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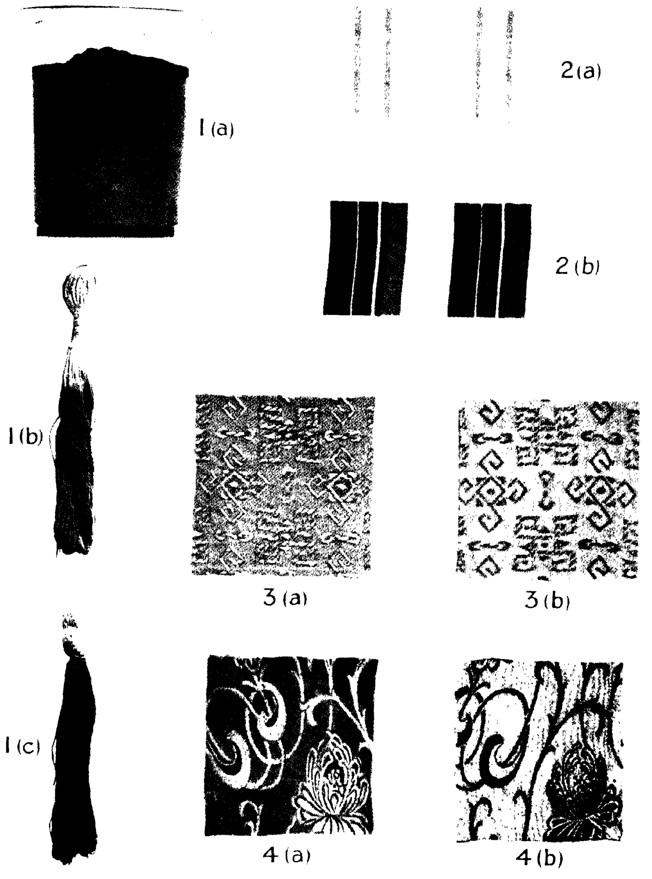

ILLUSTRATIONS OF DYEING PROCESSES

1. Vat dyeing (indigo). 2. Mordant dyeing. 3 and 4. Selective dyeing. (The material which dyed in one way gives 3a and in the other 3b has the same side uppermost in the two illustrations. The same is true of 4a and 4b.)

For the full description, see the Lecture on the Trade of the Dyer, particularly p. 176.

OLD
TRADES AND
NEW KNOWLEDGE

Six Lectures delivered at the Royal Institution

By

SIR WILLIAM BRAGG

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PREFACE

So many children like to know why this and that are done in any handicraft that I thought the Christmas lectures of 1925 might be devoted to a consideration of the way in which new knowledge is always changing the old crafts, and, in particular, those which have helped to make England. And I must admit that my lectures are meant to have a moral, in that there is much more than fascination in the history of men's work; there is also the plain and urgent lesson that we must continually improve our handicrafts by means of the new knowledge which is always flowing in. We, of all nations, have to make our living by trading the work of our hands for food, and that which we make must be so good and interesting that other nations are anxious to trade with us. Also, there is an ideal which may seem far beyond us, and yet must always be aimed at: it is this, to give everybody work to do, and make everybody enjoy doing it well.

I am very well aware that I must seem to be a Jack-of-all-trades who is a master of none, when I try to take each trade in turn as an illustration of the point that I want to make. Experts will detect many errors in this book. But I hope that some design is to be seen in my sketch, though its details are very incomplete and sometimes incorrect. Where no fault is to be found, I owe it to the many friends who have helped me in the kindest way. I have made acknowledgments in the body of the book in a number of instances; if I were to complete the tale in this preface, I should have to make it inordinately long. I would, however, express my especial gratitude to the Research Department of the Admiralty for the assistance which I received in arranging the experiments that illustrated the devices now used by the Sailor. Sir Robert Hadfield, Dr Desch, and Dr Hatfield helped me in dealing with the craft of the Smith, as did Dr Rosenhain and his colleagues in the Metallurgical Department of the National Physical Laboratory; Dr Crossley and his colleagues of the Cotton Research Association, Professor Barker of Leeds, Dr Willows and others, helped me in dealing with the work of the Weaver. From the British Dyestuffs Corporation and from Professor Green I received the most valuable assistance in connection with the Dyer's craft; while Dr Mellor and Mr Frank Wedgwood were the friends who made it possible for me to speak of the work of the Potter. Messrs Doulton kindly lent some beautiful specimens of pottery ware. Lastly, I have to thank, in connection with the Miner's trade, Dr R. V. Wheeler and Mr Batley, who were so good as to design and arrange many of the illustrative experiments.

Professor Andrade allowed me to make use of his fine collection of old books and illustrations dealing with the history of science: and was good enough to make a number of valuable suggestions. Several models of old apparatus and machinery, in some cases the historical objects themselves, were through the courtesy of Sir Henry Lyons brought from the Science Museum, South Kensington, and shown during the lectures.

It is one of the most delightful features of the task of the Christmas lecturer at the Royal

Institution that everyone is ready to help in making the lectures interesting to the "juveniles" who attend them. It may be well to add that a few additions have been made to the lectures in the course of their preparation for publication. It seemed to me that I might with advantage go a little more fully into some scientific questions than was convenient in the lectures themselves. The lecturer's form of address has been maintained; but of necessity references are here made to accompanying illustrations rather than to models and lantern slides.

W. H. BRAGG.

THE ROYAL INSTITUTION
OF GREAT BRITAIN,
October, 1926.

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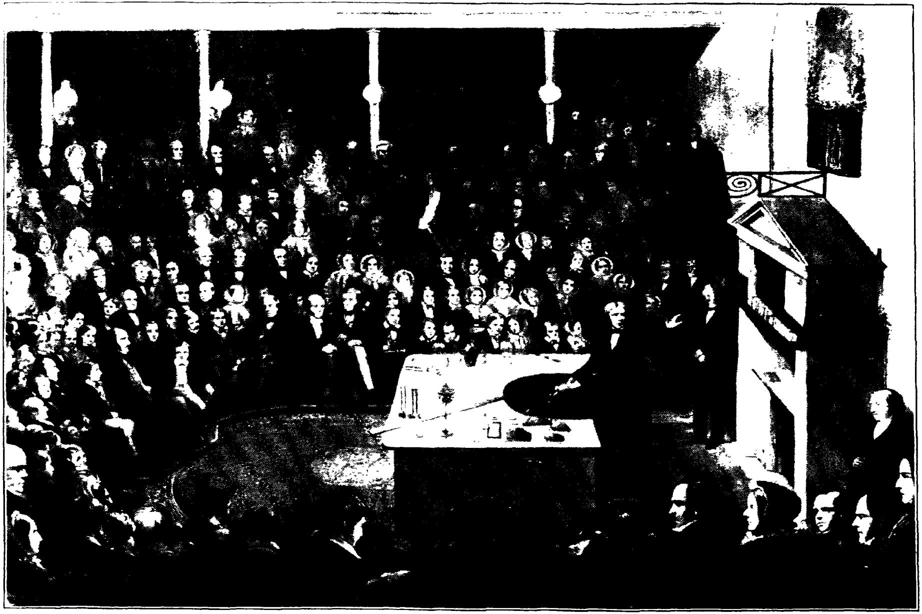


From a drawing by Alexander Blaikley.] [*Photographed by W. E. Gray.*

A Christmas lecture on "The Metals" by Faraday (1855–1856). The Prince Consort in the Chair, with the

OLD TRADES AND NEW KNOWLEDGE

LECTURE I

The Trade of the Sailor

THE history of an old trade is always of interest, because it is a story of human efforts to achieve something. Every little success has come, in all likelihood, only after many failures. The very tools of the trade have something to tell us, if we can understand their language. The shape of a hammer or of a sail, the design of a loom or a miner's lamp—each of them is the result of years of experience in actual use. Men want to make something for their own purposes and for the purpose of exchange with other men. In Kipling's story the men of the South Downs found that they did well to look after their flocks of sheep, so that they might have the wherewithal to exchange with those who lived in the forest of the Sussex weald. The latter had learned to make weapons of the iron which they smelted by aid of their oak charcoal; and the men of the Downs wanted the weapons, so that they could face the wolves that killed their sheep. No doubt, therefore, the shepherds were forced to try and improve their pastoral methods in order that, having better things to give, they might receive better things in return; and in the same way the trade of the smith grew at the forges in the forest.

As exchange grows wider, and peoples barter with each other more freely, over greater distances and in greater variety of things, crafts develop and become more skilled. Men must think how best they can please other men with their goods. They have established a trade perhaps in some article—pottery or leather or wool or metals—and they must at least maintain the quality of their work, or else they lose their trade with all its advantages of exchange. Their goods must be carried in ships, and the ships will be made by those that make them best and only sailed by the best sailors, so that the shipwright's craft and the sailor's craft change continually. That which does well at one time is displaced by something that is better adapted to new times and to new demands. New materials of construction are found, as when silk became known in Europe, and a great industry grew up. Men's tastes alter and customs change, as when printed books were made for men to read, and when the growth of reading reacted on the printing trade and made a great craft of it. A new plant is introduced into a country, such as the potato into Ireland in the sixteenth century, and the farmer's trade adapts itself thereto. Many a trade has been founded on or been modified by the introduction of tobacco. With the introduction of oil fuel we see the whole engineering trade change before our eyes. It is not necessary to go on piling up examples. We all see how trades change from generation to generation; how some grow stronger and some dwindle away, affected by a thousand influences which have their origin in the wants and circumstances and opportunities of men; and so the history of any trade is also a history of mankind.

It is always some new piece of knowledge which brings about a change. It may have been acquired as the result of long practice and observation. Why does the smith, when he wants to harden a piece of steel by plunging it into water, first set the water swirling in his bucket? Presumably because in that way he equalises the temperature; irregular cooling would lead to unnecessary and harmful straining of the metal.

The carpenter uses a wooden mallet to drive his chisel and the chisel has a wooden handle; but the smith uses a light steel chisel and a metal hammer when he wants to chip a metal casting. The latter operation involves the breaking of iron crystals, for which a sudden large force is required; the blow must be sharp and severe, but it need not last long. A less force acting for a longer time is required to make a long cut in a piece of wood. The stone-mason's work lies between these two. He has to break up a succession of little crystalline attachments; he uses a steel tool and a heavy wooden mallet. Innumerable instances are to be found in every craft of the application of knowledge of this kind, knowledge which does not come suddenly and in full force. It is acquired slowly and almost insensibly, and passes by tradition from master to apprentice.

Sometimes knowledge comes suddenly, by some lucky accident. One of the most beautiful colours that can be given to glass is said to have been discovered when a workman accidentally dropped his copper ladle into the molten glass in the pot. The colour, we know now, would be due to the dispersion of the copper in fine particles. So also Newcomen, who invented one of the first working steam-engines, as we shall see later, found that he could condense the steam in his cylinder by throwing a jet of water into it, and this was made plain to him by the fact that he had put some cold water on top of his piston to prevent air leaking past it. The packing of the piston was not good; a little cold water squirted into the cylinder and the steam was condensed.

Lucky accidents of this obvious character are not very frequent. More often they are only to be perceived by the quick eye and the mind that is prepared to notice them. Indeed, this less obvious kind of accident is the principal means by which knowledge grows. We have all had experience of that both in work and play. To take a familiar example: we may be ambitious of making some particular stroke at cricket or tennis or other game. We ponder over it, we watch other people playing, we try it again and again; and then one day we notice some little movement of another's hands or of our own which brings about success; and we should have missed it if we had not been thinking about it, so that the mind was ready. So the painter one day has a glimpse of the way to get some effect he has been trying for; or the metal worker catches a first indication of how to get a certain quality into his steel; or the potter finds his glaze just beginning to go the way he has wanted. Just a very little sign in each case, but to the craftsman it is enough. The new knowledge is only whispered to him, but he hears it.

It is strange how often the new knowledge that solves a difficulty or opens out a new possibility comes from outside the craft to which it is usefully applied. It may come from some other craft, but usually it comes from the work of some explorer who had no idea of any method in which his discoveries might be used. When Faraday first observed how variations of the electric current in one coil of wire could cause currents in a neighbouring coil, he had no thought of the huge edifice of electrical engineering that would be built on his fundamental experiment. When experimenters in the first half of the nineteenth century interested themselves in the electrical discharge in glass bulbs emptied of air more or less, they had no vision of the X-rays or wireless telephony which would in the future make use of what they observed. So often does this sort of thing happen that we have learned to store up all knowledge, though we see no use for it at the time. We never know when we may not want it. For the same reason the problems of any craft are to be solved only by a wide knowledge that goes far beyond the craft itself. Many of the great industries of to-day employ men to study their problems who are acquainted with various branches of knowledge: physics, chemistry, botany, biology, and so on; and they give these men, at least if they are wise, freedom to attack the problems in any way that seems promising. The work that is done in these research laboratories is most interesting, and is often comparatively unknown outside. It is one of my objects in these Christmas lectures to say something about it, for it is so important as well as interesting. It is important to us, because it is so necessary if our trades are to keep their place in the world's advance.

Now let us turn to the trade of the Sailor, the first of those which we are to consider in these lectures.

It is a long way from the primitive dug-out to the great liner of to-day—so simple at the beginning, so complicated and so powerful at the end. But from beginning to end certain things may be said of the sailor's craft, and corresponding things of any other. In the first place, the sailor has a proverbial affection for his boat, and a pride in his management of it. The love of a man for his work is one of the most beautiful things in the world. Improvement in craftsmanship is by no means only the result of competition. There

FIG. 1.—The boat of the bird-hunter is made of papyrus: it is very light and can easily be forced over the shallows and among the reeds. The hunter stands on a mat, so that his feet may be kept dry. Notice the nests in the reeds, and the fish and the animals in the water.

is what may be called the artistic sense, the desire to do a thing well from sheer pleasure in achievement. We need not doubt that when men launched their logs on the river, or tied together bundles of reeds or bulrushes, as the

Egyptians did, to make rafts and skiffs, they became skilful in their work and were proud of it. In the second place, men must make use of such materials as are to be had. The Egyptians used papyrus because wood was so scarce that it could only be used for heavy traffic. They "send ambassadors by sea in bulrushes," says Isaiah. The coracle (Plate II, *a*) was a basket covered with skins, used in many different parts of the ancient world where skins and suitable "timbers" were to be had. We have always read of it in our histories of Ancient Britain, but the same sort of craft was, and is, used on the great rivers of the East. No doubt there was a great art in making a good coracle; certainly Julius Cæsar was content to learn it from the Britons, and make use of it on his expeditions. The old geographer Strabo says that he sailed to Egypt in a basket made of wicker. We seem to be getting near to our nursery rhymes.

Far away on the southern seas is a boat of strange construction, the boat with the outrigger —the catamaran (Plate II, *b* and *c*). Its design must be very old; its present state of efficiency must have been reached long ago. Its plan, like that of the motor bicycle with a side-car, to which it has a curious resemblance, would seem to offend every law of efficiency; and yet it fulfils its purpose.

It makes long voyages and stands much rough weather, though it has its own peculiar dangers. It can only sail with the wind on the same side as the outrigger, since it depends for its stability on the outrigger's weight, which weight, of course, can be increased by sending out one or two men to sit on it. They speak of a "one-man breeze," or a "two-man breeze," and so on. It cannot do much in the way of tacking, since its leeway is so great; it has little hold on the water. If it has to return on its track, it must not come over on the other tack as our boats do, for the wind must always strike the boat on the outrigger side. It has to reverse, interchanging bow and stern, with the corresponding necessary changes in the position of mast and sail.

What a long time it must have taken to arrive at such a design! Probably no better could have been made, considering what materials were to hand and what purposes the boats were to serve. They trade long distances from one island to another; they are used for fishing, and their enthusiastic owners race them one against another. Dr Malinowski, from whose book[1] the illustrations mentioned are taken, tells us how the men will sit on the deck as the boat is drawn

[1] *Argonauts of the Western Pacific.*

up on the shore, discussing eagerly the merits of their own and other boats. It is easy to see how every detail of construction, every stroke of ornament, tells a story of continual profiting by experiences at sea, of endless thought and labour put into the work.

If, when we reflect, we see so much in a little boat like this, of comparatively simple build, how appalled we become when we think of all that has gone to make the ocean liner of to-day. We cannot of course attempt to consider all its details in this short hour; we should lose ourselves therein. It is not my purpose to do anything of the kind. I propose to take one phase only of the sailor's work—that of the finding of position at sea, for it makes by itself a story of great interest.

The problem under consideration arises simply enough. When the sailor is out of sight of land he has no landmarks, and when clouds obscure the sky he cannot guide himself by sun or stars. He has no general means of telling either where he is, or what direction he must take in order to get to where he wants to be. In the old days he took care not to go out of sight of land. Yet even then the sailors of Egypt and Tyre and Rome made wonderful voyages. Herodotus tells a story of an Egyptian expedition which from his account must have gone round Africa, for it sailed down the Red Sea and reappeared from the west. Herodotus tells many stories which may be doubted; this one he doubted himself. "I do not myself believe it can be true," he says, "though there may be some who do." His reason for being cautious was that the sailors said they had the sun on their right hand for a great part of their journey. Now this would really be the case if they made the journey round the Cape of Good Hope from east to west. But Herodotus did not see how that could be, and so for once he warns his readers to be careful. The very reason which he gives for disbelieving the story inclines us to believe that it may have been true.

Naturally, when men's knowledge of the extent of their world began to grow, they wanted to make short cuts which would save them long coasting voyages. They used the sun and the stars when they could; and if they had a clear view of the sky they knew north from south and east from west. But it must be borne in mind that direction and position are different things; it was one thing to be able to point to the north, but quite another thing to be able to lay a course for a given port, or to say how far it was away. When men learned to steer by the stars, and to do so not only on the sea but also when travelling on the wide spaces of the deserts; and when too they watched the passing of the night and the changing times of the year, using the sky as their clock, the science of Astronomy took shape and grew. It did not stop when the first needs were satisfied; men became interested in it for its own sake. It is very interesting to observe that many of the strange things which they learned were afterwards found to have most important practical applications. One of the immediate consequences was the discovery of the fact that heavens and earth revolved, relatively to one another, round an axis. This carried with it in the end the realisation of the roundness of the earth, and so made it necessary to speak of latitude and longitude. With these the difficulties of finding position at sea began to sort themselves.

It is comparatively easy to find latitude if the sun can be seen. The height of the sun above the horizon at noon—that is to say, the highest point it reaches during the day—gives the latitude, if the time of the year is known. The illustration (fig. 2) will help to make this clear. It represents a large globe used at the Christmas lectures to represent the earth; lines of latitude and longitude

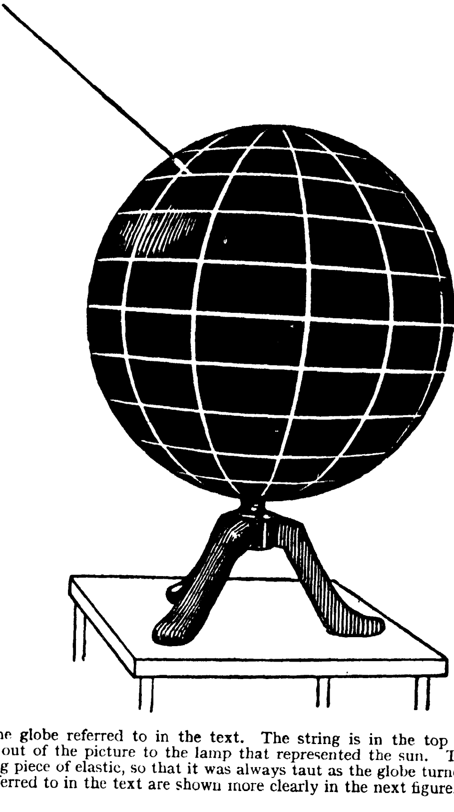


FIG. 2.—The globe referred to in the text. The string is in the top left-hand corner, going out of the picture to the lamp that represented the sun. The string included a long piece of elastic, so that it was always taut as the globe turned round. The angles referred to in the text are shown more clearly in the next figure.

are drawn upon it. At one point, representing a ship's position, a long string was attached; the other end of the string went up to a light in the gallery, which represented the sun. The globe was turned on its axis from a position in which

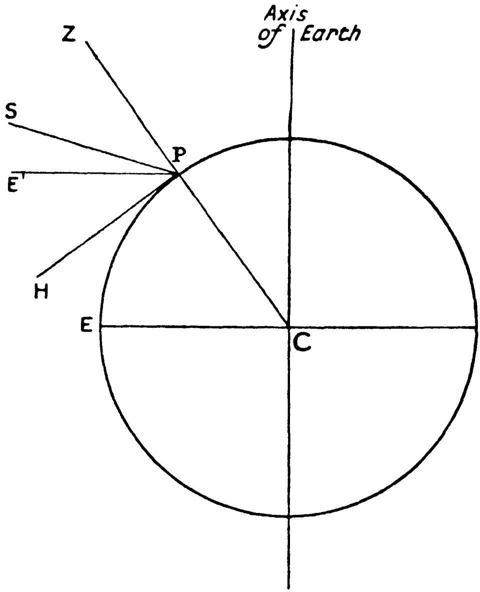


FIG. 3.—The ship is at P, and PS is the line joining sun and ship. The time is oon, and SPH is the angular height of the sun above the horizon. The angle [illegible] is the latitude.

the string was a tangent to it on one side, to the position in which it was a tangent on the other. Half-way between the two the ship's position was exactly opposite the model sun, and then the string made the maximum angle with the surface of the globe. This represented the angle which has in practice to be measured. It does not give the latitude directly. It would do that if the sun were exactly on the equator; that is to say, if in the model the light were on a level with

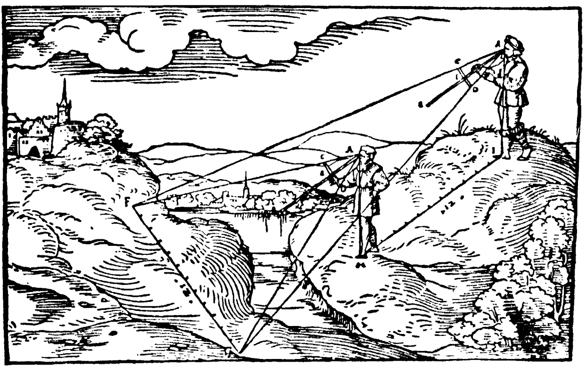


FIG. 4.—Use of the cross-staff in surveying. Two points, F, G, are used by both observers, and the subtended angles are measured. When the distance between their feet has also been measured, the length FG and the distances of F and G from the observers can be calculated. A cross-staff is drawn with fuller detail in fig. 6.

the middle of the globe. The latitude would then be the difference between the observed angle and a right angle. The sun is only on the equator twice a year, at the time of the equinoxes, in March and September. In summer time it is above the equator as in the model, in winter it is below. Usually, therefore, there is something to add or to subtract from the observed height of the sun above the horizon.

The sailor must watch the sun with some instrument which will enable him to measure the angle in degrees. The old cross-staff was one of the simplest of these instruments. One end was put

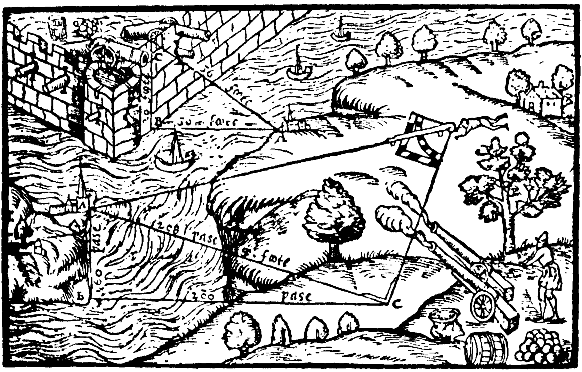


FIG. 5.—Use of a simple form of quadrant for surveying in time of war

near the eye, as the illustration shows (fig. 4), and the cross-piece moved until its two ends were on the sun and the horizon respectively. The angle could then be read off. It must have been very inaccurate; the glare of the sun alone must have made it difficult to set. The instrument was used for finding angles on land also. The illustration shows this very well; it is taken, and fig. 5 also, from Thomas Digges' *Pantometria*. There were three cross-pieces to each cross-staff, the shortest being used in finding small angles.

A more famous instrument, of which many beautiful examples survive, was the astrolabe. It was a metal disc, usually brass or bronze, which was suspended from a ring (fig. 6 and Plate III, *b*). A movable index, the alidade, was placed along a diameter of the disc and could be turned round the disc centre. It carried at each end fine peep-holes or sights. The astrolabe was held up by its ring, so that the disc was in a vertical plane which passed through the sun, and the alidade was turned until the sun's ray went through both peep-holes; or, if a star were under observation, until the star could be seen through the holes. The angle could then be read off on the disc. There are several beautiful astrolabes in the Science Museum at South Kensington. The one in Plate III was found under a rock on an island off Valentia, and is supposed to have been left there by the Spanish Armada. It is solid and heavy; evidently it was meant to hang as steadily as possible in a strong wind. The astrolabes were often engraved with beautiful designs, and extra discs were sometimes provided for use in complicated astronomical calculations.

