beam never returns of itself to its first position, hence it is not suited for ordinary work, though it can be utilised with great effect, for exhibiting small differences of weight to a large audience.

The most general form of accurate balance has the three fulcra on the same horizontal line, Fig. 24, with an arrangement for slightly raising or lowering the centre of gravity, so as to bring this quite near to the main fulcrum, but a little below it, so ensuring the return of the beam to a horizontal position. Here the weight of the beam acts at the end of a very short arm, while the weight in the pans acts on a very long one, and can consequently overcome the former. As the pan goes down, however, its effective leverage becomes less, while that of the beam weight increases, so that we get a position of equilibrium when the beam is inclined a certain way. The figures give the different cases described above, in an exaggerated form for greater clearness, the dotted lines showing the original horizontal position of the beam. The centre of gravity of the beam and pans is supposed to be at A, the main fulcrum, so that only the weights added have to be considered. B and C are the fulcra of the pans, and the horizontal distances of vertical lines through A, B, and C, measure the true arms at which the weights act.

Fig. 21 shows the balance with the three fulcra in the same horizontal line, with equality of leverage in all positions.

In Fig. 22, the fulcra of the pans are below that of the beam, with gain of leverage in the ascending lighter pan.

In Fig. 23, these pan fulcra are above, with gain of leverage in descending heavier pan, making it appear still heavier.

In Fig. 24, the three fulcra are supposed to be in the same line, with the centre of gravity of the whole below A, swinging out to D as the beam takes the position BC.

Even if a balance is correctly proportioned, care must be taken that all parts move freely, or the result may be incorrect. A curious instance of this came under the writer's notice. It was stated that a man standing on one pan of a sufficiently large and strong pair of scales, could increase or decrease his weight by touching the under or upper side of the scale beam. Experiment quite confirmed this, with certain limitations as to place of touching, which, to produce the effect mentioned, must be between the pan suspension and that of the beam. The reason is that, in touching the under side of the beam, the man causes the scale pan with his weight in to swing out from the centre, and so increases its leverage. If he pulls the top of the beam, he brings himself further in, and decreasing the leverage, consequently appears lighter.

Steelyards.—In the ordinary form of balance everything depends on the equality of the arms, but in some ways there is a distinct advantage in having the arms unequal. By so doing we can make one weight supply the place of a number and the portability of the instrument has correspondingly increased. This is the principle of the old-fashioned steel yard, once universally used by peripatetic salesmen. We say once, for it has now been practically displaced by the still more compact and handy spring balance, which is not only lighter, but shows the weight at a glance without any adjustment. The ordinary steelyard is a metal bar with a scale pan or hooks at one end, and near this is the fulcrum from which it is suspended. A small weight slides over the long arm, and by graduations on this arm marks the weight in the pan.

One excellent point is the very large range secured in the instrument. There is a second fulcrum and ring for it to work in, and if the weight is too great to be measured on the first side, the bar is turned over and suspended by this second fulcrum, the body to be weighed being now hung on the hook which before supported the whole instrument. As the distance between fulcrum and weight is now smaller than before, much heavier weights can be measured by the original moveable weight.

Another form of steelyard is the Danish one, in which one end carries the body to be weighed, and the other is loaded to act as a weight. Here the fulcrum is moveable, and the weight of the body is shown by the position of this fulcrum on the graduated scale along the bar. This scale, however, is not so simply divided as in the former instrument. A small letter balance is made on this principle, and may sometimes be met with. There is an interesting modification of this, in which the fulcrum is fixed, and the mere movement of the lever over a graduated scale shows the weight. In this a bent lever is employed, the principle of which we will discuss later. The weighted arm is longer than the other, and hangs vertically, while the other projects horizontally, or nearly so (Fig. 25). In this position the weight of the loaded arm is entirely supported by the fulcrum, and a very small weight hung at the end of the shorter arm will cause motion. In moving, the weight of the heavy arm is brought out from under the fulcrum and so has more leverage, the smaller arm getting less, so that a position is soon reached where the two arms balance. With a greater weight on the short arm, the long arm will swing farther out, and thus, by letting this long arm move over a circular scale, the weight can be read off at once. The figure shows the position of the instrument with and without a body to be weighed.

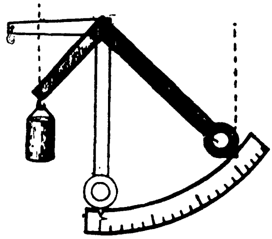


Fig. 25.

Though the simple steelyard and these various modifications of it are not extensively used now, the principle is of great value; the huge testing machines for determining the strength of metal bars or plates are only the same thing on a large scale, and the weighing machines on railway stations and at other places are an extension of it, using a combination of levers to give the desired effect.

But passing from this use of levers as weighing machines, we may notice their application in countless instances in our daily life. Our scissors are a combination of two such levers. arranged to act against each other, and so avoid the need of an external fulcrum, which would need to be secured in some way. The pincers for drawing nails act in the same way as they grasp the nail, thus giving sufficient friction to prevent the nail slipping through, and then again as a single lever when turned to one side, this motion pulling out the nail. Here the friction of the nail against the wood is the resistance to be overcome, and the fulcrum is where the pincers rest on the wood, the power being applied by the hand at the other end. Other examples that will occur to all are the claw-hammer, used instead of pincers for drawing nails; the screwdriver or crowbar, used in opening a packing case; and the knife for opening cans of tinned provisions.

Mechanical Advantage.—In all this we have spoken of a lever as a machine enabling us to balance or overcome a large force by a small one, but it is equally possible to take the other view, and by applying the power at the end of the shorter arm to make the weight lifted smaller instead of larger than the power. In the first case, where the power is smaller than the weight, there is said to be a mechanical advantage; in the other case, a mechanical disadvantage. If this disadvantage were the only result of applying the power to the short arm, there would be little practical utility in this arrangement; but when we examine the subject, we find there is a corresponding gain, not in power, but in speed. In fact, another way of stating the relation between power and weight might be that the power multiplied by the distance it moves through, equals the weight multiplied by its distance; distance moved through corresponding exactly to length of arm. Hence the familiar phrase, that what is gained in power is lost in time. So, when we work at a mechanical disadvantage, we gain in time or speed just as much as we lose in power, and for many purposes the speed is more valuable to us than the power. Many instances of the use of this principle meet us in the consideration, not only of other levers, but also of the other simple machines.

Levers, Second Kind.—All the levers considered up to this point have been of the first kind—that is, having the fulcrum between the power and the weight. In levers of the second kind, the weight is between the power and the fulcrum. Here, the distance from power to fulcrum is always greater than that from weight to fulcrum, and we always get a mechanical advantage.

One of the commonest examples of this is the wheelbarrow, the wheel being merely a device for continually shifting the fulcrum, which is at its axis. The weight is the load in the barrow, while the power to lift it is applied at the end of the handles, thus enabling a man to lift a much larger weight than he could directly. The longer the handles or the closer the weight can be brought to the wheel so much the greater is the advantage gained. Hence arises a difference in construction according to the use to be made of the barrow. The ordinary garden one has to be capacious, to carry dead leaves, cut grass, and so on, generally of no great weight, and the wheel here is generally well in front, to keep the barrow low, and the handles are short. A navvy's, on the other hand, has to carry heavy loads of earth, and has the wheel brought nearer in, with often the front of the barrow projecting over it, and the handles much longer, at the same time diverging sideways to give greater steadiness. For still heavier loads, as in ironworks, the wheel is put under the barrow, or rather in practice the axle is put under and a wheel put on each side. The hand-trucks used in railway

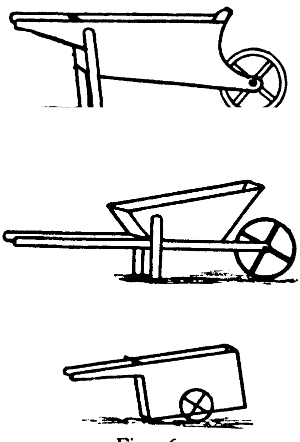


Fig. 26.

stations and for moving coal or flour sacks are of similar construction. The three kinds of barrow are roughly sketched in Fig. 26.

The ordinary pair of nut-crackers is a combination of two levers of the second kind, and this kind is also involved where motion round a fixed pivot is made to do work, as in the capstan used for hauling up boats or bathing machines on the seashore, or anchors on shipboard. There the fulcrum is really at the centre of the axis on which the whole capstan turns, the weight or resistance being applied at the circumference of this axis, or on the barrel fastened to it, while the power is at the end of the bar which moves it. A clock or watch key acts in the same way, the resistance now being the pull of the spring or weight. The small levers that work the cranks of a "Facile" bicycle are of this kind.

Levers, Third Kind.—If now, instead of having the weight in the intermediate position, we put the power there, we have the third kind of lever. This is really simply the second with power and weight changing places, but for convenience it is put as a separate class. Here we get a constant mechanical disadvantage, but, as explained above, the space passed over by the weight is proportionately increased, and the gain in speed is often of more account than loss of power.

A pair of hand-shears for grass-clipping or sheep-shearing is a combination of two levers of this kind, the fulcrum being supplied by the spring joining the blades, and the power by the hand-grasp between spring and blades. Fire-tongs and sugar-tongs act in the same way, in each case quick and wide action being of more account than a strong grip. Hence the feebleness of ordinary tongs in grappling with a large lump of coal, and the necessity in such a case of sliding the hand down towards the coal so as to reduce the disadvantage as much as possible. The actual comparison by trial of these tongs against ordinary pincers in such work as drawing a nail will impress on the experimenter the difference between the two styles of leverage. In the scythe we have another lever in which speed is the desired end. It may be considered either as of the first or third kind, according to the movement of the hands in using it; but whichever hand be regarded as the fulcrum, there is a loss of power in the blade, but, at the same time an increased speed, without which no amount of power would enable it to cut the grass on which it works.

But most important of all instances of this kind of lever are those in the limbs of animals. The bone here is the lever, the power being applied by the muscles, through the tendons, at a point always quite close to the fulcrum, the joint. In many, perhaps the majority of instances, the power acts on the same side of the joint as the resistance, as in the human forearm and lower part of the leg, giving a lever of the third kind. At the ankle joint, however, we have a lever of the first kind, the muscles acting behind it, while the front of the foot overcomes the resistance. If it were not for this gain of speed at the expense of power, most of our present active motion would be impossible. The contrast would be somewhat the same as between a modern 'cycle and a steam roller. At the same time, one is struck by the enormous power the muscles must have, to enable us to exert so much force as we do, under such disadvantageous circumstances.

In the above, we have considered the lever as a straight bar, but there is no need for it to be so. It may, in fact, be of any shape whatever, and will still act in precisely the same way and obey the same laws. The only thing to be careful of is to give the true meaning to the term "distance from the fulcrum," or "length of arm." This distance must, of course, be measured in a straight line, and not along the lever itself, and further, the straight line which joins the points where the power and weight are applied must pass through the fulcrum. If this is not the case, the effective leverage of the arms will vary in different positions, though for any given position the proportion can be found by drawing a line through the fulcrum to the lines representing the direction of the forces, these being supposed, as in all we have said yet, to be acting parallel to each other.

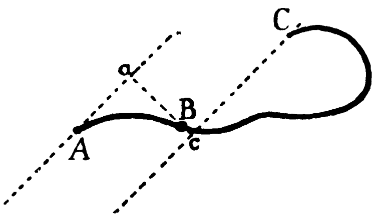


Fig. 27.

The direction of the line does not alter the proportion of the arms, but it is most convenient to draw it at right angles to the directions of the forces, as this enables us to compare one state of things with another in real measurement. Thus, if we have a lever ABC (Fig. 27), with its fulcrum at B, acted on by two parallel forces along the dotted lines, we draw through B the line aBc at right angles to these forces, and aB and cB are the real

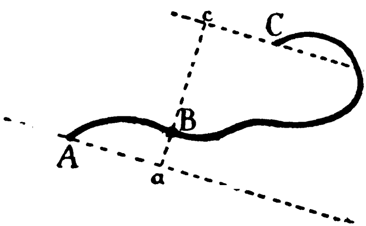


Fig. 28.

arms at which the forces act. This figure, compared with Fig. 28, where the direction of the forces is different, shows clearly the difference of leverage caused by change in direction of the forces, or, what comes to the same thing, change in position of the lever. In Fig. 27, the force at A has the greater arm; in Fig. 28 it has the smaller, though the lever itself and position of the fulcrum are unchanged. We have noticed, in fact, this principle carried out practically, in the bent Danish balance referred to above.

So far, if the forces are parallel. If they are not so, we have at once the necessity for a *bent* lever if uniform action is wanted. Thus, if one force acts vertically downwards, and the other, which we may call the resistance, acts horizontally, the lever must be bent at right angles, and will then give exactly the same effect as if it were a straight bar with the forces acting parallel to each other.

In just the same way, a bent lever can be used to change the direction of a force, giving it any angle with the original one, according to the angle of the lever. The most common case, of course, is when the forces are at right angles, a right-angled lever being used for the purpose. The ordinary bell crank is an example which will occur to all, as well as the larger instrument of the same kind which is used to communicate motion from a signalman's box to points or signals. The claw hammer, in extracting a nail, acts on the same principle, a sideways motion of the hammer handle pulling the nail out of the wood.

Continuous levers.—Thus far we have spoken of ordinary rigid bars as levers, but the slightest experience of the use of these shows that they entail serious disadvantages, except for certain strictly limited actions. For one thing, the ends of the lever move, not in straight lines, but in circular ones, which necessitates special arrangements for rectilinear motion. But a still more important defect is the very short range through which a lever can usefully act. In the most favourable case, as with a lever turning on a pivot, a simple direct force can only turn the lever through two right angles; if it begins to act vertically above the pivot, it will cease to act vertically below it. If, however, we take the more usual case of a lever merely resting against a fulcrum, there will be a much smaller range, owing to the lever slipping on the fulcrum. Any who have tried to move a heavy mass along the ground by such means will recollect at once how, after moving the mass forward a little, the lower end of the lever, which *was* the fulcrum, slips back and has to be replaced. Here the power and the fulcrum suddenly change places, the earth or floor resistance giving way and allowing the end to move, rather than move the weight, the place where the weight *was* applied supplying the new fulcrum.

The first step evidently to be taken in remedying this state of things, is to provide our lever with a fixed pivot on which it can turn, thus overcoming the liability to slip. If now, directly one lever gets so placed as to be of no more use, we can arrange to bring another into action at the place where the first started, we have another step forward; and by the time this second has finished its travel, the first may again be ready to take its turn. Suppose our force is supplied by a flowing stream, into which dips one end of our pivoted lever. This turns through a certain space, pointing first up stream for instance, and lastly down, but then can do no more. If, when this ceases to act, another lever enters the water, pointing up stream, it too is quickly carried down and round, carrying the first back through the air almost to its first position of vantage. Put a third lever in the series, and we have a machine that will work continually in one direction, the defect of the simple lever has been overcome. The work, however, is still very uneven, but it is a mere matter of adding more levers to get a perfectly smooth and even motion. We have in this way evolved a water wheel, a machine which has for ages been used by men to give them the power of a stream or river, in a more convenient form. So far for taking up the power, now for applying it to the resistance to be overcome.

Supposing the long ends of all our levers to be outward so as to dip into the water, the short ends can evidently be made to give a push forward or upward by being brought against the substance to be moved, which in this case must be of considerable length, or still better be, like water, grain, or flour, something that can flow on in a continuous stream. If the short ends of the levers could all be placed together, we should get a star, or, if they were numerous enough, a form but little differing from the well known "cog wheel." The cog wheel is merely such an assemblage of levers with the centre parts either merged into one piece, or partly done away with, the only relic being the spokes attaching the cogged rim to the axle. If the substance to be moved be a continuous solid, the best effect will be produced if that too is cut so as to correspond with the "teeth" of the wheel. We thus arrive at the "rack and pinion" movement so common in machinery. Imagine this straight rack bent into a circle, and provided with spokes and an axle, and you have another cog wheel, which, though produced in this way, still acts exactly like the first as an assembly of levers.

It is worth our while to go a little deeper into this question of cog wheels on account of their great importance. Our timepieces depend entirely on them, from the tiny watch scarcely bigger than a sixpence to the clock which tells the time to a town. The rack and pinion is seen in the focussing movement of a telescope or microscope, in the devices for opening and shutting inaccessible windows, on the sluice gates of locks along river or canal, and in the railways which take us up the Righi or Pilatus.

But in every case the lever is at work, and we require no other principle than that we have already discussed, except the practical question as to the amount of resistance due to friction. This last, however, we leave for separate discussion, and will consider our cog wheels as frictionless. The first thing that strikes us is that a simple cog wheel cannot give us any gain either of power or speed. This evidently follows from the fact that all points on the circumference are the same distance from the fulcrum, and consequently any motion given to one tooth will give exactly an equal and similar motion to all the others. To get over this, however, all that is necessary is to fix another cog wheel of different size anywhere on the same axle. Here we have levers of different lengths, and if the power is applied to the larger wheel, it acts at an advantage determined by the diameter of that as compared with the diameter of the smaller one, each tooth of which travels more slowly but exerts more power. If now this small one acts on another larger than itself, its power is again increased, if the resistance is applied at any point inside the circumference of this third wheel. Reverse the process, and have the power applied to the first small wheel, and the large wheel on the same axle gearing into the small one of another pair, and we have an arrangement of small power but of great speed. Evidently, if the resistance to be overcome is not too great, such an arrangement will allow of the original power continuing to work for a considerable time, and it is this feature that has caused the universal adoption of this form of gearing in the works of clocks and watches.

There is, however, another way of regarding the same thing, and that is to take into consideration the relative number of teeth in the respective wheels, as where one wheel works against another, it is this consideration that determines the relation of power or speed. If a wheel of a hundred teeth gears into another of ten teeth, the former will only revolve once for ten revolutions of the second, and this latter one, therefore, will be able to exert proportionately only one tenth of the power.

Rope, &c.—As already noticed, to get a smooth and uniform motion from such circular levers, we must have a considerable number of teeth. There is another way of working, however, that quite meets the point, that of using a flexible cord or rope.

A flexible body is one that, though solid, easily allows alteration in the relative direction of its particles, while opposing any breach of continuity. The effects thus produced are really very remarkable, though from their very commonness they are apt to be overlooked. In consequence of this peculiar structure, flexible bodies can exert force in the shape of a *pull* but not in the shape of a *push*. A thin wire, for instance, 6 inches long, which will support a weight of 9 or 10 pounds hanging by it, will carry hardly more than its own weight if that acts from above as a push. If now we take such a flexible cord and pull one end of it, it at once arranges itself (if we may neglect the action of its own weight) in a straight line, in the direction of the force applied. Attach one end of such a cord to any point in the circumference of a cylinder capable of turning on its axis, and wrap the cord a few times round. On pulling at the free end of the cord we have practically a force acting to turn the cylinder round its axis, this force being applied at the end of a radius and at right angles to it. If the cylinder turns, the part of the rope that is wound off at once becomes straight, and simply transmits the straight pull of the force to another similar point on the cylinder. If attached to the same axle there is a cylinder of smaller radius, with a cord passing over it the reverse way; this latter cord will be wound up as the first unwinds, and here again, as in the case of the cog wheels, we have a system of continuously acting levers. There is an advantage, however, in using this arrangement, on account of its greater simplicity and ease of application, as well as in the fact that a cord of very considerable length may be used. A rack of any great length would be very unwieldy, besides being out of the question in a confined space.

In certain cases, though, it is useful to use what we may call a flexible rack, as the gear chain so common on safety bicycles and mowing machines, which constitutes a sort of stepping-stone from rack to rope. Returning to the cord or rope, we see the necessity, in order to gain power, of having two cylinders of different diameters; a given force applied to the large ciruumference, balancing a greater force on the small one. This is the well-known wheel and axle arrangement, an example of which is seen in the apparatus for ringing Church bells; the rope running in, and being fastened to, a groove in a large wheel, to the axle of which is attached the bell, the weight of this supplying the resistance. But it is not necessary that the wheel should be a complete one. In fact, the more ordinary method of applying the principle in practice is to have the wheel in skeleton, and so approximate to the cog wheel. This is the case with the capstan, in which the ends of the bars trace out the large circle or wheel, and on the axle is wrapped the rope attached to the body to be moved, whether anchor or bathing machine. The older-fashioned horizontal windlass for ships is a similar instrument, but here the bars have to be continually shifted, as they cannot pass under the barrel, and so the resemblance to a wheel is partly lost. The common steering wheel is another good instance. Here the leverage is gained by the size of the wheel, the chains working the rudder being fastened to a much smaller axle. As the other end of these chains are fixed to the end of a lever (the tiller), there is a further advantage gained here, thus enabling the largest ships to be steered with ease. Here the wheel is a complete one, but in the common windlass used for wells it is represented by a single spoke only. In this case, for convenience sake, a handle is attached to the end of this bar, at right angles to it. The hand then gives the circular motion, and traces out the form of the wheel, but it is not possible to get the same smoothness of motion. The crank action of a 'cycle or a steam engine is another familiar instance.

The most complicated cranes are merely combinations of these circular levers, arranged so as to give great power, with corresponding loss of speed.

As the power is often only wanted in raising, there is an arrangement for throwing part of the combination out of gear when wished, so as to render the motion quicker.

In considering the wheel and axle, or any of its modifications, we see that, to get the greatest power, we must have a very large wheel and a very small axle. Neither of these conditions, however, can be carried far without reaching a practical limit; the wheel is too big or heavy for its surroundings, or the axle too weak to bear the weight. How are we to get over the difficulty without multiplying wheels? We can do it in a very simple way, by having the axle of two different sizes, as in Fig. 29. The same rope is wound on both parts, but in opposite directions, and passes over a pulley between the two. Now, as the rope is wound on to the larger axle, this tending to raise the weight, it is wound off the smaller, this tending to lower it, but of course to a less degree. The total result is to raise the weight, but the more slowly the nearer the axles are to one another in size.

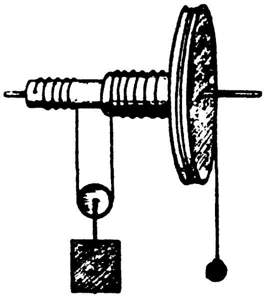


Fig. 29.

In fact, the difference between them as compared with the size of the wheel, gives us the measure of the advantage gained. Thus, if the wheel has a radius of 4 inches, and the difference of radius of these two parts is half-an-inch, there will be an actual mechanical advantage of 8 (*i.e.*, $4 \div \frac{1}{2}$); but owing to the presence of the pulley, as will be explained further on, this is again doubled, giving a total advantage of 16. This is the differential pulley so much used. In practice, however, the largest part, or *wheel*, is generally dispensed with, and the two parts of the axle are represented by two sheaves of different diameters, fitted with recesses or teeth to suit the chain employed, and so prevent it slipping. The ends of the chain, instead of being fastened to the sheaves, as above to the axle, are left long and joined to each other, so forming an "endless" chain, by pulling either part of which motion can be produced.