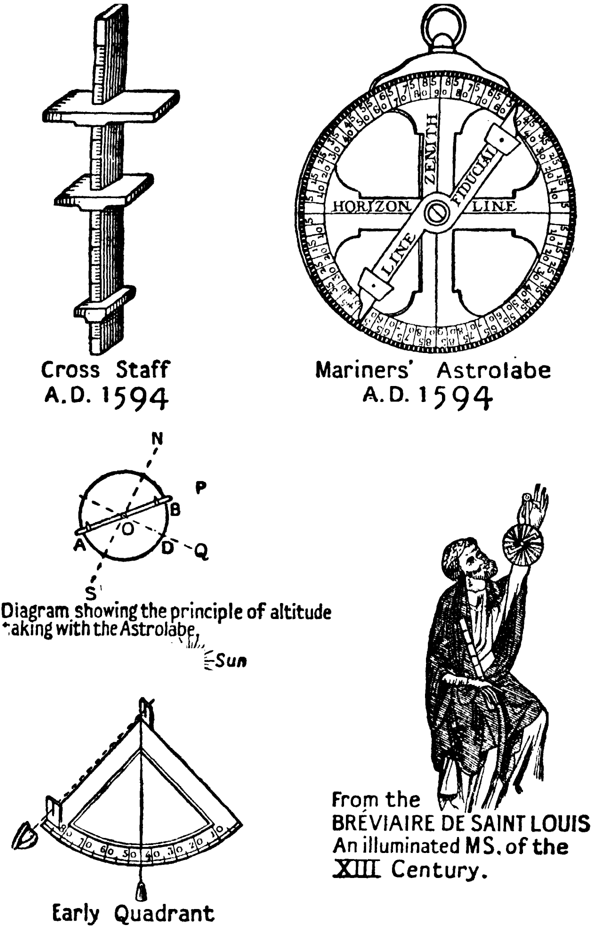
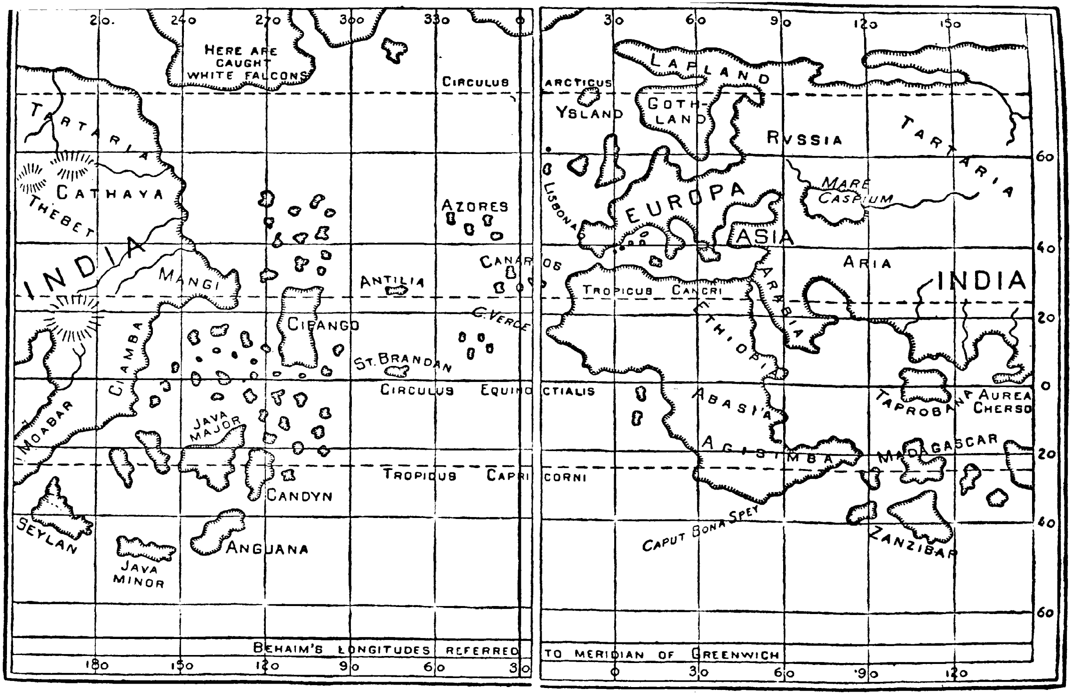


FIG. 6.—At the top, on the left-hand side, is a drawing of a cross-staff, and on the right there is a drawing of an astrolabe. Other figures show how the astrolabe was used.

Cross-staffs and astrolabes gave way at last to the far more useful and accurate reflecting sextant, invented in 1731. But they and the magnetic compass, which had lately come into general use, were all that Columbus had when he set sail westwards for the Indies. His longitude he could not find, nor, indeed, would a knowledge of it have been much use to him, for he had only the most imperfect ideas of the countries he was to reach. It seems certain that he very much underestimated the distance that he had to go. The prevalent ideas of the combined length of Europe and Asia erred in excess, and Columbus seems to have thought that the world was smaller than it really is. The maps he used show nothing between Europe and Asia save some fabulous islands and an ocean which Columbus thought he would be able to cross. Actually, of course, there is a wide space between the two continents, and America occupies the middle of it. The map (fig. 7) shows a projection made from the globe of Martin Behaim, who was a friend of Columbus. It is preserved in the town hall of Nuremberg. Its names are very interesting: Cipango is Japan, and Taprobana is Ceylon; we see Caput Bona Spey (Cape of Good Hope), and Cathaya and Tartaria, and many others that we know.



Here are caught white falcons
Circulus Arcticus
Tartaria
Cathaya
Thebet
India
Mangi
Ciamba
Moabar
Seylan
Java Minor
Java Major
Anguana
Candyn
Cipango
Antilia
St. Brandan
Azores
Canar os
C. Verde
Circulus Equinoctialis
Tropicus Capricorni
Tropicus Cancri
Ysland
Lapland
Goth-land
Russia
Tartaria
Europa
Asia
Lisbona
Mare Caspium
Aria
India
Arabia
Ethiopia
Abasia
Agisimba
Caput Bona Spey
Taprobana
Aurea Cherso
Madagascar
Zanzibar
Behaim's longitudes referred to meridian of Greenwich

The problem of longitude was not solved until well on into the eighteenth century. It had become urgent. Even as late as 1741 Anson, in his voyage round the world, could be in such error as to find himself, some time after rounding Cape Horn, quite close to the land when he thought he was ten degrees to the west of it. Again, when he was in the latitude of Juan Fernandez, which is some three hundred miles off the coast of Chili, and wished to make the island, he was so uncertain of his longitude that it was necessary to sail until he came in sight of the continent, and then run down the correct line of latitude until he came to his destination—and that, as he found subsequently, after having actually had an uncertain view of the island in the distance before he made his detour. On account of this delay he lost eighty more men from scurvy. The map (fig. 8) is taken from the account of Anson's voyages, written by his chaplain.

Let us look a little more closely into this question of longitude, so that we may understand the exact nature of the difficulty. Imagine a ship to be on the open sea, and the navigator to be able to watch the sun as it moves across the sky. He measures its height above the horizon when it is at its highest; he then knows his latitude. He

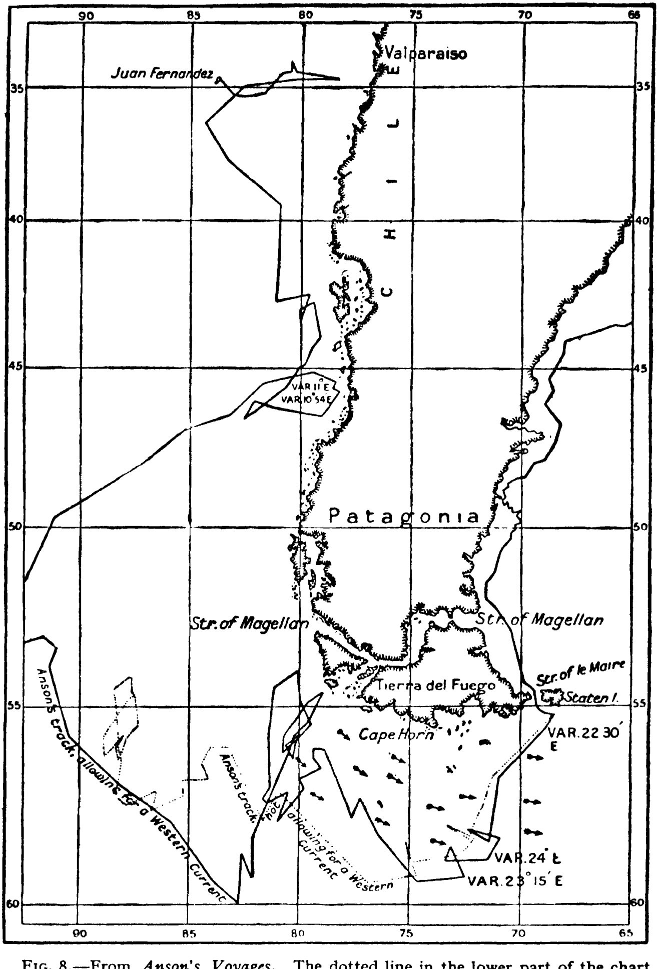


FIG. 8.—From *Anson's Voyages*. The dotted line in the lower part of the chart shows Anson's track as he calculated it; the line to the right shows his real track. At the top the chart shows the curious detour which he made in order to be sure of not missing Juan Fernandez.

can also call that moment noon, and date from it the passing of his day. But in order to find the difference between his longitude and the longitude of some standard point on the earth's surface—Greenwich, for example—he must know not only when it is noon with him, but also when it was or is going to be noon at Greenwich. If he can determine the difference in time between those two moments he can find his longitude, for the sun appears to go round the earth in twenty-four hours. If the navigator's noon is, say, four hours later than at Greenwich, then he is one-sixth of the way round the world, taking the line of longitude through Greenwich as his starting-line. But how is he to know when it is noon at Greenwich? The answer would seem obvious now: let him take a chronometer with him on his voyage, and set it right by Greenwich before he started. But no one in Anson's day could make a chronometer nearly good enough. Since this method was not to be thought of, the suggestion had often been made that the sailor should use the heavens as his standard, watching the movement of the moon amongst the stars. The position of the moon at any time could be calculated far ahead, and tables of what were called "lunar distances" could be supplied to the navigator. If they were calculated by the time of some standard place, all that the sailor had to do was to measure the position of the moon and consult his tables. He would compare his own time with the time there given and would then know his longitude.

The method is very difficult to put into practice, however. It is difficult on board a moving ship to make sufficiently accurate measurements of the moon's position, and would be all the more difficult in those days because the instruments were not good. We can see from a figure (Plate III, *a*) how much the moon moves in twenty-four hours. It is not a great deal, so that it must be measured with great accuracy. A mistake of one minute of arc would mean an error of half a degree of longitude, and even that accuracy was far beyond the shipboard instruments of the day.

Nevertheless, so urgent was the question, that the Royal Observatory at Greenwich was founded in the reign of King Charles II. for the express purpose of calculating lunar distances. In that way the great Observatory came into being, which has done splendid work for astronomy and for navigation. The calculation of lunar distances was continued until 1907, though it had long ceased to be of much use, or to form more than a small part of the Observatory's work. The invention of the chronometer had solved the problem.

But before leaving the method behind us, it is interesting to note that not many years ago it did, on one special occasion, yield good service. In the early months of 1915 the Antarctic Expedition had become doubtful of the reliability of the chronometers which they carried. Their last check had been at South Georgia in December 1914; there was indeed a little doubt about that, so that probably their last satisfactory check was at Buenos Ayres in the previous October. Since that time there had been much rough voyaging through the ice, and the ship had been shaken thereby; there had also been severe changes of temperature. So the members of the expedition began to consider the possibility of using the old method of lunar distances. There was in their case a good chance of attaining satisfactory accuracy, for two reasons: the ship had been frozen in and was drifting very steadily, and they had found a 3-inch telescope on board. So Messrs James and Worsley set up the telescope on a cinematograph tripod as soon as the dark months of winter made it possible to see the stars, and on 24th June they had the luck to see some excellent occultations. The moment when each star passed behind the moon's disc was observed very accurately. They found that their chronometer was four minutes wrong; the consequent error in longitude was a whole degree. This was very important in itself, and doubly so because later on they were drifting, according to the map, on dry land! As a matter of fact, they had 1800 fathoms of water beneath them; the map was quite wrong.

We must now go back to the break in our story. In 1714 a committee was appointed by Parliament to consider the question, and evidence was given by Sir Isaac Newton among others. Newton gave the committee a list of the "several projects, true in the theory but difficult to execute," which had been put forward for finding longitude. The first of these was a chronometer of sufficient exactness:

"One is, for a watch to keep time exactly; but by reason of the motion of a ship, the variation of heat and cold, wet and dry, and the difference of gravity in different latitudes, such a watch has not yet been made."

His mention of gravity shows that he is thinking of a pendulum clock. It is to be remembered that the pendulum had just been discovered in

Newton's time, and the balance-wheel as well, and that those two great improvements still left the time-keeper below the standard which the navigator required. How bad time-keepers were before that may be judged from the following quotation; it is taken from a precious old book, called *Humane Industry*, published in 1661 :—

"But the exactest Clocks and Watches that are, are defective, and want correction; for in Watches, the first half hour goes faster then the last half, and the second hour is slower then the first, and the third then the second; the reason whereof is, because Springs when they are wound up, and then begin their motion, move faster in the beginning then in the ending; as it is with all violent motion. But in Clocks it happens contrary; the last half hour is faster then the first, because the weights by which they move, move slowly at first, as all ponderous things do, but accelerate their motion when they draw nearer the earth. Besides, the lines or cords by which the weights do hang (being drawn out into some length) add some weight to the plummets, and consequently some speed to the motion. Both which inconveniences William Landgrave of Hessen and Tycho Brahe took into consideration how to rectifie, as Tycho relates; but how they sped in the enterprize, he doth not tell us."

Newton described to the committee the method of lunar distances, and other suggestions also, and his statement formed the basis of the committee's report. So Parliament offered a reward of £20,000 for any method which would in a six weeks' voyage to the West Indies determine a ship's longitude to within half a degree; £15,000 if the error was not more than two-thirds of a degree; and £10,000 if not more than a degree. To win the first prize the chronometer—if that was the instrument to be used—would have to keep time to two minutes in six weeks.

There were many competitors for the prize, which was won by John Harrison, the Yorkshire carpenter (Plate IV, *a*). The success of his chronometer was largely due to the compensation for temperature which he incorporated in his design. The famous chronometer, now at the Royal Observatory, is shown in Plate IV, *b*, and the temperature compensation in Plate IV, *c*. Its principle is simple but ingenious. The watch tends to lose time when the temperature rises, because the balance-wheel becomes a little larger and takes longer to swing. To compensate for that, Harrison placed in the design a bar made of two strips side by side, one of them brass, the other steel. When the temperature rises such a bar bends, because the brass expands more than the steel, and the point where the bar touches the spring moves slightly, so that the spring is effectively shortened by a small amount. This tends to quicken the motion, so that the effect of temperature on the balance-wheel is neutralised.

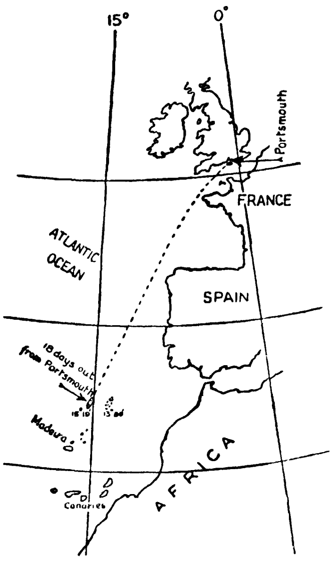


FIG. 9.—The arrow points to the actual position of the ship on which William Harrison was a passenger; the dotted outline to the right the position calculated by the captain from dead reckoning.

In 1761 William Harrison, son of John, voyaged to Madeira, and when eighteen days out from Portsmouth had sufficient confidence in his chronometer to dispute the captain's estimate of his position. From his dead reckoning the captain supposed his ship to be in longitude 13° 50′ W., so that, as the map shows (fig. 9), he would have had to alter his course to reach Madeira. But by

Harrison's calculations the longitude was 15° 19′ W., so that there was no need for a change. The captain very reluctantly accepted Harrison's assertion; the old course was continued, and Madeira was sighted next day. It was this and other successes on voyages to the West Indies which vindicated Harrison's claim to have solved the old and troublesome problem. Ever since then the chronometer has been an important part of every ship's equipment. On the Royal Observatory a double duty has correspondingly devolved. It "rates" chronometers for use at sea, and it takes accurate time from the movements of the stars across the sky. The Observatory records the time so found upon its clocks, which in these days are marvellously accurate. The temperature compensation is wonderfully good, yet, to reduce errors as far as possible, the standard clocks are kept in rooms of constant temperature. The master clock is kept underground. It is curious and interesting that the master clock has a slave clock to do what little work is required to keep the master going. The latter must concentrate all its attention on keeping the time! Now that we have the wireless telephone, we can once a day listen to the ticking of one of the Observatory clocks, and set our own watches and clocks thereby. The clock in question is shown in Plate V. Two minutes' exposure were required for the photograph, so that the minute-hand is represented by a blur, and there is no second-hand at all. Ships that can receive the wireless message can do the same, and to that extent the chronometer after all these years resigns its proud position; it is only necessary that it should keep good time for one day at most.

If clouds cover the sky, so that no measurements can be made of the positions of sun, moon, or stars, then the methods which we have been considering cannot be applied. The principal means still left to the sailor are his magnetic compass, and the dead reckoning which the compass helps him to make. It is not easy to get good results in this way. Estimations of speed were once made by various rough methods, such as dropping something overboard at the bows and watching how quickly the ship slid past it. Now, the patent log gives an accurate result. Nevertheless, there are always the effects of ocean currents to be taken into account, and the possible errors in the readings of the compass and their interpretation. When position has been calculated, the compass is used to guide the ship in the direction to be followed. The compass is far from being a perfect instrument, though we can well understand the amazement and delight which greeted its introduction to Europe. The compass does not generally point true north: its direction "varies" therefrom by large angles, so that a magnetic survey of the world is required before it can be used everywhere. It is greatly affected by the presence of iron carried by the ship or used in its construction, and the amount of the deviation caused in this way depends on what part of the world the ship is in, and what course it has been and is following. It is not surprising that some better indication of direction has been sought, for use especially on ships made wholly of steel.

At this point the gyroscope comes in, a fascinating instrument, of powers that seem almost uncanny. The fundamental principle is simple enough. If a wheel is set spinning on its axis, or a top, or any other such body, and if that body is given a second and simultaneous spin about some other axis, then the body will tend to move so that the first axis coincides with the second. An experimental illustration will make these words clear.

We take a gyroscope—a heavy top of the construction shown in figs. 10A, 10B; it is capable of spinning about a horizontal axis. The axis is carried by bearings which form part of a Y-shaped frame, the latter being so mounted that it can turn about a vertical axis, in a way which will be understood from the figure. We put the gyro-

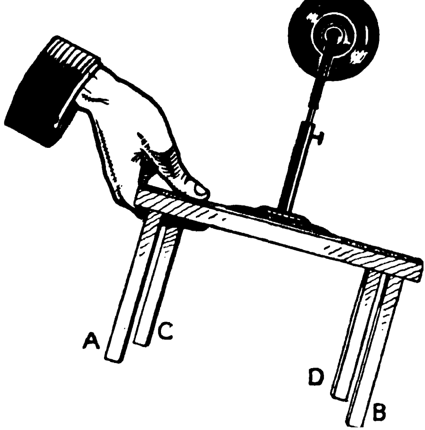


FIG. 10A.

scope on a four-legged table as shown; the feet of the table are denoted by ABCD. The axis of the gyroscope round which it is set spinning is set parallel to AC and BD. We now put our fingers under the edge of the table and tilt it so that A and C leave the ground, B and D remain on it. We are turning the table and all that is on it about the axis BD. Now the axis BD is parallel to the axis about which the top is spinning already, so that no strain is felt at the points where the axis rests in its bearings in the Y-frame, nor do we feel that we are doing any more work

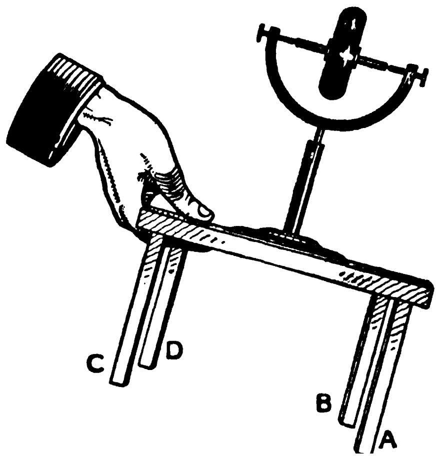


FIG. 10B.

than we should be doing if the top were not spinning. Nothing happens therefore.

We now tip the table from another side so that A and B stay on the ground while C and D are lifted from it. If the top is a heavy one, we feel we have more difficulty in doing so when the top is spinning than when it is not ; we must be exerting some force on the top through its bearings. We see, in fact, an immediate result: the top turns round on its vertical axis, the stem of the Y-frame turning in its socket, and it turns in the direction which will bring its axis of spin *parallel to AB. Moreover, the top will turn round the vertical axis in a particular sense. If,* for example, we stand by the CD edge, and the top appears to us to be spinning in the clockwise direction, the end of the axis which is nearer to us will move towards the right—that is, towards C. For the tilt of the table would be clockwise to anyone standing by AC, and so the top moves in the direction which will make its spin look clockwise to the same observer.

Another way of showing the same experimental fact is to take firm hold of a gyrostat, mounted in gimbals which permit the spinning axis to make any direction with the vertical. Now if, while we hold the frame, we turn our body about the vertical, we observe that the top, if we have set it spinning with its axis also vertical, will show no sign of disturbance if its direction of rotation coincides with our own. But if the two directions are opposite, the top is clearly in unstable equilibrium and almost immediately turns right over, the two directions thus becoming coincident.

These actions can be explained in terms of the basic principles of dynamics, but it is enough for our purpose to note the fact that the spinning-top will try to set its axis of spin, which is of course placed symmetrically in its body, parallel to the axis of any new spin that is forced upon it.

If no such new spin is given it, the axis of the top keeps its direction indefinitely. In fact, we might conceive a top made in this way to serve as a permanent indicator of a certain direction, and that direction would be fixed *in space*, not fixed with respect to the room in which the top happened to be. If the top were set spinning with its axis pointing to a particular star, it would keep on pointing to that star indefinitely. We could never, however, make use of the conception, because we could not make a mounting which would leave the top perfectly free to move its axis into any new direction; there would always be some pressure on the gimbals when the top tried to move, and the top would, so to speak, interpret that as an attempt to give it spin about a new axis and alter its own accordingly.

The method of using the gyroscopic principle in practice is more subtle and more interesting. Let us go back to the gyroscope which we used in the first illustration. We made its axis move by tilting the table. But even if we do not tilt the table, the axis turns, as we can see if we watch it very carefully. We may find it convenient to use a microscope, and keep under observation some fine mark on the gyroscope frame. The fact is that the table is being slowly tilted all the time by the rotation of the earth, the table and the room in which it stands. The axis of this movement is the axis of the earth, and so the axis of spin will in the end set itself as nearly parallel as it can to the axis of the earth. Its method of mounting prevents it from doing so entirely, because it cannot tip up, but it will point true north and south. It is quaint to think, as Perry pointed out in his book on *Spinning-tops*, that all spinning machinery, dynamos, engines, motor-car axles, and so forth, are gently tugging at their holdings, trying to tip up and point to the pole star. If the mounting is good and the gyroscope is made to spin very rapidly—for which electrical action is convenient—the gyroscope will set itself right in, say, an hour, and will stay right afterwards. Here then is a perfect compass, always pointing to the true north and unaffected by the materials used in the construction of the ship.

But it is clear that we must in some way get over the difficulty due to the movements of the ship at sea. If the gyroscope is mounted on the deck, its stand is being tilted in all directions. Now if the gyroscope which we used on land were placed on a table which was mounted on gimbals, the action just now described would not be altered. The gimbals would not, in fact, be called into play, as the room would go steadily with the motion of the earth. The axis of the compass would get to the north-south line in the end; there would be minor disturbances, but they would be negligible. A similar mounting on gimbals would at sea cut off the motion of the ship, but it would not cut off the effects of the earth's rotation.

This then is the method adopted in practice. The details of the apparatus are, however, more complicated than are indicated by this description. The mounting of the gimbals and bearings is never so free that the action of the gyroscope is unaffected thereby; great ingenuity and experimental skill are required to overcome all the troublesome complications.

The perfected instrument can be used not merely to point the true course, but to steer the ship. Electrical apparatus can be attached, so that if the ship goes more than a certain amount off its course, an electrical contact starts machinery which turns the rudder. We have what is called "the mechanical quartermaster." It is claimed, indeed, that a better course can be steered by the gyroscope than by hand.

Our navigator has therefore a compass which, though costly, is free from the uncertainties of the magnet. His dead reckonings will be more accurate and his courses better set. But still, if sun or stars happen to be invisible, there can be no direct determination of position by their aid. Here we have an opportunity of new applications of knowledge that we have gained in recent years. We can find direction by wireless signals, as I am sure we all know. The method is often very successful, though there are curious lapses which are not yet perfectly understood. In spite of that, determinations are frequently made by its means. When sending-stations become more numerous, scattered over the useful positions as lighthouses are, they will be used still more. There is a certain decision to be made as to method: shall the ships send and the shore stations measure, or *vice versa*? The former method has the advantage that the delicate machinery for determining direction is on the steady land; it can be more carefully made, with less regard to expense, and will give better measurements. But when determination of position has to be made, the message has to be sent out to the ship asking for it, and there may be many ships asking at the same time. The second method is obviously more convenient, each ship independently making its own measurements of the directions of shore stations which are sending all the time.

A different method of finding position was evolved by the needs of the war. A set of hydrophones were spread in a row in the sea, and connected electrically to a station on shore. A small charge was exploded in the water outside the ship, and the shock-wave affected the hydrophones in time and in turn. The position of the ship could be calculated from a comparison of the times at which the hydrophones received the shock. The method is extraordinarily accurate, and is very little affected by tides, currents, or any physical causes. But of course it requires hydrophone stations, which are not in existence, and the determinations made on shore must be sent by wireless to the ship. It would be most useful, probably, when a ship was only a few miles from a coast, and the weather was foggy, stormy, or in any way difficult. The method would then give the position of the ship to an accuracy of something like its own length.

Another method of giving a ship a useful indication of its position is by means of the "leader cable." The idea is some thirty years old, for it was patented by C. A. Stevenson in 1893. It was tried on the Hudson River in 1911. The principle is simple. An alternating current of electricity is maintained in the cable; a coil and telephone on board ship are affected thereby when the ship is close enough. During the war, and subsequently thereto, its application was tested very carefully. As with so many other inventions—with most of them, in fact—the first idea marks an important step, and the first trials give good promise. Then comes the critical time, when unforeseen difficulties arise and have to be met; it is often a long time, full of discouragement, but it has to be gone through. Success comes with the "second wind." There are actually such cables in use now, so laid that ships can use them for navigating intricate waters in times of fog. (At the Christmas lectures the method was illustrated by a model ship, which could be moved over a "leader cable" laid along a table. The ship carried two indicating coils, each connected through relays with a light—green in one case, red in the other. As the ship was moved by hand across the cable and back again,

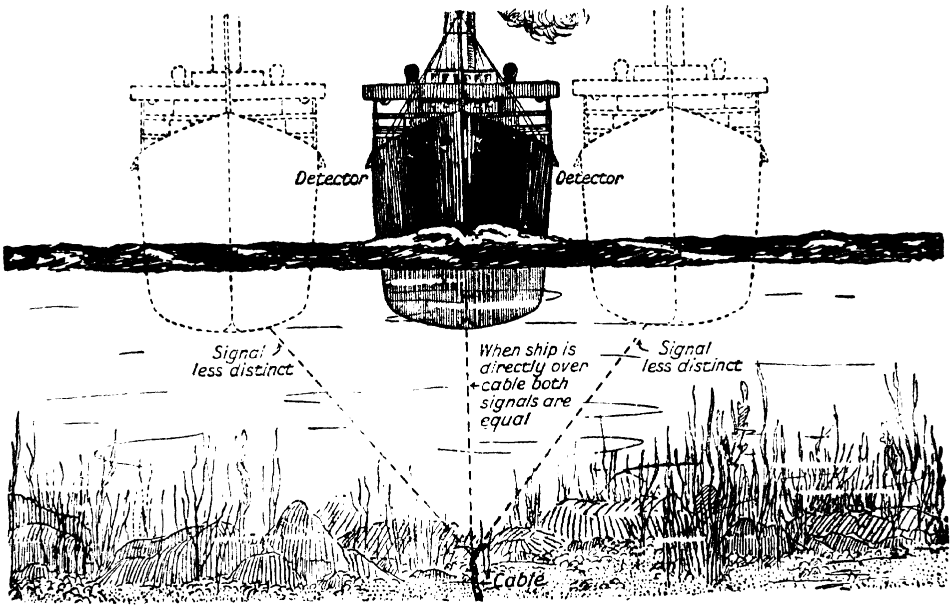


FIG. 11.—The "leader cable."

one or other or both of the lamps was lit up, showing the relative positions of cable and ship.)

We may consider one more very interesting and useful application of modern knowledge. Of recent years the problems of sound have been carefully studied, both as a part of pure science and also as being important to the development of the telephone. When it became of great importance during the war that a ship should be able to determine the depth of water below her without stopping to heave the lead, a certain method which had already been suggested was taken into consideration. A sharp and distinct sound was to be made under the ship by some apparatus connected with its hull, either just inside or just outside the skin. The sound would travel to the sea bottom, and be there reflected. The echo was to be listened for, and a measurement was to be made of the time required for the sound to go and come. This would give the depth. Two principal difficulties arise in practice. The first is that sound travels very quickly in water, about a mile a second. Consequently, a very short interval of time has to be measured very accurately. The second is that a telephone sensitive enough to observe the echo would be deafened and put out of action if it heard the

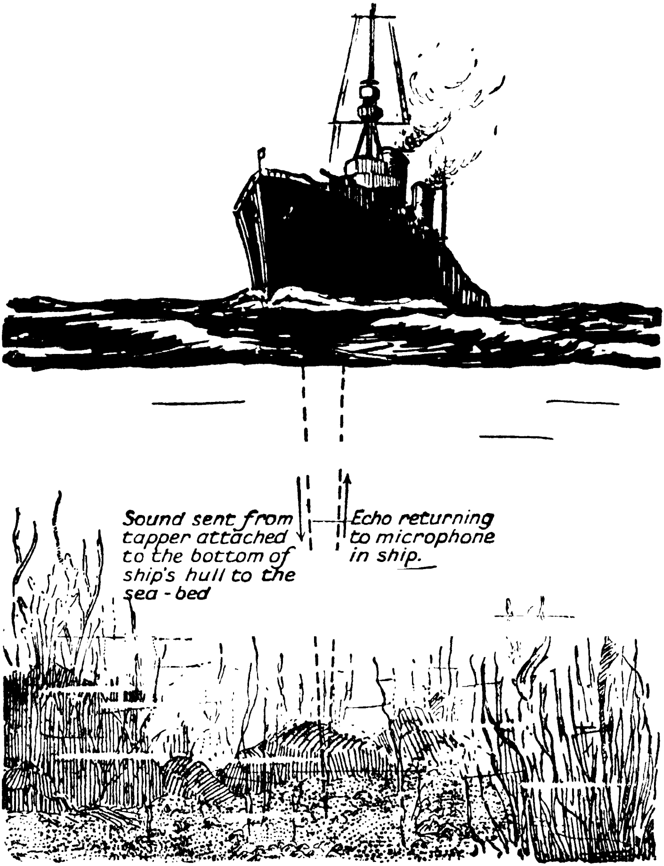


FIG. 12.—Echo sounding.

initial sound. The difficulties are got over very ingeniously by placing keys in the two chief circuits of the apparatus. One operates the electrical hammer that strikes the blow, the other throws the telephone into action when required. A revolving armature makes the two contacts at an interval of time which can be varied and can

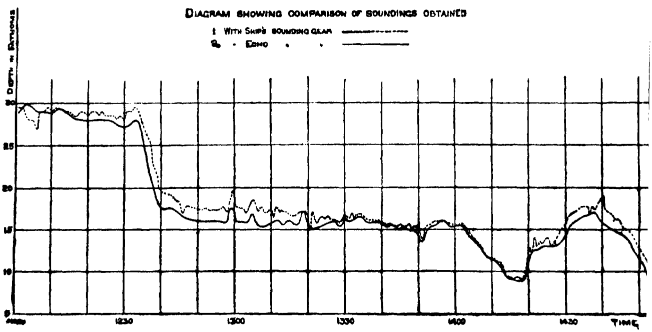


FIG. 13.—The firm line shows the soundings obtained by the echo-sounding method: the ship was in motion when they were taken. The dotted curve shows the soundings obtained on a different occasion when the ship stopped and sounded with the line in the usual way. The length of the track over which soundings were taken was six miles.

be measured with great accuracy. It is only necessary to vary the time interval until the echo can be heard. The perfection of this apparatus can be best judged by consideration of the diagram, which shows the contour of the sea-bed over a certain course in the West Indies. One line shows the depths as measured by the old and painfully slow method of soundings by line;

the other the same depths obtained by the ship using the new apparatus and travelling at speed.

In conclusion, let us observe that these new applications have been and are still being worked out in this country by our Admiralty, which now maintains several research stations for the purpose, at Teddington, Portsmouth, and elsewhere. The work which they do is of the highest importance, as I hope I have made clear, and also of the greatest interest in itself.

LECTURE II

The Trade of the Smith

THE working of metals goes back to a time so long ago that we have no clear record of how the trade of the smith first began. All that we know we gather from a few tools and weapons found in ancient tombs, or dug up here and there from the earth. We know of course that the smith is, and must always have been, an important member of his community. The development of man's powers has depended very largely on the use of metals, so that the smith has at all times been in continual demand. He has made weapons for war, tools and ornaments for times of peace. Everyone has wanted him—the hunter and the fisher, the woodsman and the farmer, the builder and every man who has practised a handicraft.

If we think of a village community in our own country, we see in our mind the smithy as an important centre of the village life ; it has been so in the past, and is so now, though it tends to trade in motor fittings rather than in horseshoes. Even more importance was attached to the trade in the days long gone by, when the smith had to make swords and armour for the men who fought as well as tools for the men who worked. Perhaps that is why there are so many Mr Smiths; we do not so often meet Mr Dyer or Mr Potter, still less frequently Mr Weaver or Mr Spinner. In old times spinning and weaving were carried on in every house, but the forge was a central spot in the village or the castle. The fact is, that the smith's trade has always required a very special skill. It is a difficult craft, full of complexities and capable of endless development; it has been growing for thousands of years, and is now growing faster than ever. It is that which makes it so interesting when we ask ourselves what there is in the working of metals to give the trade its peculiar character.

There is an advantage in trying to answer this question at once. Three main reasons can be given for the intricacy of the smith's craft. In the first place, it is no easy matter to obtain the metals from their ores, because the smelting furnace must be maintained at a great heat for a long time. We can readily imagine that centuries would, and did, slip by before the necessary skill and knowledge were gained.

In the second place, the properties of metals and alloys depend very greatly on their composition. Some are soft and ductile, some are hard, some are tenacious, some rust, some do not, and so on. The number of possible alloys is legion, though the number of separate metals is small. Each metal or alloy has its special characteristics.

In the third place, the properties of any metal or alloy depend on its internal structure as well as on its composition; that is to say, on the way in which its atoms are arranged. Now the structure can be greatly modified by heat treatment, and by mechanical treatment, such as hammering, rolling, and drawing. The behaviour of a metal at any one time depends even on its past history. This adds further complications.

When we consider these things we cannot be surprised at the length of time which has been spent in the development of the smith's craft to its present state. We may be sure, too, that the craft has passed through many interesting stages on its way. Moreover, the advances have all been made, until recently, by the simple methods of trial and error.

In the last fifty years, however, we have learned how to look more closely into the structure of metals, and have found out many things of interest and of value. We can see reasons for the difficulties which the old craftsman met, and why he succeeded sometimes, and sometimes failed. On the work of the modern smith the new knowledge has thrown a flood of light; and though we are still very far from knowing all that is to be known, it is certain that a new impetus has been given to the trade. In this light the work of the smith has been greatly extended by the discovery of many most useful alloys, and of the ways to treat them so as to obtain wished-for results. I will try presently to give a brief explanation of the new discoveries and methods. But I will first say a little concerning some of the incidents in the craft's history, in order that afterwards we may see how they can be now understood.

Let us go back to the beginning. When men first wanted weapons or tools, they took such things as were immediately at hand, flints and other stones, wood, bone, reeds, fibres of various sorts, and so on; metals no doubt came later, because they were difficult to work. Metals are mostly to be found in the form of ores, which are chemical compounds, and do not give obvious evidence of the qualities of the metals which they contain. The ores must be smelted, and it would take a long time to find out how to do that.

Here and there on the earth's surface are to be found masses of pure metal; perhaps they were the first to be used. In fact, there are good reasons for supposing that this was so. In Canada, for example, there are blocks of native copper of considerable size, and some of them show marks where portions have been severed. Masses of iron are also found which have obviously fallen on the earth's surface; they are meteorites which were travelling in space before they hit the earth. The expedition led by Ross into the Arctic in 1818 found that the Eskimos of Cape York, in Baffin's Bay, carried knives made out of pieces of iron which they had been successful in detaching from a large meteorite in Melville Bay. The "Otumpa meteorite," in the Argentine,[1] shows no fewer than six places from which portions have been severed. In Mexico there is a meteorite, weighing about half a ton, which has a gap nine centimetres long, in which is wedged a broken copper chisel left by some primitive workman. It is very likely that ancient races generally obtained their first lumps of iron in the same way; some of them, as for example the Egyptians and the Chaldeans, gave iron the

[1] A full account is given in *Iron in Antiquity* (Griffin & Co.), by Dr Newton Friend.

name of "the metal from heaven." The Greeks called it "sideros," which may be connected with "sidus," the Latin word for a star.

We do not know when metals were first obtained by smelting their ores, but we may be sure that it took a very long time to acquire any knowledge of the intricacies of the metallurgical craft. Copper and tin were obtained with some readiness by the old Mediterranean traders; they brought tin, we may remember, from Spain and Britain. Bronze is an alloy of copper and tin, so much harder than pure copper that it can be used for swords and cutting tools. It was used, as we know, for many other purposes—shields, statues, and so on; it could be moulded, engraved, and worked into all sorts of beautiful forms. It could be hardened also by hammering. The Egyptians gave such a hardness and so sharp an edge to their bronze tools that they were able to work with them on their granite blocks. Here are instances of two of the characteristics of metals of which we have already spoken—the peculiar properties of alloys, and the change of quality by mechanical treatment.

Bronze came before iron in some countries; in others the age of stone passed directly into the age of iron. In some countries again iron may have been contemporaneous with bronze. In Egypt, on the site of Troy, and elsewhere, objects of iron have been found which must be thousands of years old. Now in many cases the iron is very poor in quality. Good bronze was better than bad iron, though its preparation may have required more skill. Good iron and steel are still more difficult to make; perhaps that is why so much bronze was used when some kind of iron was to be had. In the account given by Polybius of the Celtic invasion of Italy, 223 B.C., reference is made to the poor quality of the iron used by the Celts. The Romans inflicted on them, at the Battle of Addua, near Milan, a heavy defeat, attributable to the fact that the long iron swords of the Celts were "easily bent, and would only give one downward cut with any effect; but after this the edges got so turned and the blades so bent that, unless they had time to straighten them with the foot against the ground, they could not deliver a second blow."

In the old Icelandic saga, "The Story of the Ere-dwellers," we read:

"So then befell a great battle, and Steinthor was at the head of his own folk, and smote on either hand of him; but the fair-wrought sword bit not, whenas it smote armour, and oft he must straighten it under his foot."

In an Icelandic saga of the thirteenth century we read of the last fight of Kjartan: "Then Kjartan drew his sword, and he had not with him the King's Gift. . . . The sons of Oswif and Gublang attacked Kjartan; they were five, and Kjartan and An, two. An fought well and would not move from before Kjartan—Bolti stood aloof with Footbiter. Kjartan struck hard, but his sword availed ill; so he drew it continuously under his foot." Evidently Kjartan's sword was of soft metal. Footbiter must have been a good sword—it had a name; so had Excalibur, King Arthur's sword, and Mimung, the sword of Völundr. The very fact that there were great swords or shields with famous names illustrates our point excellently. For since there was such a difference between good and bad, since iron and steel could vary so enormously through their composition or treatment, it is not surprising that the best of their kind should have a reputation. After all, their excellence was a matter of a man's life. A smith who could make such weapons was a great man. Sometimes the name of a smith has come down to us, like that of "Wayland the Smith," the hero of many romances of Northern Europe. The English version places his smithy in the Vale of the White

Horse in Berkshire. Merlin was said to have had one of the swords that he made.

There would be three elements of success in the making of a famous sword. Good material was required, yet smelting was far from being well understood, so that the material might contain many impurities. Great skill and delicacy of eye and touch would be required on the part of the smith; last, but not least, would come the need of good luck.

In some parts of the world the craftsman's patience and skill so triumphed over his difficulties that his manufactures were consistently excellent. The famous Damascene steel came from India by way of Damascus; we have all read also of the Toledo blade and the armour of Milan. When we come presently to the consideration of the effects of structure, the Damascene steel will give us an interesting illustration.

It was the difficulty of obtaining a sufficiently high temperature in the smelting furnace that was the main hindrance to the best work with iron and steel. The old practice of digging a hole in the ground, or of putting together a few stones on the hillside so as to catch the wind, was obviously insufficient; even when some ingenious persons invented the air-valve and made the first bellows (Plate VI, *b*), the advance was not enough. They could not actually melt the iron and cast it in those days ; they could only reduce it to a pasty mass in the furnace, a mass to which slag was still attached when it was pulled out of the fire. The picture from Agricola's book, *De Re Metallica*, will serve to illustrate the treatment in his time (1556). Cast iron had been made before that, but not apparently as a regular step on the way to general manufacture. Thus Agricola's picture shows the treatment of the ore in the old way. We see the master workman attending to his hearth, on which he has piled a mixture of iron ore and charcoal ; his bellows are behind the wall. The slag is melting and running away at the place marked C. The men with mallets are knocking away from a mass of iron, which has been prepared in a previous smelting, the lumps of slag that are sticking to it. The lump is then placed on an anvil, and beaten by a hammer that is worked by a water-wheel. The hammer and anvil are again used with the aid of iron knives to cut the iron into smaller pieces. Then, after they have been re-heated in the blacksmith's forge and again placed on the anvil, they are " shaped by the smith into square bars or into ploughshares or tyres, but mainly into

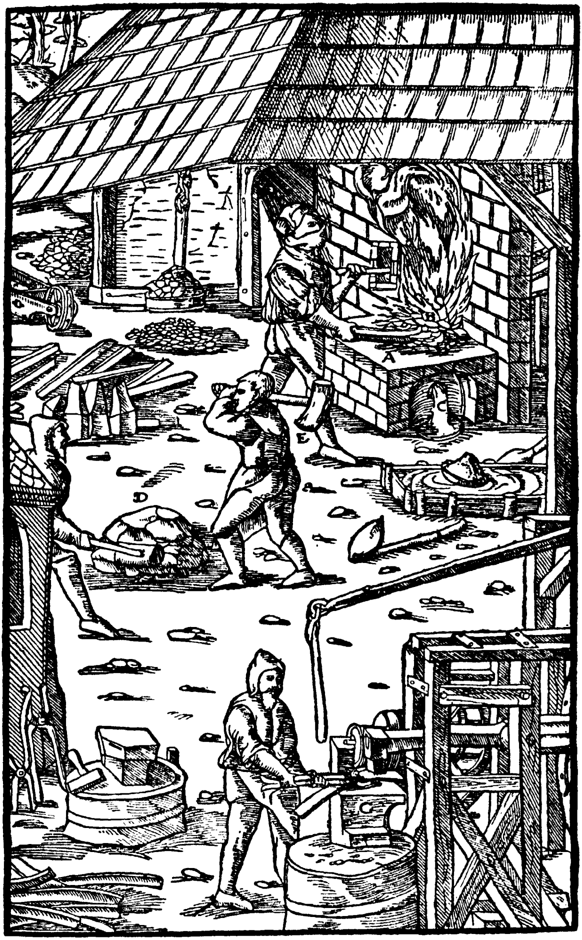


FIG. 14—From Agricola's *De Re Metallica.*

A, hearth; B, heap; C, slag vent; D, iron mass; E, wooden mallets; F, hammer; G, anvil. Notice that the man at the hearth is wearing a covering for his face.

bars." We see the workman shaping these bars in the right-hand bottom corner of the picture.

If the iron ore contained copper, or was for any reason difficult to melt, a larger, deeper furnace was used, in which a higher heat could be maintained.

The iron was not run out into moulds and cast; it was worked into lumps in the furnace, and afterwards treated by hammering and more heating. This is a most important point. The old practice limited the powers of the smith. He could only make the iron in small masses; if he wanted to make something big, he must hammer a number of small ones together. That was the method in Roman times. We find an example in a mass of iron found during excavation work in the old Roman city of Corstopitum.[1] Two pictures of this mass are reproduced in Plate VII, and show how the Romans made a large piece by hammering and welding together a number of small ones. The joins are not very good; perhaps it would be too much to say that the Romans could truly weld iron. Dr Newton Friend tells us (*Nature*, 21st November 1925) that he has recently had an opportunity of examining an

[1] Bell, Louis and Stead, *Journal of the Iron and Steel Institute*, 1912, p. 118.

iron ring found in the excavation at Richborough Castle, near Sandwich, and that there was no sign of a weld in it. It may have been made by driving a hole through a plate. A piece of iron pipe from Uriconium was examined in the same way; "on grinding down it became evident that the ring had been made by bending over upon itself a piece of sheet iron, and cementing or 'soldering' the join with molten copper or copper alloy." There are many examples of old ironwork where a weld would have been simple, and yet the workers have gone to great pains to rivet the joint, such as, for example, in old chain links. That the Romans could do beautiful work in iron is shown by the illustration (Plate VI, *a*) of an iron mask.

The production of cast iron was a tremendous step forward, one of those changes in a craft which not only make it a new thing, but even alter notably the history of the world. As soon as large masses of iron could be cast and afterwards worked up into all manner of things, the smith could launch out on greater lines. This was the turning-point from which the craft advanced to the manufacture of such massive objects as bridges, girders, steel shafts, railway lines, and many other things. The change began when the old furnaces were made larger so that larger masses of ore could be handled. The temperature would naturally rise higher in the centre of a larger mass. In modern furnaces the temperature is further increased by heating the air of the blast before it enters. On a large scale the practice is comparatively recent, on the small scale it is

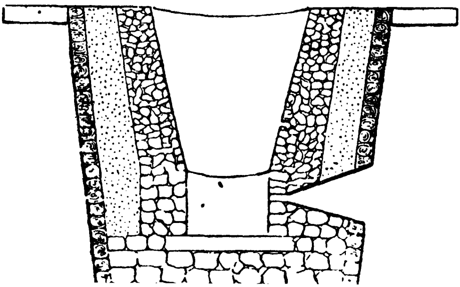


FIG. 15.—Osmund Furnace (18th century). Notice the massive walls, with wooden beams on the outside, and the mouth from which the molten material is to pour. See also Plate VI, *c*. *From Percy's Metallurgy, Iron and Steel*, p. 321.

not a novelty. The Indian smiths have long known how to use it. They sometimes build two fires—one to heat their work, the other to heat the air before it is forced into the working furnace. We have all seen, no doubt, the huge blast furnaces, nearly 100 feet high, which in the evening glow ruddily as the molten metal pours out when the stopping is withdrawn. The stream is guided down channels in the sand before the furnace and run into hollows, where it forms the "pig" of commerce (Plate VIII).

At this stage the iron contains about 2·5 to 5 per cent. of carbon, which makes it hard and brittle. The carbon has entered the iron during the smelting, for charcoal of some kind has been mixed with the ore and fired, so that the carbon might combine with the oxygen which the ore contained. The gases so formed escape into the open, leaving behind the iron and a scum or slag. Most of the impurities are removed from the iron at the same time, but a certain quantity of carbon, and sometimes of silicon, remain; and it is the presence of the carbon especially which gives cast iron its peculiar qualities. Cast iron cannot be forged into new shapes, but it can be re-melted and cast into any form desired. This is a very desirable property, so that there are many purposes for which it can be used in spite of its brittleness; the kitchen range is a familiar example.

To make steel, it is necessary to take out part of the carbon, for, when this is done, the substance becomes tougher and less brittle. It can, when heated sufficiently, be forced into new shapes, and when cooled again be tough steel and not brittle cast iron. In order to get the excess of carbon out of the pig iron, it must be heated again to melting-point, and exposed to an atmosphere containing oxygen which will then combine with some of the carbon in the pig iron and

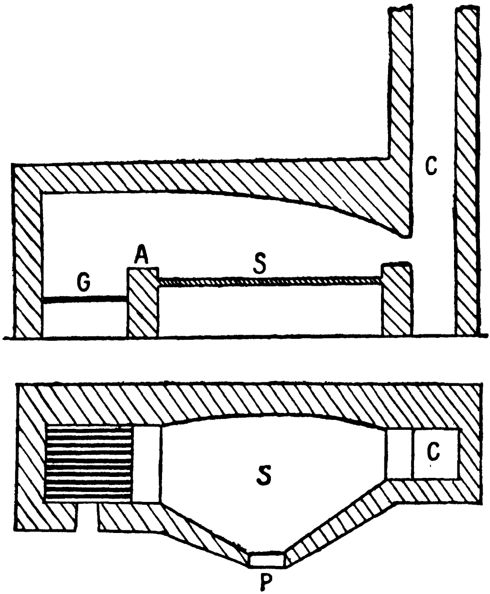


FIG. 16.—Puddling Furnace. Elevation and plan.
G, fireplace; C, chimney; S, hearth; A, fire-bridge; P, working door.

carry it away. Up to fifty years ago this was done entirely by working the iron to and fro on a hearth over which flames were passing from the fireplace to the tall chimney (fig. 16). In this process the workmen have long iron rods, hooked at the ends, which they push into the furnace through small holes about six inches square. The molten slag collects on top of the liquid iron inside the furnace and has to be continually removed; the iron gets stiffer and stiffer as it is freed from carbon, and the puddler's labour becomes greater and greater, until finally he rolls together pasty balls of dazzling white iron, and removes them one by one through the furnace door. The greater part of the necessary oxygen is supplied by the lining of the furnace, which consists of oxides of iron, and is renewed after each charge. At the last stage—the making of the ball—atmospheric oxygen plays an important part. The puddler's work is very hard and trying. The iron, refined in this way, can be hammered and wrought into convenient shapes.

But the method is not very satisfactory; it is nearly a century since any useful improvement was made in it. The furnace is not hot enough, and the labour too great in comparison with the output of iron. When Bessemer introduced, more than half a century ago, a far more efficient process, it quickly took the place of the older methods. In a Bessemer "converter" a powerful blast of hot air is driven through the melted iron. There is always a certain amount of silicon in the iron, and with this the oxygen of the air combines, so that the melt is made far hotter than before, and the whole operation is carried through much more effectively. The operation is even too rapid, and is better suited for making objects such as rails and girders, which need not be formed

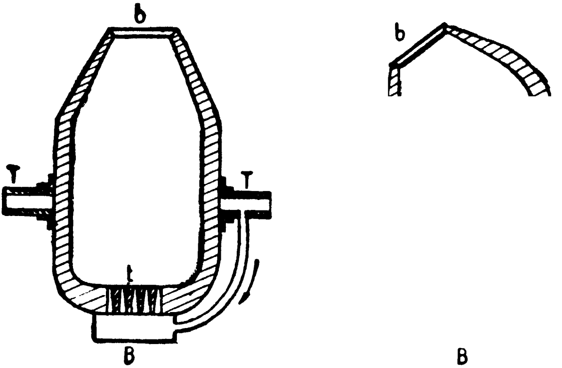


FIG. 17.—Bessemer Converter.
T, trunnion or axle; B, blast box; *t*, tubes by which air enters; *b*, mouth from which molten contents are poured when the converter is tipped up.

of the best steel. For the finer work there are other methods. In one of them the work is carried out on a hearth (see fig. 18), more slowly than is possible in the Bessemer converter. The hearth is used as in the puddling process, but the hot blast gives a high temperature, and the steel is finally poured out as a mobile liquid, not pulled out in pasty lumps.