CHAPTER IV.

PULLEYS.

WE have been considering the flexible cord as used with certain forms of lever, but it has also a distinct use by itself, depending on its very nature.

Suppose we have a number of threads, each supporting a certain weight, it will make no difference to the supporting power of the whole if either the separate threads are combined into a rope, or the several small weights into one large one, so long as each thread still bears an equal proportion. A cord or rope is, of course, simply such an assemblage of separate threads, though, under ordinary circumstances, with a certain loss of total strength. This arises from the fact that cord is wanted of much greater length than that of any vegetable fibre, and for this purpose the comparatively short fibres or threads have to be joined.

This joining is best done by twisting them together, this twist and consequent friction one against another sufficing to prevent them being pulled apart. The twist though, by destroying the straight pull on the fibre, lessens its strength; but this is of less consequence, as there is a distinct advantage in having the cord as one large rather than several smaller ones. It is extremely difficult to secure that each small cord is exerting its exact proportion of the whole strain, and if one or two are overdone, the extra strain thus thrown on the others will probably break them too.

With a rope the threads being all parts of one whole react on each other, and this difficulty to a great extent disappears.

Returning, however, to our small cords or threads, and supposing that each bears its proper load, it is surprising to see what large forces can thus be exerted. The story of Gulliver fastened down by the Lilliputians will occur to many as an illustration.

We have spoken of separate strings, but exactly the same reasoning applies to one and the same string making several turns. To tie two things tightly together, we may either have a great many short strings, each tied tightly, or one long string wrapped firmly round and round. It will be seen at once that each turn of string exerts the same power whether it is entirely separate from the others or part of a long coil, as long as the two free ends are securely tied. There is in fact some little advantage in the long coil, as the different turns will give a little, and so adjust their several pulls more exactly. An instance of this use is seen on the handle of a spliced cricket-bat, the coiled thread holding the different parts together very securely. In the same way, ropes are "whipped" at the ends to prevent them from unravelling, and a broken stick or such like article "spliced."

Now, such an arrangement, though admirable for holding a body in position, would be quite out of the question if motion were required, the friction in this case being enormous. Hence the necessity of some means of lessening or overcoming friction, this means being given us by the Pulley.

A pulley in its simplest form is merely a wheel turning on an axle, with a groove round its circumference to hold the cord. In practice the axle is generally supported by side and end plates forming the "block," the wheel being called the "sheave"; the block serving not only to suspend the wheel, but also to guide the rope and keep it in the proper groove.

If the sheave were unable to revolve there would be no gain in any way, as the rope would have to slide along the groove. But, as it can turn, it does so, and gets rid of this sliding and friction of the rope, substituting for it the friction of the sheave on its axle. But this is less than the other for two reasons—first, that for each revolution a point at the axle travels a much smaller distance than one at the circumference, so that even if the friction at the axle is equally powerful there is less of it. But there is a second reason: as the same surfaces are continually in contact, it is possible not only to make them of materials which will not have a great co-efficient of friction, but also to keep them well lubricated. In the first case, instead of speaking of distance travelled, we might point out that the friction acts at a much smaller leverage than the rope, and hence with less effect.

These considerations show us that the larger the pulley can conveniently be made the more power we have for overcoming friction, or the less space in proportion for the friction to act through. A limit is of course soon reached in practice, from considerations both of size and weight, but in some cases a large pulley is needed for another reason,—that is, to avoid bending the rope beyond a certain point. This is especially the case with ropes of wire, hence the large pulleys seen over the mouths of coal pits.

We can now turn to the question of using the pulley in connection with the rope to gain power.

If the pulley cannot move, the sheave simply acts as a lever with equal arms, which, though useful in diminishing friction, cannot add to the power. The great advantage however remains, that the *direction* of a force may thus be changed without any limit whatever. It is for this reason that the pulley is so often employed both at sea and on shore. The labourer, pulling up bricks or mortar to the brick-layer at the top of a building, uses it, not to gain power, but to convert his downward pull into an upward one, and so avoids having to lift his own weight as well as that of the bricks.

Another interesting application is designed to make easier the passage of a barge round a sharp bend in a river. The tow rope in this case would be unable to pull the boat forward to the bend, and would drag it ashore. To prevent this a sort of pulley is used, a long barrel placed with its axis vertical, as near the extreme point of the bend as possible. The tow rope works on this and enables the horse to exert a pull *forwards* for a much greater time than without it. Fig. 30 gives an idea of its use, *a* and *a′* showing the position and pull of the horse with and without the pulley shaft, this being represented by the small circle at *b*. Numberless small household contrivances might also be mentioned, including the pulleys used for drawing curtains across a window by a cord at the side, those in which run the cords of a venetian blind or of a common roller one, and those for opening windows in house or schoolroom. In all these we have the pulley as a useful means of diminishing the friction of a cord, or of changing the direction of its pull, but in all cases causing a small

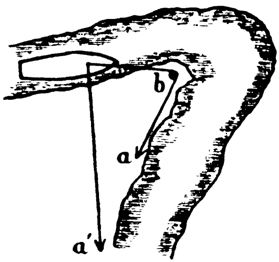


Fig. 30.

though certain loss of power through the outstanding friction.

Suppose now we allow the pulley to move, and tying one end of the cord passing round it to a firm support, either hold the other end or attach it to a suspended spring balance. The weight in this case (Fig 31), is hung from the block of the pulley, and is evidently supported by the two parts of the string round the pulley. The string, neglecting its weight, is pulled at with equal force at every point, because if one point were strained more than another movement would ensue, till the various forces were in equilibrium. Hence, as there are two parts of the string sharing in the work of supporting the weight, that weight must be equal to the two pulls together, or double the pull at one end of the string. This pull can be easily read off by aid of the spring balance, and it will then be found to be just half the total weight supported. In this total weight the pulley must be included; but if we may neglect this, or could get a pulley without weight, we should always in this simple moveable pulley get the ratio, between the power and the weight it will lift, as one to two.

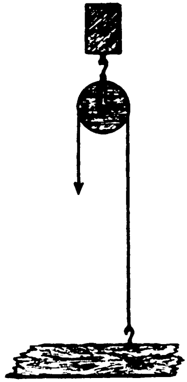


Fig. 31.

The pull need not of course be exerted upwards, but in any direction whatever, the only thing necessary being to fix one end of the cord and pull on the other. Perhaps it should be noticed here that, in all discussion of the effects of pulleys, the best effect can only be obtained when the different cords or parts of a cord are parallel to each other, as only in that case will there be no opposition in their pull.

To take one instance from this single moveable pulley, if the parts of the cord are at an angle of 120° the weight supported will be only just equal to, instead of double, the force acting at the end.

To keep the parts parallel or nearly so, it is usual to employ a second pulley, not itself moveable. Over this the string passes, after leaving the moveable one, and is thus able to take any direction without altering the position of the other parts. This arrangement constitutes the simplest combination of pulleys, and will be more fully discussed in that connection. The single moveable pulley, from its convenience and simplicity, is much used, especially at sea, where it is technically known as the "whip purchase."

It is natural that attempts should be made to combine several pulleys, to increase the mechanical advantage gained; and the methods of so doing are very varied, though but few are of practical use. By common consent there are three recognised "systems" of pulleys, though these by no means exhaust the subject. Of these three systems the first and third are very closely related, and will therefore be considered together, leaving the other, which is of far more practical use, till afterwards.

First System.—In the first system there are as many strings as there are pulleys, each pulley having one attached to it and one passing round it, and one end of each string being attached to the beam that supports the whole. Fig. 32 gives an idea of the arangement. W is the weight, and the power is applied at P. Neglecting the weights of the strings and pulleys, which evidently act in opposition to P, we have the first pulley supported by two parts of the first string in which the tension is P, so that the first pulley will act on the second string, to the end of which it is fastened, with a force of twice P, and in the same way that will produce in the second pulley a lifting force of four times P (or 4 × P). Then again, as this pull is given to the third string, two parts of which support the third pulley, this last will be pulled upwards with a force of 8 × P. The weight is attached directly to this, and must, in order to maintain equilibrium, just balance this pull. In other words, in this system, with three pulleys, a power of 1 will

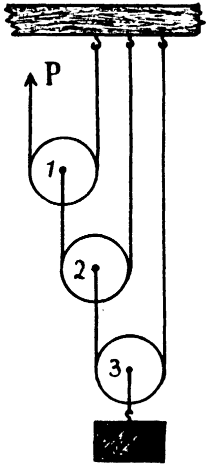


Fig. 32.

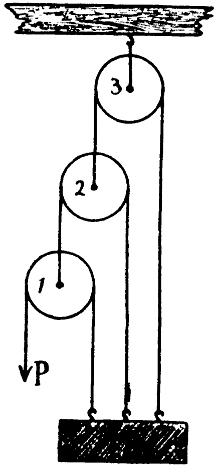


Fig. 33.

balance a weight of 8. That is not, of course, the same as raising a weight of that amount, as friction then interferes, but it is the first step to a correct allowance, and at all events serves as a sound basis for comparing this system with others.

Third System.—The so-called third system is merely the first turned upside down, all the strings now being attached to the weight, as in Fig. 33. The consideration is, however, a little different owing to this, as each string exerts a special action on the weight. Thus the first string has a tension P, and while drawing down the first pulley with a force twice P, pulls the weight W upwards with a force P. The second string again pulls W with a force of twice P, at the same time drawing down the second pulley with a force of four times P, this force being given to the third string and so acting upwards on the weight. If we go on to the third pulley, we see that drawn down by a force eight times P, which is exactly what we found to be the relation between weight and power in the first system, the beam in this case receiving the strain instead of a moveable weight. But, examining the raising action on our weight in this third system, we see that each string lifts a certain part of it, so that the total weight that can be balanced by P is the sum of the tensions in the three strings, that is P (in the first) + 2P (in the second) + 4P (in the third) or seven times P altogether.

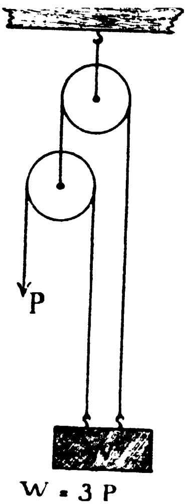
The difference between this and the first system is evidently due to the fact that in the latter, P must act upward to help lift W, so that W is supported partly by P and partly by the beam, the latter exerting seven times as much force as the power itself, the two together of course being exactly equal to the weight raised, or $7P + P = 8P$.

In the third system, on the other hand, the beam, with a resistance equal to 8P, supports both the power P and the weight, which, as we saw, equals 7P, or again $8P = P + 7P$.

We are apt to overlook the pull on the beam, but may be unpleasantly reminded of it, if it is not of sufficient strength, by collapse of the whole.

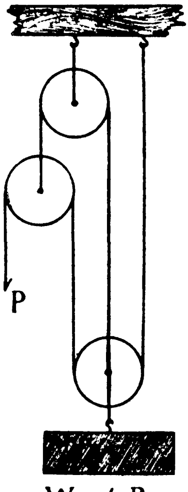
In considering generally these two arrangements, we notice that in the first case the weight of the pulleys is a disadvantage, but in the second actually a gain. It is clear too, that the third pulley in each case undergoes most strain, and therefore has greater friction on its axis, while the second has more than the first. To compensate for this, the pulleys should vary in size, the third being largest and the first smallest. Even as sketched the friction is very small, in comparison with the mechanical advantage gained; the pulley that has most friction also turns most slowly, which to some extent compensates. The real objection to both these systems, however, is the practical one, first of multiplicity of ropes; and second, of the comparatively small range possible. This is due to the unequal motion of the pulleys, the first ascending or descending with twice the speed of the second, and the second with twice the speed of the third. Thus, if they start together, the separation soon becomes very great, and the first becomes practically useless. The first system is apparently never used practically for these reasons, and the third only under special conditions, where there is plenty of space for the movements of the pulleys. It is thus used on shipboard, particularly for unloading coal from the hold of a vessel, a use that must be familiar to many of our readers, though few perhaps think of it in that way. Memory will recall the peculiar downward motion of one pulley so characteristic of the system. As used thus, there are generally two pulleys only, the arrangement being technically known as the Burton (or Barton) purchase. With three pulleys it appears, though seldom, as the Double Burton.

It may be as well to mention here one of those combinations that come under neither of the three "systems," the "Spanish Burton." This is really a modification of the single Burton, the cord from the power, instead of being attached directly to the weight, passing round a pulley on it, and thence up to the supporting beam. The two figures will make this clearer,—Fig. 34 is the Single Burton, and Fig. 35 the Spanish Burton. In the latter, there are two attachments to the beam, and one to the weight, instead of two to the weight, and one to the beam. There is a slight



W = 3 P

Fig. 34.



W = 4 P

Fig. 35.

advantage in the use of the other pulley, the gain of power increasing from 3 to 4.

Second System.—In the remaining system of pulleys, the "second," only one cord is used that passes round all the pulleys, and is attached to the power, reminding us of the use of a cord for binding two bodies together when wrapped round both several times. Here the pulleys are divided into two sets, each set containing the same number of pulleys, and being firmly fastened together to form one block. The upper block is fastened to the supporting beam, and the lower one to the weight. If the upper and lower blocks each consist of one pulley, we have practically the single moveable pulley as already mentioned. As the lower block moves all in one piece, we have the possibility of motion through practically any distance, hence the great convenience of this arrangement, not to mention its only requiring one attachment at each end. We may have this in two main forms, one with the pulleys below each other, the other having them side by side on one axis. The former, shown in Fig. 36, is more theoretically correct, as the strings can then be kept parallel, by suitably adjusting the size of the various pulleys, and thus each part of the cord is giving its best possible result.

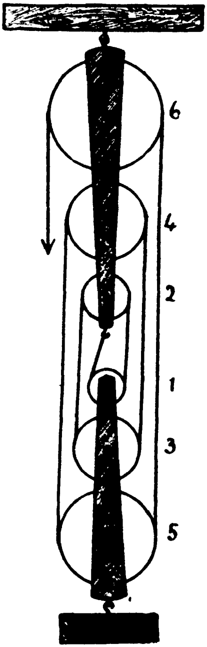


Fig. 36.

To ensure *all* the strings being parallel, the diameters of the pulleys must be in the same proportion as the numbers that show their order, but all except the innermost can be kept so if each pulley is larger than the one before it by a constant amount, enough, of course, to keep the ropes clear. This is the case in Fig. 36.

Another advantage in this form is that the parts of the string, as they move through greater distances, have larger sheaves to pass over, so that the friction is to a great extent equalised. It should be noticed that the cord should in all cases, go first round the smallest pulley, or these advantages will be lost. But though this form has its good points, it is condemned, practically, by the length of the blocks, which are not only liable to get out of position from this cause, but prevent the weight being drawn close up to the supporting beam, while they are very liable to accidental injury.

Hence in practical use this has been displaced by the common form in which each block has its sheaves side by side on one axis. The gain in portability and handiness is great, but there is a corresponding loss in wear and tear. The cords on one side are parallel to each other, but not to the cords on the other side, and so there is a tendency to twist the sheaves, which makes them wear unequally, and much increases the friction.

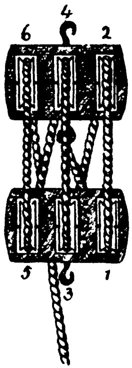


Fig. 37.

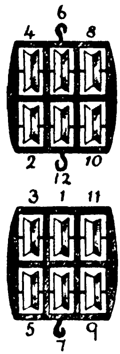


Fig. 38.

Thus, in Fig 37, which exaggerates the breadth, the course of the cords may be traced, and it will be seen that, speaking of the side nearest the reader in each pulley, Nos. 1, 2, 4 are twisted to the right, and 3, 5, and 6 to the left. To lessen this evil in large blocks, Smeaton put two rows of sheaves one above the other, a sort of combination of the two forms just discussed, Fig. 38. Two blocks of this sort used in combination give great power with less friction in proportion than the ordinary blocks, though even this is only a lessening and not a removal of the difficulty. The numbers show the order in which the cord passes round the sheaves. It will be noticed that we begin at the centre and end there as well.

There is another invention of great theoretical interest, White's (or Brunell's) pulley, in which friction is still further reduced, though again practical difficulties have prevented its common use. In this, shown in Fig 39, each set of sheaves is in one piece and turns on a single axis, at once getting rid of a great deal of unnecessary friction. The separate sheaves of other forms are represented merely by grooves in this solid piece. If we consider any combination of pulleys, we find the sheaves nearest the power have much more cord passing over them, and consequently have a greater surface velocity than the ones nearer the weight. Such a greater velocity would be fatal to the use of White's pulley if its sheaves were all of one size. But, by enlarging these in proportion, it is possible to compensate for this by the increased size, so that all the sheaves, even if disconnected, would turn round at the same rate, or have the same angular velocity, the velocity of the rim of course varying with the diameter. In order to secure this uniform motion, the sheaves must have their diameters proportionate to the numbers 1, 2, 3, &c., these numbers giving their order from the centre as before. Thus, in the bottom block, the circular grooves or sheaves will have the relative diameters 1, 3, 5, &c., and in the top one 2, 4, 6, &c.

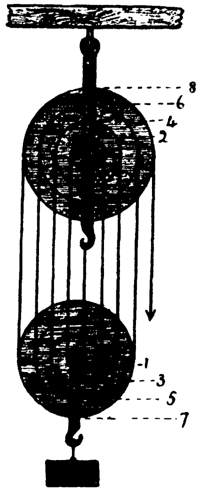


Fig. 39.

In this way there is only the friction of one bearing, for even a large number of sheaves, and the strings are at the same time kept very nearly parallel, the whole width of the block being very slight, while this width is the only thing that interferes with their perfect parallelism. Unfortunately, the thickness of the cord has to be taken into account in calculating the relative diameters of the grooves, and as any variation in thickness destroys the adjustment, the machine is not adapted for practical purposes. The sheaves could of course be made to turn independently, but all the disadvantages before spoken of would so be introduced.

So far we have been following out the various practical aspects of this second system of pulleys and its varieties; it remains to glance briefly at its mechanical advantage. This is found very simply indeed, being dependent only on the number of parts of the string that help to support the weight. With six pulleys there will be six of these parts, so the weight supported will be six times the power.

The sixth pulley is not absolutely necessary for this effect, which can be got without it if the power acts upwards. This, however, is not generally so convenient, the figures representing the usual arrangement. But if a further gain of power be an important point, it is easy to make the six pulleys exert a force seven times the power by reversing the whole series, so that the block before attached to the beam is now fixed to the weight, or, which is practically the same thing where the ordinary blocks are used, by altering the attachment of the cord from the one block to the other, but in both these modifications the power and weight must act in opposite directions.

Before leaving the consideration of pulleys, it may be as well to notice what a capital illustration they afford of the relationship between speed and power in any machine.

As already mentioned in connection with the lever, we cannot increase the magnitude of a force at our disposal without at the same time, and to the same extent, diminishing its range of action, so that the product given by multiplying the force or power by the distance it moves through is always the same, at all points of a machine, assuming, of course, that nothing is lost by friction. From their long range of motion, pulleys, especially the system last considered, give us admirable opportunities of exact measurement. Supposing we take a system of six pulleys, giving a mechanical advantage of six, then the proportionate space through which the weight can be raised is diminished six-fold. If the power can move through six feet, it can raise the weight only one. If we suppose a mechanical disadvantage to be no objection, we get, by interchanging the positions of power and weight, a movement of six feet produced in the weight for every foot traversed by the power. This particular arrangement is usefully employed in various hydraulic hoists; the enormous power of a hydraulic press forcing apart two many-sheaved blocks, so giving the free end of the rope or chain a very rapid motion and long travel, used in many cases for lifting sacks of flour or other goods into the upper stories of lofty warehouses.

CHAPTER V.

THE WEDGE AND INCLINED PLANE—THE SCREW.

AMONG the vast buildings of bygone days which still command our wonder and admiration, are sometimes found wedges of bronze, which have evidently been valuable tools in the hands of the builders. We are thus led to look upon the wedge as perhaps the most ancient in its application of any of the so-called mechanical powers, as it still remains one of the most important in its applications at the present time. It is supposed that the stones of the Pyramids, for instance, were to a great extent raised by this means.

In our own day, the use of a simple wedge for such a purpose as lifting a mass any distance would not be thought of, it having been superseded by other and more handy appliances. But for a short distance it is still unapproached, and we use it thus to fasten firmly our doors and windows, against the attacks of a gale, and to adjust properly the level of heavy pieces of furniture. Every householder knows the value of a wedge for restoring to a vertical position a leaning case of heavy books, or for supporting any desired part of a sideboard or wardrobe. Many, no doubt, would look on it merely as an easy means of finding the correct thickness to be inserted, which indeed it is; but if a piece of wood of exactly the correct thickness were taken, it would be much more difficult to get it properly into place. The wedge, of course, will find its own position without difficulty. One advantage in the ordinary way of using it is, that percussive action is employed, the inertia of the moving hammer expending itself in moving the wedge forward. In this way it is used largely for splitting wood, especially stumps of trees and other large masses. It is only necessary to separate the particles of the wood a little way in order to make them come entirely apart; just the sort of work for which the wedge is suited.

Another valuable point is, that it moves with very considerable friction. In speaking of the other mechanical powers we have had to treat friction as an opposing element, here we meet it as an ally. It is true it opposes the forward motion of the wedge, but it also prevents its moving backwards, and thus enables it to hold the ground it has gained, prepared again to advance as the hammer strikes it. It is friction which keeps it in position in door or window, or under the body it may be supporting.

A wedge moved by a screw was at one time a favourite method of securing the seat bar of tricycles at any given height, though now generally discarded in favour of the simple clamping screw.

A nail is simply an adapted wedge, as, even if its body is uniform in size, its point is either a single wedge or a combination of many. A wood screw, too, is generally of a wedge form, so as to allow it to enter more easily.

But all this is of little account compared with what we may call the principal use of the wedge—that is, as forming the effective part of all the useful tools classed together as cutting instruments. From the schoolboy's pocket knife and the carpenter's chisel and plane, to the gigantic machines that cut thick sheets of metal, or turn or plane it into shape, we are dependant on this for our effects. It is the wedge shape of the cutting edge that overcomes the adhesion of the particles, the other parts of the tool serving merely to give support to this cutting edge or to direct the fragments cut off.

In considering briefly the general principles of such tools, we are led to examine first the action of an ordinary wedge. To find its effect in forcing apart two bodies, we must take care to get rid of friction as far as possible, as that is a variable quantity, and can be allowed for separately in practice. To do this, we may use two moveable arms, or perhaps better, one fixed and the other moveable, furnished with rollers or friction wheels where the wedge acts. It is easy to bring these together with any required force by means of weighted strings or levers, as in the apparatus shown in Fig. 40. Here one arm is fixed, and the other, AB, moveable, while a string attached to AB and passing over a pulley D to a weight, keeps together the two anti-friction rollers at A, with a force depending on the weight used. If now a wedge of known weight is used to force apart the arms, it can only do so when there is a certain relation between its weight, which acts downwards and tends to separate the arms and the weight acting over the pulley, which tends to keep them together.