Generally speaking, the more exacting are the requirements for the steel that is to be made, the more special does the furnace become, and the greater the expense required to work it. Often, too, the quantity required is not very

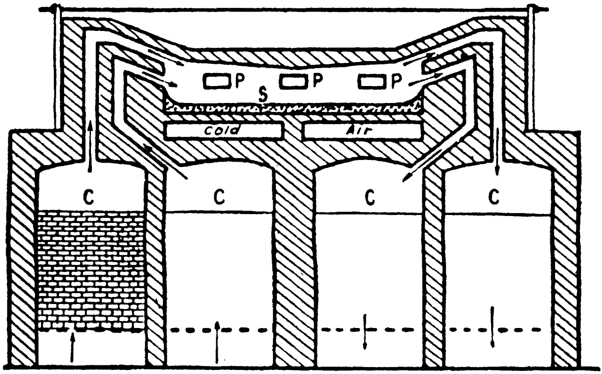


FIG. 18.—Siemens-Martin Furnace.

S, hearth; P, door; C, regenerator.

The furnace is heated by burning gas. The gas is collected from a separate plant where it is produced and led into one of the chambers, C, on the left, under the furnace. The gas and air enter the furnace together as the arrows show, and the heated products of the combustion afterwards go down into the other two chambers on the right and then up the chimney. These last two chambers become very hot, and when, after half an hour or so, the flow of the gases in the furnace is reversed by opening and shutting the proper doors, the gas and air on their way in each pass through a heated chamber before they enter the furnace. This greatly increases their heating power.

great, and the huge furnace is replaced by a comparatively "small" furnace, which, however, may contain several tons. Such a furnace is often heated by the electric current passing between huge carbon rods (Plate IX). In the ordinary arc lamp the carbons are about as thick as lead pencils;

in this case they are almost as thick as a man's body. It is a wonderful sight when the furnace is tipped up, and the dazzling stream of molten steel pours out into the "bucket," from which it is afterwards poured into moulds.

The reduction of the amount of carbon in the cast iron from 3 or 4 per cent. to 1 per cent. or less has converted the cast iron into steel; it is not a large change in composition, but the properties of the metal have been entirely altered. It has become strong, tenacious, and malleable, and it can be welded. It now possesses the very valuable property of becoming hardened by being plunged, when heated, into a bath of cold water, oil, or other liquid. Pure iron is a very soft material; steel is iron with a small amount of carbon; cast iron is iron with a larger amount. Wrought iron from the puddler's furnace may contain as much carbon as steel, but it is called "iron"; the same product obtained from the Bessemer or other furnace is called "mild steel." The names are a little confusing to the layman.

The hardening process is extremely interesting; it has lately been one of the most widely discussed problems of metallurgy. I want to tell you presently of the insight into its nature which new knowledge is giving.

There is a sense in which it may be said that the great processes of to-day are only the repetition on a larger scale of the actions of the smith in all ages. The furnace and the forge, and the anvil and the hardening vat, and the subsequent tempering of the steel are still the essential features of the smithy, though the scale has changed so strikingly. But it would be quite unfair to the smith if we forget that even the change of scale is in itself a difficult task and a wonderful achievement. We are apt to undervalue the skill and perseverance involved in it. If, say, a screw shaft has to be made twice as long and of greater cross-section than has ever been made before, it is not a matter of mere increase in the size of the furnace and the handling machinery and the charge of fuel. New problems arise from the difference in the time required to heat a greater mass and to cool it ; methods of handling must be changed, and a new technique worked out. Thus the progress from the small to the great is no simple matter ; it is a triumph of skill and energy to have made these large things simply because they are large.

But when we look more closely into the work of the modern smith we find that increase in size is only one of the changes that he has achieved.

We find that he has learned how to make his materials stronger and more enduring; how to produce them in far greater variety, a material for each purpose and use, having any special qualities that are wanted. Once there was just steel; now there are steels that are extremely tough, others that are extremely hard; steels that are magnetic, others that are non-magnetic; steels that are hard and strong when red hot, others that will resist the corroding actions of sea-water, of acids, and so on. What a difference this makes to the use of steel we can easily imagine.

Here, for instance, is one of these new alloys of steel—one of the first to be brought into use in any great quantity. It is known as Hadfield's manganese steel. Sir Robert Hadfield is one of our own members, and was lately a manager of the Royal Institution, and we may look on it as a mark of his friendship for us and of his interest in the Christmas lectures that he has sent us some fine specimens of this and other steels which were made at his works in Sheffield.

Manganese steel has very strange properties. When heated and then quenched in water it becomes tough, not hard, and it has no magnetism. The specimen on the left (Plate X, *a*) has been toughened at one end, the other has been left in the state which it reached when it cooled down after it was made. This end is magnetic ; the other is not. The one is hard and is even brittle to some extent, though I could not show you that it really is so. The non-magnetic end can be bent and has, indeed, been curled over into a loop, as you see. It is the latter steel that is so useful, because it is both tough and strong. The piece on the right in the same illustration has been stretched to the breaking-point. It began to yield at 26·7 tons to the square inch ; increase of stress caused it to stretch until its length was nearly doubled ; actually the increase was 85·6 per cent. When it broke, the pull was 73 tons to the square inch. Alongside it is shown for comparison a similar piece that has not been put into the testing machine. It is interesting to see that the bar has not developed a waist where it has broken, and further, that the non-magnetic character is preserved.

Now, another strange property of this steel lies in its response to rough treatment ; it becomes harder in places where it is beaten or rolled. Consequently it is of great use in such a case as is shown in the picture (Plate X, *b*)—a set of intricately crossing railway lines. The wear and tear round such sharp curves is excessive, and ordinary steel rails are quickly destroyed. We have all seen the deep grooves worn in tram-rails at places like this. But the alloy steel hardens itself to its work, and the "lay-out" that is made of it lasts several times as long as when the older material is used.

Another kind of steel with which we are all familiar is that which is known as "stainless" steel. It was quite by accident that Mr Brearley, of Messrs Brown, Firth & Co., when searching for a fit material for the linings of large guns, found that an alloy of iron with chromium resisted the rusting action of water. The alloy, as now used, contains 14 per cent. of chromium; the rest is iron. It is largely used in the manufacture of cutlery. Its virtues have been even a little harmful to its reputation, since the knives are no longer rubbed on the knife-board, and miss the sharpening which they received while they were being cleaned. An alloy of iron with 18 per cent. of chromium and 8 per cent. of nickel is more resistant even than the original mixture; it is tough, and yet is soft enough to stand pressing and punching into the form of bowls and such-like things.[1]

[1] Messrs Brown, Firth & Co. were good enough to send an exhibit for display at the lecture: turbine blades, golf-clubs,

Then there are steels which can be used in making "high-speed" tools; that is to say, tools which will keep their hardness on the lathe even when they are turning off such thick strips of metal that they become red hot. Other steels are made which will stand the higher temperature of a furnace without scaling; such steels are invaluable in the manufacture of pincers, travelling furnace bars, and so on.

If we consider other metals than iron and its alloys we become lost in their multiplicity, and the number of uses for which they are adapted; aluminium alloys and magnesium alloys are very light and yet strong enough for use in aeroplane structures or in the moving parts of motor-car engines. There are alloys for use in dynamos and motors, others that are used by jewellers; alloys for bells, for gear wheels, and so on to an endless list. Perhaps one of the most remarkable of modern alloys is permalloy, or mumetal, which is of nearly the same composition. Four-fifths of permalloy is nickel, the rest iron; mumetal contains 5 per cent. of copper and less nickel. It is

and instruments made of chromium steel; dishes, trays, candlesticks, drawn tubes, and wire of the second alloy. One sample had been towed behind a ship to New Zealand and back, and was as bright as when it started.

easier to magnetise even than the softest iron, and loses its magnetism the moment that the magnetising current ceases. A simple illustration can be given (as shown on Plate X, *c*). Two exactly similar electro-magnets are made, the cores being of soft iron and of mumetal respectively. The same current can be made to pass through both. The second magnet holds up a given weight when the magnetising current is too small to make the first magnet do so ; on the other hand, when the current is sufficient to make both coils act, so that equal weights hang from the two, the second coil drops its weight the moment the current is cut off, but the first does not. It retains its magnetism for a time. The properties of permalloy were discovered in the Western Electric Company's Research Laboratories during a methodical examination of the properties of nickel iron alloys of various proportions. The discovery is of immense importance from an economic point of view. When a submarine cable is served with a tape made of permalloy, the cable can carry three times as many readable signals in the same time. It is as good as three ordinary cables. I am afraid it would be quite impossible to explain this difficult point in our short hour ; anyone who wishes to understand it must study the theory of the subject. Our interest is in the simple fact that the choice of a certain proportion in an alloy of two well-known substances, nickel and iron, has unexpectedly increased by several times the working capacity of submarine cables.

I have taken these few examples of alloys as illustrations, not only because they are interesting and important, but because they give us an idea of the complications of the subject. We feel that we should like some key, if it were to be had, to unlock these mysterious effects. Now we shall find something of the kind if we consider what various workers in research laboratories and elsewhere have been doing in the last half-century, and more particularly in recent years.

A great step forwards was made at Sheffield in the middle of the last century when Sorby showed how much could be learned from the microscopic examination of polished specimens of metals. If, for example, we look at the first of the micrographs (shown in Plates XI–XIII)—a specimen of pure iron, magnified 150 times—we see the remarkable division into " grains " which is so characteristic of a metal. Each grain is a separate crystal of iron. It must not be thought that the grains are easily separated from one another; the grain boundaries are quite strong. The next four illustrations are micrographs of steel containing various percentages of carbon. The spiky objects in the last of them are cementite, which is a definite compound of iron and carbon; their presence tends to harden the steel. These two steels differ greatly in appearance, and also in their properties. The next four figures represent manganese steel. The first of them (Plate XII, *c*) is a specimen that has been heated to 1000° C. and then quenched in water; the next shows the effect of subsequently heating the same steel to 500° C., and keeping it at that temperature for sixty hours, after which it was slowly cooled. This steel is hard and magnetic; the former was far stronger, tougher, and non-magnetic. The next two show the effect of mechanical treatment. The first of these has been greatly strained in the testing machine; we can see how the grains (Plate XIII, *a*) have now the appearance of packs of cards on edge; they have formed internal layers which have been sliding on one another. The last is even more complicated still.

These few illustrations will serve to show how quickly the appearance under the microscope changes with composition and treatment. The metallurgist who has devoted himself to the study of these changes learns to connect certain appearances with certain properties, so that his microscopic examinations tell him a story of the results of various treatments, of what is to be done to change the properties, of similarities and differences, and so on. He learns, of course, to know the nature of the various grains and needles and other structures which he sees. In fact, he begins to know what is going on, and what has been the treatment which any particular specimen has received.

Let us take an example, which has an interest of its own. Not long ago a bronze "celt" or chisel was found in a field near Shrewsbury. Pieces were cut from various parts of it and prepared for examination under the microscope; the results are shown in Plate XIII, *c*. From these the metallurgist learns that the back of the celt was cooled down steadily from its heat during the making; that the edge was subsequently hammered to harden it—the marks of working are to be seen on the grains in the original photograph; and, lastly, the celt was heated to a moderate temperature and cooled therefrom, because the hammering had made it too brittle.

This examination by means of the microscope has done wonders for the advancement of metallurgy. It has been backed up by new and accurate methods of measuring the temperature of the furnace. The changes in the internal structure of metals which occur during heating will take place if a sufficient temperature is maintained for a sufficient time. It makes an enormous difference to the control of an operation if its progress can be watched and measured accurately. There are other measurements of various kinds which in these days are attended to very carefully. It is in all these applications of new knowledge that we find the explanation of the discovery of so many new steels and other alloys.

Within the last few years another new method has come forward to help in the understanding of the processes of the craft. The X-rays are able to look into the structure of metals 10,000 times more deeply than the microscope, and I am anxious to show you something of what they tell us, because it brings some order into the mass of facts that the smith has to reckon with. The X-rays take us down to the very foundation of things. It is rather a relief to begin to build up from below, instead of working our way down from above.

They tell us that the atoms of a metal are piled together, in general, in some very simple manner. We take, for instance, a square tray, and put into it a layer of balls as shown in Plate XIV, *a*. They are to be spaced a little, the distance between each pair being adjusted according to a rule which will be explained in a moment. On this layer we lay another, which is exactly like the first, except that its level is different. On this we lay a third; the balls of the third will lie exactly over those of the first. Of course the layers are shrinking in area as we go up, because the balls cannot be supported at the edge unless we build a square tank with glass walls. The adjustment spoken of a moment ago has to be such that the height of a ball in the third layer above a ball in the first is the same as the distance between two neighbouring balls in the same layer. If we go on adding layers, we find we are building a structure in which every ball lies at the centre of a cube formed of eight neighbours.

This is the way, we are told by X-rays, that the atoms are arranged in iron. The distance between the centres of two iron atoms which touch each other is just the hundred-millionth of an inch. Only X-rays can measure such small distances; they are far beyond the range of the microscope.

If a number of iron atoms are laid together in this regular order they form a true crystal. It is true that when we think of a crystal we have in our minds a body of regular shape and glassy surface, like a piece of quartz or of sugar-candy. But the iron is just as much a crystal. All three—quartz, candy, and iron—possess regularity of arrangement; but the iron does not show it externally.

If we go back to the microscopic picture of Plate XI, *a*, we can look at it with more understanding, for, in fact, each of the grains is a crystal. The atoms do not lie in the same way in two neighbouring grains, so that the two do not dovetail into each other perfectly. There is actually a sharp line of division between them, which comes out in the etching of the specimen. This junction is not a weak place, however; why not, we do not know, for certainly we might have expected it to be. The different lines in the various crystal grains are clearly seen in Plate XIII, *a*, where the strain has caused layers of atoms in each crystal to slide over one another; it is clear that the lines in one crystal are not parallel to those in its neighbours. The sliding of the layers and the consequent appearance of lines on the face may be illustrated by the distortion of a pack of cards.

Now the X-rays tell us that there is a second manner in which the iron atoms can be arranged, and that they take up this arrangement when the temperature is raised beyond a certain point —about 900° C.—which is the temperature of a bright red heat. This is really where the influence of temperature on the structure of iron and steel comes in. The new arrangement can be shown by piling up balls on a triangular tray, as in Plate XIV, *b*. In each layer the balls now touch their neighbours, and in the whole structure each ball has twelve neighbours—six in its own layer, and three in each of the layers above and below. In the former condition each ball had only eight neighbours—four in the layer above, and four in the layer below—so that the atoms are more tightly packed when the iron is hot than when it is cold.

There is a beautiful old experiment which demonstrates this point (Plate XIV, *c*). An iron wire, 6 feet long or so, is heated by the passage of an electric current. One end of the wire is fixed, the other moves as the wire stretches with the heat ; it is easy to contrive a magnifying arrangement so that a pointer is made to move visibly across the scale. The current is turned on, the wire stretches, and the pointer moves. When the critical temperature is reached the pointer halts slip will occur all over a certain plane. If we had two blocks of glass, let us say, held together by grease, as in fig. 20, and pulled them, they would give along the plane between them. Naturally they will slide over one another on this plane rather than themselves be torn to pieces. We

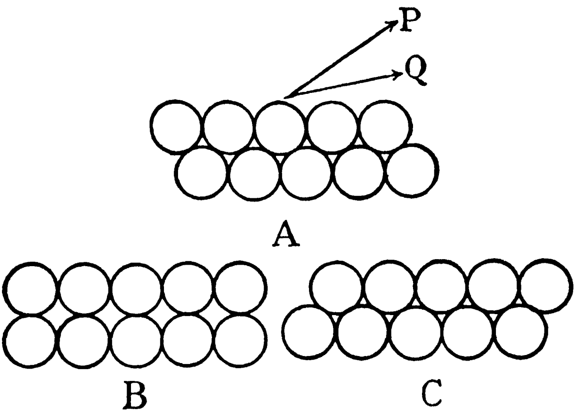


FIG. 19.—Model illustrating the occurrence of slip in a metal. The top row of spheres is pulled, in one piece, by a force P or Q, so that after passing through the position B it settles itself again, as at C.

might represent the crystal by a set of lines, as in fig. 21, *a*, which, if pulled in the direction of the arrows, would yield, as in fig. 21, *b*. Often, when a single metallic crystal has been stretched, we can see the marks on its surface which show the lines along which slip has taken place.

A very beautiful example of the marks due to slip is shown in Plate XVII, *b*. The figure represents a sodium wire, which has yielded to a stretching force; the marks are circular. If we look a little closer we see that these are, in fact, two sets of circles criss-crossing one another, which brings out a very interesting point. Not every plane in

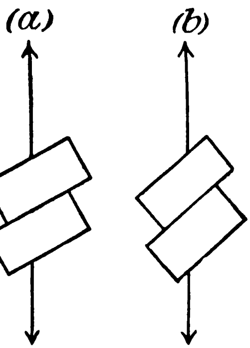


FIG. 20.

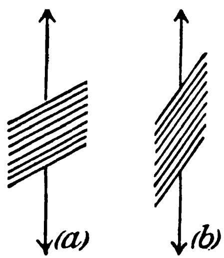


FIG. 21.

a crystal is a slipping plane; there are certain planes along which slipping takes place most easily. But in each crystal there are several sets of these planes. If, for instance, the arrangement of the atoms is as in Plate XIV, *b*, which is the arrangement of iron above 900° C., of aluminium, and of copper, the four possible sets of slip planes are parallel to the four faces of the tetrahedron.

When the crystal planes slip on one another they become more nearly parallel to the line of pull. This is illustrated in fig. 21, *a*. Of two sets of planes along which slip might take place, the set along which it does take place is the one which is the more nearly at right angles to the line of pull. This is an experimental fact. Perhaps we may think that it happens because a more perpendicular pull, as at P rather than Q in fig. 19, will tend to lift the atoms in one layer over the hills they must ride over on their way from the arrangement in A to the arrangement in C. So a sort of see-saw arrangement sets in ; the crystal slips on one set until this becomes too nearly parallel to the line of pull, and then it slips along another set. Finally the two sets become equally inclined to the line of pull, and the slip goes almost simultaneously on the two. This is why we see the two sets of slip lines on the sodium crystal.

In the case of the test-pieces stretched to rupture (Plate XV) the whole piece has given way in each case because of the slipping on the planes of a single crystal. In Nos. 1 and 2 the planes run mainly from side to side, in the others from back to front. The former set, therefore, show the development of a waist ; in the others the specimen becomes thinner from back to front before it breaks, and this is, of course, not visible in the photograph.

A single crystal of a metal may generally be bent or distorted with the most surprising ease. If one of the aluminium test-pieces is held in the hand, a mere flick will bend it double. Now, an ordinary piece of aluminium of the same dimensions is quite stiff. Clearly we must suppose that when some force tries to distort the metal, the separate crystals all want to slip in different directions; and since that cannot happen, the material is able to resist the force; it is tougher and harder. We have to suppose, at the same time, that the junctions of the crystals are strong enough to withstand the force. Here is a fact of which we should like to know more. The general conclusion is clear enough, that a single crystal easily gives way in certain directions; and since a chain is no stronger than its weakest link, we must say that a single metal crystal is in general a weak thing.

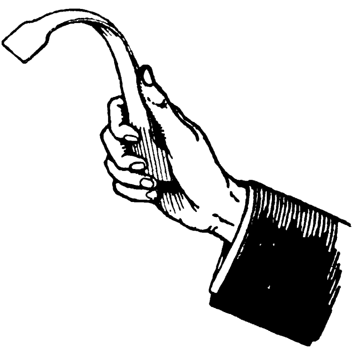


FIG. 22.—A single crystal of aluminium is easily bent by a flick of the hand.

We go a little further, and say that anything which causes the arrangement to depart from the regularity of a single metal crystal tends to harden it. This may happen when the specimen contains many crystals; it may also happen when any single crystal is internally strained by the presence of stranger atoms or from other causes.

Now we can see how an alloy can be stronger than a pure metal; it is because the arrangement in the alloy is not as regular as the simple arrangement of the pure metal. It is somewhat distorted and strained. This certainly is one of the reasons why the presence of a certain amount of carbon in iron gives the latter the strength of steel. The carbon combines with the iron to form cementite, a crystalline substance containing three atoms of iron to every one of carbon. If there is not too much carbon, a substance called pearlite appears, which is a mixture of iron and cementite in fine alternating layers; it is this which gives to steel its peculiar strength and toughness. If there is 0·9 per cent. of carbon, the whole of the steel is made of this tough mixture. Above that percentage needles of cementite are to be seen under the microscope and brittleness appears. An interesting example of their effects is found in the old Damascus steel—a steel which contains much carbon, and would, when first brought under the hammer of the sword-maker, contain many of the crystals. The smith heats the metal in his tiny furnace; for a moment it becomes slightly malleable, and he can forge it and mould it to the shape he desires. But the heat soon leaves it, and he must put it back in the fire. Each time he hammers it the needles break up a little, and their sharp corners are rounded off. The steel becomes more pliable when this takes place, and finally, after many heatings and hammerings, the smith produces the steel which is so famous.

The "damask" appearance of Plate XVII, *d* is due to the presence of innumerable light-coloured specks of cementite. They are arranged in layers which were formed during the making of the steel, and have been laid and overlaid until the wavy pattern appears, as it does sometimes in much-folded pastry.

We now begin to see why the steel becomes hardened when it is heated and plunged into cold water. When it is hot, the atoms of iron are arranged as in Plate XIV, *b*, and the carbon atoms are distributed through it in some way which will involve as little strain as possible. When it is cooled suddenly the iron atoms rearrange themselves, and do it so quickly that there is no time for the carbon atoms to take up the positions of least strain in the new arrangement. We may be sure that the most convenient arrangement of the carbon atoms is not the same in the two cases; in fact, if the metal is allowed to cool slowly, we see the carbon separating itself from the iron to some extent. The iron gathers in little masses of nearly pure iron, which are technically known as ferrite; much of the carbon forms with the iron the crystalline cementite. In this condition the material is soft, if there is not too much carbon. When the quenching in cold water stops the metal from acquiring this easy arrangement, it is tougher and harder. The natural arrangement is interfered with; slip planes cannot act.

The more complicated case of manganese steel, as well as of other iron alloys of similar nature, can now be explained as well. It seems to behave in a sense exactly the opposite to that which is found in steel. It is tough and ductile after being heated and quenched. It is hard if it is heated and allowed to cool slowly. It becomes hard also if, after having been heated and quenched, it is again heated to a temperature lower than the critical temperature and kept there for some time.

The fact is, that the presence of manganese and certain other substances has the effect of delaying the change in arrangement. When the steel is heated and quenched, the change-over is delayed until the metal is cold, and it is too late. Consequently the molecules of manganese steel when so treated are still in the arrangement of Plate XIV, *a*. With this arrangement the steel is non-magnetic. The steel is ductile and tough because the arrangement of the carbon atoms in it is that which suits this arrangement. But if the steel is now heated moderately, the delayed change in the arrangement of the iron atoms takes place, because the heat increases their movements, and they slip into new places. The steel at once becomes magnetic, and it would appear that the carbon atoms do not take up positions which allow of slip. The difference between the two states is well illustrated by the specimen of Plate X, *a*.

During the war the army was supplied with helmets of manganese steel, which were capable of resisting the fragments of shrapnel. It was found, unfortunately, that the hats could be used as cooking vessels. An order had to be issued hastily, forbidding the practice, because obviously the heating over the fire replaced one arrangement of atoms by the other, and spoiled the helmet entirely (Plate XVII, *a*).

For the same reason the presence of tungsten and chromium prevents any rearrangement of atoms when the steel containing them is raised even to a red heat. That is why such steels are used for tools that become red hot when cutting other metals on the lathe.

Hardening may be produced in yet another way; the aluminium piece which gave way so readily to a flick of the fingers will not yield in the same way an indefinite number of times. It becomes harder and harder. In some way or other the simple arrangement is disarranged; perhaps the layers that slide over one another become rumpled, or little groups become disarranged; it is a matter still under discussion. There is obviously far more to be discovered yet before we can connect perfectly the hardening of metals, which is so fundamental to the smith's work, with their internal structure. Progress is being rapidly made, however, and I think that the new knowledge which I have just been describing will bring its harvest, as did the information which the microscope gave first to Sorby, and after him in due time to all those who work in metals.

LECTURE III

The Trade of the Weaver

It is very interesting that in making clothes for ourselves and coverings of various kinds we still use, for the most part, the same materials as were used long ago. Wool and cotton, flax and silk, have been known for thousands of years; the so-called artificial silk is our one novelty. Further, the methods of spinning and of weaving them into fabrics are essentially the same as in ancient times. It is only the scale of the work that has changed; great machines do that which was once done by human hands, and is still so done in many parts of the world. Each movement of the hands of the spinner and the weaver has its counterpart in the modern mill. This has to be so, because the fibre is really a very complicated affair in itself, with special characteristics that demand special treatment—a treatment which is necessarily the same whether it is applied by hand or by machine.

Now, the skill acquired by the spinner and by the weaver is amazing. One cannot look into the structure of a product, such as an old hand-woven Paisley shawl, in which the fine silks are interlaced into a most complicated and delicate pattern, without a feeling of wonder. Think of the fineness of touch of the Indian cotton-spinner who could, so it is said, produce from a pound of cotton a thread 250 miles long. Machinery is hard put to it to reproduce such work. Its special value is that it can go a long way towards doing so, and by its power of multiplication it enables an immense number of people to enjoy beautiful things. If *no* good work could be done except by hand, the average share would be very small indeed.

Let us watch someone setting out to spin a woollen thread in the old way. We may suppose that he has cleaned and washed his wool, and has come to the stage of arranging its fibres for spinning ; he is now to " card " his wool. He has two small boards, each covered on one side with bent hooks, as is shown in Plate XVIII, *c*. He puts a little wool on to one of his boards, and pulls the other across it in such a way that the two sets of hooks pass through each other, pointing opposite ways as they do so. This operation repeated a few times " combs " the wool ; the fibres are then lying approximately side by side. They can be made to lie wholly on one carder by reversing the direction in which one carder passes the other; the hooks on the two sets point the same way, and the set that is relatively moving faster in that direction takes all the wool. By a little manipulation the wool is finally arranged in a roll-shaped, very light pad, called "sliver." The fibres are now well separated from one another, and uniformly distributed through the mass. When a sufficient quantity of sliver has been prepared, the spinner takes his spindle and distaff.

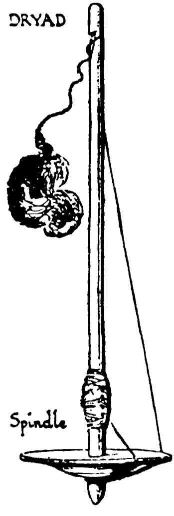


FIG. 23.—A spindle. The hank on the left is the wool for spinning. When the spindle is in use it hangs by the half-made thread attached to the hank, and is set spinning so as to twist this thread.

The spindle is just a rounded slip of wood with a little bob of clay, wood, or metal, to which spinning energy can be given. At one end is a notch, to help in fastening down the first fibres to be spun. The spindle is set into quick motion by the action of the hand, or by rubbing between hand and thigh, as the Italian peasants do. Wool is fed into the twisting thread from the loose mass, already cleansed and combed, on the distaff, and the thread grows in length. The first question one would ask is fundamental: how do the fibres hold together, and in what way does the spinning help them to cling? If the natural fibres are examined under the microscope, it is found that they all show irregularities. The wool fibres have scales; flax fibres have knots like a bamboo; cotton fibres have many kinks and twists. If they are pressed tightly together, friction and irregularities of surface keep them from slipping past each other (Plates XVIII, *a*, *b*; XXVII, *a*). The requisite pressure is given by the twist.

There is also a very interesting compensating effect which has to be borne in mind, an effect which is essential to the spinning process. Suppose that the hands draw out a little sliver to be fed into the thread. There must be one point in it which is weaker than the rest, and will give way if the hands draw out the wool too much. As it begins to give, a neck is formed at that point. But if twist is being given to the thread, the thin part takes up more of the twist than the rest, and as the fibres there are drawn more closely together, they cling to each other more firmly. In the end, the thin part becomes stronger than the thick, and so some other part next takes the draw until it also is strengthened by twist. The point is illustrated in the accompanying figures. If, therefore, twisting and pulling go on together, the thread tends to become uniform throughout its length.

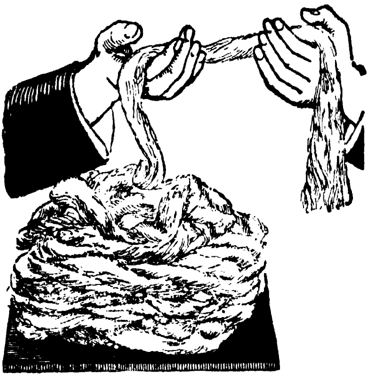


FIG. 24.—Sliver.

When the spinner has completed a certain length, feeding in wool as required, the portion which is finished is wound on to the spindle and fastened there; then the operation goes on as before.

FIG. 25.—The sliver has been pulled out, and a weak place has developed itself. The sliver is now spun, and the thinner part takes all the twist.

The spinning-wheel is more elaborate than the simple spindle, but in one of its methods of use it goes through exactly the same simple operations. The spindle is made to revolve rapidly by the driving band that links it to the wheel.

The spinner holds his thread more or less in the direction of the axis of the spindle to which the thread has been fastened, and spins as with the simpler apparatus we have already considered. When he has finished a convenient length he changes the position of his hand, so that the thread is perpendicular to the wheel, and as the spindle turns it winds on the thread. The illustrations in Plate XIX will make this clear.

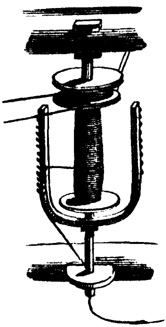


FIG. 26.—The flier is the Y-shaped body furnished with hooks. It revolves about the common axle, and is driven by one of the wheels shown. The bobbin is driven by the second wheel, which revolves more slowly than the first. The thread from the distaff enters the tubular axis at the bottom of the picture, comes out at a hole just above the bearing, passes to one of the hooks on the flier, and then to the bobbin. The two driving cords from the small wheels go to the big wheel, which is not shown. (*By courtesy of "Chambers's Encyclopædia."*)

The other method of using the wheel is more ingenious and elaborate, for it spins and winds at the same time. For this purpose the "flier" is introduced; the illustration of fig. 26 will explain its action. It is like a mechanical hand, which runs round and round the spindle, winding the spun thread on it; and it carries little hooks over which the thread slips, just as it would slip through the fingers and thumb of the hand. It has to revolve a little faster than the spindle. If the two revolved at the same rate, there would be no winding, of course, but there would be a maximum of twisting. If the flier went much faster than the spindle, there would be too much winding and too little twisting. So flier and spindle are driven at different rates. In this process spinning and winding go on together without alternation.

If we understand these simple methods and machines which have been developed in the course of the ages, we can equally understand the essentials of a modern spinning-mill. We may at first be appalled by the multiplicity and complexity of the whirring machinery; but we must soon realise that what we see is an attempt—and a very successful attempt—to replace the intelligent hands of the spinner by the action of wheels and rollers and guides, and to multiply the spinner's simple tools. We see thousands of spindles in rows on each side of us; each is, after all, one spinning-wheel.

The wool or cotton seems at first to be going through many more processes than when it is treated by hand, but this is only because more and shorter steps are taken to reach the same end. The washing and cleaning are done by a succession of machines. The simple carders are replaced by a huge affair (Plate XX, *b*) with many great hook-studded rollers, which comb the fibres and pass them from one to another, finally delivering an even flow of sliver at the far end of the machine.

Again, in the old style of spinning there is a simple action of the hands, which takes the wool from the distaff, and draws it out to a suitable extent before passing it on to the thread. This finds its parallel in the action of the pairs of rollers through which sliver is passed in succession, each pair moving a little faster than the pair before. Thus the loose sliver is drawn out uniformly and without break; sometimes several slivers are drawn, joined together, and again drawn, so as to make the combined sliver more uniform. A little twist can be given on each repetition of such a process, so that the sliver can be stretched without fear of breaking, and in the end a coarse loose thread is formed known as "roving." There is little twist in it, so that it is very weak; it is the final operation of spinning that gives it strength. This very general description applies to both cotton and wool, but there are important differences of detail in the treatment of the two.

It was about the middle of the eighteenth century that machinery began first to be employed. We can easily imagine how it would happen. Here was an active and intelligent set of people, living in the hills of southern Lancashire and Yorkshire and the neighbouring lowlands, each man spinning and weaving in his own cottage. If he lived in the country, he carried his finished goods by pack-horse to the neighbouring town. The old footways, like a series of stepping-stones, are still to be seen in many places. And, as he brought back his money and the raw material for fresh work, he must have wondered how he could multiply the simple operation which he knew so well. He could spin with scarcely a thought of what he was doing; why should he not spin several threads at once, and bring in more money to his home and his family? In the end that is what James Hargreaves, a weaver of Blackburn, actually did, in 1767. He made a frame on which were mounted a number of spindles (Plate XXII), each the equivalent of a spinning-wheel. A travelling carriage held the bobbins on which were wound the "rovings," *i.e.* the sliver which had been stretched and slightly twisted to give it strength. The operations are best described in the Textile Machinery Catalogue of the Science Museum at South Kensington, where a replica of Hargreaves' machine is to be seen:

"The spinning-jenny, which marks one of the first steps in the development of cotton-spinning machinery, was invented by James Hargreaves, a poor weaver of Blackburn, between the years 1750 and 1757, and patented in 1770. The principal merit of the invention lay in the fact that one spinner could spin 120 different threads at a time, whereas previously, on a spinning-wheel, he could only spin one thread at a time. Other new features of great importance were: the travelling carriage, which drew out from the bobbins of roving definite lengths, stretched them, and, by the rotation of the spindles, twisted them; and a wire guide which, pressing on the twisted yarn, formed it into cops on the spindles as the carriage returned. The method of drawing out a roving finer by passing it between pairs of rollers revolving at different speeds had been invented by Lewis Paul in 1738, but Hargreaves may not have heard of it, for, although the patent had expired in 1752, he did not use it in his jenny. Arkwright, however, incorporated the arrangement in his water-frame in 1769.

"The spinning-jenny led directly to Crompton's mule, but lacked most of the motions which enabled the latter machine to spin the finest counts and, when made automatic by Roberts, to survive without essential alteration until now."

Crompton's mule, referred to in the extract above, was devised between 1774 and 1779. It worked on the same principle as the "spinning-jenny" of Hargreaves, but with many important improvements. Moreover, it contained "drawing rollers" to draw sliver finer before spinning. It "holds" the yarn very carefully while spinning, so that it can spin finer threads than any other machine. It is fascinating to watch its working in a great mill (see Plate XXI), its actions are so intelligently devised and so perfectly balanced. One sees the great travelling frame carrying hundreds of spindles, starting from a position close up to the reels that carry the "rovings" to be spun. It moves backwards, drawing off roving as it does so, and giving it a slight spin because the spindles are revolving a little. When a sufficient length has been drawn, the further delivery is stopped; but the carriage still goes on a little, stretching the rovings, which will stand it now because of the twist they have got. The carriage stops, but the revolving spindles go on putting in the necessary twist, and the carriage returns a little on its track to ease the increasing strain. Suddenly the motion stops; wires come down on each spindle to stop the yarn from slipping continually off the end as it does while it is being spun, and back goes the carriage, winding the threads on to the spindles as it does so. It is going back for more.

The jenny and the mule are the mechanical development of that method of using the spinning-wheel which is illustrated in Plate XIX, the method in which spinning and winding alternate. It is in certain respects better than the alternative continuous methods, for it can spin finer and more delicate yarns than the latter; perhaps because better work can be done in each of the two operations, spinning and winding, by keeping them distinct. The continuous method, in which spinning and winding go on together, also has its mechanical development. It was Richard Arkwright who devised it. The Science Museum contains the original machines which he made. The second of these, made in 1775, is shown in Plate XXIII. It has eight spindles, each fed by a "flier," as in the spinning-wheel. The thread passes down the hollow stem of the flier; it is spun by the revolutions of the flier and wound by the difference in speeds of the flier and the bobbin, just as in the use of the spinning-wheel in Plate XX, *a*. Arkwright had a frictional arrangement for altering this speed difference. He also included in his mechanism a device for winding the thread evenly on the bobbin. In the spinning-wheel there are separate hooks on the flier, which are used in turn, the thread being shifted from one to another by hand. But Arkwright adopted the much more efficient method of moving the bobbin continuously up and down, so that the threads were wound evenly over their whole length; the idea is said to have been due to Hargreaves.

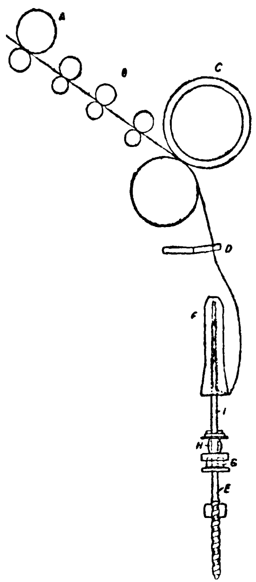


FIG. 27.—The "cap" spinning device. The yarn which is coming down from the rollers at the top passes on to the bobbin I over the edge of the cap F. The bobbin is revolving rapidly, and there is enough friction between the yarn and the rim of the cap to prevent the thread from following the bobbin too fast, so that it is wound as well as twisted.

An illustration of a modern spinning-machine is given in Plate XXIV, *a*. In these days there is more than one substitute for the flier. One of these, known as the cap device, is illustrated in fig. 27. Another which is specially fitted for quick working is known as the "ring." But it is not easy to follow the working of these devices without actually seeing them in use; they are all devised to combine spinning and winding in proper proportion.

From these early models have grown the immense machines of to-day. No one can look at the old machines without feeling what they meant once to the men who made them. They stand motionless now: a few idle threads link together the worn rollers, the reels, and the spindles. But once the inventor's eager hands shaped every detail, and his eyes followed their rapid movements; and there would be many a weary moment and many a happy one when ingenuity surmounted some difficulty. And then at last they really worked. But even success brought its pains. Hargreaves made his jenny, and worked it secretly in his garret. His neighbours became alarmed when they found that the tale of his work was greater than could possibly be achieved by his small family, working in the old way. They spied on him, discovered his secret, broke up his machinery, and drove him from his home; he was forced to flee for his life to Nottingham. After all, we can understand that too. The neighbours looked on him as a greedy man, trying to take more than his share of the work that was to be done, so that they would be deprived of their own living. It has happened over and over again. "In Dantzick," says an old writer, "there was set up a rare invention for weaving of 4 or five Webs at a time without any humane help; it was an Automaton or Engine that moved of it self and would work night and day; which invention was supprest, because it would prejudice the poor people of the Town; and the Artificer was made away secretly (as 'tis conceived), as Lancellotti the Italian Abbot relates out of the mouth of one Mr Müller a Polonian that had seen the device."

Can anyone see the answer to this riddle? Why should not a man use his brain and all his powers to enable him to do something better than it has been done before? And how is it that, when he does, he may for a time bring harm to his neighbours? Perhaps we ought to leave such questions to the political economists, and yet I doubt if they can supply any other answer beyond that which we all can give: that when a man does his best it must not be only for himself.

It is strange to think that all this machinery, and all the millions of people whose living depends on it, revolve round this single fibre—wool, or cotton, or whatever it may be. If the fibre became longer, if its strength were altered, or its behaviour to moisture, or any of its physical properties, new designs of machinery would be required and readjustments of the work. The properties of the fibre govern all its treatment. It may well be that even now there is much to be learned about it which may greatly affect manufacture; indeed, this is surely the case. That is why the research associations which have been formed in recent years to help our country's manufactures are impelled, in the case of the textiles, to give minute and careful examination to the fibre itself. It is necessary to know its structure and its properties in every detail, and to watch their every change during all the stages of manufacture. Botany and biology, chemistry and physics, and engineering are all brought in; really abtruse problems are met with, in testing, in explaining mishaps and failures, and in suggesting new possibilities.

As in spinning so in weaving, the essential features of the work are to-day the same as they were thousands of years ago. When the first stage was past, in which long grasses or rushes or shreds of bark were interwoven in the simplest way, the warp and the weft appeared at once.

Sometimes the long threads of the warp were hung vertically, as in the old Egyptian picture (fig. 28). The interweaving or darning method was replaced by the method still used, in which a certain number of the warp threads were moved relatively to the remainder, leaving an open space between them, now called the "shed." Through

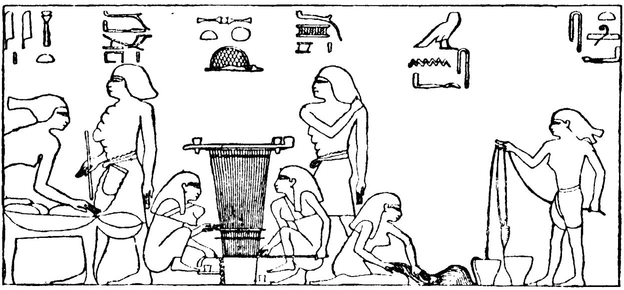


FIG. 28.—On the right the flax is being unravelled and spun. The figure on the extreme right is using the spindle. On the left centre is the weaving, and the man standing up is the overseer.

this space the shuttle was thrown in one action, instead of being passed above and below each warp thread in succession, as when a stocking is being darned. A "comb" was used to keep the warp threads the right distance apart, and each weft thread was beaten into its place in turn. Each throw was followed by the proper re-adjustment of the warp threads: those pulled one way being now pulled the other, and *vice versa*.

The hand-loom of all nations has contained the same elements, arranged in the same way, except that the warp has been horizontal instead of vertical. It was not till 1733 that John Kay, of Bury, made the first great change by arranging a different method of throwing the shuttle. Instead of throwing from one hand, catching it

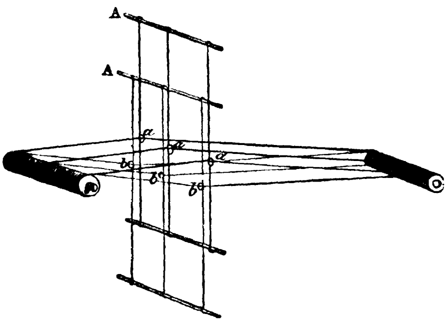


FIG. 29.—Diagram to explain the action of the "healds." One has lifted the warp threads *a, a, a*, the other has depressed the threads *b, b, b*. The space between the lifted and depressed threads is the "shed." (*By courtesy of "Chambers's Encyclopædia."*)

with the other hand and returning it, the shuttle was caught at each end of its run in a box; both boxes were connected by cords to a stick, which the weaver held in the right hand. By a quick jerk the weaver gave a tug to the proper box, the shuttle was shot out, passed along the shed, and was caught in the other box. The weaver's foot pressed a treadle, which lowered one "heald" and its threads that had been lifted and raised another that had been depressed, and the jerk of the weaver's hand threw the shuttle back again. Robert Kay, the son of John, invented the drop-box in 1760. This was a box that held several shuttles, containing as many weft threads of

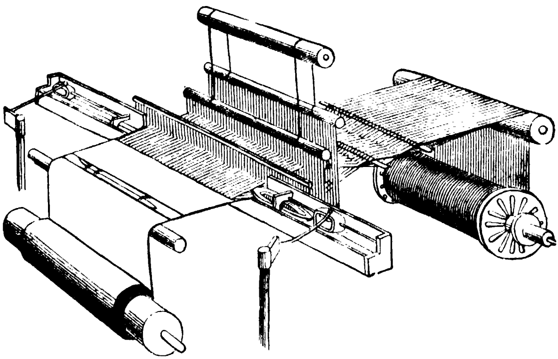


FIG. 30.—This figure shows more details of the loom than fig. 29. On the right the warp threads are coming off the large roller, and on the left the woven cloth is being rolled up. The "healds" are visible, and the shuttle which passes to and fro. The uprights that look like small signposts are the "pickers," which, each at the right moment, revolve suddenly on a vertical axis and give a twitch to the box then containing the shuttle, so that the shuttle is shot right across through the "shed." (*By courtesy of "Chambers's Encyclopædia."*)

different colours. It could be lifted and dropped so that the weaver's jerk threw out the particular colour that was wanted.

The power-loom lightens still more the actual work of the weaver. He has now only to watch a certain number of looms working automatically, to repair any broken threads, and see that all goes well.

It is interesting that the development of the power-loom did not wait for the introduction of steam. The age of multiplication, as we might well call it, set in independently. It was first intended that one man, by his own strength, should be made able to operate many machines, as Hargreaves wished to drive many spindles at the same time. But it would become obvious, as soon as this was successful, that any unintelligent source of power could now be used, if only man was left to arrange and watch and direct. So horses were sometimes used, and sometimes water-power, whence the name of Arkwright's "water-frame." The first power-loom was made in 1785 by the Rev. Edmond Cartwright, D.D., and it contained many of the devices found in the most modern machines. When he started a spinning and weaving factory in Doncaster, in 1785, the machinery was first driven by a bull; four years later he introduced a steam-engine.

The modern loom is a very complicated affair, in which ingenuity has surpassed itself in the devising of mechanical arrangements for manipulating the threads of the warp, so that the most intricate pattern can be woven. In some of them great cards, through which holes have been punched in their proper places, are brought forward in succession, so that each in turn allows a certain set of keys to pass through the holes, and lift a corresponding set of warp threads. But still the machine is just multiplying the motions of the hands. In some respects, indeed, it cannot entirely replace a pair of hands with a single brain to direct them. There are, for example, many thousands of hand-looms still at work, engaged in the manufacture of the more delicate silk fabrics.

The fibres that are used by the weaver can all take up a certain quantity of moisture. In the first place, this adds to their weight, and in the second it alters their properties. The change in weight is an important matter to the trader. It is impossible to keep a fabric completely dry. Even if it were heated in an oven so that all the moisture was driven off, a certain quantity of water would be regained the moment it was exposed to the open air. It is necessary, therefore, to specify the amount of water which, for example, the woollen materials are allowed to contain when bought and sold, the amount being known as "the regain." In the districts where woollen manufacturing is carried on the regain is fixed by the Bradford Conditioning House at amounts varying from 16 to 19 per cent., according to the form of the material. When you buy so much cloth, you buy so much water with it; there is no inconvenience in that provided you know how much it is.

The effect of moisture on the physical properties of fibres is a much more complicated subject, very interesting and very important. We are all conscious of it, in a general way. We know, for instance, how it spoils the shape and set of our clothes when we get them wet. Sometimes they actually shrink; sometimes they merely lose their form. The trouble which we experience in this way is much more acutely felt by the manufacturer. We may shut our eyes, some of us, to little damages of this sort; but the manufacturer has to prepare his goods for sale. While the yarn is spun and the cloth is woven, there are many occasions on which it is strained, wetted, heated, and indeed treated more violently than we treat our clothes. Sometimes strains that are put into the material during one stage of manufacture suddenly reappear at another stage; the material may, therefore, become uneven, puckered, and patchy. That is a most serious fault. Of course, if a piece of cloth is not uniform in appearance, it loses its attraction for the buyer. The patchiness is often much intensified when the cloth is dyed, because the amount of dye absorbed generally depends on the condition of the material and the presence of any strains in it. This is peculiarly the case with artificial silk, which has to be handled very carefully, lest it should be differently strained in different places. The weaver has evolved from long experience his methods of overcoming the troubles that arise in this way. Research associations, having in view the improvement of these methods, if possible, and the removal of difficulties encountered in applying them, have begun to investigate the effects of moisture, heat, and strain on the single fibre. It must be easier to get to the bottom of things if the single fibre is first examined, and the complex woven material is treated subsequently. The problem is not completely solved as yet, though much work has been done on it ; and all workers do not agree entirely with one another. But some general results are acknowledged by everyone to be correct in the main, and I will try to explain them. They help us to understand all these things so readily that it is better to consider them before we think of the many complications of actual experience.

A single fibre can always be stretched, but it does not always behave like a spring, which recovers its old form the moment that it is released. If it is quickly stretched and released, its behaviour is like that of the spring; but if the stress is applied for a long time, it stretches more and more up to certain limits. When the stress is removed, it immediately comes back a little, but takes a long time to recover its old form completely, if indeed it ever does so. A little model devised by Dr Shorter, of the Cotton Research Association, will help to make this behaviour clear. A piston can be moved up and down in the cylinder as shown; the cylinder is filled with a viscous liquid of some sort, which can pass from one side of the piston to the other through a small

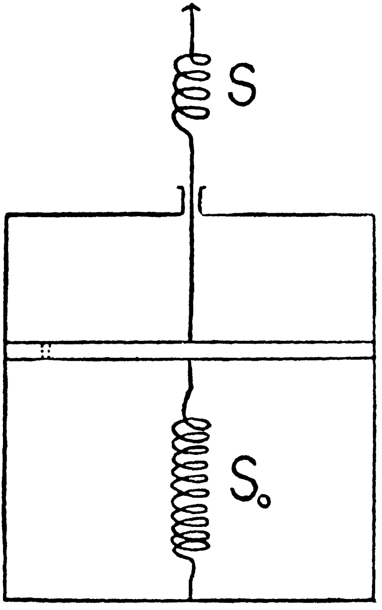


FIG. 31.—Shorter's model.

hole. Two spiral springs are attached to the piston, one of which is outside the cylinder, so that the other end of it can be grasped and pulled; the other connects the piston with the bottom of the cylinder.

If, now, the top springs (fig. 31) are quickly pulled out and let go, the piston has not had time to move appreciably, because the viscous liquid prevents it from doing so. When the top spring is released, it flies back at once. This corresponds to a quick stretching of the fibre. Moreover, if the top spring is suddenly stretched, it may break under a force which would not be exerted if the force were applied slowly and quietly, so that the piston had time to rise. Just so a fibre can stand a larger extension if it is not imposed too quickly. Again, if the piston moves up an appreciable distance under a continuously applied force, and if the top spring is then released, there will be an immediate recoil in the top spring; but it will take time for the bottom spring to recover. This illustrates the second fibre effect which we considered just now.

The effects which are shown by the single fibre are, of course, shown in the material that is woven of many fibres. A piece of cloth that is strained quickly recovers quickly; but if it is strained for a long time it seems to have acquired a permanent set. Nevertheless, it will largely recover itself if left free to do so. That is why our clothes regain their shape when put by for a time. If a stretched fibre is moistened its recovery is quicker; it is as if the liquid in the model had been made less viscous. The effect of moisture on cotton can be illustrated by a simple but striking experiment. Cotton is compressed into plugs when wet, and dried while compressed. The plugs retain their shape when the pressure is removed. If one of these plugs is dropped into benzine, it remains unaltered because the cotton does not absorb the liquid; but if a plug is dropped into a jar full of water, the expansion is rapid and great (Plate XXVI, *a*). Or again, we may make a sharp crease in a piece of calico, cut out a piece of the creased portion, and tease out of it small lengths of cotton bent into V shape. If these are placed on a glass slip in front of the lantern, and wetted, they straighten out at once.

The practical consequences are numerous and important. If in the process of manufacture a material has received strains of various kinds, they will all work out together when the material is wetted. They would have come out in time under any circumstances, though perhaps a very long time. But moisture releases them quickly. Consequently cloth may shrink unevenly, which would be a serious fault, as already explained, if the strains put into it during its making were not removed in some way. To understand their removal, we must take into account one more point, namely, the action of heat on the fibre. Heat alone, moderate heat at least, acts like water; it makes, so to speak, the liquid in the model of fig. 31 less viscous, and so helps to remove strains which are slow in coming out. That is why, when clothes have been lying in creases in the drawer or the suitcase, it does them so much good to hang them before the fire; the heat, as we say, takes out the creases. But a high temperature does far more; it permanently alters the fibres. We can represent its action in the model by supposing the springs to be changed, set to new positions. If any strains are left in the cloth, they can be removed altogether by passing steam through the material. Cloth is sometimes "crabbed," heated with boiling water while in the form of a tight roll. All the fibres lose what strains they have, and the form of the material becomes its natural shape; it is usual to give this treatment before the washing, which gets rid of oil and dirt.

Uniformity is often given to a material by stretching it, while wet from washing, on a frame, to which it is fastened by hooks all round the edges. The process is called tentering, and the hooks "tenter-hooks." It is allowed to dry while it is so stretched; and since this drying takes place at a temperature much below the boiling-point of water, the strains acquired on the frame become subpermanent—that is to say, they will take a very long time to come out. Wetting will, however, bring them out at once; that is why some materials shrink so much at times. But if they are treated with steam while on the frame, the strains ease out, and the stretched form becomes the natural form; the process is called "blowing." To make certain that no strain is left in the cloth, it is sometimes treated by a process known as "London shrinking." This consists in wetting the cloth thoroughly and allowing it to dry, taking care to apply no more tension than is absolutely necessary.[1] The finishing processes involve, as Dr Shorter puts it:

1. The action of cold water in releasing latent strain.

2. The action of boiling water or steam in destroying strain.

[1] Shorter, *Transactions of the Faraday Society*, vol. xx, 1924.