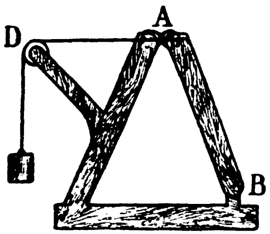


Fig. 40.

By using wedges of the same weight but with the angle between the working sides different, two facts are at once evident,—that the smaller the angle the greater the mechanical advantage, and that at the same time the tendency to slip back is less. Into greater detail it is not worth while to enter, owing to the disturbing action of friction in practice. But, however modified in actual working, the above facts stand out clearly, and are sufficient as a basis for reasoning out the action of a cutting edge.

Evidently, to get the best effect, the edge should be as sharp as possible—that is, the angle between its sides should be very small, so that the force pressing it forward may more easily divide the substance cut. This is especially the case where the substance to be cut is of a yielding nature and it is impossible to bring any great pressure to bear on it. A razor, for instance, has to cut hair, one end of which is free to move, and it must therefore be extremely sharp, a fact to which we owe the "hollow ground" razors now so common, in some of which a mere web of steel is left at the edge. But, though admirably adapted for its special purpose, a razor would be unfitted for general work, soon losing its edge, and breaking up when cutting harder and less yielding materials. For these we must have more support given to the edge, even at the sacrifice of its delicacy, and we thus arrive at the various forms of knife, which in various hands have such manifold duties to fulfil. For greater strength still we get such forms as those in the chisel and plane iron, which are used with great force and can overcome the resistance of even hard wood. These again would be too weak for metal working, and for this we must make a still further sacrifice of sharpness to get strength, compensating for it by the greater pressure that we can apply to force the tool to its work. The diagrams

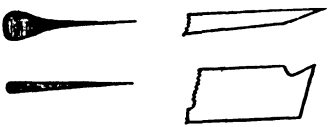


Fig. 41.

in Fig. 41 give roughly the different forms referred to, the razor and knife being seen in cross section.

In use such edges get dulled and rounded, and are then unable to do their work properly. To restore their condition we resort to grinding, by which we remove the worn parts and leave a new edge. It is here that the skill of the workman is seen, as compared with the tyro. The former grinds the tool so as to leave a perfectly flat or slightly concave surface where the stone has acted, Fig. 42 A, while the latter makes it convex, or more usually with a number of different faces, Fig. 42 B. In the first case, the wedge is uniform in angle throughout, in the second it varies in different places. Moreover, in this second case, the angle at the edge is always greater than the general average slope, and, as it is just by this edge itself that the effect of the tool is really produced, it is thereby rendered less useful. In Fig. 42 B, the effective cutting angle, is shown by the dotted line.

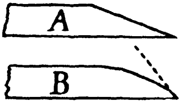


Fig. 42.

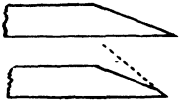


Fig. 43.

The operation of grinding, however, is, for delicate edges, not final, as a rough, serrated edge is left, which is unsuited for clean work. To remove this is the object of "setting" on an oilstone, which perfects the tool and leaves the edge smooth and still nearer to a mathematical line than before. Even this, though, may be so done as to spoil instead of mending matters, as there is a great temptation, for the sake of quickness, to raise the body of the tool too much away from the hone, thus forming a facet at the edge of greater angle than before and thus lessening the sharpness, as in Fig. 43. On the other hand, if the ground surface is perfectly flat, it may take a long time to finish it on the hone, if kept at the same angle, and it may seem better to save time even at the cost of having to put a little more force into the tool when at work. This difficulty, however, disappears if the ground surface is made very slightly concave, as then, when put on the hone, only the edge and heel touch, and the tool is soon brought to proper condition, as in Fig. 44.

A point that may be noticed here is the difference in use of various tools, some acting by pressure, as the knife; others with greater velocity, using inertia to some extent, as the plane and spokeshave; others depending on the inertia of a hammer or mallet, as the mortising chisel; while there are some that we may look on as a sort of union of wedge and hammer, as the axe and billhook. The diamond for cutting

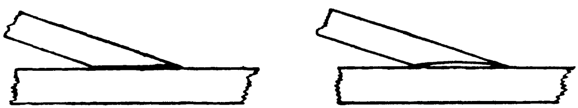


Fig. 44.

glass acts by pressure, as does the needle in splitting a mass of ice. This last case well illustrates the enormous power exerted by a sharp wedge of small angle.

Inclined Plane.—The wedge at one time was considered as a separate mechanical power, and for the sake of convenience it may be treated thus, but inseparably connected with it; in fact, only a modification of it, is the Inclined Plane, which we must here discuss, not only as interesting and useful in itself, but as enabling us to see more clearly the principles underlying the advantage of the Wedge.

What then is an Inclined Plane? The term evidently supposes some other plane to which it is inclined, and this is understood to be the plane of the horizon at that particular place. This horizontal plane is at right angles to the direction of gravity, and hence any body supported by a horizontal surface of sufficient strength, will be unable to obey the attraction of gravity, and, as far as that force is concerned, will remain motionless. If, however, it be quite free to move, a ball on a smooth table for instance, and one end of the surface be raised, gravity will no longer be entirely neutralised, and the body will begin to move towards the lower end, to roll down hill in fact. The more the other end is raised, or, in other words, the more the plane is inclined to the horizontal, the quicker the ball will move, and the less its weight will be counteracted by the plane. If at last the inclination becomes 90°, or the plane stands vertically, it no longer resists the ball's motion, and this will now descend with the full velocity of an ordinary falling body. The form of experiment here outlined is of historic interest, as it was in this way Galileo carried out some of the earliest known investigations on the action of the force we know as gravity. Having no means of measuring short intervals of time, he used the device of lessening the rate of motion, thus increasing the time of observation, and found in the inclined plane exactly the instrument for his purpose.

The inclined plane may be said to differ from the wedge in its mode of application, as, while the wedge is moveable and used in motion, the inclined plane is stationary, and the body acted on is in motion.

Evidently one of the first steps in our investigation is to find some method of stating how much the plane is inclined to the horizon, in order to be able to state clearly the results arrived at. We may do this by a measurement of the angle enclosed between the plane and a horizontal line in the same direction, but for our purpose a much simpler method is by direct measurement of the relation between the height of its highest point and the length of inclined surface.

In all that follows we will assume that we are dealing with a simple inclined plane, sloping regularly from top to bottom. Fig. 45 shows more clearly than mere words, the meaning of the terms we shall employ. *xy* is a horizontal plane, and *ab* the inclined plane, the bottom of which *b* is in the horizontal plane *xy*. If then a line *ac* is dropped from *a* at right angles or perpendicular to *xy*, *ac* represents the "height" of the plane, and *ab* its "length." In the same way we may call the space *bc* the "base" of the plane, and as all other parts of *xy* beyond *bc* are of no concern to us, they may be omitted.

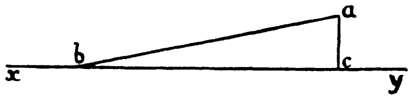


Fig. 45.

The inclination of the plane may now be stated in terms of the relation of any one of the three lines to any other, but the one most to our purpose will be the relation of height to length, a plane being said to rise 1 in 5 for instance, when height *ac* is 1 and length *ab* is 5. It is true that engineers use the ratio of height to base, but it is on the whole more natural, as well as far more convenient, to speak of rising 1 in 5, when you actually cover a distance of 5, than to speak of it as 1 in $4\frac{9}{10}$, or to speak of rising 1 in 5 when you really have passed over $5\frac{1}{10}$. It is at all events possible to measure the *length* directly, which is not so often the case with the base.

The action of an inclined plane may be easily examined by aid of simply constructed apparatus, consisting mainly of the following parts (Fig. 46). A long piece of smooth wood, as straight and true as possible, is hinged at one end to another similar piece, and can be supported at any angle by blocks pushed between the two. A metal roller of definite weight, and moving freely on its axle, is used for the travelling load, to lessen friction as much as possible. A cord attached to the yoke in which the axle

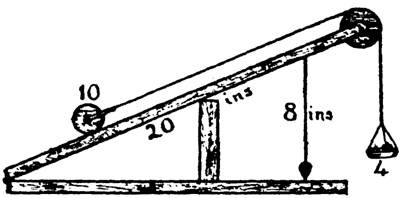


Fig. 46.

turns, passes up the plane, and over a fixed pulley at the top, care being taken that this cord is parallel to the surface of the plane. By now altering the inclination of the plane, and hanging different weights at the end of the string, the mechanical relation between power and weight may be found, as related to this inclination.

As the question is simply one of proportion, any length of the plane may be taken as most convenient, but the height must, of course, be measured from the same point as the length. A good way is to hang at a definite length from the hinge a small plumb-line, which can be raised or lowered to suit the height of the plane. The point where this strikes the lower board shows the point to which the base is measured.

To get accurate measures, these should be taken on the inner surfaces of the two boards as shown, as these alone meet at the hinge. In the figure the plane is represented as rising 8 in 20, and the weights so balancing each other to be 4 and 10. This proportion is, in fact, always true, the power (or small force) being to the weight (or large one) in the same ratio as the height of the plane to its length. If the height is lessened to 6, the length remaining 20, the power to balance 10 will be $\frac{6}{20}$ of 10, that is 3.

The reason for this gain in power is not at first apparent; but it is due to the fact that the weight of the roller is partly supported by the plane itself, and hence is not pulled downwards so violently, while the smaller mass hanging over the pulley is acting with its whole weight, and so much more efficiently.

If we measure the spaces passed over, we find the same relation as in the other simple machines, what is gained in power being lost in time. It seems at first as if both power and weight moved through the same space, but we must notice that the weight is really raised against gravity, which acts vertically downwards, and so, *as referred to gravity*, it only passes through a distance represented by the height to which it is lifted, in other words, the height of the plane, while the power moves a distance equal to the length. We see at once that the less the height of the plane the greater the mechanical advantage, a fact borne out by universal experience. A sharp wedge, is, of course, only an example of an inclined plane, whose height is very small in relation to its length.

A hill is nothing but an inclined plane, and a flight of stairs merely a modification of the same thing, the steps preventing us sliding down as we should tend to do on an equally steep slope, and, at the same time, allowing a much more natural position for the foot. The difference in sensation while ascending an "easy" and a "steep" flight will occur to every one; more steps have to be taken in the former case, but less exertion is required for each. Between the complete steps and the plain slope come such contrivances as a fowl ladder, or the cross bars often met with on steep foot-bridges. A ladder is an extreme case, in which but little of the advantage of the incline is retained.

The slopes at the end of railway platforms for the conveyance of luggage will occur to many, the porters being able by their means to raise or lower many times the weight they could actually lift. Heavy barrels are raised from cellars and into drays by an inclined "skid," the process being all the easier because the barrel will *roll* up, so reducing friction.

All that has been said about raising applies equally to lowering, less force being required to prevent the body slipping down the less the inclination of the plane. In this case, however, friction aids us, still further reducing the force necessary for support, hence a barrel is not rolled down a skid, but slid down endways to introduce as much friction as possible.

Supposing we have a definite and fixed inclination, we cannot, of course, make it any steeper, but we can do the opposite and practically make it less steep, not by any alteration in it, but by our method of progress up or down it. The steepest possible line of ascent will be one as straight up as possible, but any divergence will make the length greater, as far as we are concerned, and so reduce the effective inclination. To get as long a line as desired, it is only needful to describe a zigzag instead of a straight path, a well-known way of making the best of a steep hill. So natural is the process, that whether from training or native instinct, some horses, especially in hilly districts, require considerable effort to keep them in a straight line on even a moderate hill, the tendency to zigzag being almost irrepressible. A very curious instance of the same thing is afforded in the St Gothard railway, in which the ascent from the lower to the higher level of the mountain is all compressed into a comparatively small area, by means of a series of circular inclines, or spirals, which to a great extent are actually in the interior of the mountain.

The relation of height to length, as representing that of power to weight, is true for the ordinary case of a force acting parallel to the plane; but it may be as well to shortly point out that if the force acts parallel to the base it will have to be larger, the relation between power and weight then being that of height to base.

There is another point to be thought of, and that is, what effect the weight will have on the plane along which it moves. Two extreme cases may be taken—first, when the plane is horizontal, when it supports the whole weight of the body, and, of course, must be of sufficient strength to do so; and second, when the plane is vertical, and is not pressed at all, it may in fact now be removed without producing any alteration in result, and need have no strength at all. Between these lie the other positions the plane may assume, the pressure on it, with a given weight, varying between the full weight and nothing.

This pressure is most simply considered as acting at right angles to the surface, and may be measured experimentally by the same apparatus as before, if we have another wire loop suspended by a cord over a pulley, the other end of the cord being weighted, so as just to support the roller, and care being taken to have the string from the roller at right angles to the plane. In this way it is found that the relation between pressure and total weight is that between base and length of plane. Thus, as above, when the height is nothing and the plane horizontal, base and length are equal, and so are pressure and weight; while, if the plane is vertical, the base is nothing and the pressure also nothing, whatever the length may be. In our first instance above, where the height is 8 and length 20, the base is $18\frac{1}{3}$; so that the pressure on the plane with a weight of ten would be $\frac{18\frac{1}{3}}{20} \times 10$ or $9\frac{1}{6}$, and if the plane could not bear this, it would break.

To return to the first principles of the inclined plane, we see that to gain great power we must have our plane of small inclination, which means, if we are to raise our weight any height, that it must be of great length. But the practical difficulties of using a straight plane of great length are insuperable, especially if we wish to raise our weight vertically upwards, which necessitates the movement of the plane underneath it. But if we can get our plane curved and not straight, in the fashion of the St Gothard tunnels, we are able to get the whole incline within a very small horizontal area, and so render it very compact.

The Screw. — In so doing, we pass from the simple inclined plane to the modification of it known as the screw. An extremely simple experiment will make this clearer. Cut out in paper an inclined plane of small angle, and after marking the sloping edge for greater clearness with a dark line, wrap this, beginning with the broader end, round a cylinder, such as a ruler or pencil. We have at once the familiar appearance of a screw.

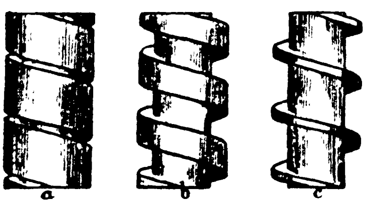


Fig. 47.

In order to render this of practical use, the spiral line thus shown must be made capable of resisting a downward pressure, by making it either recessed into or projecting from the cylinder itself. Whichever method we adopt comes eventually to the same thing, as shown in Fig. 47: *a* shows the line as a groove, *c* as a projection, while in *b* the width of groove and projection are equal, which we may get either from *a* by widening the groove, or from *c* by widening the projection.

A simple groove or projection, however, would give but little support unless the weight be somehow fastened to the cylinder, to prevent falling sideways. This is attained by having a sort of collar entirely round the screw, and with projections or grooves to fit those on the screw. This in very varied forms constitutes the "nut." For the sake of clearness, we may notice that the projecting inclined plane is called the "thread" of the screw. Having thus our screw and nut fitted to each other, and supposing the weight to be raised to be supported on the nut, there are two methods we can use to raise it. We may either turn the nut round the fixed screw, when it will ascend or descend according to the direction of the movement, or we may prevent the nut from turning, while still allowing it to slide up and down, and turn the screw round on its axis. In either case, we must prevent the screw from moving *along* its axis. If the weight is supported on the screw, instead of on the nut, the latter must be prevented from moving along the screw axis, but the relative motions will be the same as before.

To take a few simple instances of the use of a screw, we get the best perhaps in the case of an ordinary wood-screw, fastening a brass plate, for instance, to a door. The screw when turned round makes its own nut in the wood, and travels forward, till its projecting head pulls the metal plate into close contact with the door.

The advantage of a screw is, however, enormously increased by the possibility of using a lever to turn it, the lever, in the case above, consisting of the bulging handle of the screwdriver. Another common example is the "screw jack" used for lifting heavy weights, and carried, in case of accident, on many locomotives. With a lever handle the calculation of the mechanical advantage is very simple, though a great allowance has to be made in practice for the effects of friction. If the distance between two adjoining turns of the thread is half an inch, then for every complete turn of either nut or screw there is an advance of half an inch in the direction of the axis, or in other words, the weight moves through that distance. If now, our lever is 2 feet long, and the power acts at the end of it, to turn the screw once it has to describe a circle 2 feet in radius, or roughly 12 feet in circumference, that is 144 inches. Here the power travels 288 times as far as the weight, and that is the mechanical advantage. Allowing about 50 per cent. to be lost in friction, we still have a very great advantage in the arrangement: a force of 23 lbs. for instance will raise a ton and a half.

The limit of power is, in fact, decided rather by the strength of the materials than in any other way. The use of the lever for turning screws is seen not only in the case of the jack, but in the common case of an ordinary clamp, where the lever takes the shape of an expansion of the screw. The long "spanners" used to tighten the bolts at the junction of rails on a railway is another familiar instance, as also the smaller spanners used for sewing and mowing machines and in adjusting the parts of 'cycles.

This large travel of the lever in proportion to that of the screw can also be used in another way, not to gain power, but as affording an accurate measure of distance. Taking a screw having 10 threads to the inch, and fastening to it a disc 10 inches in circumference, we may divide this latter easily into tenths of an inch, giving 100 parts. If a fixed pointer is used to rest against the disc, the least turn of the latter can be detected. For each complete revolution the screw goes forward $\frac{1}{10}$ of an inch, so that if the disc only turns one division or $\frac{1}{100}$ of a revolution the screw will only move forward $\frac{1}{1000}$ of an inch. Even with these comparatively large divisions the delicacy obtained is great, but the subdivision is capable of being carried much further than this, giving any required degree of accuracy. This principle is carried out in the manufacture of measuring instruments, calipers, &c., but perhaps with most refinement in the micrometer attachments of large telescopes, and to it much of our present astronomical knowledge is due.

In all the above the screw has been supposed to work in a nut, but there is another way of arranging things which has an interesting practical bearing. Instead of the nut the thread engages with the teeth of a cogged wheel, giving us the "worm wheel." In Fig. 48, by turning the screw in the direction of the arrow *a*, the thread will push forward the separate cogs of the wheel in the direction of the arrow *c*, thus raising the weight on the rope round the axle. The bearings *bb* must, of course, be rigidly fixed to prevent endlong motion.

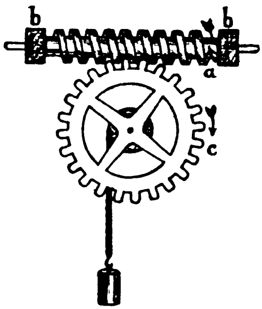


Fig. 48.

Hindley's worm wheel has a worm of greater diameter at the ends, in fact fitting the curve of the wheel, and so enables many teeth to be in gear at the same time, thus lessening risk of a breakdown.

If a grooved wheel with endless chain or cord be fixed on one end of the screw spindle, we have a very handy and powerful hoist. In this case, we get several distinct steps of gain in power, first the leverage of the cord on the groove of the wheel, then the inclined plane of the screw, then the greater leverage of the cog at the circumference as compared with the smaller axle on which the weight acts. A great practical advantage in this hoist is, that owing to the friction of the screw the weight will not run down if let alone.

This friction again, though in some respects a drawback, is also of great practical use in preventing the unfastening of screws in use. In some cases, when a large amount of vibration takes place, the friction is increased by a separate nut, called from its purpose a "lock nut," screwed tightly against the first, so entirely preventing its motion.

A few words ought to be said as to the varieties of thread adapted for various uses. As a general rule, the more yielding the material, the greater projection must be given to the thread, the difference between an ordinary wood screw and one of the same size for metal work being apparent at once. If we have to work in water, we must have still greater projection, as in the screw propellers of ships; but it is not found necessary in this case to have more than part of the complete circle presented to the water. A screw for working in air, as in the possible flying machines or propelled balloons of the future must have still greater projection in proportion, the real working surfaces being, with advantage, as far from the centre as possible. There are many toys on this principle which will illustrate the idea.

Another point worth notice is the different shape given to the screw-threads, according to the work the screw has to do. Here we are practically confined to metal work, as there is not the same necessity for careful design in ordinary wood-work, and the screw-thread is in the main designed as well for cutting its way through the wood, as for holding on when in.

The ordinary metal thread is of a V shape, but in this case, as pressure is put upon it, there is a tendency for the parts of the nut to be pushed outwards in all directions, towards the top of the sloping threads—that is, with the liability of bursting the nut. This action, however, renders it easy to get such a screw to "jam" and so keep its position. In order to do away with the side pressure on the nut, the square thread is used, the only tendency of pressure here being to shear off the thread.

In cases where the pressure is very considerable, a still

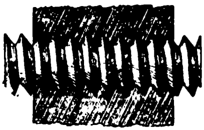


Fig. 49.

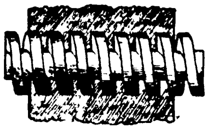


Fig. 50.

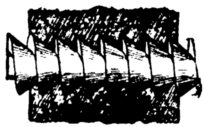


Fig. 51

further improvement is made, in the "buttress" thread, in which, while the bearing face is still square, it is supported by a sloping mass or buttress of metal at the back. This is the form used in the breech screws of some large guns, and is sufficient to make the breech practically as strong as the other solid parts of the gun. It can, of course, only be used with effect where the pressure always comes in one direction. Figs 49, 50 and 51 show the V, square, and buttress threads, the nut in each case being shown cut through to expose the screw. We have thus passed in gradual succession from the wedge of the old Egyptian builders of the Pyramids to the screw breech-piece of the modern 100-ton gun, and, in spite of all the difference in finish, appearance, and power, we find between the two a closer relationship than between the Englishman of to-day and his Saxon and Norman ancestors.

CHAPTER VI.

FRICTION AND WORK.

IN considering the effects of the various simple machines as above, our conclusions have in all cases required qualification. When we attempt to use even the simplest in actual work, we find it impossible to get the full theoretical gain of power or speed; there is in all cases a loss, which in the more complex machines may reach enormous proportions. This loss is due to what we may call, from its effect in diminishing motion, a force, and to this we give the name of Friction. If we examine the subject experimentally, as we may easily do by placing two surfaces in contact, and measuring the force required to move one over the other, several broad facts stand out as the characteristic properties of Friction.

First, we find the friction varying with the character of the surfaces in contact, and increasing as these surfaces are more roughened. Here the roughnesses of one surface interlock more or less with those of the other, and, before motion can take place, these overlapping parts have either to push each other aside, or cause the two bodies to separate sufficiently to allow their summits to glide over one another.