The first of these is represented in the model by changing the viscosity of the liquid, and the second by readjusting the springs.

When the tailor presses clothes, he lays a wet rag on them and then applies the iron: both heat and moisture are required to set the fibres permanently.

There must be something in the fibre to correspond to the two parts of the model, the springs and the liquid. The very fact that the fibres can take up so much moisture hints to us that there is something jelly-like in their character. A jelly is supposed to have a framework, which swells up readily so as to hold more water in its pores. The fibre must have a framework, and a very viscous medium in the framework. Cold water and heat both make the medium less viscous, but do not injure the framework much, if at all. But steam actually affects the latter, setting it afresh. When clothes go to be pressed, it is this fact that is made use of. Probably the structure of the fibre is not entirely unaffected by the operation, because the result of the pressing is less permanent at each repetition.

These things are generally true of all fibres; there are, however, differences in detail between them. For instance, the strength of yarns and fabrics made of cotton and linen increases with moisture, but that of woollen goods and artificial silk decreases. The wool fibre becomes weaker when it is wetted, which will account for the loss in strength of the spun yarn ; but the cotton fibre is not much affected. The increase in strength of the yarn seems to be due to the fact that the threads cling more closely together. We have to remember that the strength of a yarn depends on two things, the strength of each fibre and the force with which the fibres cling together.

One of the most interesting of the attempts to make materials attractive is that which is devoted to the increase of their lustre. It is very difficult to define lustre. We all know roughly what we mean by it ; but if we were asked severally to put our meanings into words, there would be great variations in what we wrote. We might agree more closely if we illustrated our meanings by examples : we should all say that silks and sateens were lustrous, and we might agree as to mother-of-pearl. We speak of lustrous hair or eyes : the former seems correct, the latter may be correct, but if so the word has in this case a different sense. Are a cat's eyes lustrous when they are shining in the dark ? And what is the lustre of lustre ware ? The main point is, it seems to me, that light shall be reflected when we do not expect it. A lustrous object is not merely a good reflector. If that were so, a quicksilvered mirror would be the most lustrous object of all, whereas we should all agree, I think, that it has no lustre whatever. Perhaps we would call a diamond lustrous. Now, the fascination of the diamond is that, owing to its high refractivity, it swings round the rays of light that enter it, and emits them in all sorts of unexpected directions—unexpected, that is to say, until you sit down to calculate them. So the diamond sends flashes of light to you that have come from sources which you would not think had anything to do with it; it seems as if the diamond were luminous. Some diamonds do, of course, phosphoresce in the dark; but that is another thing altogether.

So important is this point in the manufacture of materials, that much trouble has been taken of recent years to define what is meant by lustre, and then to devise an instrument for measuring it. For the success of various processes intended to produce lustre cannot be accurately determined without some quantitative measurement. It is waste of time if we have to depend only on the eye and the judgments of different individuals.

Most of the instruments depend on the measurement of the amount of light which the material reflects in different directions, and especially in those which are not the direction of reflection for a smooth surface, such as a mirror. Without going into details as to their construction, we can illustrate their general character and at the same time test our idea of lustre by a simple experiment. A light from the lantern falls at an angle on a piece of sateen; a coloured sateen is the best for our purpose. The source of light is behind you, and the reflected light from a mirror put in the place of the material would not enter your eyes at all. But if I turn the sateen round in its own plane, each of you sees it flash out for a moment—in fact, for two moments—during each complete revolution. To make this plain, all other lights in the room are turned out (Plate XXVI, *b*). Now where does the flash come from?

If the material is examined under a magnifying glass, the threads of the warp are seen running parallel to one another. The material is so woven that on one surface of it, the shining side, the threads run over several of the weft threads before dipping under; the illustration (fig. 32) will help to make this clear. There is therefore a large display on this surface of threads all parallel to one another. Now when the reflected light

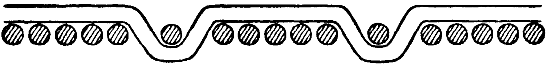


FIG. 32.—Illustrating the manner of weaving of a sateen.

flashes out in the experiment I have just described, these threads are perpendicular to the line bi-

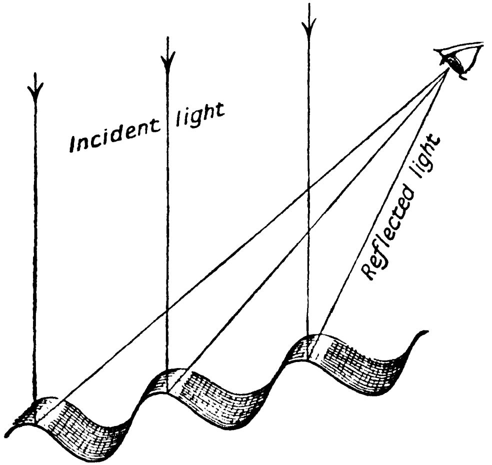


FIG. 33.—A diagram to illustrate lustre. A rippled surface will throw light so that the eye in the figure sees reflections in the sides of the ripples. The parts made bright in the figure are meant to indicate the parts that seem bright to the eye. If the ribbon was flattened out, the eye would get no light at all. The line of the ripples is perpendicular to the paper; the incident and reflected rays are in the plane of the paper.

secting the angle made by the two lines joining the material to the light and to your eyes respectively (fig. 33). The surface is, in fact, furrowed, and the reflection of the light takes place at the edges of the furrows. Each thread must have a good reflecting surface, of course; apart from that, the effect is obtained by laying them parallel with each other. On the under-side of the material, where there is not such an obvious arrangement in one direction, there is far less lustre. The regular arrangement of the furrows is clearly at the bottom of the effect. One gets the same effect in a newly ploughed field, where the sides of the furrows are still shiny from the stroking of the plough.

For this reason the furrowing is sometimes intensified by machinery. The material is passed between heated rollers, on which fine parallel grooves have been cut, and this has the desired effect. The process is known as "schreinering," being named after its inventor. The lustred fabrics so produced are very much used, for we all like brightness—at any rate, in the right place.

If we look into the matter a little more closely, we find that certain threads give better results than others, and certain ways of spinning and weaving than other ways. It has been shown by the British Cotton Research Association that the best cotton threads are those that have the most rounded sections, as perhaps we should expect. The lustre depends on the reflections all taking place from different parts of the material at the same moment—of course in the unexpected direction, as already explained. If the cotton fibres are irregular in form, the effect is not so good; well-rounded fibres will clearly lie more regularly on the surface. This is why the lustre of cotton materials can be so greatly increased by the very important process of mercerisation, which is simply the treatment of the cotton with an alkaline solution. The cotton, when soaked in the solution, absorbs some of it, drawing it through the covering skin of each fibre into the cellulose forming the layer between the covering skin and the central cavity or "lumen," as it is called. The cellulose swells up and causes the fibre to become more circular in section; its covering skin tightens and becomes more shiny. Some illustrations of this effect are shown in the illustrations on Plates XXV and XXVII: the difference between the form of the fibres before and after mercerisation is obvious. One of the illustrations shows the action of the mercerising fluid on very short pieces of fibre; the swollen material can be seen bulging out of the ends, so that the pieces have assumed a dumb-bell form. In one of the illustra-

FIG. 34.—The relation between the twist of the fibres in the single yarn and the degree of twist of the two yarns in making the doubling is such that the fibres run parallel to the axis of the latter.

tions the fibres were somewhat damaged by acid before treatment. The weakened skins have burst. There is a moral in this picture, namely, that boys who handle electric batteries, as they very frequently do in these days, should not wipe their hands on their handkerchiefs, especially if they are made of cotton! The casings of the fibres are attacked by very slight traces of acid; the material becomes "tendered," to use the technical term.

Lustre can also be increased by the choice of the proper methods of weaving. A good type of lustre yarn is obtained by doubling two single yarns, the doubling twist being in the opposite direction to the twist of the single. Each yarn consists of a number of twisted fibres, and the doubled yarn is shown in fig. 34. Now it is found that a certain relation between the doubling twist and the single twist gives more lustre than any other. On examination it appears that this is the case when the individual fibres in the single yarn run parallel to the direction of the doubled thread. The experimental test of this consists in putting different ratios of the two twists into a few yarns, laying them side by side on a dark background, and illuminating them in graduated light, the strength of which fades off uniformly from left to right in the picture. The camera sees the threads from one point only, and in a general way the more lustrous threads are the brighter, and look bright further along their length (Plate XXVI, *c*). The brightest threads are in the middle, and these are found to be twisted, as described in fig. 34.

Again, therefore, it appears that to get the best effect all the threads which are actually the reflectors of the light must lie as nearly as possible in one direction. When that direction is symmetrically placed with respect to the eye and the source of light, as in our first experiment—in other words, at the reflecting angle—then the strength of the reflection is greatest. When in the process of schreinering the grooving in this direction is made clearest and most uniform, the lustre is at its best.

Lastly, we come to the one case in which artificial fibre is used instead of the natural fibres, vegetable or animal. Artificial silk, so called, is valued for its extraordinary brilliance. It is quite natural that the sight of spiders and other insects spinning their webs should suggest to ingenious people the possibility of preparing a useful thread in the same way. I believe the oldest suggestion of this nature is to be found in Hooke's *Micrographia* (1667). Hooke was one of the keenest observers of his time; indeed, he was one of our greatest English men of science. He had a microscope, a new thing in his day, and wrote a book describing all the objects which he had examined by its aid. Amongst other things he studied materials woven of silk: "Of fine waled Silk or Taffety" is the title of his special discourse on this subject. At the end of it he discusses the possibility of making an artificial silk in the following terms:

"And I have often thought, that probably there might be a way found out, to make an artificial glutinous composition, much resembling, if not full as good, nay better, then that Excrement, or whatever other substance it be out of which, the Silk-worm wire-draws his clew. If such a composition were found, it were certainly an easie matter to find very quick ways of drawing it out into small wires for use. I need not mention the use of such an Invention, nor the benefit that is likely to accrue to the finder, they being sufficiently obvious. This hint, therefore, may, I hope, give some Ingenious inquisitive Person an occasion of making some trials, which if successfull, I have my aim, and I suppose he will have no occasion to be displeas'd."

The idea has been realised in these days, and a very beautiful material is made in the way which Hooke foreshadowed.

Artificial silk is much more closely allied to cotton than to silk in its nature; in fact, it is not silk at all. It conducts electricity as cotton does. It conducts heat as well, so that it is cold to the touch; one has only to press a hank of it against one's face to feel that it is so. Woollen fibre is warm by contrast. It is prepared mostly from wood pulp, so treated as to extract the cellulose therefrom; and this material is further treated chemically so that it becomes viscous. It is then ready to be squirted through fine holes into a liquid which hardens it. (See Plate XXIV, *b*.)

The thread is of indefinite length; it is not made up of short pieces which must be linked together by spinning in the way that all fibres except silk are spun. It is hard, shiny, unyielding, cold to the touch ; it has only half the strength of cotton, and though the single fibre is stronger than the single fibre of wool, yet it does not spin so well because it lacks the interlocking quality of the latter. Wool, it may be remembered, has a peculiar structure (Plate XVIII, *a*), which enables its fibres to hold together in a yarn. Artificial silk is much weakened by wetting. But in spite of these disadvantages, it is a very attractive material because of its brilliant colours. It also stands wear well, because its surface is slippery. It is very largely used in these days in conjunction with wool or cotton, giving to the union brilliance and a certain power of resisting rubbing wear.

It is interesting because it is the first manufactured fibre, the first that is not gathered directly from natural sources. The sources from which it comes are practically unlimited in extent, and their supply does not depend on the accidents of good seasons. It may be the forerunner of others, possessing more of the qualities that are valuable—warmth, strength, resistance to moisture, and so on—though at present it cannot compete with the natural fibres in many of their uses.

LECTURE IV

The Trade of the Dyer

THERE is a special feature of the dyer's trade to which I should like to draw your attention at once. It is a consequence of the fact that the chemist has discovered the molecular structure of the principal dyes, and, as the result of his new knowledge, is able to produce them by methods previously unknown and from sources hitherto unused. He has multiplied this number of different colours and shades until there is no need of more; and he rightly claims that he can make new dyes which are as fast as the old. There are very many problems still awaiting solution, but they are related to simplification in the processes of manufacture, to improvements in fastness to light and wear, and to adaptability to new materials.

This, therefore, is the peculiar feature of the dyer's trade. He has got down to the very element of his craft, which is the dye molecule; and because he has done so he has a special mastery over his work. Other trades are working in the same direction; the smith is investigating his metal crystal, the weaver his fibre, and the potter his clay. But the dyer has gone further than the others, along his own lines. The advance has only been made in the last fifty years. It is most interesting to consider the history of the trade in its older form and compare it with its present state. Let us see what the dye chemist has done.

We will, to begin with, review some of the main facts about colour and colouring matters. The first great principle is that colour is always produced by the destruction of colour. We are so apt to think that a piece of red glass, for example, turns white light into red on its way through, that we find it curious when we realise that red is the one colour with which red glass has nothing to do. Light from the sun or any other source of light contains a whole series of light waves, ranging in length from about a forty-thousandth of an inch to half that amount. Collectively the series is white; if any part is missing there is colour. The red glass absorbs some of the shorter waves that try to go through it; the longer waves are allowed to pass on. The shorter waves give the eye the sensation of blue; the longer, the sensation of red. So the glass is red simply because the short blue waves are held up, while the long red waves are not interfered with. All stains, dyes, and paints act in the same way.

A very simple experiment will illustrate this

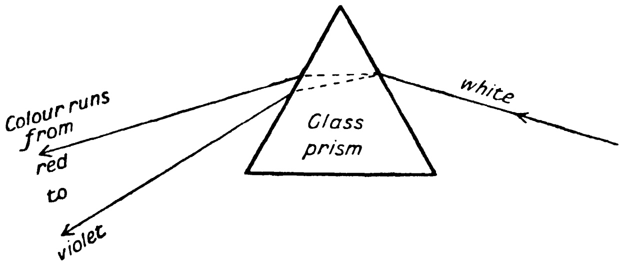


FIG. 35.

point. The white light from an electric arc is passed through a prism which swings round the beam into a new direction. But since it turns the

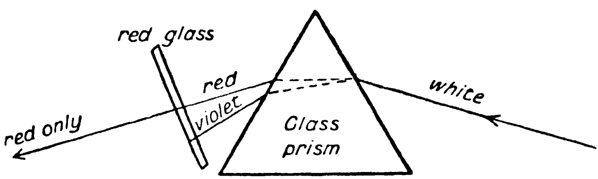


FIG. 36.

blue more than the red, the short waves more than the long, the various wave-lengths are displayed in a series on the screen. At one end are the long waves which we see as deep red, at the other, the shortest which appear to us to be violet; the rest are arranged in order between the extremes. If we place a piece of red glass in the way of the beam, either before it enters the prism or after it leaves it, we see that all the colours are held back but the red.

It happens very often that the colouring matter absorbs well-defined groups of wave-lengths from different parts of the whole series, so that dark bands appear in the spectrum at various places. The remaining wave-lengths combine to form some colour which the eye takes in as a special shade. The eye, of course, has no idea of the composition of this shade; it cannot analyse it into sections from different parts of the spectrum. Its powers in this respect are sharply contrasted with those of the ear, which can analyse a mixed sound or chord, and, with practice, a very complicated chord. If we sound together two tuning-forks giving the notes C and G we all know there are two notes, making together as it happens a pleasing harmony. No other combination of notes sounds the same to us. But the eye cannot do the corresponding thing. If colours of two different wave-lengths enter the eye, we have a simple sensation of colour which we cannot distinguish from the sort of colour given by a single wave-length. In fact we combine wave-lengths from different parts of the spectrum in many different ways, all of which will give the same effect to the eye. We certainly cannot make up different chord-combinations on the piano which will give the same sound to the ear.

We may now place in the road of our ray of light one or two of the well-known dyes; for example, Turkey Red and Indigo. We can see in the spectrum which wave-lengths are absorbed and which are left, and alongside we can see by means of a suitable arrangement the particular colour which the latter combine to make.

The surface of a body, to which a stain or dye has been applied, appears to us to be coloured, because white light penetrates a certain very small distance into the colouring matter and is turned back again; and it is on the way in and the way out that certain wave-lengths are abstracted. When we use water-colours we depend on the white paper at the back for turning back the light. That is why when we go over the same ground in a water-colour too often, and without judgment, our painting loses brightness and becomes muddier and muddier. Each new application of paint destroys some more of the reflection from the white paper. When we use oils we use the white particles of the "body" that we put into the colouring matter; so that we can paint with one colour over the top of another. With new paint we add new reflecting material.

The apparent colour of a body must depend, not only on the state of its surface, but also on the colours of the light which makes it visible. If the piece of red glass is placed in front of a ray of light which consists only of the short waves of blue, it can transmit nothing; it appears black. If we light a room by the light of sodium vapour from ordinary salt rendered incandescent in the colourless flame of a Bunsen burner, the only waves that are present are yellow; it being a peculiar property of sodium to emit yellow waves only. Any object in the room that absorbs yellow looks black, anything else is yellow; there will be, of course, many intermediate shades. That is what we see when we make ourselves look ghastly in the old Christmas game of snap-dragon. But we can observe the same thing every day to a less striking extent. When a ray of sunlight streams into a room and falls on some bright-coloured object, the room is filled with that colour, and the relative shades of the different objects change accordingly. In the evening when the sun is just setting, the waves of blue have mostly been turned aside on their way to us through the air, and we receive only the red of the evening glow; at that time the red flowers stand out more than the others. We all know how different colours look to us by daylight and by artificial light, especially the yellower lights of candles and oil lamps and the older forms of electric lamps. In dye-works and in many shops to-day, rooms are arranged to have a special illumination in which the blue has been augmented so as to bring the artificial light to the constitution of daylight. In this way yarns, fabrics, and flowers can be seen in their true colours.

The sensation of colour which the eye receives and the brain interprets is affected in yet a third way. The nature of the original light has its influence; and the nature of the colouring matter; but besides these the mechanism of vision does not always interpret the same thing in the same way. It depends on what the eye has been doing just before. We know, perhaps, the old experiment in which the two hands are placed for a minute or so, the one in cold and the other in hot water. If they are now plunged together into the same basin of lukewarm water, one hand feels hot and the other cold. In the same way if the eyes have been staring at something red they will see a bluer shade in some intermediate colour, say a green, than if they have been previously staring at blue. They become tired with respect to the colour they have been looking at. We look steadily at a red disc for a while, then shift our vision to a white paper alongside; a blue disc appears on it because our eyes are tired of red, and the white

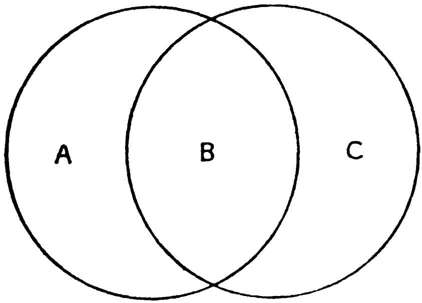


FIG. 37.

light from the paper produces in our eyes a sensation correspondingly deficient. The same effect is well shown if we take two lamps and make them show overlapping white discs upon the screen. If we put a red glass in front of one of the lamps so that A (fig. 37) appears red, the portion C which is illuminated by white light only appears a greenish blue. If we put a yellow glass before the same lamp, C appears a purple, and so on. We have always to remember when we try to produce colour schemes that the effect of one colour is strengthened by putting alongside it other colours which tire the eye to all colours but the first.

Now let us try to understand something of the details of the absorption process; perhaps they are best explained by an analogy, so much at least as they can be explained at all.

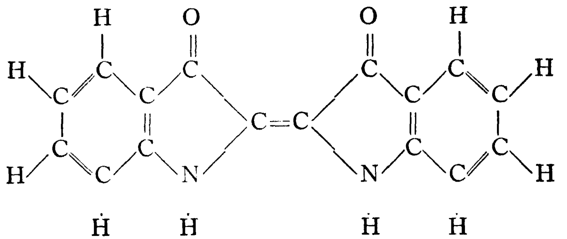
It is a principle of wave-motion that if a wave sweeps past anything which can itself be the source of similar waves, its energy is partly absorbed in the passing. Imagine a boat that rocks to and fro as the waves of the sea pass under it. As it rocks it starts secondary waves in all directions, and the energy of the secondary wave-motion must have been provided by the energy of the primary wave-motion. The latter is therefore diminished; as we say, it has been partially absorbed in passing by the boat. Or if we strike a tuning-fork so that it emits sound-waves, another fork of the same pitch picks up energy from the waves that pass by and re-emits the same kind of wave-motion; in other words, it begins to give out sound itself. The experiment is well known and is easily demonstrated. If, however, the second fork is not of the same pitch as the first, the effect does not happen; the second fork does not respond to the first. In the case of the boat rocking on the waves the necessity for timing is not so obvious; but in the case of the tuning-forks the two must be closely tuned to one another to cause an appreciable amount of resonance. Now, if the original wave has given some of its energy to the second fork which has redistributed it in all directions, it must have been weakened in doing so. We might imagine an experiment in which hundreds of forks of the same pitch formed a screen between a listener and a single fork of the same kind which was emitting its note. The mass of forks would intercept some of the sound and scatter it in all directions, so that the listener would get less than he would if the screen were removed. But the experiment would be very troublesome to arrange, and we must be content with imagining the illustration. In another form the principle is well known to those who experiment with electrical oscillations in telephony or wireless. Troublesome oscillations can be abstracted from a circuit by connecting up electrical oscillators of the same pitch, which are set in motion by the energy of the oscillations and redistribute the energy in harmless directions.

Now, although we are not very well acquainted with the mechanism by which light is absorbed and emitted, because the details of the mechanism are far too small to be seen by the eye and can only be studied by indirect methods, yet we observe that there is a strong analogy with the illustration we have just been considering. When a substance absorbs red light it must contain in some form or another resonators which are capable themselves of emitting the red waves which they absorb. Now there is only one place in which to look for the resonators. A simple stain or dye like any other pure substance is a collection of molecules which are all alike. It is found that changes in the form of the molecule are liable to change the colour which the dye absorbs. We assume that the seat of the absorbing action is in the molecule, which must therefore contain something in the form of a resonator, something which can absorb and scatter the energy of the waves that try to pass through. Let us, therefore, look into the structure of the molecule, if perhaps we can get some idea of what this resonating mechanism may be.

Let us remember, in the first place, that a molecule is a little company of atoms which are tied together in some way, and remain as a company as long as no agency comes with sufficient strength to break any of the ties. The molecules of many substances contain only a small number of atoms, as, for example, water or carbonic acid or salt, but the dye molecule is a somewhat complicated affair made up of many atoms, twenty, fifty, or more. The atoms are carbon, oxygen, hydrogen, with generally an odd atom or so of some other kind, such as nitrogen, sulphur, chlorine, or in some cases a metal. Now the properties of a molecule depend not only on its composition, but also on the design. We may use pieces of wood and nails to make many kinds of structure—a boat, or a shade-house, or a stepladder; and the properties of each structure depend not only on the materials we have employed, but also on the way we put them together. It is just the same with the molecule.

This may seem a simple fact; but it has taken us a long time to grasp it fully. The molecule is so very small compared to the things which our eyes are made to see that we do not quickly realise the significance of the arrangement of its parts, although we are personally and closely affected thereby. A hundred million molecules of an ordinary size, placed in a row, cover about an inch. It is not surprising that we are apt to think of them as so small that there cannot be much importance in the details of their structure, which must be still smaller. No one, of course, has ever seen a molecule, and it is certain that no one ever will. The characteristics of the molecules, their very existence indeed, have all to be inferred from an accumulation of observed facts. It is to the great credit of the chemist that he has succeeded in so arranging his facts that no one can dispute his conclusions. The X-rays, which have now given us a deeper insight into the structure of matter, entirely confirm the work of the chemist; their contributions to knowledge of the molecule are nearly always additions rather than alterations.

The chemist infers, as I say, the composition and the structure of his molecules from the experiments which he makes. It is a long and intricate process, a full description of which would be a treatise on chemistry; and how long that may be we quickly realise when we visit a chemical library. We have no need to go into the details of the chemist's work or to understand his methods; the result is all that we want. To express the result we must use the chemical diagram, but that need not alarm us; for it is really a very simple matter though it looks forbidding. Let us take at once a complicated molecule, which is just as easy to understand as a simple one; here, for instance, is the formula for indigo:



Indigo.

Now let us try to understand what this means. In the first place each C represents a carbon atom, each H a hydrogen, each O an oxygen, and each N a nitrogen. The straight lines drawn between the letters mean some sort of tie between the atoms which they join; there is no attempt to say what that tie must be. Thus the diagram tells us that the indigo molecule consists of such and such atoms, so many carbons, so many hydrogens, and so on; and, further, it tells us that each atom is bound by ties to certain of its neighbours. The molecule is not merely a handful of atoms thrown together; the atoms are fastened together in such ways as the diagram shows. But that is all; the diagram contains no more. There must be a great number of mysterious things in the structure of the molecule which we should like to know, many which we cannot even express by our present stock of words. There are no answers even to such simple and obvious questions as the following:—What are the atoms like in form and in size? What are their distances apart? Do they all lie in one plane as the diagram seems (but does not really pretend) to indicate? What are the links? How long are they? We might go on with an endless string of questions of this sort, and to no one of them is an answer given in the diagram. Suppose that the diagram were handed to a builder as the plan of a house, in which C was to be a bedroom, H a bathroom, N a dining-room, O a drawing-room, and the lines some sort of passage or stairs. The plan would surely be looked on as imperfect; it would give information of some sort, but the builder would think that he had been left in ignorance of much that he would like to know. For one thing, how many stories were there to be?

It would not be right to say that the chemist knows no more than what is put into the diagram. He knows that the atoms are not all in one plane, and that the properties of the molecule depend not only on the composition, and not only on so much arrangement as is shown in the diagram, but also on the arrangement in space which is not shown.

He has even found out something about the latter kind of arrangement. But all such additional knowledge is rather vague at present. The main points are, first, that such knowledge as is displayed in diagrams of this sort represents the result of patient and skilful work. Baeyer actually worked for eighteen years before establishing the structure of the molecule of indigo. In the second place, when once the diagram has been found, imperfect as it is, it becomes a starting-point for further work; in this case it was the foundation of a huge development of the dyer's trade. It became possible to make indigo, the molecule being pieced together, by methods which the chemist understands, from various products of the distillation of coal. It was, in fact, enough for the chemist to know what atoms were in the molecule and which were linked to which; then in the exercise of his business he brought together certain substances, including especially the coal-tar products, in such ways and under such conditions that the various molecules he had now forced into each other's company broke up in part and formed fresh combinations and molecules; and one of these was indigo. It did not take long to discover a process for the manufacture of indigo, though it was not until this century that it became possible to produce it on a large scale from the coal-tar products more cheaply than it could be derived from the indigo plant.

The molecule of indigo must contain something which acts as a resonator, as I have said. We should like to know where it is. When the trained chemist looks at the diagram he is at once aware that it represents a substance with dyeing properties. What does he see?

The answer to this question is in two parts. There is something in the molecule which gives it the power of resonance. We will take this first. There is also something which gives it the power of adhering to the substance to be dyed, which makes it more than a mere stain; and this we can take later.

The existence of the resonance power is certainly bound up with the nature of the ties that link the atoms together in the molecule. There are certain rules governing such linkages generally; rules which can be illustrated from the very molecule that we are considering. If we look at the hydrogen atoms we observe that they are never tied to more than one atom. This is found to be a rule, not only in this, but in all cases. The hydrogen atom is never bound to more than one neighbour. If we consider the carbon atoms in the indigo molecule we observe that it is always associated with three other atoms. Now this is not the general rule, because the full complement of neighbours for a carbon atom in combination is four; for example, in the diamond every carbon atom has four other carbon atoms as neighbours. But there are many exceptions to the rule; only, when the number is less than four, there is some incompleteness which manifests itself in various ways. For instance, the carbon atom is often inclined to add another neighbour, or can be made to do so without much trouble; and also when it is in the so-called unsaturated state, the molecule has special properties, as indeed it has in this case. The nitrogen atom in the indigo molecule has three neighbours; and this is the general rule for nitrogen. But the oxygen atom has only one neighbour, whereas it can have and generally has two—as, for example, in the molecule of water, H_2O. It will be observed that in the diagram the oxygen atom is represented as connected with its carbon neighbour by a double line. This is used by the chemist to express his belief that the carbon and oxygen are tied together in this case in an especial way; in fact, if the linkage is supposed to be equivalent to two ordinary linkages (though it is not easy to say exactly what the word "equivalent" would mean in this case), then oxygen has two linkages and carbon four, each having a full tale of linkages even though it has not a full tale of neighbours.

Such statements as these may well seem indefinite, even a little unreal, but they express the results of experience in a way which has been found convenient. It has to be left to future work to give them a more definite meaning and to draw us a more detailed picture of what is really happening. When different molecules are brought together under various conditions, there are exchanges and rearrangements of neighbours; old molecules break up and new ones are formed. It is the work of the chemist to learn all about such happenings and to acquire skill in controlling them. To him these rules mean something important, even though their full meaning is yet to be discovered.

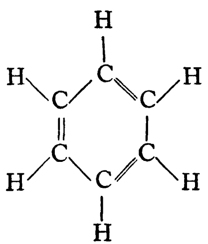
If, as I have said, we were to show this indigo diagram to a chemist, and could suppose that he had never seen it before, he would certainly say at once that he could make a dye of it. There are certain features in it that would catch his eye immediately as being found in the vast majority of the thousands of dyestuffs now known. In the first place, at each end of the structure is the famous hexagonal ring of carbon atoms, the benzene ring. Every dyestuff contains the ring; there are coloured substances, of course, that do not include it in their molecular structure, but they do not make dyes.

The benzene ring has a peculiar interest for us in this place. It is just a hundred years ago since Faraday first isolated benzene from the residues in the cylinders then used to contain illuminating gas. Faraday found out the composition of benzene, but he did not discover its structure; he was not aware of its ring form. That was not known for forty years afterwards. The ring is not only fundamental to the structure of all dyes, but also of numberless other important substances; in fact, a whole branch of chemistry springs from it. So important is its discovery regarded that a few months ago[1] chemical societies from all parts of the world sent delegates and messages to a Centenary Meeting held at the Royal Institution to commemorate the original discovery which Faraday made in our laboratories.

Now benzene itself is colourless; the waves of light pass freely through it without absorption. It cannot, therefore, be the resonator we are looking for; it must somehow contribute to the

[1] In June 1925.

resonator, and has to be built into the dye-molecule for the purpose. Yet when we look more closely into the matter we find that benzene does absorb waves of the same character as those which our eyes perceive, but of a different quality. Benzene absorbs a set of very short waves, much shorter than the violet waves which are the shortest in the visible spectrum. There is a beautiful experiment



Benzene.

which we can use in order to show this effect. It depends on the fact that there are substances which degrade the light that falls upon them; they absorb light of one wave-length and emit light of another which is longer than the first. They are said to "fluoresce." Curiously enough they are never quite pure substances; some little trace of foreign matter must be mixed with them, otherwise there is no fluorescence. Such a substance is sulphate of quinine, and this substance has been spread upon the screen which we are about to use. The spectrum of an arc light is thrown upon the screen; the arc is passing between iron points, because the light so formed is found to contain a very large admixture of the short wave-lengths which are wanted for the experiment. Glass is apt to absorb these short wave-

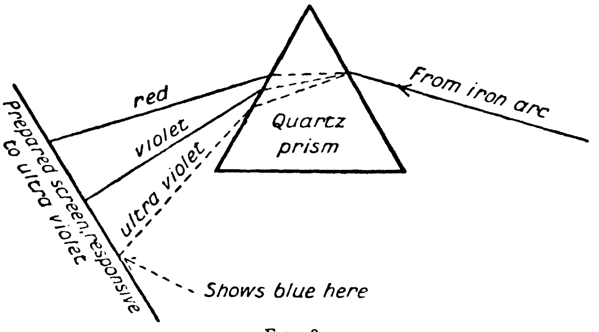


FIG. 38.

lengths, so the lenses and prisms on our apparatus are made of quartz which lets the short waves through. When we use the fluorescent screen the spectrum seems far longer than it was, because the short waves beyond the violet, though invisible themselves, produce a visible effect. They are absorbed by the fluorescent matter on the screen, which emits their energy in the form of a blue light that we can see. There are, in fact, pictures of the slit through which the rays from the iron first left the lantern, pictures of a pale blue colour, far beyond the violet end of the visible spectrum. We have now only to place benzene in a quartz tank before the slit of the lamp, so that the rays must pass through it, and the blue strips disappear at once, though the spectrum is not affected otherwise. We see, therefore, that benzene though

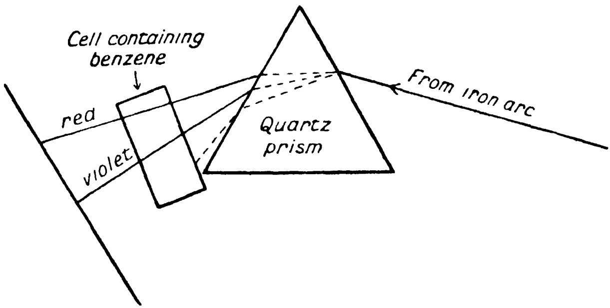
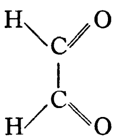


FIG. 39.

colourless does absorb a certain part of the spectrum. If our eyes used that part, benzene would be a coloured substance, though, of course, the colour would be none that we know.

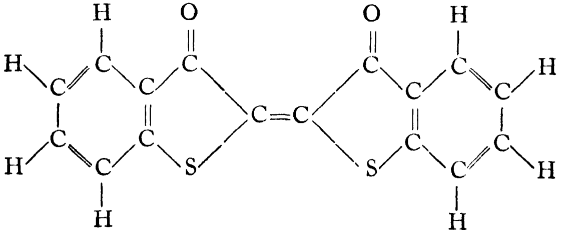
The carbon atoms of benzene do not possess, as we have already remarked, their full quota of neighbours. In chemical phraseology they are unsaturated. It is always found that the unsaturated carbon is somehow an important part of the colour mechanism. Perhaps, though this is only a crude picture, the atoms, having less than their proper number of links, are not held sufficiently tight; they can rattle, just as a machine rattles when some of its bolts have worked loose. It seems, however, that there is no visible colour with only one loose joint in the molecule, there must be two; that is to say, there must be two places in the diagram where the joins between the atoms may properly be represented by double links such as occur in the indigo molecule. It is also necessary for some reason that the two places where double lines are wanted are to be separated by one join of an ordinary character. The simplest molecule that can be made to satisfy these conditions has the construction :—



Glyoxal.

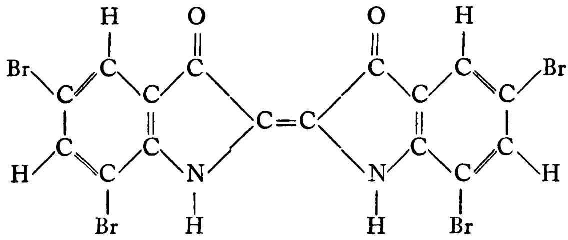
It is called glyoxal, and is only slightly coloured. Benzene, which also has unsaturated carbon atoms, may be said to follow the rules, because the insertion of double links in three sides of the benzene gives every carbon the proper number of links, and so seems reasonable. And when this is done the rule is clearly satisfied. If benzene is not a coloured substance it is because it gives out and absorbs waves that are too short to see. When, however, it is built into the structure of a bigger molecule, and when that molecule also contains other parts where the rule is satisfied, then the wave-lengths that are absorbed drop into the visible spectrum, and we have a dye or, at least, a coloured substance. If we look into the indigo molecule we find that the rule is satisfied in several places as well as in the two benzene rings which the molecule contains.

Now comes the very interesting point, that once the colour-producing structure has been formed, the colour can be modified by attaching other atoms or groups of atoms to the frame-work. For instance, the nitrogen atoms with their attached hydrogens can be taken out of the structure of indigo and replaced by sulphur atoms, so that the diagram becomes :—



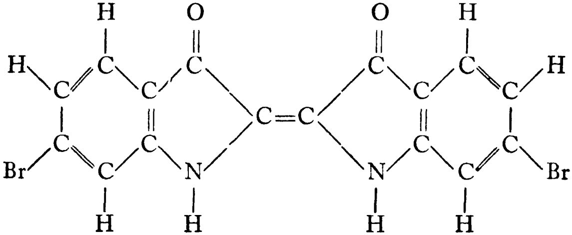
Thio-indigo red.
S = sulphur.

This gives a red colour known as thio-indigo red. If, again, bromine atoms are put in place of some of the hydrogens as in the following diagram:—



Ciba blue.
Br = bromine.

the dye becomes a blue, known as Ciba blue. Lastly, if bromine is substituted for hydrogen, in yet another way the molecule is that of Tyrian purple, the imperial purple of Rome.



Tyrian purple.
Br = bromine.

We have not yet finished the relation of those features of the dye-molecule which make it what it is; and we must give attention to a few dyes besides indigo, but we may well pause at this point to consider what effect the knowledge of such things has upon dyeing as a trade.

The number of known and much used natural dyes is very small. It is to be remembered that they are something more than mere colours. They must be capable of attachment to the material so firmly that sun and rain and wear have little effect upon them; they must be fast to light and to washing and to rubbing. Not many colouring matters can satisfy these conditions. Men have tried great numbers of them, extracting them from plants, from the earth, even from insects and shell-fish. Very few, indeed, have been found of real use. There are indigo and madder, Tyrian purple, and woad. The "scarlet" of the Old Testament was obtained from an insect found on a species of oak; another well-known scarlet has been in more recent times obtained from the cochineal insect of Mexico. The insect is a beetle, of which the females when dried and crushed give the colour. It is used for dyeing the scarlet tunics of our army. The Romans obtained yellow from the crocus. Logwood comes from Central America and is largely used because it makes an excellent black. It is to be observed that the dyes so obtained from natural objects are not used by Nature as dyes. Nor, indeed, does Nature in her colourings make so much of fastness as man does; her garments are still beautiful as they fade. When she does require a permanent colouring, she does not use dyes or stains at all, but what are called diffraction effects, the coloration due to the effect upon light of ordered arrays of fine points, or lines, or fibres, as in the feathers of birds and the wings of butterflies and the wing-cases of beetles.

Indigo is perhaps the oldest of all the old dyes, for its use in India is described in old Sanskrit writings. It was extracted from various plants cultivated for the purpose, and the Hindus knew how to prepare the solid indigo in a fairly pure condition and how to dissolve it once more when it was wanted as a dye. The Egyptians learnt the use of indigo from the traders that brought it from India; mummy wrappings that are five thousand years old are found to have been dyed with it. Greece and Rome obtained it from Egypt; Pliny wrote about it, calling it indicum. He says that it came from India, whence its name; that it was nothing else than a scum found clinging to canes and reeds. He says also that it was often imitated, but that the true substance could be tested by fire, for it gave a beautiful purple flame and smelt of the sea, for which reason, indeed, some people thought it was gathered *from rocks* standing in the sea. This test shows that Pliny really was talking about indigo, though his views as to its origin were incorrect. Curiously enough the Romans do not appear to have used indigo as a dye, but as a paint.[1] This means that they applied the indigo to the material in its natural state, whereas true dyeing requires that the indigo should first be put into solution, which operation requires a special chemical treatment; it must then be put into the material, and finally be changed back by further treatment into its original form. It is only when these conditions are fulfilled that the dye becomes fixed or "fast"; a real dye and not a mere stain. We shall come back to this point later.

When and how the use of indigo as a dye was introduced into Europe no one knows; it was certainly more than five hundred years ago. The use of woad was well established in Europe when indigo made its appearance, and the woad cultivators of Europe fought hard to keep out the new

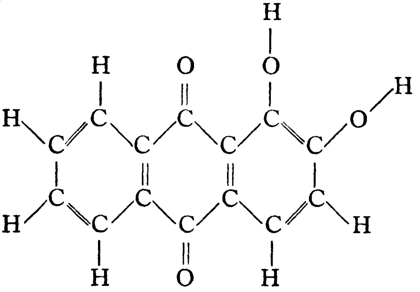
[1] *Vat Colours*, Thorpe and Ingold, p. 22.

dye. Many laws were made forbidding its use under severe penalties; it is said that the English statute on this point has never been repealed! The essential dye-molecule of woad is the same as that of indigo, but it is obtained from a different plant; the reason why the former has given place to the latter is that one plant responds to treatment better than the other.

The purple of Tyre and the Roman Emperors was obtained from the "murex," a kind of shell-fish; but so difficult was it to obtain in any quantity that it was extremely costly. Fifty years ago Friedlander extracted about a grain and a half of the colouring substance from many thousands of the fish. He did not determine its structure in full, for there are two constituents and he was successful in analysing one of them only. It turned out that this dye-molecule also was connected closely with indigo, as I have already explained (see diagram on p. 158). The two atoms of bromine which replace two atoms of hydrogen show its relation to the sea. The Imperial purple thus obtained is considerably inferior to modern colours.

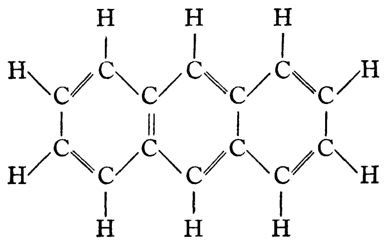
It is strange that of all the colouring matters that have been extracted from the innumerable products of the world, three of the best known are of practically the same structure.

The molecule of the dye extracted from the madder root is quite different from that of indigo; it is known as alizarin and its structure is shown in the figure:—



Alizarin.

Here also are to be observed the benzene rings, and the curious assemblage of double and single linkages which are found in indigo and in the molecules of dyes generally. Madder, like indigo, was cultivated in India and in Egypt in the earliest times, and it has been extensively grown in Europe until quite recently. Its structure was discovered and the substance was prepared artificially more than half a century ago, but the method of preparation now used is more recent. The alizarin molecule bears a strong resemblance to the molecule of a substance found in coal-tar and known as anthracene; the structure of the latter is given in the diagram:—

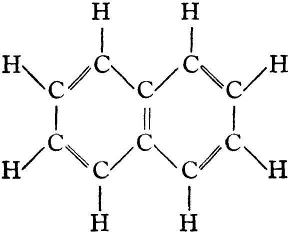


Anthracene.

If we compare the two diagrams we see that the skeleton of the structures is the same; certain of the fringing atoms alone are different. A process by which one could be converted into the other on a manufacturing scale was discovered after many attempts, and is so simple that the cultivation of the madder root has practically ceased.

The chemical achievements of the last few years have therefore changed entirely the conditions of the production of dyes. A fraction of the indigo required by the world is still obtained from plant sources, but otherwise the whole of the indigo and madder dyes are obtained from the products of the use of coal. After all, the source is still the same, though the plants lived millions of years ago.

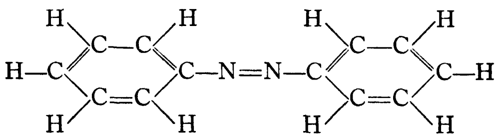
We must observe here that the great change which has come over the industry extends much further than a substitution of one origin for another. The molecule of indigo or alizarin can be altered by the addition of other atoms at various points of the structure, or by groups of atoms such as the benzene ring; and such changes alter the colour of the dye. Because the structure is known, all such changes can be handled with understanding, and so an immense variety of shades of different colours have now been made, all founded on the two original molecules.



Naphthalene.

The anthracene molecule, which is used in modern commercial processes as the starting-point for the manufacture of alizarin, is a three-ringed structure (p. 164). Benzene, it will be remembered, consists of a single ring (p. 153). Intermediate between these is the double-ringed structure of naphthalene (p. 165); it is very remarkable that naphthalene is the foundation on which the manufacture of the indigo dyes is built.

There is one other type of dye molecule which we may well consider before proceeding further. Like the others it is extracted from coal products, but it has not, like them, been obtained from other sources. Its skeleton structure, which may be modified by attaching other atoms and groups of atoms in all sorts of ways, is known as azobenzene and is shown in the figure:—

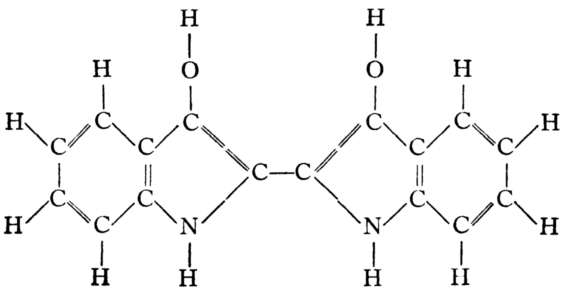


Azobenzene.

Here again we see the benzene rings and pairs of double linkages separated by single linkages. The reason why a double linkage is inserted between the two nitrogen atoms is that nitrogen is usually attached to three neighbours, but here to two only; and so the connection between the nitrogens is supposed to be of the same type as that between the oxygens and their neighbouring carbons in indigo and alizarin. The colouring power of azobenzene is thus accounted for; nevertheless the molecule is of no use as a dye in its skeleton form, because it cannot be made to attach itself firmly to the material to be dyed. Some attachments have to be made before it becomes a real dye, and this brings us back naturally to our enquiry as to what makes a dye. We have tried to understand what gives the molecule the colour; we have now to consider what feature in the molecular structure gives it the power of fastening itself to the material to be dyed.

A true dye cannot be removed from the material by the same means as were used to put it in; the process cannot be reversed. It is quite different with a paint; if, for example, we apply a wash of water-colour to a piece of white paper, and allow it to dry in the usual way, we can afterwards apply clean water to it and remove it more or less, or shift it to a different part of the paper. But if we dye a material by dipping it into some solution of the dye, and complete the process in whatever may be the way prescribed, we cannot get the dye out again by using the liquid in which it was first dissolved. The fact is that the dye has undergone a change which has rooted it to its place on the material, and it is no longer susceptible to the influences that once caused its solution. The dye is now "fast," to this disturbing influence at any rate. If also it is fast to light, to rubbing, to soap solutions, and so on, or at least to some of these, so much the better.

Let us look again at the indigo molecule. As it stands it is not soluble in water, and cannot therefore be forced into the material to be dyed. It can, however, be made soluble by a slight change; here it is with the necessary alterations. Each of the two oxygens has now two neighbours instead of only one; and this change makes it soluble. In the original state the molecules of the indigo had so much attraction for each other that they kept together; and, I expect, they tried to arrange themselves regularly so as to form what we call a crystal. If they were surrounded with water they preferred each other's company to that of the water molecules.



The indigo molecule altered so as to become soluble.

The change to the new form is made by placing the dye in water containing an alkali and some hydrogen-giving substance. It is not much use, I am afraid, asking for full explanations of the why and the how of the process. The chemist would expect this change to occur, basing his anticipation on previous experience; but that is not really all the explanation that we should like. As in numberless other cases of chemical reactions, we should like to magnify the operation until we could see the molecules of the dye and alkali and water actually carrying the operation through. It may be that the X-rays will in time give us the realisation of our wishes in some form or other since they show us so much detail that has escaped us before. But at present we accept the word of the chemist, based on experiment, that the change occurs and is of such and such a character.

Now the new molecule will and does dissolve in water. Observe that there has been a serious change in that part of the molecule with which colour is associated, and we need not be surprised that the new substance is no longer blue; it is now yellow, and would be white if the solution were quite pure. We dip into it the material to be dyed; the fickle molecules of the dye forsake their water neighbours and settle on the material.

Again, this is a very simple statement to make; but there is so much that we should like to know about the details of the process. Perhaps we can most clearly bring it into line with what else we know if we remember that the surface of any substance has scattered all over it points of electrical attraction, certain of the surface atoms, or even parts of atoms, being positive, others negative; and that if other wandering molecules go by they may be attracted and settle down, some on a positive point, some on a negative. Indeed, a molecule may itself have both positive and negative points; and may settle in various positions. And if it can settle one or more of its positive points on negative points of the body, and at the same time one or more of its negatives on positive points of the body, the hold is so much the stronger. To take a very simple case, the face of a crystal of ordinary salt contains positive and negative points in a regular square arrangement; the crystal grows in a solution of brine, because the atoms of sodium in the brine are positive and the atoms of chlorine are negative, and want to settle on negative points and positive points respectively. Or if in the brine chlorine and sodium are already tied together, their arrangement and their spacings are such that they can fit exactly on the surface of the salt positive to negative, negative to positive. As a less simple case we may take a molecule of naphthalene. When the substance crystallises either from a solution or by cooling, it lays itself up against neighbours so that the positive parts of the one fit on the whole the negative parts of the other, and this is done so perfectly that the crystal grows with absolute regularity.

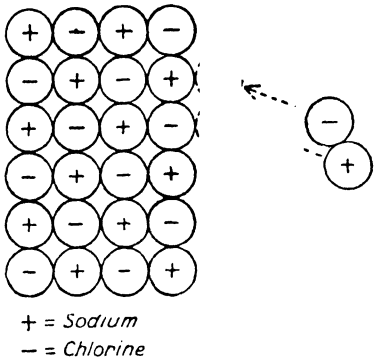


FIG. 40.—The growth of a crystal.

So when the dye molecules leave the solution and settle on the material, it must be because the surface of the material presents points of attraction; it may be that some are positive and some negative, or they may be mainly of one sign, any mixture of the two, in fact. Wool, cotton, and silks of various kinds differ very much in these respects. The dye molecules attach themselves thereto; and there may be wide differences between the total strength of the attachment when dyes and materials are varied. We can imagine that the dye molecules, being arranged with some regularity so as to conform with the arrangements of the positives and negatives on the surface, may find themselves in a position to attract each other, and so add to the permanency of the arrangement. We do find such things taking place where crystals are growing. Indeed, we may carry our imagination still further and suppose that sometimes, as in crystals, a second layer of the dye molecules may be arranged on top of the first, and a third on top of that, and so on. I do not think any one of these points is really settled; all that can be said is that experience with crystal studies makes them something more than possible.

Now we come to the last step of the process of dyeing with indigo. We lift the material out of the bath and expose it to air and light. Immediately the dye molecules are attacked by the oxygen in the air, the light assisting; the hydrogen molecules lately attached are pulled off by the oxygen molecules which want them as partners, and the dye molecules revert to their first form and regain the blue colour. The dyestuff is once more insoluble. It is "fast" to washing. Also light has done all it can to the molecule; it is fast to sunlight. Indeed, as is well known, indigo makes a very fast dye.

Let us again observe that the process is very, very old. What, then, has been gained by the knowledge of the structure of the indigo molecule and of the changes through which it passes? It is this, that once the facts are known it becomes possible to prepare a vast series of dyes of all shades, having the same fundamental structure as indigo, applied in the same way, and equally fast. In the place of one good dye, we have a thousand.

There is a very interesting difference between the modes of application of the indigo and the madder dyes. The latter can be put into solution, but they will not go into the material and stay there unless the latter is first treated so as to have a special hold on them. Various substances known as mordants are stamped on to the material. The molecule of the mordant often contains a metal atom for which the dye molecule has a great affinity; when, therefore, the material is placed in the solution, the dye molecule, containing the essential part which is responsible for colour, attacks the mordant molecule, and exchanges one of its oxygen-attached hydrogens (see p. 163) for the metal atom. The new molecule is now firmly attached to the material, the metal atom serving to settle it there. It is as if a boat went into a harbour, found another boat at anchor there, cut it adrift, and took its anchor for itself. In this case the colour of the dye is affected by the nature and the weight of the metal atom to which it has become attached. It is possible, therefore, to place a pattern in different mordants on a material which will then seem to draw different colours from the same dye-bath.