This then gives us an idea of the way in which friction acts, and it is clear that one method of reducing it is to give to all rubbing parts as smooth a surface as possible, or, to use the common expression for this process, to give them a high polish. This is done in fact in all rubbing parts of machinery, though even then a little actual working together increases the polish and so reduces friction, which explains the common experience of difficulties met with in the trial run of a new engine, and disappearing with use. In the highest class of watchwork, the utmost care is taken to not only burnish but polish the pivots and other rubbing parts, to ensure the best results.

Secondly, Friction varies with the pressure exerted between the two surfaces, becoming greater as the pressure is increased. Evidently this is to be expected from our previous results, increase of pressure causing closer interlocking of the surfaces.

We make use of this fact in many ways. In drawing out a nail, the first object of the pincers is to grasp it so firmly that its friction against the jaws of the pincers is greater than that against the wood, and so, if it moves at all, it will leave the wood rather than slip from the pincers. In climbing a rope, we have to grasp it firmly enough to make the friction able to sustain the weight of the body, and if we cannot exert sufficient pressure we shall slip down rather than ascend. In clamping a mincing or sewing machine to a table, the screw simply acts in producing greater pressure, and so greater friction, than the mere weight would do ; and again, in the "tension" screw of a sewing machine, we have a somewhat similar arrangement for increasing the friction of the thread. A vice is another instance of the same use, but in this instance the "jaws" are roughened as a further aid.

There is another way in which friction varies, and that is with the velocity of the moving surfaces. It is a matter of common experience that a body may rest for an indefinite time in a position (on a slope for instance), which it will not keep if once started, the friction while it is at rest being greater than when it is moving; though a further increase of velocity, unless very large, does not make much difference. It is clear that if the surfaces are moving past each other the projections on each will not interlock so deeply as if at rest, and we may explain the effect in this way. A curious practical use of the principle is seen in the manner of applying the brakes of railway trains. To stop the train in the shortest time we must employ the greatest possible amount of friction between the train and the earth, that is, of course, between the wheel and the rail. If the wheel is prevented from turning on its axle, it simply slides along the rail with the speed of the train, but if it can turn, the point in contact with the rail at any instant is at rest, and hence the friction between wheel and rail is greater in the latter case than in the former. It follows that to get the quickest possible stop the pressure applied by the brake blocks should be just not sufficient to "skid" the wheels (prevent them turning). Skidding the wheels is, of course, in any case undesirable from the unequal and destructive wear on both rail and tyre of wheel, the latter being worn flat in places, a circumstance that does not conduce to comfortable travelling.

The next point to be noticed in connection with friction is the influence of amount of surface, or area, in contact. The common idea, it would seem, is that friction can be lessened by lessening the surfaces in contact, and many would point, in confirmation, to the greater ease of motion obtained by reducing the pivots in a clock or watch. But this instance is really one of reducing leverage rather than friction, as explained above, and careful experiments show that, with the same substances in contact, and with the same total pressure acting, the friction is the same whether the bearing surfaces are large or small. The friction would, of course, be smaller if the bearing surface could be reduced without increasing the pressure on that surface; but if the total pressure remains as before, while the surface is halved, the pressure on each square inch must be double what it was before, so equalising matters. It follows that we may without disadvantage, except perhaps of expenditure in oil, make the bearings of machinery of considerable length, and so distribute and equalise wear, instead of having it all concentrated at one spot.

We have now considered general facts common to all kinds of material, but we enter upon quite a fresh field when we speak of the influence of the materials themselves. Here the individual characters of different bodies come into play, and we have to find some way of expressing the intensity of the friction, so as to compare one combination with another.

Co-efficient of Friction.—We find this in the relation between the force of friction and the pressure, the latter being taken as normal to—*i.e.*, at right angles to—the surfaces in contact. The fraction represented by $\frac{\text{Force of Friction}}{\text{Normal Pressure}}$, both forces, of course, being expressed in the same units, is called the "Co-efficient of Friction," and gives us the means of comparing different cases and calculating effects. It can be found experimentally for any two bodies by placing their common surface horizontal and measuring the force required to pull the top one over the other. This force may well be supplied by a weight attached to a string over a pulley; and by then dividing this weight by the weight of the upper body (which is of course, the normal pressure), we have a fraction which is the Co-efficient of Friction in this particular case.

A still simpler method is to raise one end of the lower body till the upper one will just remain supported, but ready to slide if started. If now we measure height, base, and length of the inclined plane formed by the upper surface of the lower body, we see that the force pushing the upper one down the plane is $\frac{\text{height}}{\text{length}} \times$ its weight, and as this is just counteracted by friction, we may say that the force of friction is of the same magnitude, but, of course, opposite in direction. But the pressure on the plane, as before, is equal to $\frac{\text{base}}{\text{length}} \times$ the weight, and if we divide the first by last we have the Co-efficient of Friction as $\frac{\text{height}}{\text{base}}$, so that it can be found here by simple measurement.

The following table gives roughly a few of the ordinary cases of friction, with the co-efficient in each case :—

Steel and Ice	$\frac{1}{69 \cdot 8}$	or	·014.
Hard wood and hard wood .	$\frac{1}{7 \cdot 1}$	or	·14.
Brass and Steel	$\frac{1}{6 \cdot 6}$	or	·15.
Do., with lard . .	$\frac{1}{14 \cdot 3}$	or	·07.
Steel and Steel . . .	$\frac{1}{6 \cdot 8}$	or	.15.
Brass and Brass . . .	$\frac{1}{5 \cdot 7}$	or	·17.
Do., with olive oil .	$\frac{1}{16 \cdot 6}$	or	·06.
Tin and Tin	$\frac{1}{3 \cdot 3}$	or	·30.
Sandstone and sandstone . .	$\frac{1}{2 \cdot 8}$	or	·36.
Cloth and Cloth . . .	$\frac{1}{2 \cdot 3}$	or	·43.

It is clear, however, that all such tables must be approximate only, as so much depends on the state of the surfaces. One or two general conclusions can, however, be drawn. The charm of skating is evidently due to the very small friction experienced, and the unusual sense of freedom so obtained; while we learn the reason for letting the steel pivots of watches and clocks run in brass holes, and for lining the bearings of large iron or steel axles with brass or gun metal, as is done in railway work and other machinery. We also see the great difference made by the introduction between the solid surfaces of a liquid such as oil, or a greasy substance such as lard. These lubricants, as they are styled, play a most important part in the reduction of friction, and the two cases cited illustrate the principles of their action.

Lubrication.—In some cases graphite (black lead) is an excellent lubricating material. In it we have a solid substance of smooth surface, and yet easily reduced to powder, which acts by forming a coating on the surface of the wood or metal, at the same time filling up to a uniform level the hollows originally existing. It is specially valuable for soft substances like wood, and in cases where oil would be liable to collect dust, as on the driving chains of 'cycles.

With oil, however, we act by interposing a film or layer of liquid between the two solid surfaces, the friction then being no longer of solid against solid, but of solid against liquid, the latter being much the smaller. To get the best effect, this film of liquid must be continuous, and on this account different classes of oil must be used in different cases. The greater the pressure the more likely is the oil to be forced out, so that it must then be of a thick, tenacious nature. For this reason, thick, viscid oils are used for heavy machinery, the brilliant yellow grease for railway axles acting as such as it gradually melts and works in. But, for lighter work, sewing machines and clockwork for instance, these thick liquids would introduce too much resistance, and here thinner ones are used, thick oils such as sperm being often thinned down to the required extent with paraffin.

But lubrication, valuable as it is, is only available where the same surfaces are continually in contact; and we want another method for ordinary work, such as carrying goods from one place to another. As long as the load is not great it may be drawn along the ground on a sledge, as is still the practice in some country districts, not to speak of those countries where frozen snow levels inequalities and lessens friction, and where the sledge is the best as well as the simplest conveyance. But on an ordinary road, and with heavy loads, the case is different, and other methods must be employed. Of these the earliest probably is the roller, still used in cases of emergency and for special purposes, on account of its simplicity.

Rollers and Wheels. — If we place two flat surfaces on each other, and test the force of friction experimentally, and then place between them two or three rollers of hard wood, or metal (pieces of brass tubing, for instance), we find the friction is now reduced to a very small quantity, a minute fraction of what it was before. If we take an enlarged roller, to examine it better, we see at once the reason of the lessened friction. There is now no rubbing at all, the roller acts by continually offering fresh points of support as the body moves forward. The difference indeed is the same as between allowing a rope to slide through or over the hands, and moving the hands with the rope, continually passing it on from one to the other. In Fig. 52, if the upper surface is moving in the direction of the arrow, the roller at the moment supports it along the line AB, but a moment later will support it along CD, and so on. It might seem as if there should be no resistance to motion in such a process, nor would there be if the rollers could be made and remain perfectly circular and uniform, and the other surfaces perfectly flat.

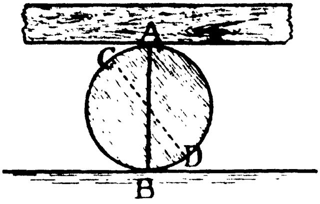


Fig. 52.

But owing to the yielding of even the hardest substances, if we started with perfect cylinders and perfect planes, the pressure of their weight would make depressions in the lower surface, so that the rollers would have a small hill to surmount, so giving some resistance. We have, however, in this rolling friction a great advantage over sliding friction,

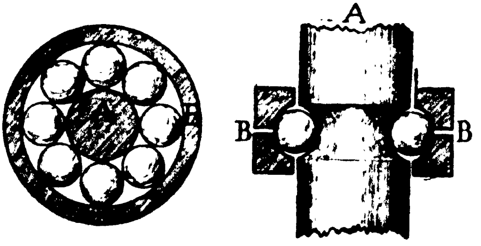


Fig. 53.

though we must, to get the best results, not only have the surfaces as true, but as hard and rigid as possible. If these conditions are fulfilled, and the pressure is not too great, spheres or balls will do as well as cylinders for the rollers. They, are, in fact, so used in the "ball bearings" applied to cycles. The principle is shown in Fig. 53, A being the axle, and B the axle box, hard steel balls just fitting into the space between the two. The distance between A and B is made capable of adjustment, to allow of taking up wear of the balls. A little sliding friction is, however, present, as the points where the balls touch one another are moving always in opposite directions, but this is not of much account.

These bearings are a very ingenious application of the roller, especially as they get over what is really its great disadvantage, that namely, of having continually to shift the rollers as the weight moves, taking them from behind and replacing them in front. The weight, in fact, as a whole, moves faster than the rollers, though it is always in contact with them.

This rather curious result is worth a moment's consideration. The question is sometimes put as a catch whether the top or bottom of a wheel moves faster, and the answer often given is that they move at the same rate. This is true, on the whole, *if* a definite point on the wheel is marked as top, and another as bottom, and *if* the wheel is allowed to make one or more complete turns, though in the process the top and bottom, so called, are continually changing places. If, however, we use the words in their true sense, and by the top of the wheel understand that point which is above the axle for the time being, then the top is always moving faster than any other point in the wheel, and the bottom is for the moment at rest.

This is easily shown, experimentally, by rolling a cardboard disc along the edge of a ruler on a sheet of paper, marking the top and bottom points at any particular moment, and noting the alteration in these when the disc has moved slightly forward. We may, in fact, consider the disc as a lever, with its fulcrum where it touches the ruler, and as the uppermost point is twice as far from this as the centre is, it must move through twice the distance. This is only rigidly true as long as the same point is at the bottom, but as soon as that point leaves the position another one takes it, with the same result as before, hence we may, in this sense, say that the top of a wheel or roller is always moving with twice the velocity of the centre, the velocity being measured in a straight line *along* the path of the wheel.

If we let a flat surface rest continually in contact with the top of the roller, this will move forward twice as fast as the centre, while the centre is necessarily always over the bottom point, so that we may say the upper body will move forward twice as fast as the roller itself. The diagram in Fig. 54 shows the result more clearly. The roller has two diameters marked on it, and the load starts with its end resting on one of these (marked with a full line) vertically over the centre of the roller. As the whole moves forward, this line, which *was* vertical, slopes forward carrying the load forward with it, so that this projects beyond the centre of the roller, and will eventually leave it entirely behind. This, as already noticed, is a serious drawback to the use of rollers for ordinary purposes, and some means of overcoming the difficulty must have been early sought for.

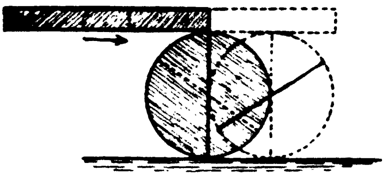


Fig. 54.

By a study of the diagram above, it is easily seen that, in any given distance moved, the excess of forward motion of the load is the same in amount as the length of the our aim must be to reduce this if possible. If we reduce the circumference (or diameter) of the rollers as a whole no advantage is gained, as whether they are large or small the load gains the same amount, that is twice the distance travelled by each roller. But if we retain the large roller in contact with the ground, and, at the same time, put a small one in contact with the load, the case is different, and a much longer distance can be covered without disturbance of the roller. This is effected practically by reducing the diameter of the roller along its central portion, leaving it the shape of a cotton reel, or even further of two wheels connected by an axle, as in Fig. 55.

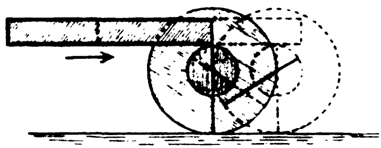


Fig. 55.

This suggests a further development. As the excess of forward motion is now very small, why not attach the roller in this form permanently to the load, still permitting it to turn in a smooth bearing? We do so, and now have the ordinary arrangement of wheel and axle as used on railways, while, if we fix the axle and let the wheels turn separately on it, we have the plan familiar in road vehicles. We have some sliding friction, it is true, but, as explained when speaking of the pulley, it is under specially advantageous conditions, and the gain in convenience of the wheel over the detached roller more than makes up for the small loss.

Uses of Friction.—In all this we have been treating of friction as a disadvantage, and have been considering means of reducing and, as far as possible abolishing it. There is, however, another side to the question, and we find that the advantages of friction far outweigh its disadvantages. In most cases, indeed, we rely entirely on friction to stop the motion of a body, and in many actually increase the friction as much as possible, as in the various brakes used on vehicles. The friction is called into play by the pressure exerted to force the brake block against the wheel, but in some instances it is increased by the application of such a substance as resin, which raises the co-efficient of friction. Resin acts powerfully in this way, which is, of course, the reason it is applied to violin bows, to give them a grip of the strings: without friction to aid him, the most accomplished violinist would find his instrument dumb. Upon friction, too, nails and screws depend for their hold, and dire would be the ruin if it were suddenly to disappear.

And further, while friction is essential for stopping motion, it is also in many cases essential for starting it. In the early days of locomotive engines an insufficient recognition of the fact led to various attempts to work the engine along a cogged rail, but it has long been seen that the friction between wheel and rail is amply sufficient under ordinary circumstances. If the rails should be wet and slippery or the train exceptionally heavy, it may be necessary to temporarily increase it, especially for starting, and then a sprinkling of sand answers the purpose. The driving belts for transmitting power also depend on friction for receiving motion and for passing it on. Without it walking itself would be impossible, as we may realise to some slight extent on a smooth sheet of ice. In fact, if we can imagine ourselves transported to a frictionless world, or friction abolished in our own, we should soon begin to regret its absence. Nails would be driven easily, but would in most cases fly out as the hammer was raised for another blow. Screw would come twisting out of their holes, however many lock nuts we employed. Locomotives as we know them would be impossible, as would bicycles and tricycles. Every table would have to be provided with a ledge all round, or the least touch or even draught would otherwise drive the things upon it on to the floor. A cup with a handle it might be possible to hold, but certainly not a tumbler in the ordinary way. Walking might be possible with spiked shoes, but with our ordinary flat-soled boots it would be necessary to get a start by pushing some fixed body, and when once in motion, we should glide on till brought up by collision with something else, while the descent of a hill would be a terrible experience. Life would lose all balance and be a succession of rude shocks, and we should be glad to pay any price to revert to our present conditions.

Work.—Among the familiar words that carry to different individuals widely different ideas is the word "work." To one man it means violent exercise in the open air or in the glare of a furnace, to another solitary reading or writing in a quiet room, to yet another a ride or walk over grassy down or through forest paths. To some it signifies teaching, to others learning, to others again such various things as watching a child, dusting a room, preparing a meal, tending a machine, guiding a horse.

To all, *work* is real, whatever its kind and however much those with different tasks may depreciate it, and the work just consists in this, that resistance of some sort, mental or material, has to be overcome. To confine ourselves to material work, which alone we are capable of measuring, we find that to overcome this resistance *force* has to be applied, and that the amount of work that can be done depends not on the magnitude of the force only, but on the distance through which it can act. Thus a powerful spring with a short range of action may be far less useful, because able to do less work, than a weaker one of large range. We may, in fact, measure the work done in any case by the product of the force acting and the distance it moves through, or, which is exactly the same thing, by the product of the resistance to motion and the distance moved against it. In other words, if a body is moving either with a force P, or against a resistance P, and moves a distance *d*, the work done is represented by $P \times d$.

It may be as well to notice here that motion is essential to our idea; without motion there can be no work. A column supporting a building may, and does, exert great force in resisting the force of gravity, but though exerting force it is doing no work.

Carrying out this idea, it is evident that measurements of work can be expressed by using a sort of double unit. Taking as the practical unit of force the pound weight, and as the unit of distance the foot, any amount of work may be expressed as either so many pounds raised one foot, or one pound raised so many feet, the action in each case being against gravity, and the work done being described as so many "foot pounds." In this case, the agency raising the body is said to "do the work," while the raised body "has the work done on it." If now, after being raised, it be allowed to fall, it will itself do work, partly on the air, in moving that out of the way, partly on the ground when it strikes it.

We have here brought before us the possibility of giving to a body the power to do work, this power being given through work done on it by something else. This power of doing work is expressed by the word Energy, and we may at once distinguish roughly two kinds of energy, that of position and that of motion. The energy of a raised weight is, of course, that of position, its power of doing work depending on its weight and the height at which it rests. Under the same head, if we follow out the idea carefully, comes the energy of a stretched spring, a bent bow, compressed air, and even of such compounds as gunpowder and nitro-glycerine.

The cannon ball or bullet, on the other hand, possesses energy of motion, by virtue of which it can overcome the resistance of an obstacle, and the same is true of a moving flywheel. But just as we may have a raised weight resting for centuries with its energy of position unused, so we can imagine a body moving for ages without doing any work, simply from its having met with no resistance. In such a case the body will have the same energy at the end of its motion as at the beginning. The earth and other planets are, as far as we can tell, in this condition, as regards their motion round the sun.

In all these cases we have energy stored up, ready for use when wanted, whether the storing is effected by altering a body's position or by enduing it with motion. The practical usefulness of being able thus to store energy is very great. It will be enough to mention one or two examples. In burning coal we use the energy given by the sun to plants in ages past, a fact recognised by George Stephenson when he said that his locomotives were driven by sunbeams. In a flywheel the energy imparted by the piston rod at its most advantageous position is stored up to be given out again at the dead points, so equalising the motion; or we may have a flywheel driven by small power able to do short spells of very heavy work, as in punching and shearing machines. Here the energy is accumulated for two or three revolutions and given out perhaps in a fraction of one, thus doing work that the engine would be unable to do directly.

In a storage battery or accumulator we have a particularly interesting case. Motion, derived either from coal, water, or other source, is converted in a dynamo into current Electricity. The current of electricity makes certain chemical changes in the materials of the storage battery, and these changes are ready to reverse themselves and reform current electricity when allowed. This current when sent through a motor again produces actual motion, and can do work. Of course such a round of changes involves a good deal of waste of available energy, but the convenience of application often more than compensates for the price thus paid for it.

What happens, however, if this energy is used, if the weight is let fall, or the moving body strike another? Work is done in each case, and if all this work be concentrated without loss on another body, we shall have that in the end possessing the whole energy of the first, which will then have none. The energy will be transferred from one to the other, and this transference of energy is a necessary part of the process of doing work. We said "without loss," but it is impossible in practice to so concentrate energy, and an apparent loss is unavoidable. If not, it would at once be possible to drop a ball and see it rise to the same height again, to make clocks wind themselves up, in fact to perform all the wonders so often sought under the head of perpetual motion.

But, though it is true that the energy is not all available, it can all be accounted for; it has only taken another form. A moving body is stopped by the work it does, but besides appearing in this work, some of its energy may take the form of heat, some of light, some of electricity or chemical action or sound. We find, in fact, that any one form of Energy can be transformed more or less directly into any other form, but that we have no power of altering the total amount of energy either towards increase or decrease,—this generalisation being known as the doctrine of the Conservation of Energy. Thus Heat can be transformed into Electrification, Chemical Action, Light, Sound, Motion, while Electrification gives us all the others, and Magnetism. Chemical Action again gives the same wide range, while Motion is easily turned into Heat or Electrification, and through them into the other forms.

This consideration naturally leads to the enquiry whether there may not be one fundamental form of Energy underlying all the others, and from which they spring. This we cannot at present answer, but as we trace back the various manifestations of Energy on our earth to their source, we find this source in the attraction of gravitation, acting partly on the earth itself, but mainly at and from the sun.

Animal life and movement are supported by the assimilation of vegetable matter, and the appropriation of its stored energy. The vegetable in turn was enabled to make this store by the light energy received from the sun, this enabling it to unburn the carbon dioxide in the air. The *light* of the sun is intimately related to, and may be said to be dependent on its *heat*, and this heat is produced by the falling together of the sun's mass and the falling on to it of bodies from outside, the first being probably far most important. This falling in either case is the effect of gravitation, to which we thus trace all our supplies of energy for animal life.

A careful consideration will show, besides the sun's energy, two stores in the earth itself, one being the internal heat, best shown in the earthquake or volcanic eruption, again due to gravitation, as in the sun, the other the double motion of rotation and revolution round the sun given at the Creation. This motion, in connection with gravity, gives us the tides, which are to some extent already used as a source of power, and may be more used as other supplies fail. For it must be evident that though the total of energy in the universe remains, as far as we can tell, the same, the amount in our solar system and in our earth must be decreasing, as the sun gives out far more than it receives. With coal-fields exhausted, and with the sun cooling, and so giving a smaller rainfall and less available water power, the energy of the tidal wave might become of vast importance.

One more point remains to be noticed in connection with work, and that is the introduction of time. We have sometimes to consider not merely the amount of work, but the rate at which it is done, or the amount of work done in a given time. The *power* of an engine or an animal depends on the rate it can work at, and the ordinary English unit is the horse-power, which corresponds to the lifting of 33,000 lbs. one foot every minute, or to 550 feet-lbs. per second. A man is considered to be able to exert about $\frac{1}{10}$ of a horse-power.

CHAPTER VII.

THE CENTRE OF GRAVITY.

AMONG the commonest of ordinary experiences is the necessity of placing a body in a definite position if it is to remain standing, as well as the recognition of different degrees of steadiness in differently shaped bodies. We make our chairs and tables with four legs rather than three, if utility rather than ornament is our object, while, if the body is required to move freely, we get as close as possible to the form of a sphere, as in a billiard ball. We have now to consider the principles underlying these and other facts, and we find them all grouped round one great idea.

In the first place, we have to define a term which we have frequently used in the earlier chapters without explanation. When a body is at rest, under the action of forces, it is said to be "in equilibrium," as well as the forces themselves. When a body is not in equilibrium there is some outstanding force acting on it, which will make it move till, as a rule, it gets into a position of equilibrium.

Why will some bodies stand up and others not, and why again will some stay in any position indifferently, while others will only stay in one or two? The answers to these questions can only be arrived at by experiment, and, fortunately, the experiments are such as can be carried out with the simplest of apparatus. A sheet of paper, a pin or two, and a thread attached to a small weight, with some vertical surface of wood such as a door panel, will give us all we need to investigate the subject. What we want to do, is to begin with the simplest forms and work upwards, and the simplest thing is evidently a thin uniform flat plate, which is the nearest approach we can make to a mere flat surface, and which, for our purpose, will do equally well. Taking then a piece of paper, cut into any shape whatever, we hang it by a pin on the wooden panel. It at once swings round into a definite position, to which it will return if dislodged. Here the weight of the body is pulling it downwards, and the pin is supporting this weight. Now, as the two forces counteract each other, they must act along the same line, which must pass through the pin. The direction of the pull of gravity is shown by hanging a small weight by a thread from the pin, and the weight of the whole surface must act in the same direction. If then we mark the direction of the thread on the paper, we have a permanent record of the line of action of this surface weight when it is hung in this particular manner. Now, alter the position of the pin (Fig. 56), and the paper takes a new position, in which the same relations must hold, but the direction of the plumb-line will now cross the former one. We may do this again, and we then find the third line also crosses the first, and at the same point as the second did, and however often we repeat the experiment the result will be the same, all the lines crossing each other

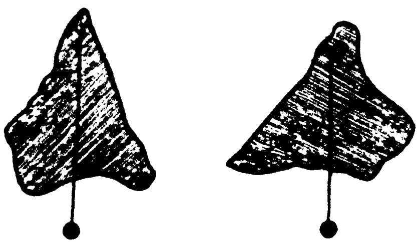


Fig. 56.

at one particular point in the surface. This point, then, evidently has some special relation to the weight of the surface, as it always places itself vertically under the point of support. The body behaves, in fact, as if all its weight were concentrated at this particular point, which is consequently distinguished as the "Centre of Gravity" of the body, or rather in this case, of the *surface* under examination.

In this investigation of the subject we have not only come across the "centre of gravity" itself, but also the simplest method of discovering its position. In some special cases, however, we can find the centre of gravity by simple reasoning, as in regular geometrical figures. We may look on the centre of gravity as the point where acts the resultant of all the weights of separate particles of the body, and, if the surface is of regular shape, the centre of gravity will have a definite position dependent on that shape.

Thus in a triangle, if we draw a line from the middle of any side to the opposite angle, we cut the triangle into two equal halves of equal altitude. Here the centre of gravity of each half must be equally distant from the dividing line, and the triangle will consequently balance about it. It will also balance about the other two lines that can be similarly drawn. The point where these three lines cut one another is such that each of them is divided into two parts, one double the length of the other; the shorter part being the one near the bisected side. The point where the lines meet must evidently be the centre of gravity of the triangle, and we may find it geometrically by bisecting any side of the triangle, drawing a line from the middle point to the opposite angle, and dividing this line into three equal parts. The centre of gravity is at the point in this line one-third of its length measured from the side first halved. Thus, in Fig. 57 ABC is a triangle, BC is halved at D, DA drawn and trisected at E and F, the centre of gravity being at E.

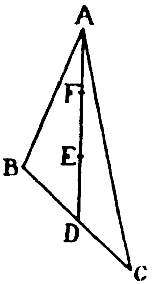


Fig. 57.

In a parallelogram, the centre of gravity is still more simply found, being where the diagonals (lines joining opposite corners) cross each other, or, what is the same thing, at half the length of a diagonal.

In a circle the centre of gravity must be at the centre, as the figure is symmetrical about that point. Supposing, however, we cut out from the circle a smaller circle round the same centre, we have left a simple ring of uniform breadth, which is still symmetrical about the original centre, but is not connected with it. We have here an example of a curious class of cases, in which the body has the centre of gravity outside itself.

Suppose now that we take any of the previous cases, with the exception of this ring form, and let us support the body *at* its centre of gravity, by putting the pin at that point. We now have the whole weight of the body acting at its point of support, and consequently entirely counteracted. Hence the body will now stay in any position, and if set in motion round the pin, will continue turning till stopped by friction and the resistance of the air. Here is a different kind of equilibrium to those already considered; there is not one position of rest alone, but many, in fact an infinite number. This case is known as that of *neutral* equilibrium, the essential condition being that motion of the body does not alter the height of its centre of gravity above the general level of the earth, or, in other words, its distance from the earth's centre. In the more ordinary cases this height does change, the general effect, if the body moves far, being to lower it.

Before entering more fully into this point, however, we can extend our result from mere surfaces to actual solid bodies. All such bodies may be considered as made up of numbers of thin plates or surfaces, and if we know the position of the centre of gravity in each surface, that of the whole body may be found. With rough and irregular bodies, such a method would be far too laborious, but with regular solids, especially those with parallel faces, the case is very simple.

Take an ordinary cube, we may look on it as a number of squares of very small thickness placed side by side. We find the centre of gravity of two opposite sides, and if we imagine a line drawn through the cube from one point to the other, all the separate laminæ will have their centres of gravity on this line, so that the centre of gravity of the whole cube must be somewhere in it too. Further, as these laminæ are all the same size and substance, the whole weight must be equally distributed on each side of the centre of the line, and so, by cutting this in half we find the centre of gravity of the whole cube.

If we wish to find the position experimentally, we might use the same method as for a surface, namely, suspension at two different points, marking the direction of the vertical in the different positions, the centre of gravity being where these intersect. But the method would require modification in practice to avoid boring holes through the body. Perhaps the simplest way is to suspend it at two points instead of one and draw round it a line in the same vertical plane as the two points. If this is done in three different positions, we shall have the outlines of three planes crossing each other, as in Fig. 58, and the centre of gravity will be the point where all three intersect. When suspended, the centre of gravity must hang vertically under the point or line of support.

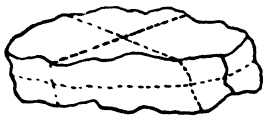


Fig. 58.

We are more familiar, however, with standing than with hanging bodies, and have now to see how these principles apply to this condition. We can conceive a body standing on a single point, with its centre of gravity vertically above this, as a cone balanced on its apex, but such a position would be one of extreme instability, the least movement putting the opposing forces out of the straight line, and so forming a couple which turns the body over. This state of things is shown in Fig. 59, and is said to be that of ,‘unstable equilibrium”; the least disturbance destroys the equilibrium altogether, and there is no tendency to return to the first position. The reason is, that in this case the centre of gravity is in the highest possible position, and any movement must lower it, and the body continues to move till it cannot be lowered further.

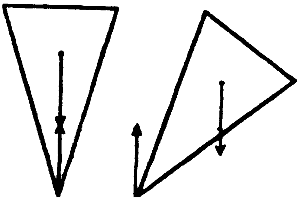


Fig. 59.

If the body is of such shape that motion does not lower the centre of gravity, as in a sphere or ball, a change in position does not necessitate further movement, and we are able to place it in any position we like, if the surface it rests on is level. Here we have the state of “neutral” equilibrium already spoken of. A cone or cylinder resting on its curved surface is in neutral equilibrium as far as force in one direction goes.

If now, instead of supporting the cone on its point or side, we place it on its base (or broad end), the case is different. Here the centre of gravity is indeed raised above the base, but the vertical through it falls a long way inside the line that marks the base out. (In the case of a body supported on points or legs, the base is described by drawing straight lines to connect the various points of support.) The effect now of tilting the cone a little, is evidently to *raise* the centre of gravity, as in Fig. 60, where the dotted lines show the position assumed by the cone as it is tilted, and if released, it will resume its former position. Here we have stable equilibrium, and we may now sum up the characteristics of the three kinds of equilibrium. If we displace a body slightly, and when released it returns to its former position, it is in *stable* equilibrium; if it moves further from it, it is in *unstable;* and if it remains where it is put, in *neutral* equilibrium.

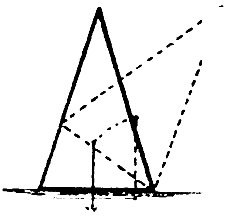


FIG. 60.

As the stability depends on the relative height of the centre of gravity in the different positions, it is evident that in bodies of irregular shape we may have several positions of stable equilibrium of different degrees of stability. Thus we may lay an ordinary brick on its face, side, or end, the stability for each position being different. And further, the direction of the motion makes a difference; it is easier, for instance, when a brick is standing on its edge, to tip it on to its face than on to its end.

We have now to notice the general conditions that make for greater or less stability. The stability must necessarily be increased by lowering the centre of gravity, and lessened by raising it. All know the danger of too high a load on a cart or waggon, a small inclination being then enough to overturn it; and accidents are continually happening from people rising incautiously in a boat, and so causing it to overturn. An instructive experiment illustrating the point is shown in Fig. 61. The lower block stands quite steadily, the line of direction falling with the base, while, if we increase its height by adding another block on the top, it falls.

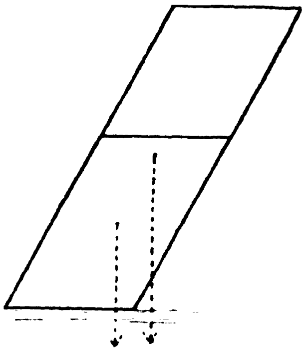


Fig. 61.

The stability must be increased too by widening the base, or lessened by narrowing it, as on the distance of the vertical from the edge of the base depends the arc of the circle

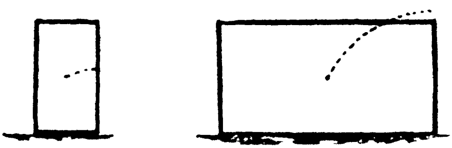


Fig. 62.

that is described by the centre of gravity, from its position of rest, to that of unstable equilibrium, as in Fig. 62. The further the vertical is from the edge, the longer is this arc, and the greater the height to which the centre of gravity must be raised to overturn the body.

In the human body the base is formed by the feet, or rather the line drawn outside and connecting them. In standing, the vertical through the centre of gravity must fall within this base, or we should fall. This base being comparatively narrow and the centre of gravity high, a man with his feet together is easily pushed down; but by separating them the base can be readily widened, and the stability in that direction increased. In sitting the vertical falls between the legs of the chair, the feet being free. To get up again, however, it must be made to fall within the line of the feet, hence either force must be applied to the body, by the hands or otherwise, to place it in the proper position, or the feet must be brought back either under or on each side of the chair, till the base so formed includes the vertical, before rising is possible. If the feet are still and a man leans forward, the lower part of his body must go backward at the same time, or he will fall over.

In the same way, in carrying a load on the back the body must be thrown forward, and backward if the load is in front. A pail in one hand necessitates the bending of the body in the opposite direction, but two equally heavy on opposite sides do not displace the centre of gravity, and the person so loaded can walk upright. These attitudes are assumed unconsciously and instinctively, and the small base is no great disadvantage, but it would be very unadvisable to arrange inanimate structures in the same way. To stand firmly, an ordinary body, such as chair or table, must have at least three points of support, and even with three the stability is very imperfect, unless these three points are widely separated.

There is a certain advantage in three points for some purposes, because each point is necessarily in full contact with the surface it is supported on, and there is no possibility of rocking, such as happens in a thing with four or more legs if these are of unequal length or the surface is uneven. It is for this reason that three supports are used for most scientific instruments, as well as for camera legs, camp-stools, and easels, and for the "shears" used in dock-yards.

But in all these cases the strain comes on a very small area, and the legs can easily be separated sufficiently to keep the centre of gravity well within the base. If, however, the body to be supported is large and the weight unevenly distributed, the case is different. In an ordinary three-legged table for instance, a considerable portion of the top overhangs the base line, and any heavy weight put on this overhanging part will tend to upset the table. Thus Fig. 63 shows a circular table, with feet touching the ground at three points vertically under ABC. The triangle ABC then is the real base on which the table is supported, and any weight outside this tri-angle, as at D, tends to bring the centre of gravity of the whole outside the triangle, and so overturn it. With the square top the danger is still greater. A triangular top would be better, but inconvenient for practical purposes. If we have four legs we have a much more stable arrange-ment, especially if these are put, as usual, almost at the extreme corners of the table.

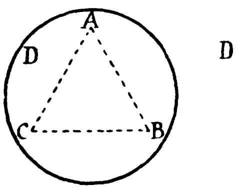


Fig. 63.

In speaking of the effect of width of base, it should be noticed that sloping the base practically narrows it, and so tends to instability. But, besides this, a slope throws the vertical from the centre of gravity nearer the edge of the base, and so further decreases stability, this latter effect being indeed of more consequence than the former. Fig. 64 shows the first effect, the body being able to shift so as to keep the centre of gravity over the centre of the base; it is evident that the distance of the vertical from the ends of the base is less when the base slopes. Fig. 65 shows the second case.

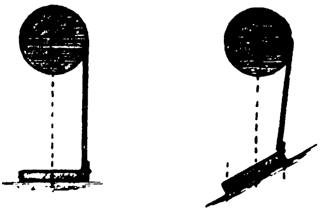


Fig. 64.

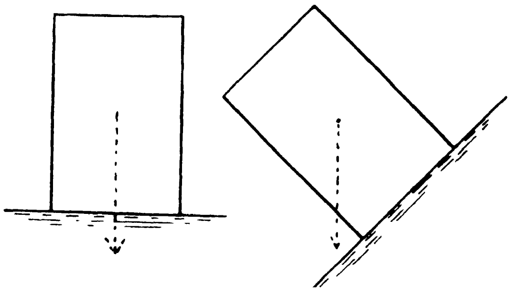


Fig. 65.

An important instance of this is met with in ordinary roads. In order to carry off rain these are made with a "crown," the upper surface being curved, as in Fig. 66 (*a*). The disadvantage of this form, however, is that not only is the centre the flattest, from which part water has the longest journey to the drain, but the steepness increases rapidly towards the sides. A cart with its centre of gravity low may be able to pass in safety along any part of such a road, but if it is at all topheavy, as with a load of hay, or as a coach with many passengers on the top, it may be quite safe in the centre of the road, but overturn if it has to go to one side. The

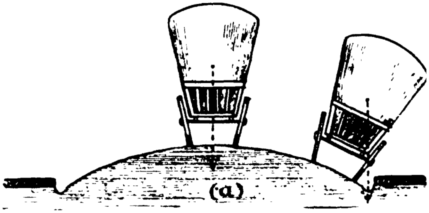


Fig. 66 (*a*).

preferable form, if consistent with solidity, would be two flat surfaces meeting at a small angle at the centre. Such

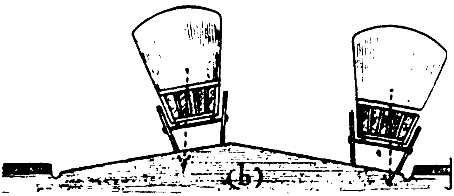


Fig. 66 (*b*).

would give equal drainage facilities and equal safety for vehicles at every point on each side, Fig. 66 (*b*).

There are two cases of apparent contradiction of these principles, which, however, are both dependent on the additional element of motion. The first is that of a weight balanced on the finger, with its centre of gravity above. Here the balancing is actually easier the higher the centre of gravity is, a stick loaded at one end being far more easily kept up when the loaded end is at the top. It is not, however, in any more stable equilibrium, but the higher the centre of gravity the longer the arc it must describe to fall and the flatter the top of this arc. So, with a long arm the downward motion is very slight for a few inches on either side of the vertical, while, with a short arm it is much greater, Fig. 67. The slower motion with the long arm enables the finger to be shifted so as to again bring the point of support under the centre. In the same way, the older bicycles with large wheels are more easily ridden, as far as balancing goes, than the newer lower ones.

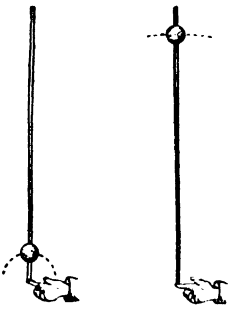


Fig. 67.

We have really in the case mentioned an inverted pendulum, the same law regulating the time of swing in each case. In a pendulum, of course, the centre of gravity is permanently below the point of support, and if it is displaced, it oscillates from side to side of its position of rest. The shorter the pendulum the quicker it vibrates, and, as for small angles the time of each swing depends on the length alone, it is possible to use it as a time-keeper. This discovery was first made by Galileo, and the hanging lamp which gave him the idea is still shown in the Cathedral at Pisa.

Not to speak of its general use in clocks, it is used in the metronome to beat time for music. The main part of the metronome is a sort of double pendulum, the position of whose centre of gravity may be varied by a sliding weight, and which may thus be made to vibrate at different rates. Before the introduction of this instrument, music was sometimes set to definite time by giving the length of pendulum that would swing with the required frequency. In some music of Handel's, set by Dr Crotch, the quaver (♪) varies from "Pendulum 5 inches" in *allegro moderato*, to "Pend. 12 ins." in *largo*, and 18 ins. in *grave* time. The crotchet (♩) in *temp. ordin.* is given as 18 ins., and the minim (𝅗𝅥) *allo breve*, as "pendulum 22 ins."

The other apparent exception to the laws of equilibrium is found in bodies rapidly revolving on an axis. A top, for instance, as long as it spins will stand or move with its centre of gravity far above its point of support, while the gyroscope top will travel along a stretched string or wire, or, if hung by a loop of string, will remain with its axis actually horizontal. Without pretending to go further into this subject, it may be stated that these effects are due to the tendency of rotating bodies to keep their axis of rotation continually in the same direction, and to resist any change of that direction.

CHAPTER VIII.

WATER LEVEL—THE HYDRAULIC PRESS.

HITHERTO the subjects of our experiments have been rigid bodies, resisting any change of shape, otherwise known as *solids*. In water and air we have quite different characteristics, and in consequence a very different mechanical use, so much so, that the mechanics of air and water are often treated of in separate works. But, though the methods of application are different, the principles underlying them are the same as those already discussed, and these agents too may be included in our survey of the mechanics of daily life.

The first great property common to both water and air is the extreme mobility of their particles. The different molecules are capable of moving past each other with great ease, and so readily making way for the passage of a solid body. In consequence of this, both air and water at once take the shape of any vessel into which they are put. But here we come to a difference; while the air occupies every part of the vessel equally, the water only does so to an extent depending on the quantity of water present. All the water keeps to the lower parts of the vessel, and its upper surface is practically flat and horizontal. The surface *must* be level if the particles move freely, as all try to get as low as they can, and there is no reason for any being above the others. On a small scale such a surface is flat simply because the roundness of the earth is inappreciable; but on a large lake or the sea the surface, though still level, becomes a curve, all the particles as before trying to get as near as possible to the centre of the earth. The level is disturbed to some extent in the open sea by waves and currents, and is subject at any particular place to alteration according to the state of the tide, but the general average sea level throughout the world is constant.

Taking now a vessel of water, with this level surface, the level will not be affected by inserting a partition at the surface, or several, whatever their shape may be, as long as the water can get under or through the partition at some point. Carry this to its logical conclusion, and instead of one vessel with a broad partition use two vessels connected together under the water line by a tube. The level must still be the same in both vessels, and whatever shape these are. There is no reason to confine the number to two, one hundred or a thousand may be thus connected and the level will be the same in all. If, however, the tubes connecting them are very small, time must be given to enable the water to get through. If one vessel is large and placed at a higher level than the others, it will fill all these to the same level as itself, and water can be drawn from any of them. Here we have a miniature representation of our modern system of water supply, with one or more central reservoirs on high ground, feeding the various pipes and cisterns of the consumers. If one of these pipes, opening upward, is left open, the water will flow out of it in a jet to a height depending on the height of the reservoir level. It cannot, however, attain the same height in this case, as the friction of the air soon checks it. Fountains are thus supplied, and the hydrants so useful for attacking a fire in absence of a fire engine.

This property is also used in the "water level," which consists of a long tube with glass ends at right angles to the body. This is filled with water, which will rise to the same horizontal level in each limb. If now a sight is taken along the tube, from one surface to the other, the line of sight will be horizontal, and any point seen along it will be at the same level as the two water surfaces. Though very simple in construction and principle the instrument is rather clumsy in use, and it is now generally replaced by the spirit level. In this we have a slightly curved glass tube, fastened with its convex side upward on a wood or metal base and filled with spirit of wine, as being more mobile than water and hence more delicate in its indications. A small bubble of air is allowed to remain, which rises to the highest part of the tube, or, in other words, allows the liquid to exhibit a horizontal surface at that point. If the curve of the tube is very slight, a very slight tilting of one end will cause a movement of the bubble, so that if this is in the proper place, marked out once for all on the tube, the base is known to be level. A telescope with cross threads is often attached to the level, so as to mark more definitely the line of sight. In this way a true or apparent level is obtained, but, the surface of the earth being curved, as already pointed out, allowance must be made for this if a natural or dead level is required, as in making a canal or railway. This allowance is nearly eight inches in a mile.

Capillarity.—Before speaking further of the application of this property of liquids, we have to notice an exception to the rule. In the wicks of lamps, and in the use of blotting paper, we have the liquid rising above the main level, and in the case of the lamp continuing to do so till the whole has been consumed. On examining such bodies as cotton and paper with a microscope, they are seen to be composed of an assemblage of fibres, with small spaces between them, forming what may be considered a number of very small irregularly shaped tubes. It is to these small tubes that the effect is really due, as may be shown by placing one end of a sufficiently small glass tube in a liquid, which will at once rise in it. From the *hair like* nature of the tubes in question the effect is called "capillarity." It depends on the cohesion exerted between the solid and liquid in contact. As long as the surface of the liquid is large most of it is too far from the solid sides of the vessel to be sensibly attracted. But if these sides contract, the attraction has more play and is able to overcome the downward pull of gravity. The smaller the tube the more pronounced the result, as can be well shown by bringing two glass plates together at a small angle, in some coloured water in a plate, when the water will rise highest where the plates touch, and gradually fall to the main level at their opening (Fig. 68). Even with a large vessel the effect is seen at the sides, the liquid there curving upwards above the rest, Fig. 69 (*a*). All this applies, however, only when a liquid wets the surface applied to it; if it does not, there is no attraction, but repulsion; and consequently, as is well seen with mercury in an ordinary barometer tube, the liquid curves downward at its edges instead of upwards, Fig. 69 (*b*).

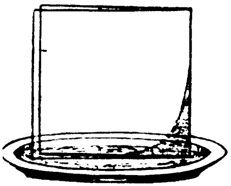
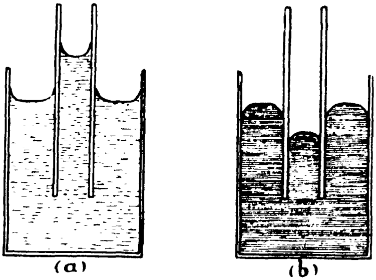


Fig. 68.

Capillarity, however, does not effect the general result found, that water will if possible rest with a level surface, or tends to find its own level.



(a) (b)

Fig. 69.

If now there are two vessels of water communicating by a tube, and a moveable weightless door is put across the tube, this door will not move one way or the other, wherever it may be put. In any position it is in equilibrium, because the liquid itself is so. In other words, each side of the door is exposed to an equal pressure, these equal pressures neutralising each other. This will be the case whatever size the vessels are. But if now one vessel is raised, the equilibrium is disturbed, and the water will tend to flow from that into the lower one, and so give more pressure to that side of the door nearer the raised vessel. The more the vessel is raised the greater does this pressure become, and as the *quantity* of water is not concerned, the height alone is evidently the thing that determines the pressure. And further, it does not at all matter in what direction the pipe lies. It may be vertical and the door horizontal, with the increased pressure acting on its lower side, but in all positions the pressure will be the same as long as the door is at the same respective distances from the liquid surfaces.

In fact, owing to the free motion of the particles over each other, the pressure is communicated equally in all directions upwards, downwards, and sideways. The upward pressure is easily shown by placing against the end of a lamp chimney, a flat piece of metal faced with leather, and plunging this end downwards into a vessel of water. If the plate be held on till well below the water level, so as to keep the water from getting inside the chimney, it may afterwards be released, and will be found still to cling on, owing to the water pressing it upwards against the chimney end. The pressure may be felt indeed in the effort necessary to push the chimney downwards. To show that pressure alone is concerned, the chimney may be slowly filled with water, and as soon as this nearly reaches the top the metal plate will fall off. The water poured in gives the same pressure downwards as the outer water gives upwards, when it reaches the same level, but just before this happens the weight of the metal makes itself felt, and causes its fall.

The experiment may be reversed and the pressures exactly measured by suspending the metal plate from one arm of a delicate balance, as by a wire passing along the inside of the chimney. The chimney itself is firmly grasped in a clamp or stand, and the plate, previously counterpoised, can be pressed against its lower end with any desired force, by putting weights in the other pan of the balance (Fig. 70). If now water be poured in till no more can be added without pushing the plate down, the pressure of the water on the base of the chimney is shown by the weights balancing it. If the chimney is a perfect cylinder, as for an Argand burner, it will be found that when equilibrium is established the *weight* of the water is equal to the pressure. But it is not at all necessary to use a *cylinder*, a vessel either narrowing or widening towards the top can be used, the bottom of course being kept the same size, and in every case the balance will be obtained when the water is at the same height, showing in the clearest way that the pressure on a given surface depends on the *height* of the water column above it, and not on the absolute quantity of water used.

With a cylinder, however, as noticed, the pressure of the water is the same as its weight, so that we have an easy method of calculating the pressure on any surface. For

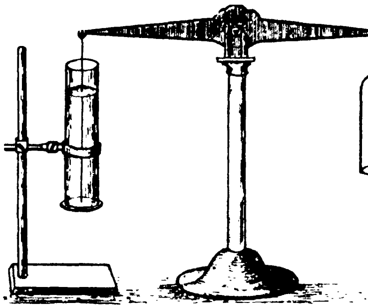


Fig. 70.

the weight of the water depends on the quantity there is of it, and this can be at once found if we know the area of the base and the height of the column. Thus if the base has a surface of 2 sq. ins. and the column of water is 6 ins. high, there are in it 2 × 6, or 12 cubic inches of water. We know by experiment that a cubic foot of water (1728 cubic ins.), weighs 1000 oz. ($62\frac{1}{2}$ lbs.), so that 12 cubic ins. will weigh $\frac{1}{144}$th part of that, or nearly 7 oz. Now, as this is the real pressure on the base for this height, whatever the *shape* of the vessel may be, we can find the pressure on *any* horizontal surface by multiplying together its area and its depth below the surface, and finding the weight of that number of cubic inches of liquid. If the surface is not horizontal we can still apply the same rule if it is flat, only noticing that the *depth* measured must be that of the centre of gravity of the surface, which will give its *average* depth. Owing to the great increase of pressure with increase of depth, the walls of reservoirs and canals have to be much thicker at the bottom than at the top.

The principle can be carried a great way and give rather startling results, as, if we only have a small enough and long enough pipe and a large enough base, we can get almost any pressure on this base by the very least quantity of water. The hydrostatic bellows is an arrangement of this kind. It consists of a bellows the top of which is not hinged to the bottom, but is free to move upward bodily (Fig. 71).

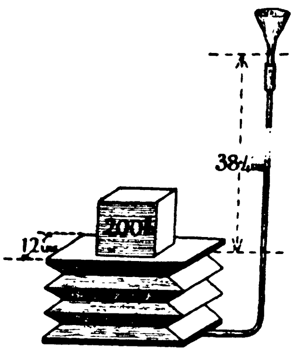


Fig. 71.

Water is introduced by a pipe between the top and bottom boards and presses them apart with considerable force, so raising the upper one, and with it a weight depending on the height of the water in the tube. If the upper board whose pressure we are considering is 12 inches square, then to raise a man 200lbs. (14st. 4lbs.) in weight, the water column need only be 38·4 inches high, even with quite a small pipe. It must not be forgotten though, that to raise him an inch, enough water must be poured in to fill the bellows that amount, and the smaller the pipe the longer time the water will take getting in, so that gain in power will as before mean a corresponding loss in time.

There is another way of looking at this gain in pressure. Imagine the long column in the pipe cut off at the level of the water in the bellows, and the water above this point replaced by a piston fitting the tube, and of such weight as exactly to represent the former pressure due to the water. Then, on comparing the areas of this piston and the top of the bellows, they will be found to be in the same proportion as the weights supported on them, or, what comes to the same thing, the pressure is the same on each unit of area in the same horizontal plane. We may then consider the total pressure on the bellows top as consisting of the pressure in the tube, multiplied as many times as the area of the tube section is contained in the area of the top. If the tube is small its pressure is small too, but the number it has to be multiplied by is correspondingly large, so that whatever its size the total effect is the same, other things of course remaining equal.

Next replace the dead weight, causing the pressure on the piston, by a moving force acting on a lever handle. Exactly the same effect is produced as before, and the bellows may similarly be replaced by a cylinder with moveable piston, with a great gain both of strength and convenience. We have then reduced our hydrostatic bellows to the form of two cylinders, one large and one small, in which work moveable pistons, and any given force applied to the small piston may be multiplied almost indefinitely by increasing the area of the large one. The instrument thus outlined is the well known Hydraulic Press, first suggested by Pascal. Practical difficulties, however, prevented its use; directly pressure was applied the water escaped round the edges of the large piston, however perfect the fit seemed. Bramah overcame the difficulty, and so gave his name to the machine. Instead of attempting to perfect the fit of the piston he allowed it to work loosely, but provided a groove in the cylinder in which is placed a ring of leather, bent into semi-tubular shape (Fig. 72). The more the water tries to get through the space the more closely it presses this collar or cup-leather, against the cylinder on one side and the piston on the other, thus entirely preventing leakage, but allowing free movement backwards when the pressure is removed. To complete the machine valves are used to regulate the flow of water, as more fully described later on under pumps.

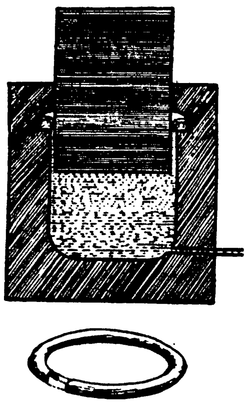


Fig. 72.

From the time of Bramah's invention the applications of hydraulic power have enormously increased, and it would be difficult to give anything like a complete list of them. Hay and cotton are thus compressed for storage or shipping, heavy goods are lifted through great distances, and the loading and movement of heavy guns performed with the greatest ease. Hydraulic machinery is used for pressing the oil from various seeds in the manufacture of linseed, cotton seed, and other oils, as well as for metal working. With comparatively small machines holes are punched through solid metal, and rivets can be worked in the cold, the immense pressure causing the iron to flow into shape far more perfectly than with the older method of hammering while hot. So perfectly is the work done that if such a rivetted joint be cut through along the rivet it is often almost impossible to see where the join is.

One great feature of a modern hydraulic system is an arrangement for saving time by having a store of force always ready. This is effected by attaching to the pump a large cylinder, with a piston very heavily loaded. If this is raised, it will press on the water in the cylinder with the same force that it took to raise it, and if the pump is disconnected for any purpose, this water in this "accumulator" will be able to continue the work. Or, instead of working apart from the pump, the two may work together, and so give increased range and speed to the working piston. In this case, too, if the power is only wanted at intervals, a small engine can be used gradually to fill the accumulator, and so, with that, do work that would require a much larger engine if acting directly.

In speaking of the power of this contrivance we must not forget that this no more creates power than does the lever. Power may be gained, but time is lost to a corresponding extent, as will at once be seen if we take a simple case. If we want to have twice the power we are getting at any time, we must either double the area of the ram or halve that of the pump piston. If we do the former, double the amount of water will be necessary to raise the ram a given height, and if the latter, we must take double the number of strokes, as each only gives half the quantity of water. In either case, the gain in power is balanced by the loss in time.

CHAPTER IX.

SPECIFIC GRAVITY.

WHY does a cork float? The fact is one of our earliest scientific observations; it seems an exception to the general rule. We throw a stone, or drop accidentally a coin or penknife into the water, and they sink, but a cork or piece of wood floats merrily on the roughest sea.

There is a fact, though, intimately connected with our question, that is not so generally noticed. The cork on the water seems to lose its weight, it can actually support a heavy body from sinking, but the point of interest is, that the stone and penknife lose weight too, just as the cork does. Why they sink, and the latter floats, turns out to be a mere question of degree, and by suitable means we can either make iron float or cork sink. In a question of weight we must, of course, turn to the balance as the true test, but the simplest makeshift will show the *fact* to be as stated.

Attach a pound weight by a string to one end of a pencil or penholder, support the pencil by another string half an inch from the same end, and with a small weight sliding along the pencil, steelyard fashion, balance the pound. If now, this pound weight is dipped in water, the long end of the pencil at once falls, showing the pound is not exerting the same pull as before, in other words, it has lost weight. A more accurate steelyard (a boxwood rule with needles run through it for pivots answers very well) will enable us to not only see but measure this loss of weight. It will be found that the larger the body we are experimenting with the larger the *loss** will be, and this suggests the trial of bodies of different material but exactly the same size, cylinders or cubes lending themselves most readily to this condition. Suppose, then, we take cylinders of various materials, all the same size and of the following weights:—cork 1 oz.; pine 2 oz.; glass 12 oz.; iron 29 oz.; lead 45 oz. We hang the cork on the steelyard and balance it in air with the weight at the 1 oz. mark. On putting it into water the balance is entirely upset, and it apparently weighs less than nothing. To find what the upward force on it really is, we have to devise some means of forcing it entirely under water. This may be done by removing the plain suspending hook, and using instead a pan for weights, furnished with a pointed wire at the bottom (Fig. 73), which will pierce the cork, and keep it steadily below the pan when sufficient weight is on this to just overcome the rising of the cork. The new pan must of course be allowed for in the weighing, or still better, be independently counterpoised by a special weight on the steelyard, so as not to alter the direct weight-reading. When things have been thus adjusted, on putting the cork into the water it will be found necessary not only to move the sliding weight from 1 oz. to the zero mark, but to add 3 oz. to the pan above the cork before this latter will sink.

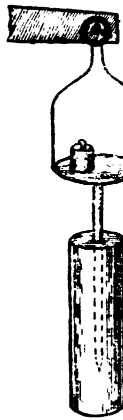


Fig. 73.

* The student must carefully distinguish between the weight of a body, and its *loss of weight* when immersed.

Thus it now weighs 4 oz. less than it did before. If we take the pine cylinder in the same way, we shall have to move the sliding weight from 2 oz. to zero, and add 2 oz. in the pan above the cylinder, again giving a loss of 4 oz. With glass there will be no such difficulty, but instead of weighing 12 oz. as in the air, it will only weigh 8 oz. in the water. The iron will go down from 29 to 25 and the lead from 45 to 41. However the experiments may be varied, and whatever different substances may be used, the same effect will ensue; as long as the size is the same the loss of weight will be the same.

Now, this fact must have some connection with the liquid, as the bodies are of different materials. Each cylinder when immersed takes up the position of a certain quantity of water, the weight of which would have been exactly supported by the upward pressure of the rest of the water. As the cylinder takes the place of this water, it is exposed to the same upward pressure, namely that equal to the weight of that quantity of water, and it is this upward pressure that gives rise to the apparent loss in weight. The loss is the same for the different bodies, because the water displaced is the same, and we have here the secret of the difference in floating power. The actual weights of the bodies are different, as we have seen, and yet the loss of weight, or upward pressure of the water, is the same for all. If, then, this upward pressure is greater than the whole downward pull, or weight of the body, the latter cannot obey the attraction of gravity, but is kept partly above the surface of the water. If, however, the weight is greater than the upward pressure of the water, the body, though losing to that extent in its apparent weight, will fall through the water or sink.

Specific Gravity.—We have, in this way, impressed upon us another important fact, that different bodies have very different weights for any given size or bulk. Matter is, so to speak, more closely packed in some bodies than in others, and as gravity only concerns itself with the quantity of matter present, the weight depends on that, and not at all on size. The word *density* is used to express the quantity of matter in a body, which is said to be more or less dense as it contains more or less matter in the same volume or bulk.

In ordinary conversation the word heavy is often used in the sense of "dense," as, for instance, lead would be described as a heavy metal, or as *heavier* than iron or wood, where the word *denser* would be more correct, the reference to volume being understood. An instructive experiment may be performed by taking two cardboard boxes of somewhat the same shape and appearance, but of very different sizes, and filling the smaller one with shot or sheet lead (such as that used for packing tea), and the larger with paper only, taking care to make them exactly the same weight. On handing the two to any one, the probable exclamation would be that the smaller one was very heavy, and the large one light. This would be the case even if the smaller one were really only about half the weight of the larger, as it is not so much actual weight as density that is referred too. Still, the impression is so strong that, if asked which is really heavier, most people would say the smaller one. If, however, the two are hung by strings so that the hand has the same substance to grasp, the truth is more easily perceived, especially if care is taken not to see which is which.

The experiments with cylinders described above not only show the fact of a difference in density, but also give us an easy method of finding the density of a solid as compared with any particular liquid. For convenience sake, it is necessary to have some standard of density with which all can be compared, and for this purpose water is universally taken; and the density of any body as compared with water —that is, *its weight as compared with the weight of an equal bulk of water*, is called its Specific Gravity.

How then can the specific gravity of a body be found from our previous experiments? Take the cylinder of cork, for instance, weighing in air 1 oz. This in water loses 4 oz. of its weight: it can support itself, and 3 oz. more. That is, its density as referred to water (its specific gravity), is as one to four, because 4 oz. is the weight of water displaced by the cork, and, of course, equal to it in bulk. So that if we call the specific gravity of water 1, that of cork is $1 \div 4$, or $\frac{1}{4}$. So in every case, to get the specific gravity we divide the weight in air by the loss-of-weight in water. Thus, in the case of the lead cylinder, we have a weight in air of 45 oz., and in water of 41 oz., a loss of 4 oz. Hence its specific gravity is $\frac{45}{4}$ or $11\frac{1}{4}$. To put this in another way, 1 cubic inch of lead would weigh as much as $11\frac{1}{4}$ cubic inches of water, and 1 cubic inch of water as much as 4 cubic inches of cork.

As, however, both water and other substances alter in size by differences of temperature, and different bodies to different extents, it is necessary, when great accuracy is required, to always make the observations at one standard temperature, in England, generally 60° or 62° Fahrenheit, though on the Continent, and generally for scientific purposes, 4° Centigrade. This latter is chosen because water is then more dense than at any other temperature.

Many other ways of finding the specific gravity might be mentioned, but all depend on the same great principle of finding the weight of a body, and of the water it displaces. We are now able to give more definite expression to the floating power of a body. We may not only say that if its specific gravity is less than 1 it will float on water, and if more will sink, but that its specific gravity tells us how much of it will float above the surface. The cork, for instance, has a specific gravity of $\frac{1}{4}$—that is, the water equal to it in weight is only one quarter the bulk, so that when $\frac{1}{4}$ of the cork is immersed the two will balance, leaving $\frac{3}{4}$ above the liquid. So with the pine, $\frac{1}{2}$ will be below, and $\frac{1}{2}$ above.

If by any means we can lessen sufficiently the specific gravity of a mass of iron or lead, that too will float. This may be done by forming the material into a hollow vessel, so that the same weight displaces a much larger quantity of water. The general use of iron and steel for ship-building is a common instance, and the ponderous ironclads weighing thousands of tons, and with armour sometimes two or three feet thick, show how far the idea may be carried.

A few words must be said as to the influence of the shape of the body on its position and stability when floating. An ordinary bottle cork will float on its side but not on its end, though it will stand on end easily enough on a solid support. To float at all, its centre of gravity must be supported, and the question resolves itself into how this support is given in a liquid. Suppose a block of wood floating in water as in Fig. 74 (the Fig. for clearness, showing it in section), AB is the water line, the shaded part representing that under water, and C is the centre of gravity of the block, which is here on the water line, the block being supposed to have a specific gravity of $\frac{1}{2}$. The weight of the body acts vertically downwards at

C, as represented by the arrow. To counteract this, we have the upward pressure of the water, acting as if to support a mass of water equal to D, the submerged half. To this end, the upward pressure would have to act at the centre of gravity of the bulk D, and we may represent this centre by W, the arrow showing the direction of the force. If now the block be disturbed so as to occupy the position (*b*), Fig. 74, the centre of gravity of the body is, of course, unaltered, but the water displaced takes a different shape, as D′, the pressure acting upwards at W′, the new centre of gravity of D′. The forces at C and W′ are no longer in the same line, but form a couple tending to turn

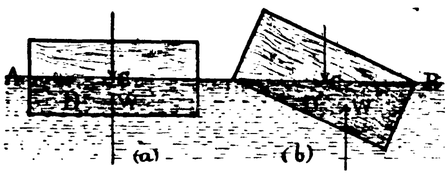


Fig. 74.

the body back into its former position, showing that it was at first in stable equilibrium, though the centre of gravity was above the centre of pressure. Here still, however, stability is increased by lowering the centre of gravity, the arm of the couple being longer the lower this centre is. For this reason, ships, especially sailing ships, have to carry ballast to ensure their safety, unless the cargo can be made to act in that capacity. Careful attention too has to be given to design if a ship has to carry much top weight, as in a battle ship, where the guns must be above water. The ill-fated *Captain* capsized because the weight of her top-hamper prevented her recovery from more than a very moderate roll.

Not only do solids differ from one another in density and floating power, but the same is true of liquids and gases as well. The well-known difference in buoyancy between sea and fresh water is simply due to their different densities. The difference is carried to its extreme in the Dead Sea, where, owing to the quantity of dissolved matter, the density is very high. Those who have braved the half-pickling effect of this water, describe it as enabling a person to sit in it, but quite preventing ordinary swimming.

The specific gravity of liquids is referred to water as before, but a slightly modified method must be followed to find it. Besides weighing a body first in air and then in water, we weigh it also in the liquid given, and note the loss of weight in the two cases. The loss in water is, as already seen, the weight of a volume of water equal in bulk to the solid, and the second loss must be the weight of an equal volume of the given liquid. The two amounts of loss then show the weights of equal volumes of water and the other liquid, and if we divide that in the liquid by that in water, we get its specific gravity. If a body weighed, for instance, 15 oz. in air, 5 oz. in water, and 6 oz. in oil, the loss in the two cases would be 10 and 9 oz. respectively, and the specific gravity of oil to water would be as 9 to 10, or, taking water as 1, would be $\frac{9}{10}$, or ·9.

In this method we use an indirect method of weighing a certain volume of the two liquids, but it is just as easy to weigh them directly, if we take exactly the same measured volume in each case. If a measure is put on one scale of a balance and counterpoised with sand or shot, and first filled with water and the weight of this found, then emptied and filled with the other liquid and the weight of that found, we have at once the relative weights of equal volumes and so the specific gravity. The method may be made as accurate as we please by increasing the accuracy of our measure on the one hand, and of the balance on the other.

In this way we find that liquids as well as solids show great differences in specific gravity, ether being ·72, absolute alcohol ·80, olive oil ·91, sulphuric acid 1·84, and mercury 13·60. That is, a pint of ether would be nearly the same weight as three-quarters of a pint of water, and one pint of mercury rather heavier than thirteen and a half of water.

If two liquids of different specific gravity are put together, as long as they do not affect each other, the one of less specific gravity will float on the other, and as both are free to move, each will assume a level surface. As already noticed, sea water is more dense than fresh, and at the mouths of rivers, where tide does not interfere, the fresh water may often be found flowing on the top of the salt for a considerable distance out to sea. At the mouth of the Amazon it is thus possible to get fresh water from what is apparently the sea, completely out of sight of land.

If the quantity of floating liquid is comparatively small, it spreads out into a very thin film, often so thin as to show iridescent colours. Oil thus floats on water, and it is owing to this power of spreading out that it can be used to quiet the waves round a ship or at the entrance to a harbour. A very moderate quantity of oil suspended in the water in a porous bag that allows it slowly to escape, will cover a large extent of sea with an oily film that seems to lessen the friction between wind and water, and so prevent at all events the breaking waves that do such mischief. Many cases are on record where a ship has been saved in this manner.

The specific gravity of liquids can also be found on another principle, that of the different powers they possess of floating any given body. A ship fully loaded in sea water will sink still deeper on entering a fresh water channel; while, on the other hand, bodies such as nails, marbles, or lead weights, that would sink in water, float easily in mercury. If, then, we take some solid body that is not acted on by the liquids used, we can compare the specific gravity of these by seeing how far it sinks when immersed in each. For the purpose of accurate observation, the body must be comparatively very small where it cuts the surface. Then even a small difference of liquid displacement will correspond to a considerable difference of depth immersed, and the greater this difference of depth, the easier it is to read correctly, or to subdivide if necessary.

The instrument used takes the form of a cylinder with rounded or pointed ends, one end being weighted so as to make it float upright, the other having a long slender projection fastened to it, the whole being so adjusted that when put in the standard liquid it sinks to some convenient point on this stem. If, then, it be put in a denser liquid, the stem will project farther above the surface, or if in a less dense one, not so far. It can evidently be graduated once for all by immersing it in liquids of different densities and marking the points to which it sinks. This is the hydrometer so commonly used for various purposes, the graduations being adapted to the special use for which each is designed.

The lactometer, at one time so much recommended, is a hydrometer of this kind, graduated to show the amount of water above the normal quantity in milk. Unfortunately for its general use, though the average composition of milk is fairly uniform, the amount of water in perfectly pure milk, varies very greatly from time to time, according to the food of the cows and other circumstances, so that it is impossible to tell merely from the lactometer whether the milk has been diluted or not. The instrument, graduated differently, is used for testing the alcoholic strength of wines and spirits, though to make the test accurate it is necessary to distil off the spirit and water from the sugar and other substances, which would affect the result. Alcohol is lighter than water, so that the more of it there is present, the lower the hydrometer will sink.

It should perhaps be noticed here that for these accurate measurements it is more usual to take the specific gravity of water as 1000, so that that of any other substance can be expressed as a whole number without fractions. Thus absolute alcohol on this plan would be 800 (strictly speaking 793), while sea water would be 1026, and mercury 13,598.

Other instruments of the same class, but with different graduations, are used for various scientific and technical purposes; but for certain purposes we can do without any graduations at all, namely when a liquid is wanted continually of some special gravity.

Thus, in making salt provisions, the brine must be of a certain strength, and the housekeeper's simple method of testing it is by putting into it an egg. In pure water, the egg (if good) will sink, but it will float in the brine if sufficiently strong. If fresh water be poured on the brine, the egg will rest where the two meet, not being able to float in the water or sink in the brine. If the two are thoroughly mixed in certain proportions, the egg will stay anywhere it is put, either at top, bottom, or midway. (It is also stated that an egg may be tested for soundness by its specific gravity, sinking in fresh water if good, and floating if bad.)

Instead of using an egg for testing the brine, we might take anything else of the same specific gravity; and if we wish to make a liquid very exactly of a particular strength, we can use three floats, one adjusted so as just to sink, another just to float, and the third to be of the same density as the liquid, and so capable of resting anywhere. Then, if the liquid is too dense, all we have to do is to add water till the heaviest one just sinks, confirming this by testing with the third in various positions.

Instead of allowing the hydrometer to sink to various depths, we may have only one fixed mark on the stem, and make it always sink to that point. To this end the top of the stem is provided with a pan on which small weights may be placed, the instrument being so made that in water some weight is always required to sink it properly. Fahrenheit's and Nicholson's hydrometers are made in this way, but they are not so convenient in application as the other kind, and are seldom used in practice.

CHAPTER X

THE BAROMETER AND AIR-PUMP.

THE characteristic properties of liquids which we have examined group themselves under two heads—the tendency to rest with a level surface, and the power of transmitting pressure equally in all directions. Both may be said to depend on the free movement of the particles over and past one another, and yet by an extension of this freedom the first may be so modified as practically to disappear. In liquids the particles are nearly free, but not quite; there is still a balance of cohesive force which gives the rounded form to a drop, though it is so small as hardly to be noticed. But in the case of air, which may be taken as an example of the great family of gases, cohesion disappears entirely, its place being taken by a repulsive force tending to push the particles from each other, and with the exception of collisions from time to time with each other and the walls of the containing vessel, these particles may be said to be entirely free. This freedom prevents the formation of a surface like that of a liquid, the repulsive force carrying the gas against the force of gravity equally into every part of the space.

This must not be understood as meaning that gas is not affected by gravity, or has no weight, quite the contrary is the fact; but, in any small space the difference between the force of gravity at top and bottom is inappreciable as compared with the mutual repulsion. If our vessel could be made of sufficient size, reaching up, say, five or ten miles into the air, there would be a distinct difference in the quantity of air at top and bottom, but with vessels of any ordinary size there is practically none. The bulk and form of a gas are in no way characteristic of it, they depend simply on the vessel it is contained in.

In spite, however, of this apparent indifference to gravity, it is easy to show that air, or any other gas, does possess weight. For a long time the contrary was believed, and an experiment was cited as proving the point. A bladder was weighed, first empty, and then again when filled with air, and as no difference in weight was found, it was concluded that the air inside weighed nothing. The fact was overlooked that the experiment was performed at the bottom of the air-ocean in which we live, and that as the bladder was filled with air, it occupied a larger bulk, and so had greater displacement and greater upward pressure acting on it, just as in the case of a liquid. This increase of upward pressure, in fact, exactly balanced the increase of weight, so that the bladder apparently weighed no more than before.

To render the experiment conclusive it was necessary to have a vessel of constant displacement, that is of constant size, instead of the yielding bladder. A glass flask fitted with a tap answers the conditions, but the question then arises, how it is to be emptied. Two very simple methods are available to partially empty it, sufficiently that is to show the fact that the air has weight though not to measure the weight itself. One is to *suck* air out, using the lungs as an air-pump, the other to heat the flask as strongly as possible. The heat expands the air, and if the tap is open forces some of it out; if the tap is then closed and the flask allowed to cool, it contains less air than before. If a fairly large flask be first carefully counterpoised on a delicate balance, and then partially emptied in either of these ways, it will, when weighed again be distinctly lighter than before, showing that even in small quantities air has a sensible weight. Further confirmation may be given by adjusting the balance and then opening the tap on the flask. Air will be heard to rush in, and the weight previously lost will be exactly restored.

If the experimenter has the use of an air-pump, the air can be removed much more completely and the effect rendered more evident. In fact, in that way an actual measure of the weight of a given quantity of air can be made.

Air Pressure.—Now, as the air has weight, it must exert pressure on bodies exposed to it, and as it is a fluid, its particles being able to move perfectly freely over one another, this pressure, as in the case of water, must be exerted equally in all directions. It may be said that if this were so, bodies ought to lose weight in air just as they do in water, according to their bulk. As a matter of fact this is really the case, though owing to the small density of air it is not apparent to casual observation, and as bodies are always weighed in air, it is of no special practical account. Still, if we wish to find accurately the weight of a body, we have to allow for the air pressure, or make the weighings in a *vacuum*, a space as nearly as possible void of air.

The fact of the upward pressure of the air helping to support bodies can be well shown by the little piece of apparatus in Fig. 75. The two balls are of the same weight in air but of different sizes, one, for instance of cork, and the other of lead. On putting this into a glass vessel and withdrawing the air, the larger ball is seen to fall; showing that it is really heavier than the small one, but in air appears equal to it, because displacing more air and so buoyed upwards with greater force.

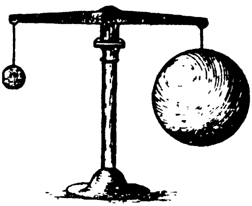


Fig. 75.

That the actual pressure of the air on any body is very considerable may be shown in several ways. If a metal or glass cylinder have one end closed by a piece of bladder, or thin india-rubber or gutta-percha, and the other end connected air-tight with an air-pump and the air exhausted, the bladder is pressed downwards as the exhaustion proceeds. If the cylinder is a wide one, so as to offer a large surface to the pressure, the bladder will even be broken, while the rubber, more elastic, will line the cylinder, returning to its former position when the air is again admitted underneath it. To show that the pressure is not only downwards but in all directions, the cylinder might be made to lie horizontally or upside down, with exactly the same effect.

Another experiment of like nature is that of the Magdeburg hemispheres, so called from the place of their invention and first exhibition. Two closely fitting hemispheres of metal are furnished with a tap, so that the air may be pumped out, and the globe disconnected from the pump without again admitting any. They are furnished with handles by which a pull can be exerted to separate them. The force required to do so depends on the size of the hemispheres, or rather on the area of the section where they join, and with large ones is very great.

Otto von Guericke, the burgomaster of Magdeburg, who invented and first exhibited them in 1654, used a pair a foot in diameter, which six of the Emperor's horses tried in vain to pull apart.

If an air-pump is not available, we may show the pressure by taking a thin tin vessel of some size, furnished with a nozzle in which a cork can be put to close the whole air-tight, a sort of large tin bottle, in fact, but for this purpose of thinner metal than those ordinarily used. Some water is put in this, and boiled till all the air has been driven out, and the vessel is filled with steam. The cork is now put in, and the tin cooled, preferably quickly under a tap. As the steam condenses, a partial vacuum is formed inside, and the sides are crushed in in all directions.

Still further proof is at hand, and one that not only shows the fact of the pressure, but enables us to measure it. Galileo was appealed to by some pump makers at Florence for the reason their pumps would not act, and he found that they were situated at too great a height above the water, and that, however good the pump might be it would not suck water from a greater depth than about 32 feet. His pupil Torricelli carried the matter further, and showed the reason of this limit. He pointed out that 32 feet of water could be sustained because a column of that length balanced the pressure of the air on its base. As further illustrating the principle, he tried mercury, which being thirteen and a half (rather 13·6) times denser than water, should only be supported to a proportionately smaller height. Experiment showed this to be the case, and confirmed his conclusions, the mercury standing at a height of 29 inches when the water was at 32 feet.*

* The height of the water column, calculated from the relative

To perfectly exclude the air Torricelli took a glass tube, about three feet long, closed at one end, and entirely filled with mercury, and inverted this in a cistern of the same metal. The mercury then sank in the tube till the top of the column was 29 ins. above the level of that in the cistern, and there remained. The effect was evidently due to the pressure of the air, as the length of the tube made no difference, and again, if it was sloped, the mercury rose along it till the *vertical* height of the top above the cistern was the same as before.

Another proof came later, when, at the suggestion of Pascal, the experiment was repeated at the summit of the Puy de Dôme, one of the mountains of Auvergne. Pascal reasoned that if the mercury were sustained by the pressure of the air, this pressure, and consequently the height of the column, should grow less the greater the elevation at which it was placed. At the top of the mountain, as was expected, the mercury was found to rest some 3 inches lower than at its base.

Torricelli's discovery was thus confirmed, and the instrument has come down to us with the significant name of Barometer (weight- or pressure-measurer), because it really shows the pressure of the air. We can measure this pressure, not only in inches of mercury but in pounds, if the tube be uniform in size throughout, by weighing the quantity of mercury in the column, and measuring its cross section. Thus, if the tube is one square inch in section, and the column 30 ins. high, it would contain 30 cubic inches of mercury, which would weigh $14\frac{3}{4}$ lbs. This, then,

specific gravities, would be nearer 33 feet; the difference is due to the fact that water gives off vapour at ordinary temperatures, which partially destroys the vacuum and depresses the column of liquid.

would be the pressure on each square inch of surface, though for the sake of using round numbers the air pressure is usually spoken of as 15 lbs. per square inch.

This pressure gives a very large total amount when the surface is large; taking the average surface of a man's body as 2000 square inches, the total pressure on it is 30,000 lbs., or about 13 tons. That we are unconscious of this pressure is due to the fact that all the hollow parts of the body are filled with air under the same pressure as the atmosphere, so that equilibrium is maintained between the inner and outer pressures. But this equilibrium takes some little time to adjust itself, and hence, if a man be quickly brought into air under greater pressure, as in a diving bell, or into a region of less pressure, as in a balloon ascent, inconvenience, sometimes amounting to acute pain, is experienced, till time has allowed the adjustment to take place.

If the outside pressure be removed locally from any part of the body, the internal pressure shows itself by raising the flesh and skin, and eventually forcing the blood through the pores. This method, known as cupping, was much used in the old days when "bleeding" was the universal remedy. A partial vacuum was made by burning some spirits of wine in a small glass cup, and when the air had been displaced by the hot vapour, placing the cup on the part, and letting the vapour cool and condense.

Barometric Changes.—One of the first facts noticed after the discovery of the barometer was, that its height was not constant, but subject to continual changes, and further, that these changes were in some way connected with the state of the weather.

To follow these it was necessary to find some method of quickly and accurately reading the height at various times.

Apparently the most simple way is to have a scale by the side of the tube, and notice the height by that, but two objections occur—firstly, that the variation is not large and wants careful reading, and secondly, that as the liquid falls in the tube it rises in the cistern, and *vice versâ*, so that the apparent fall or rise, looking only at the tube, is less than the real one, which must take into account both levels, and not one only. If, instead of having a cistern in the ordinary sense, the tube is bent round, so that it is of a U shape, with arms of unequal lengths, the rise in one will be equal to the fall in the other and then the movement at one end will have to be doubled to give the true amount. Evidently, in this case, the delicacy of the instrument is correspondingly reduced, and to make up for this, a magnifying device must be adopted.

In the common "wheel" barometer, at one time almost universally adopted for private use, this magnification is effected by having in the shorter leg of the tube a small glass or iron float connected with another similar but lighter float, by a string passing over a grooved wheel. On the axis of this wheel is a hand, moving over a dial face, and pointing to the weather that may (but generally does not) follow its indications. Fig. 76 shows the arrangement, with the dial removed, but the hand on. The counterpoise of the float is steadied by sliding in a short open piece of glass tube. This form, however, is very rough in its indications, and where accuracy is wanted, another arrangement is used. Probably the best method is to have a cistern with a moveable bottom, by means of which the level in the cistern can be adjusted to a uniform height, and the height can then

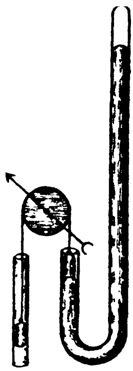


Fig. 76.

be always measured by a fixed scale, starting from this fixed level, and using a device called a vernier for accurate reading.

But another very simple plan is to take a liquid lighter than mercury, so as to get a longer column, though this of course interferes with portability. Thus water has been used, the indications then being thirteen times as great as usual, and the column being 34 ft. high when the ordinary barometer is at 30 inches. Perhaps a better liquid to use is glycerine; the height is more manageable, only about 16 ft., and the movements large enough for any purpose.

Many other arrangements have been proposed and used, which this is not the place to discuss. We must notice, though, that the mere height of the barometer by itself shows nothing, it is the variation of height with which we are concerned if we wish to forecast the weather, and each locality must be considered by itself. The general connection seems to be somewhat thus. If the barometer falls, it evidences a state of lower pressure than before, and air will rush in from the areas of higher pressure to equalise matters, thus giving wind; the direction of this and the consequent weather depending on the relative position of the high and low pressure areas. Again, the lower the pressure the less dense the air is, and the less its power of holding water, either as rain or snow, in suspension.

In the Aneroid barometer the place of the mercury is taken by a metallic box, one side of which is flexible. To the centre of this side is attached a system of levers to magnify its motion. As the pressure increases, this flexible side is pushed inwards, springing out again as the pressure lessens. The great advantages of this form are the delicacy and portability obtained, but the indications must be checked from time to time by a standard mercury barometer.

As already mentioned, the pressure becomes less as we ascend into the air, and so the barometer can be used to give the height of a mountain. The small pocket aneroids now common are frequently fitted with an altitude scale for this purpose. But here we come on one great difference between air and water. In water, as we ascend from the bottom to the surface of the ocean, the decrease of pressure is regular, each mile of ascent giving practically the same lessening of pressure, within a very small amount. But in the air the first mile gives a greater decrease than the second, and the second than the third, and so on.

Further, if we take a pint of water at a depth of 3 miles, and another at the surface, and weigh the two, we find the two weights almost exactly the same, but a pint of air from the sea level would be heavier than one taken at the top of Mount Blanc in the proportion of 20 to 11, or nearly twice as much, the barometer at the top of Mount Blanc (nearly 3 miles above sea level) reading about 16½ inches. The reason of both facts is that air alters in volume under alteration of pressure, while water hardly does so at all. The relation of volume to pressure is very simple, and is the same within very small limits for all gases. It is that the volume varies inversely with the pressure—that is, that if the pressure is doubled or trebled, the volume is reduced to a half or a third respectively of its original amount. Hence, as the greatest pressure is at the lowest part of the atmosphere, the air there is densest; while, in ascending, it becomes continually less and less dense, so that in the upper parts many miles would have to be travelled to make a sensible difference in the height of the barometer. From various observations on shooting stars, which are rendered luminous by friction against our atmosphere, it has been calculated that this must extend, though in an extremely attenuated condition, to the height of 150 or 200 miles. This is the length of the column of air which is balanced by 30 inches of mercury, but the greater part of the weight is below; in fact, at a height of $3\frac{1}{2}$ miles, the barometer stands at about 15 in., so that even at that elevation half the total weight has been passed. Probably beyond 30 or 40 miles from the surface, the atmosphere would be so rare as to be almost inappreciable to us. Even at comparatively moderate heights breathing is difficult, on account of the rarity of the air, each inspiration taking in a much smaller amount of oxygen than at the sea level, though the volume is the same.

Elasticity of Air—The Air-Pump.—This alteration of volume under differences of pressure is the great characteristic of all gases. We may associate it with the mutual repulsion of their particles, and notice that to overcome this repulsion force has to be applied, and the greater the force is the nearer the particles are brought to each other. It is due to this property that we can use an air-pump; as we pump we continally remove air from one spot, and the other air in communication with that spot expands into it and is itself withdrawn. But, at the same time, it puts a limit on the exhaustion it is possible to reach, because after a time the air left in the receiver is so rarified that it can no longer lift the valves of the pump, and action then ceases. Besides the possibility of thus making air expand to a larger volume, we can also make it take a smaller one. We have only to reverse our air-pump, so that it draws from the air and forces into a receiver, and we obtain the air-compressing pump. The amount of air got into any given reservoir can be increased to any extent within the limits of strength of the pump and the reservoir, noticing that the more it is condensed, the more pressure has to be employed, and the more pressure it exerts in turn to rupture the vessel. This property was early turned to practical account in the air-gun, in which a reservoir of compressed air takes the place of the gunpowder in an ordinary gun. When the trigger is pulled, a certain quantity of this air is allowed to escape into the barrel behind the bullet, which it drives out with sufficient force to penetrate some inches of wood. The air itself in this state acts almost like a solid body, and if such a gun be discharged without a bullet against a sheet of paper, held a little way in front of the muzzle, the paper will be pierced as if by a stone. The air-gun has now practically fallen into disuse, but compressed air is very largely employed in more pacific ways, such as driving detached machines at a distance from a central engine, the air being conveyed by pipes to the spot where the power is wanted. Such a plan is specially adapted for working rock drills and such like machines in tunnels and mines, because not only is it a convenient way of supplying power, but the waste air continually liberated is a valuable aid to the ventilation. And further, in expanding and doing work, the air becomes cooled, and so helps to reduce the temperature, another important point. The principle has been very largely used of late years, in making the long tunnels so much talked of. It has also been proposed to supply air compressed in reservoirs for driving tram-cars and omnibuses, but the idea has not found much favour in practice. In some places compressed air is supplied to private houses or workshops, by pipes from a central station, to drive small machinery, and in Paris a number of public clocks are worked synchronously by this means.

An interesting natural application of the compressibility of air is seen in the swimming bladder of many fishes. This is an air bladder which can be contracted or expanded at the will of the fish. As it expands, the fish displaces more water, and becomes relatively lighter; while, if wishing to descend in the water, it contracts the bladder and so becomes relatively heavier. If the air be removed from the surface of the water, the reduction of pressure is too great to be counteracted by the muscles of the fish, the bladder is abnormally distended, and the fish is forced to float at the surface. The little toys sometimes met with, of a glass cylinder containing small hollow figures, which ascend or descend in the water at will, are on the same principle. The top of the cylinder is covered with a sheet of bladder or india-rubber, by depressing which, greater pressure can be produced in the cylinder. The greater pressure forces the air in the figures into a smaller space, so lessening their displacement, and they descend, ascending again as the outside pressure is removed.

All these results follow from the different volumes that a given quantity of air can assume under different circumstances, but hitherto pressure alone has been considered as producing the alteration. Another cause, however, must be considered, that of heat. If a gas is heated, it expands very considerably while the pressure remains the same, and in this way becomes less dense than at first. But in gases as in liquids, the less dense matter will tend to rise through the more dense, and heated air will therefore rise through cold. We are constantly reminded of the fact in the draught of our chimneys and lamps, and the way in which hot air collects at the top of a room. But a more striking application of the principle is seen in the construction of balloons.

The first public exhibition of a balloon was made by the brothers Montgolfier, paper manufacturers at Annonay, near Lyons, in June 1783. Their balloon was of paper, of spherical shape, with an opening at the bottom, under which was hung a basket of combustibles, by the burning of which the air inside the balloon was heated sufficiently to raise it. The first ascent made by man was on the 21st November in the same year, when the Marquis d'Arlandes and M. Pilâtre de Rozier ascended about 3000 feet, and passed over Paris. They were able to regulate their altitude by controlling the fire. From that time the "fire-balloon" has been a popular favourite, the ease with which it can be made and inflated commending it to the public. It must be confessed, however, that it is now a toy and nothing more, mostly to be seen at summer entertainments and school festivals. As an adjunct to a firework display it forms a very imposing feature, carrying a magnesium light or other devices to a commanding elevation.

But as soon as it was proved possible to thus make a body rise in the air, it was seen that heated air might advantageously be replaced. Its ascending force is not very great, unless the temperature be very high, which is prevented by the nature of the materials of the balloon, while the large surface necessarily exposed quickly reduces what heat there is at first. There are, though, gases lighter than air, just as there are liquids lighter than water, and the use of these naturally suggested itself. Of all these, hydrogen is the lightest, and in the same year as the Montgolfiers' experiment, M. Charles, a French Professor of Physics, ascended in a balloon inflated with it, and ascents soon became common. As soon as coal-gas was introduced, that took the place of hydrogen, because of the ease of obtaining it, though it is about eight times as dense. This density, however, is to a certain extent an advantage, as hydrogen, from its lightness, very quickly diffuses through the sides and neck of the balloon and escapes, while coal-gas does so much more slowly.

In consequence of this lightness of coal-gas relatively to air, it tends, if escaping, to collect at the top of a room, and there may be sufficient there to cause a serious explosion if lighted, while, at the lower levels only a slight smell is noticed, and the danger not suspected. In the same way, in dealing with an escape of gas so serious as to threaten suffocation, it may be possible to breathe comfortably close to the floor, while a person on a bed might be in danger of death.

The well-known maxim of keeping close to the floor in the case of fire depends on the same fact, only that here the dangerous gases are the products of combustion, and rise because they are heated, and not from any inherent difference of density.

The chief one, in fact, carbonic acid gas (carbon dioxide), is considerably denser than air at the same temperature, and is a good instance of a gas that will sink in air. It will, indeed, to some extent, and for a short time, give more or less the effects of a liquid, assuming an almost level surface, and being capable of being poured from one vessel to another. Its properties in this way are very striking, and, at the same time, very easily shown. It is enough to put some crystals of ordinary washing soda in a jug, and pour over them some strong vinegar, or some weak sulphuric or hydrochloric acid, at the same time loosely covering the mouth of the jug with a card. In a short time the jug will be filled with the heavy gas, which can be carefully poured off from the liquid and examined. The gas extinguishes flame, and the jug can easily be tested to see whether it is full, by lowering into it a lighted match or taper, which is extinguished the moment it gets below the level of the gas. If a lighted candle be put at the bottom of a glass jar, the gas from the jug can be poured over it, and the flame will be extinguished.

This carbonic acid gas is formed in many natural processes, such as fermentation and burning, and exists also in large quantities in the earth, especially in coal seams, being one of the gases given off in the gradual conversion of wood into coal. Hence, in disused mine workings and wells, especially in coal districts, this gas is apt to collect in large quantities, so that until its removal life is impossible. In brewers' fermenting vats, when the beer has been drawn off, this gas remains, and many lives have been lost by men descending into the vats too soon. In this case, the remedy is simply to leave all the taps from the vat open for some time after the beer has run off, to allow the carbonic acid to do so too. In a well or pit, another way must be tried. One is the curious one of either pumping it out with a good pump or ventilating fan, or of repeatedly filling buckets at the bottom of the shaft with the gas, and emptying them out at the top, though nothing can be seen to flow out. The experiment can be repeated on a small scale, by filling a jug with the gas, and removing it gradually by a small ladle. The level at which a candle is extinguished will be found to get lower, as the gas is ladled out, till at length the whole is clear. Another method, sometimes adopted, is to heat the gas sufficiently to make it rise of itself. As a small flame is at once extinguished by it, a mass of flaming material, such as straw or shavings, must be used, or something that contains its own oxygen for burning, as gunpowder or fireworks of some kind. The heat, and commotion of the air so produced, soon sweeps out the gas.

CHAPTER XI.

THE PUMP AND THE SIPHON.

FROM the very earliest times of man's history the supply of water has been of supreme importance. As long as rivers were available they served all purposes, but in journeying from them other sources had to be sought. It must soon have been discovered that water was often to be obtained at a moderate depth below the surface, and wells were sunk, the water being reached either by making steps down to it, or by letting down the pitchers by a cord. Our modern bucket is the descendant of the pitcher as so used.

But whether with pitcher or bucket, such a method of raising

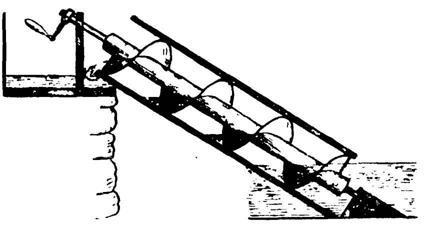


Fig. 77.

water from any depth is slow and laborious, and attempts must soon have been made to improve it. The ancient Egyptians and Persians contrived wheels to be turned by the current of a river, which, as they turned, raised water in buckets on their rim, and discharged it into a trough at the side, so getting a continuous supply, mostly for irrigation purposes. Later on, Archimedes invented the spiral or screw known by his name, and shown in Fig. 77. This may be either a tube wound round a cylinder, or, as in the figure, a spiral blade working inside a tube. As the screw is revolved the water in the lower coils flows by gravity into the higher ones, and gradually reaches the top. To work in this way, the rotation may be quite slow, but the inclination of the axis must not be too great; but, by increasing the velocity, it is possible to force the water up by its inertia, even with a vertical axis, if the height be not too great, and the angle of the screw threads is suitable.

After being in use for thousands of years with prac-

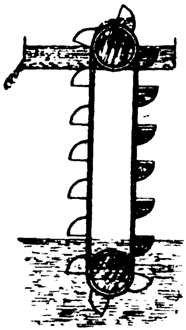


Fig. 78.

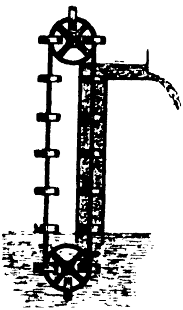


Fig. 79.

tically no alteration, the Persian wheel already mentioned, with buckets on its rim, received a new development. The rigid wheel, which, to be available for any distance, had to be of large diameter, was replaced by two smaller ones, at the top and bottom respectively of the lift (though the bottom one is not really necessary), over which passes a flexible chain carrying buckets, motion being imparted to the whole by means of the upper wheel (Fig. 78). We have here one variety of the chain-pump, which can evidently raise water to any height, depending on the length of the chain. The dredging machines for deepening harbours and river beds are simply very large machines of this kind, fitted to deal with mud instead of water only. But this capacity for dealing with mud and slush is the point that gives chain-pumps their special advantage; they can be used where ordinary valve-pumps could not.

It is, however, more usual in a chain-pump to replace the buckets by flat plates working in a tube, as in Fig. 79. Centrifugal pumps are also used in many cases, the water being taken in at the centre of a hollow wheel, with spokes of curved plates, and thrown out at the rim into a casing enclosing the wheel, from which it is delivered by a pipe as required.

In all these cases the water is lifted or driven upwards to a height depending solely on the size and power of the machine. But in one of the most important machines for raising water, the common pump, there is another limit, entirely independent of the machine. The great difference between the construction of a pump and of the machines hitherto described is in the use of what are called valves. These valves are simply small doors, in different forms, which are capable of opening one way only, and so keeping the flow of liquid or air through them constantly in one direction. Fig. 80 shows the plan of an ordinary pump, with its valves in three different positions, to illustrate its mode of action. It consists of a cylinder or barrel with a pipe leading to the water, in which cylinder works a closely fitting piston or "bucket," in which is a valve opening upwards. At the top of the pipe from the well is a similar valve, also opening upwards. Thus water can pass upwards through the whole, but not downwards. If the piston moves downwards as in (*a*), the lower valve remains closed, but the air in the cylinder becoming compressed opens the piston valve and passes out. As the piston rises, as in (*b*), its valve shuts and prevents the return of the air, and a partial vacuum is caused in the cylinder. The water in the pipe is thus in connection with a partial vacuum at its upper end, while the full atmospheric pressure still acts through the water on its lower end. In consequence of this difference of pressure water is forced up the pipe, through the lower valve, and into the barrel. As the piston again descends, its valve opens, while the lower one closes and prevents the return of the water to the well. In this way water gets above the piston, and on the next upward stroke (*c*) is lifted up to the level of the spout and flows out.

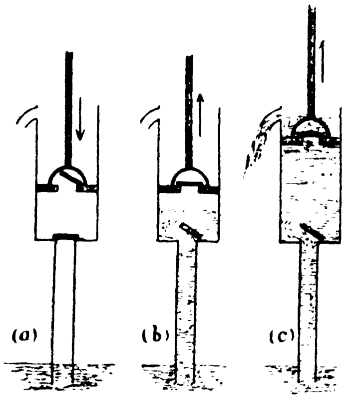


Fig. 80.

As already noticed, it was early found that there was a limit to the height water could be raised by this machine, Galileo fixing it by experiment at 32 feet. That is, the lower valve must not be more than that distance from the surface of the water in the well. With the barometer at 30 inches, however, it would indeed be possible to raise it 34 feet, if the valve could be opened without effort, and if water gave off no vapour; but owing to the variations in pressure from day to day, 32 feet is the greatest height it is safe to count upon, even with a perfect pump, as that corresponds to about 29 inches of mercury.

It is perhaps worth noticing here that the great advantage of an ordinary pump over the devices previously mentioned, is that the pipe leading from the well, may be bent in any way that best suits the circumstances, the only condition being that the vertical height is not too great. The pump may be in the house and the well several yards outside it.

But some method had to be found to get over the difficulty of height, and as the *pull* of the pump could not be increased, it had to be made to *push* the water on as well, and raise it in this way to the proper place. Take, for instance, the common case of wishing to fill a cistern at the top of a house, from a well at the bottom, by means of a pump. Here the pump could not act if placed at the top, especially if the well were deep. It is therefore put at the bottom of the house, and another valve is added at the top of the barrel, opening upwards like the others, and connected with a pipe to the cistern (Fig. 81). But, in order to use this valve, all other openings at the top of the pump must be closed. The spout is easily provided for by attaching a tap to it, so as not to prevent water being drawn directly from the pump if wished. The top of the barrel is a little different, as the piston rod must still be able to move up and down. This is arranged for by having a

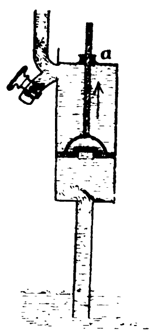


Fig. 81.

close fitting lid, with a "stuffing-box" (*a*) in the centre, tightly packed with tow and tallow, through which the rod passes. It is thus able to move freely, but no water can escape. The figure shows the piston rising and the water flowing up through the third valve to the cistern. If the tap is opened, the water in the cistern is not affected, but the instrument behaves exactly like a simple pump.

Another arrangement of valves for the same purpose is shown in Fig. 82, and is known as the force-pump. Here one valve is dispensed with, as well as the stuffing-box, and the second valve, instead of being as before, in the piston, is put in a pipe leading from the bottom of the barrel to the cistern. The piston in this case is solid, and is often spoken of as the plunger. This form is consequently a good deal simpler and less liable to derangement than the lift pump, and it is difficult to see why it has not entirely displaced it. If it is wished to use it for delivering water either at the higher or lower level, it can be fitted with a tap, the valve being put just above it as in Fig. 83.* There is another point that may be considered to some extent an advantage, and that is, that the amounts of work done in the up and down strokes are more nearly equal than in the lift pump. In this latter, no work is done in the down stroke except raising the weight of the handle, while

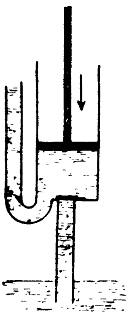


Fig. 82.

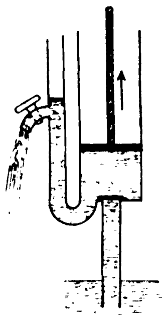


Fig. 83.*

* The arrow by mistake is drawn the wrong way. The piston is really descending.

in the up stroke we have to raise not only the water in the pipe above the valve, but also that in the pipe from the well. In the force-pump, on the other hand, the up stroke lifts the water from the well, and the down stroke passes it into the cistern, so giving a much more uniform effect. Both pumps are usually worked by a lever handle, except the very simplest kind of force pump, represented by the common squirt and garden syringe.

The levers, however, are of different kinds, according to whether the pump is of the lift or force description. In the former, the lever is the "first kind," so that the hardest work is done as the handle goes down; in the latter, to get the same convenience, the lever is of the "second kind," so that handle and piston go down together. The two kinds are contrasted in Fig. 84, *a* being the lift and *b* the force pump.

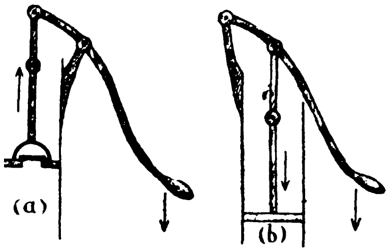


Fig. 84.

The force pump is very largely employed in various industries, for watering gardens, putting out fires, working hydraulic presses and so on. In order to get a continuous stream of water from such a pump, it is usual to employ an air vessel, into which the water is forced. The delivery tube descends nearly to the bottom of this, and the mouth of it is soon covered by water, which prevents the air from escaping. As more water is forced in, the air above it is compressed and acts as a spring, continually forcing water out of the delivery pipe, and so keeping the stream almost uniform. In the fire engine, to ensure still greater uniformity and larger supply, two pumps are connected with one air vessel, and are so arranged that as one piston is going up the other is going down. We can get the same effect as with two cylinders by having one double acting one—that is, drawing in at one end while driving out at the other, working like the cylinder of a steam engine. Such machines, however, require much more accurate fitting than the simpler kind, and are less easy to repair if they get out of order.

While speaking of pumps, we must notice that it is possible to pump air as well as water. In fact any pump, when first set to work, has to act as an air-pump before it can reach the water. But as valves and pistons have to fit very much better to keep out air than water, there is frequently difficulty in getting them to start, especially if long disused, and water has to be poured in at the top to render the parts air-tight. Where, however, it is of great importance to prevent leakage, as in the air-pump proper, the valves are made of pieces of oiled silk, resting on a flat surface of metal, pierced with one or more holes, and well oiled. In other respects the air-pump is constructed on just the same principles as the water-pump. If we wish to compress air, we use the force-pump arrangement, and can thus condense it into very small space. The cylinders of compressed oxygen gas, used in producing the lime-light for lantern exhibitions and stage effects, are filled in this manner to a pressure of 120 atmospheres, or 1800 lbs. on the square inch.

For simply pumping air from one place to another, ordinary leather valves are quite enough; and instead of a cylinder and piston, a box with flexible sides is used, the capacity of which can be increased or diminished by moving the top and bottom backwards and forwards. This is the ordinary bellows, holding to air the same relation that the squirt does to water. The addition of the leather valve, though, greatly facilitates the filling process. To the same end, the better class of syringes have a ball valve at the same end as the rose or jet, so letting the syringe fill easily, without the labour of drawing the whole of the water through the fine holes of the rose.

In bellows, as in pumps, a constant supply is often wanted, and to take the place of the air vessel above mentioned, a reservoir is provided, opening against a spring or a weight. In the organ a very large reservoir is used, with the top weighted so as to give always the same carefully adjusted pressure, which is necessary to give the proper effect on the pipes. For the purpose of a blast for forge or blow-pipe work, this absolute steadiness is not required, and a spring is often used. The most handy arrangement of the kind has simply a sheet or two of india-rubber stretched over a ring on the top (in some cases the bottom) of the bellows, under which is a valve from the bellows, and a pipe to carry the blast. As the top of the bellows is depressed, air is forced through the valve, and distends the rubber, the elasticity of which forces it through the exit tube at a fairly uniform rate. On a small scale, the same thing is seen in the spray apparatus of a chemist's shop.

Something must now be said, not of the raising, but of the fall of water. If an opening be made anywhere below the water line in the side of a vessel containing water, the water will flow out in a jet, the size and form of which depend on the form of the opening and the pressure at that point. If the vessel is free to move, it will move backward in the opposite direction to that in which the water flows—a very good illustration of action and reaction, the water pressing against the air and being itself pressed back with equal force. A machine to revolve in this way is called Barker's Mill from the inventor, and on this principle are made the turbines so much used for utilising water power.

If, instead of simply making an opening in the vessel, we attach a tube to it, the water of course flows through the tube, and its flow can be directed to any point by bending the tube. As long as the tube in no place comes above the level of the water in the vessel, water continues to flow through it in the endeavour to find its own level. But it would be expected that directly any part of the tube were raised above this main level the flow would cease; instead of that, it flows on just as well as before, if the end of the tube is still in its former place.

Here water seems actually to flow uphill, and we ask what force is there acting on it to make it behave thus. If our tube is long enough, we may try the experiment of raising the bend higher and higher to see how far we can do so, but we should have to go upwards about thirty-two feet before the flow stopped. This height is at once seen to be connected with the height of the water barometer, and to be dependent on atmospheric pressure. To prove this point we repeat the experiment on a small scale, with a slowly running tube, and put the whole under the receiver of an air-pump. On exhausting the air, the flow stops directly the pressure is reduced to a certain point, depending in any particular case on the distance of the discharging end below the water level in the vessel.

Such a bent tube is termed a siphon, but it need not be in any way connected to an outlet as in the case given. Usually it is a detached tube bent into something of a ∩ form, with one leg longer than the other, the shorter leg being immersed in the liquid to be discharged. This is, in fact, the way in which its peculiar advantages are apparent: a vessel of liquid can be emptied without disturbing the contents or piercing it in any way. The liquid is raised *over* the rim instead of being run away *under* it. The instances are numerous in which this freedom from disturbance is invaluable.

Before touching further on its uses, a word must be said as to the principle of its action, referring to Fig. 85, which shows one at work. The part *ab* is under the water, and would consequently be full whether the rest were there or not, and so has no influence on the result, and may be neglected. The liquid in the part *cb* is above the level, and tends to run back into the vessel, while that in *ce* is also unsupported, and tends to run out at *e*. Thus the two columns of water meeting at *c* tend to run different ways. If now we draw a horizontal line through *b* at the surface of the water to the longer leg of the siphon at *d*, we see that the columns *cb* and *cd* are of the same *vertical* height, and consequently pull each other at *c* in opposite directions with equal force —that is, they balance each other. But this leaves *de* unsupported, and this runs down the tube, tending to form a partial vacuum at the top. Then the pressure of

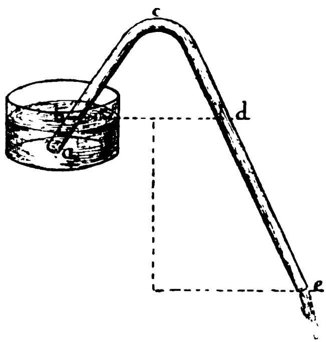


Fig. 85.

the atmosphere on the water surface forces more water into the shorter leg, and over into the longer, and this effect continues as long as the end *a* is under water. The effect is very much the same as when a chain or rope hangs over a pulley, with the ends of unequal lengths. The longer end falls and drags the shorter after it. With the siphon, however, the chain of water is only kept together by the air pressure at each end of it, which will not allow it to sever if not too long, and if the tube is not so wide as to admit air at *e*. The flow depends, other things being equal, simply on the height of *d* or *b* above *e*, just as if the pipe were inserted in the side of the vessel anywhere below *b*, still ending, of course, at *e*.

It will be seen that to start the siphon it must be filled with liquid, and that directly the air enters in any quantity it must cease to act. It may be started by sucking liquid through it, but in many cases this would be objectionable. In these cases, another tube is attached to the lower end of the longer arm, as Fig. 86. On stopping the lower end with the finger or by a tap, and sucking air out at *a*, the siphon is filled without much risk of getting any of the liquid in the mouth. Where a liquid has to be drawn off from a sediment or precipitate, the short end of the siphon is advantageously curved slightly upwards.

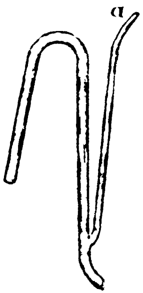


Fig. 86.

It is not necessary that the tube itself should have arms of unequal length, so long as the outer end is below the liquid level. The longer leg may, in fact, be in the liquid as long as these conditions are fulfilled. If a siphon, with the longer arm immersed, be set to work, it will lower the liquid till this is level with its outer end and then stop. But the siphon remains full, and ready to start again as soon as the level in the vessel rises. By using this arrangement we can keep the level of a liquid fairly constant, and this is perhaps the simplest kind of self-acting siphon. If both arms dip into water there will be a flow from the higher to the lower level, till both are equal. Then the siphon stops, ready to correct any fresh inequality.

But a more interesting kind of self-acting siphon is that in which the longer leg is outside the vessel, so that the siphon eventually empties itself of liquid, and becomes filled with air. No mere difference of level will then restart it: it must be filled in some way, at least up to the bend. If this bend is not too high, the water will at last reach it, if it rises in the vessel, and flowing over will fill the siphon. If the inner leg of this reach the bottom of the vessel, and the water is not flowing in too fast, the siphon will now empty the vessel completely, and will then cease to act till the water once more rises over the bend. Such an arrangement is now largely used for delivering large quantities of water at stated intervals, for the purpose of automatically flushing drains and sewers. The interval between the discharges may be made long or short as desired, by regulating the flow of water into the cistern containing the siphon.

A similar arrangement is often used for washing substances that require frequent changes of water, such as photographic plates and prints, the things to be washed being placed in the cistern. A very complete change of the water is thus effected, far more so than by a simple stream of water; but it is sometimes objected that entire removal of the water in this manner is not advisable, for fear of partial and unequal drying.

This arrangement of siphon has been long known to the Hindus, who manufacture a miracle-working image, of Vishnu on his mother's knees, with a concealed self-acting siphon beneath. As water is poured in, it rises to his feet, and then flows out and empties the vessel, he being supposed to command it back. Tantalus cups were at one time fairly common, which had a siphon of the same kind, either apparent or concealed in the handle. They were carefully filled to nearly the top of the bend, then anyone trying incautiously to drink disturbed the water and filled the siphon, so that the water soon disappeared. They took their name from the old classic story of Tantalus being condemned to stand up to his neck in water and yet never to be able to drink, the water flying from him as he tried.

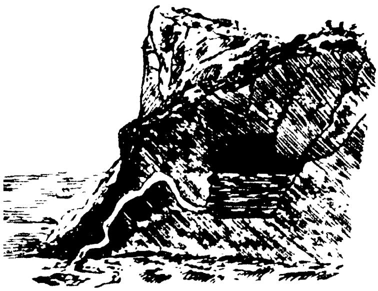


Fig. 87.

On this principle, too, depend the curious intermittent springs in various places, as shown in Fig. 87: a sort of natural siphon leads from a reservoir, which is slowly filled from any sources. When the water in the reservoir rises to the bend, the flow commences and continues till it is emptied.

One other point must be noticed in connection with flowing water, that is its momentum. We find that water, just like iron or wood, has inertia, and acquires momentum if put in motion. It is this momentum which is applied to turn the water wheels and turbines that enable us to utilise the force of rivers and streams, but these have been already spoken of. In these the momentum is not so much noticed as it might be, from the gradual way in which the water is applied and shut off. If, however, we take water in motion in any enclosed pipe, and suddenly stop its path, the momentum gives rise to a violent shock, often able to burst the pipe. To this reason, among others, is owing the large use of screw-down taps instead of the simpler plug taps. These latter, if turned quickly, cause a jar and vibration highly injurious to the pipes, while the screw form, by its slower action, prevents the sudden cutting off of the water and consequent strain.

This momentum can be employed to do useful work in raising part of the water to a higher level. The machine used is called the hydraulic ram, and its principle is shown in Fig. 88. Water flows down a large pipe fitted with a nicely balanced valve (*a*). When the flow is fairly established, the current shuts this valve with a sudden crash, and the full momentum of the water is brought to bear on the tube. At one point is a smaller valve (*b*) communicating with an air vessel, from which water is led to the higher level. The pressure of the inclosed air, due to this column of water, keeps the valve *b* generally shut, but the extra pressure on the tube when (*a*) closes, opens it, and some water passes into the reservoir and up the tube. The small valve instantly closes again, and the large one opening, the whole process is repeated.

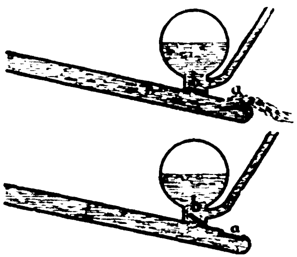


Fig. 88.

We are reminded, by the inertia and momentum of liquids, of the elementary facts with which we dealt in the opening pages, and have thus completed a circuit and come back to the point from which we started. Here, then, we may suitably close this brief outline of the "Mechanics of Daily Life," carrying with us, as one final thought, the great idea of the unity and harmony of Nature's laws, and their testimony to the wisdom of the great Creator.

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