The two methods of dyeing which I have briefly described, the one for indigo and the other for alizarin, will serve to illustrate the way in which the essential part of the dye molecule is fastened to the material. It is not necessary to consider further examples. What we should note is that a true dye molecule should contain two things: in the first place, a colouring, mechanism; and in the second, a means of attaching itself firmly to the surface which has to receive the dye.

Alizarin was first made artificially in 1868, indigo in 1880; but the discovery of the structure and afterwards of the process of construction was a consequence of the famous discovery of "mauveine," the first artificial dye by W. H. Perkin in 1856. Perkin was at the time an assistant to Prof. Hofmann at the Royal College of Chemistry in London, and had been inspired by a remark of

Hofmann on the great value of quinine to attempt to make it artificially. He tried to make it from aniline, a coal-tar product then being made in quantity by an English chemist, Mansfield. Perkin expected it might be possible to carry out his idea because aniline and quinine have many features in common. He was looking for quinine and found a new dye, and had the wit to recognise the value of his discovery.

The aniline dyes, as they have been generally called, though most attractive on account of their brilliancy and variety, were found to be somewhat fugitive, and earned, in that respect, a poor name for the new artificial dyes. They have long ceased to be used; mauveine was last used to make penny stamps in Queen Victoria's reign. Their place has been taken by newer dyes of the types we have been discussing, discovered by Perkin himself and by other great chemists. The point is that all the work was begun by Perkin because he made the first of the artificial dyes and set the chemical world wondering at the marvellous results to be obtained from coal-tar when the search was made with understanding, and in the right way. The romance of the dyer's trade lies not only in the ages-long story of its attempt to meet the natural love for colour and for design, but also in the sudden unveiling of new knowledge only seventy years ago, which enormously increased its width and dignity and beauty. It is no longer a collection of rules and methods very imperfectly understood; it has become an ordered science already rich in fruit and bursting with the promise of further growth.

Explanation of the Colour Frontispiece

The colour frontispiece illustrates some of the processes of dyeing. The beaker at the top on the left contains indigo in solution: it is yellow, though a blue tinge appears where it is most in contact with the air. One of the hanks of cotton has just been dyed, and though it was yellow when it came out of the bath, it is rapidly taking on the characteristic colour. The other hank has been out of the bath for some time and is truly dyed by the indigo. This illustrates *Vat Dyeing*.

On the top right is an illustration of *Mordant Dyeing*. The cloth has been printed with aluminium and iron mordants in various strengths and proportions; the upper piece shows the appearance of the cloth so treated. It is then dyed with alizarine, and the lower piece shows the result.

Below these are two specimens of cotton-celanese mixture. The one on the left has been dyed with " Duranol Red G Paste ": the celanese has taken the dye, but not the cotton. In the specimen on the right " C.R. Chlorazol Fast Scarlet 4BS " has been used, which dyes the cotton but not the celanese. The remaining pair of specimens are of viscose-celanese mixture. In the left the dye is " Duranol Blue G Paste ": in the right it is " C.R. Chlorazol Sky Blue FF." These illustrate *Selective Dyeing*.

LECTURE V

The Trade of the Potter

THERE is a remarkable contrast between the trade of the potter and the trade of the dyer of which I spoke in the last lecture. The chemist has been successful in determining the structure and properties of the dye molecule to an extent which gives the dyer a remarkable mastery over his craft. The dye molecule is the element of the trade on which everything depends; when the worker knows the nature and the important characteristics of that which he is handling as his tool, he goes to work more directly and with more understanding. He knows better how to get what he wants; if anything goes wrong he can find the fault more quickly, and his imagination is quick in suggesting new things to try for.

So also the smith has of recent years made great progress because he has learnt to look closely into the structure of his materials and to recognise the properties of the small crystals of which they are composed. The weaver builds the whole of his work on the structure of the fibre; he accepts the fibre as nature gives it to him and shapes his work accordingly. Only when he begins to make artificial fibres, as in these later days, does he break away from old practice. It becomes an extremely interesting question whether he can improve on the natural fibres or no; perhaps in time he may do so in so many respects that the natural will give way to the artificial. But that may be a long way off, and meanwhile the weaver must learn all that he can about the fibre that has been the basis of his craft for ages past.

When we come to the potter we find him dealing with a unit of which far less is known than of any of the others. If we ask the simple question, "What is clay?" we can get no complete answer. Even the textbooks are content with giving us several definitions to choose from. Of course we all know roughly what clay is, and the potter knows better still; his trained hands and eyes can appreciate qualities and differences which we do not recognise at all. We are all familiar with its plastic character; it can be moulded into any desired form and will retain that form perfectly without flowing or springing back. We know, too, that it can be fired so that its nature is changed and it becomes hard, unaffected by heat and cold, almost imperishable. These are the qualities which have led man to choose clay out of all the materials on the earth's surface for the manufacture of vessels of all kinds, of tiles for roofs and floors, and writing tablets, of pipes and conduits, as well as of objects which satisfy his love of beautiful things (Plates XXVIII and XXIX).

But when we ask what plasticity is, we again receive no definite answer; many have tried to give a good working definition of the quality, but have come to no common agreement on the point. There is the old test of the potter's thumb, which must make a perfect impress on the clay without becoming wetted or soiled thereby. But what does this test really imply as to the essential nature of clay?

We might be inclined to think that so long as potters can produce such beautiful and useful wares, it cannot be of much importance to seek for a more intimate knowledge of the nature of clay than that which they possess. If, however, we take that view we make two great mistakes. In the first place we forget that as long as the fundamental material of any craft is imperfectly understood, the process of manufacturing is always liable to be held up by unforeseen troubles. When something goes wrong various methods are tried, and at last one may be found which is a cure, or the difficulty may disappear of itself, to crop up again another day. If a cure is found, it is generally of a rule-of-thumb nature; if an explanation of the cure is given, it is often an unreal explanation because one cannot speak precisely of what is imperfectly understood.[1] This leads sometimes to serious losses. A simple example was once shown to me at one of the great factories at Stoke-on-Trent. Certain green spots appeared now and then on the surface of large earthenware baths, beautifully made and costly. But the green spots rendered them unattractive to the buyer. If the whole process of manufacture were perfectly understood, from the molecule and from the crystal upwards, the cause of the coloration and the means of avoiding it would be known immediately. As things were, it was most difficult to avoid loss, and most costly to make the experiments necessary for the discovery of the trouble.

The second mistake is this, that however beautiful and useful pottery may be now, it is almost certain, if we may argue from similar cases, that new opportunities for beauty and usefulness will open out indefinitely as soon as the fundamental material is mastered. Experiments always cost

[1] Hind, *Trans. Ceramic Society*, xxiii, p. 234.

time and materials and labour, but they are terribly expensive if they are carried out on a mere trial and error basis, without understanding as a guide.

The reason why the fundamental nature of clay is not better understood lies in the nature of the material itself. It is not due to want of attention, for numbers of workers have given time to the investigation; nor due to any lack of skill on the part of the workers, for some of the very best physicists and chemists have been interested in the problem. There is an extraordinary difficulty in finding out what is the real cause of its fundamental property, plasticity. Why does it vary so much from one clay to another? Why is it so greatly affected by causes which would seem at first sight so ineffective, such as a trace of acid, or alkali, or of organic matter?

It is, of course, these variations and uncertainties that have made the potter's trade so full of unexpected developments, of secrets and mysteries, of traditions, of recipes forgotten and rediscovered, of excitement and romance. A certain kind of clay is found in some country which has qualities that are prized, and an industry grows up which may bring out the workmanship and the art of the people that make it. Trade carries the products far and wide, sometimes also the methods of manufacture. Sometimes a transplanted process takes on fresh life because it meets with some new material or some new knowledge. For example, salt-glazing was introduced into Staffordshire early in the eighteenth century and was applied to the pottery already made there. In this process a quantity of salt is thrown into the furnace as the firing is approaching completion, with the result that a glaze is formed over the ware; we see examples in many of the common objects of the house and the street, from teapots to drain-pipes. The result was the development of a special pottery which became famous not only in England, but also in Europe. So with all this coming and going there grows up a wonderfully interesting world-wide craft, characteristic both of countries and peoples, and very human. The very imperishable nature of the products adds to the interest, since for ages their record exists for all to see; their story is not conveyed by oral tradition, nor even by perishable writings.

The constituents of clay are aluminium, silicon, and oxygen, coupled up with a variable amount of water. In the compounding of the three elements there is some subsidiary grouping into alumina and silicon dioxide. The first of these is known to us in its crystalline form as corundum, of which ruby and sapphire are coloured varieties. Silicon dioxide, in its crystalline form, is rock crystal or quartz. The single molecule of alumina contains two atoms of aluminium and three of oxygen, its chemical symbol being Al_2O_3. In the crystalline form of corundum its atoms are put together into a structure which the modern use of X-rays has permitted us to discover; all three of the varieties I have mentioned have the same structure. So also the structure of quartz is built of atoms of silicon and oxygen in the proportion of one to two; in this case also the X-rays have enabled us to determine its formation, curious on account of the spiral arrangement which it contains. Now the clay molecule, assuming the existence of something so definite, is made up, so far as mere assemblage of atoms goes, of one molecule of alumina, two of silicon dioxide, and two of water (H_2O). But no one knows how they are grouped together. Our best, indeed our only means of finding structure is by means of X-rays. When molecules of any substance are grouped together they tend to form a regular pattern, which, when it grows large enough, is recognised by the eye as a crystal. Even when the growth is far too small to be detected in this way, the X-rays can make it plain and find the pattern on which the molecules are arranged. They can even go further, and in many cases can find how the atoms in the molecule must be grouped together.

When we apply X-rays to the clays we find at once that there is a crystalline structure even in the clays composed of the finest particles. Unfortunately, the information, while quite conclusive on this point, is not easy to interpret because our knowledge of the new X-ray methods is only in its first stages, and some problems are too hard for us as yet. All we can say is, that there is a crystalline structure which is not that of alumina, nor that of quartz. Even this small amount of information is useful.

Clays from different sources all show the same structure, though they may show others as well; some show the existence of separate quartz crystals. That is not at all surprising, because clays are supposed to be due to the action, deep down in the earth, of heated acids on granite and similar rocks, and these rocks often contain quartz. The clays have been carried about by water from place to place, and the quartz crystals are ground down during the transit to the form of fine grains of sand, which are mixed with the clay.

Chemical analyses of all these clays show that there are many possible constituents. Some of them are obvious impurities, such as the sand just mentioned, mica in considerable quantities, silt, gravel, and powdered rock of many kinds. Many of these can be removed by the simple process of mixing the clay with plenty of water so that the particles of all kinds are suspended in it, making a turbid mixture such as we see when the streams run off the clay lands. The larger particles settle more quickly than the others, so that it is not difficult to get rid of most of the impurities in a settling tank, or a succession of such tanks. We must all have noticed how in rivers and lakes the heavier sands settle in one place and the lighter in others; the differences depending on the rate of flow and other physical causes. It is never possible, however, to get rid of all the impurities in this way, the particles of mica and other substances are often as small as the fine grains of clay and have about the same density, so that the process never comes to an absolutely successful finish. The further it is carried, however, the more nearly does the remainder approach the composition already given, one of alumina, two of silicon dioxide, and two of water. Probably, therefore, there is a real crystalline structure of this composition; in any given mass of clay there will probably be crystals of all sizes, from those containing a few molecules only to others which are big enough to be seen under the microscope, when they appear as minute flakes.

Clay is found all over the world. After all, oxygen forms half of the earth that is known to us, silicon a quarter, and aluminium about 7 per cent. Alumina, and quartz, and clay which, in a sense, contains both these, are the natural groupings of the three elements. Clay, therefore, has been everywhere ready to hand, and wherever and whenever its peculiar qualities have been observed, it has been put to use. The whole of its excellencies may not have been discovered at once; in the most primitive times it would be sufficient that pots could be made of dried clay, good enough to hold grain, and even water. The first great properties, plasticity when wet and firmness when dry, would be seized upon before anything else was found out. Then when the pots were used on the fire, it would be observed that the material sometimes altered in texture and became firmer still; and, finally, the firing-oven came into existence in which greater heat was obtained and the process of firing was carried to a more complete stage.

Though clay is found so universally it varies in quality so greatly that clays from some sources are far more valuable than others. One of the most famous of all clays is often called kaolin; the use of the term implies no more than that the Chinese used a clay obtained from a place or places of that name—it means "high ridge"—and that clays of similar character which are found elsewhere in the world are grouped under the same name, even though their similarity is not absolute. Kaolin was used by the Chinese for the manufacture of porcelain, which, as we all know, is a white, hard, translucent kind of pottery, highly valued for the possession of these properties. Much of the excellence and the reputation of English pottery depends on the fact that there are quantities of fine kaolin in Cornwall; there are famous masses of it in Germany and France also. Another well-known clay is the ball clay of Devon and Dorset; these are remarkably similar to kaolin in composition. Both china clay and ball clay contain small quantities of other substances; ball clay contains 2 or 3 per cent. of sodium and potassium—not as free metal atoms, but as parts of molecules,—of which metals china clay contains only a trace. There are other small differences. Now it is very curious that ball clay is highly plastic and china clay is remarkably deficient in that respect, so that this most important quality can vary very greatly when the composition of clay varies little; we may see some explanation later on, of how this can happen. Kaolin is an extremely refractory substance; that is to say, a very high temperature indeed is required to melt it. Some other more easily fused substance is always put with it, which when it softens and runs —"vitrifies" is the correct term—binds the mass together. A very suitable mineral for this purpose is also found in Cornwall and is known as Cornish stone; it is very mixed and even variable in composition, but always contains quartz and felspar, which melt much more easily than china clay. In the manufacture of china-ware, it is an English practice to add also the ash from burnt or calcined bones; this also helps to bind the mass together. Bone ash has also the very valuable property of giving translucency to the ware. In this way the English variety of porcelain is made, which has been and is so well known that the factory names are almost household words. We have Chelsea and Bow, Derby, Worcester, Plymouth, Bristol, and Staffordshire, which last includes Minton and Spode, Wedgwood, Davenport, and others.

Porcelain is, in a sense, the first of all varieties of pottery ware, so hard and strong, white and translucent. It has a wonderful history attached to it. In the fifteenth century when Europe was for the most part making a rough pottery of inferior clay, coarsely glazed, and the countries of Western Asia and those parts of Europe which were under Mohammedan rule, such as Spain and Sicily, were making a somewhat better pottery, brilliantly decorated, the Chinese craftsmen were far advanced in porcelain manufacture. There came a time when their goods began to make their way into Europe, and potters everywhere began to imitate them. We can imagine how difficult the hunt would be, for we must remember that clay when fired is entirely changed in character, and gives little hint of its original form; in those days, also, there was no chemical analysis to help them. The first success was a pottery made in Florence at the end of the sixteenth century, but this manufacture did not last long, and the next attempts were French. The right materials had not yet been discovered, but a pottery very like the real porcelain was made by fusing together hard clay with substances which form a glass when melted by themselves. The first European porcelain, which was really the same as the Chinese, was made by Böttger at Meissen in Germany about 1710. We can realise how keenly the search had been when we read of the precautions that were taken to keep the secret when it had been found. Under the direction of Augustus II, Elector of Saxony and King of Poland, the workmen made their wares in what was practically a closed fortress. At last a workman escaped, as sooner or later some workman was bound to do, and factories sprung up at Vienna and later at many places in Germany.

The fact that we possess in England the true ingredients of Chinese porcelain was discovered in 1755 by W. Cookworthy of Kingsbridge, in Devonshire. He found not only the true china clay, but also the right stone to go with it, both of them at a place called Tregonning Hill. Afterwards they were found in other parts of Cornwall. The factory at Plymouth did not last long; very little existing porcelain is known to have been made there. The works were transferred to Bristol, and there developed greatly.

It is a very curious fact that clay was largely eaten at one time in Europe, as it is still eaten by some races in other parts of the world. A few years ago M. Solon, a well-known expert in the history of pottery, was writing from time to time a series of very interesting papers for the Ceramic Society on different sections of the history. The papers were printed privately and have not been accessible to many; but they are now being published under the general title of "Pottery Worship." One of them discusses the extent of this clay-eating practice. It began long ago when a china clay from Lemnos in the Ægean Sea was exported for this purpose, made into cakes, and stamped with the symbol of Diana. This, according to Solon, is the true origin of the term *terra sigillata*—earth marked with a seal. In the fifteenth century Crete was in the hands of the Turks, but the export still persisted. Indeed it increased, and rival clays were mined in different parts of Europe. Böttger, therefore, had not far to go to look for clays for his experiments; he would get them at the nearest apothecary's shop. In the prospectus of the works founded by Augustus of Saxony, it is said that "vases, figures, table-ware, etc. are to be manufactured in the Royal Works, of a porcelain as fine as any that was ever imported from China and Japan, made out of the *terra sigillata* found in Saxony." Not only were natural clays eaten in those days, but even clays that had been fired. Absurd superstitions grew up as to the properties of vessels made of various clays in different countries. Pottery varied so greatly with its source, and was so resistant to imitation, that certain kinds, valued for special reasons, were greatly sought after; all sorts of legends grew up as to their powers. There were the famous scented vessels from Mexico, afterwards copied in Portugal, which were known as the "noble Buccaros," and were said to be so powerful as to be able to turn negroes white if they drank from them! It was believed of many such potteries that they could detect a poisoned draught. When they came to grief, their fragments were set in gold and silver, and used as amulets, or were ground up for medicine. There is in existence a pamphlet—so Solon states—by a certain physician, Dr Daniel Geyer of Dresden, 1735, in which the author describes his being called in to prescribe for a lady who had gone a little too far and eaten a whole cup and saucer. In China, also, kaolin is mentioned as a medicine long before it is described as an ingredient of pottery.

When the materials of fine porcelain were found in England and were used to make wares that became famous, the reputation of the country for the manufacture of pottery was greatly strengthened. Porcelain was not, however, the only or indeed the chief product of the English factories. The end of the seventeenth century saw the beginning of the construction of the white English earthenware which has spread all over the world. The old pottery made of red-burning clay, roughly finished and glazed, gave way before it; in the first half of the nineteenth century the industry had grown so much that English pottery was carried everywhere. It was valued for its good appearance, neatness, high finish, strength, and general usefulness. Naturally, other nations took it in hand to make the same wares, importing English potters when necessary, so that now the Staffordshire potteries, where our industries have for the most part drawn together, have many competitors. Nevertheless, our pottery industry is still one of the greatest of its kind, and there is no reason why it should not maintain its pre-eminence. The potters who have worked there for the past two centuries have gradually accumulated a great mass of technical knowledge and a remarkable skill in applying it. An industry which has gathered together in one place a body of efficient workers is in a favourable position for striking out in fresh directions, for taking advantage of discoveries, and for devising new methods and new styles.

Let us follow quickly the steps of the processes in the making of a pot. We go down to the mines in the south-west of England where the various clays and rocks are extracted and purified. Let us take the case of china clay for an example. The masses lie near the surface and are worked in the open way like quarries. Powerful jets of water are directed upon the clay face as the illustration shows (Plate XXXI, *a*), and a turbid stream flows down the face, carrying with it lumps of various sizes which are broken up as they go. The water runs into a "sand pit," where much of the coarse rock and sand falls to the bottom. The clay water, partly purified, flows over into pits from which it is pumped into "mica drags" (Plate XXXII, *a*), where sand and mica are deposited as the water slowly makes its way through a tortuous set of channels; the water passes through a second set at a much slower rate, the settling going on all the time. The clay water is then run into settling pits where the clay itself falls quietly down; after a time the water is run off and the deposited material is run into a second set of settling tanks, where it remains until the deposit has attained such a consistency that it can be handled as lumps and placed in what is called a "Dry." When sufficiently dried, it is ready to go to the potteries. The plasticity of clay is often improved by age. The clay is kept damp and cool, and the action of bacteria is encouraged by saturating the clay with cheap organic material, such as plant infusions, tannery waste, peat, old vinegar, and all sorts of refuse. Sometimes a short period is considered sufficient, and again the clay may be left for weeks, or months, or even years. It is said that the Chinese potters kept clays for their finest work for a hundred years.

Besides china clay, "Cornish stone," ball clay, flints (Plate XXXI, *b*), are collected, each in its own way. At the potteries they are ground (Plate XXXII, *b*) to powder and "slopped up" with water, separately. They are mixed in large underground tanks; the famous earthenware consists of ball clay, china clay, flint, and stone, in the proportions 3:3:4:2 approximately. For bone china, calcined bones, china clay, and Cornish stone are mixed in the proportions, roughly, of 2:1:1. The addition of a minute proportion of very finely divided oxide of cobalt helps to keep the resulting products white; this is quite analogous to the bleaching of linen by blue powder in the laundry. The mixture must be strained by sieves, called "lawns"; specks of iron which were present in the original materials, or have been introduced during the manufacture, are removed by powerful magnets. Then the excess of water must be removed by an operation known as filter-pressing, and, finally, the material is passed through a glorified sausage-machine from which emerges a "pug" (Plate XXXIII, *a*); the name seems to fit the result exactly. The object of the latter treatment is to distribute the water uniformly and to remove all air bubbles.

It is quite important to get rid of these last, for their presence in any clay article put into the oven would be disastrous. For this purpose clay has always been kneaded, or "wedged," to use the technical term. Even now the old methods survive when it is more than usually essential that there should be no breaks in the consistency of the mass (Plate XXX, *a* and *b*). Such a case is that of the pots into which steel is poured from the crucible in which it has been melted; the pots are still made in Sheffield in the old way, which has been described to me as follows:

"The material used for making the pots is a mixture of china and Stourbridge clays with a small amount of ground coke dust, generally ranging from 1 to 3 per cent. (by weight) of the mixture. Sufficient water is added to make a very stiff paste; this is spread out in a shallow iron pan or trough about 10 ft. square.

"The pot maker and his assistant then commence to tread the clay with the ball of the foot, working across the clay in one direction, and then afterwards at right angles. This treading takes from four to five hours before the clay is brought into the proper condition for pot-making. In this time they approximately prepare one ton of clay, which makes from sixty to seventy pots, the average weight of the pot being thirty-two to thirty-three pounds. After this treading operation, the proper weight of clay is taken (thirty-three pounds) and balled up; this is done by the man lifting the ball of clay to the height of his shoulders, and then dropping it on to an iron slab about 2 ft. to 2 ft. 3 in. from the ground; the slab is covered with a piece of damp sack-cloth.

"The purpose of this balling up is to get rid of any air (or shuts as they are called by the pot-maker) which may have been trapped in the clay."

It is always interesting when we find that machinery has not been able to displace an old method. Our attention is naturally attracted to those points in a process where intelligence and care are wanted all the time; where something has to be done which cannot be made up of mere repetition such as can be entrusted to a machine designed for the purpose. We are sure to find something not only interesting but important.

Let us return now to our mixtures which are ready to be moulded and fired. It would not be possible to give complete answers to any questions as to the why and wherefore of the particular compositions. They are the result of long and costly experience; the few recipes that have proved satisfactory when hundreds and thousands of others have failed. Something can be said, nevertheless, though it may be incomplete. Kaolin is a highly refractory substance which burns white, but it is too refractory when used alone. Thus a "fluxing material" of some kind is introduced, which will run and form a vitreous mass holding the whole together. That part is played by the Cornish stone, helped by the bone ash. The compound is tender to handle during the moulding, as one sees when watching the skilled man working at his task. On the other hand, "earthenware" composition is very plastic to work; the flint is added to diminish the shrinking which is so prominent a result of the firing. Again, the Cornish stone helps to bind all together, and this gives the ware a close texture; it gives out a ringing sound when struck.

In moulding the objects to the form that is desired, the ancient potter's wheel (fig. 41*a*) is used still, as for example in Plate XXXIII, *b*, where a Staffordshire potter is shaping an ordinary china plate. But more often a new and very interesting method is employed, which has been largely developed in this country. The clay is

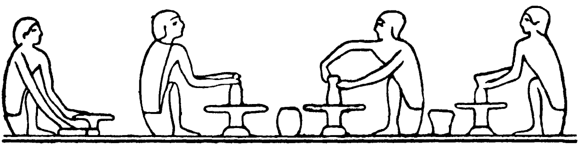


FIG. 41*a*.—The Potter's Wheel. (*From an Egyptian painting, "Encyclopædia Britannica," 'Ceramics.'*)

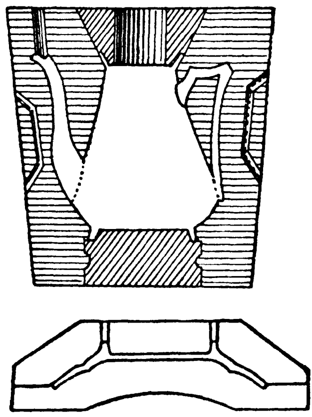


FIG. 41*b*.—Casting Moulds in section: (*a*) Teapot; (*b*) Plate.

made into a "slip"; that is to say, enough water is added to it to make a creamy paste which will run freely. A plaster of Paris mould is made—illustrations are given in fig. 41*b* and Plate XXXIV, *c*—and filled with the slip. The water of the slip is drawn into the plaster from those portions of the liquid which lie next to the walls. The clay thus "de-watered" settles on the sides, and after the mould has stood half an hour or so, or an hour, the time varying with the casting in question, a deposit of reasonable thickness has been formed. It is now turned upside down for a few minutes, and that part of the slip which is still liquid is poured away. When the draining is complete the mould is turned the right way up and left for an hour or so in order that the casting may dry somewhat. Then the mould is taken to pieces and the newly made pot is revealed. Such a method is, of course, suitable to the construction of vessels of irregular form, and having moulded surfaces. It is, in fact, extraordinarily valuable. After a further drying period in a warm room, it is ready for its firing.

The process of drying has to be conducted with great care, because one of the properties of clay is its very considerable shrinking when it parts with the water it contains. The volume of wet clay may be diminished by an eighth to a third of its amount. It is clear, therefore, that the moulded object must shrink all over at the same rate, or it will crack; if it cracks it is ruined, because its strength is gone, in rough proportion to the size of the crack. Especially must care be taken if the object is of very irregular shape, because the thin portions may dry and shrink more quickly than the rest.

Sometimes it is necessary to put a foreign substance into the clay to keep it open when drying, so that it may dry more evenly. It has to be made possible for the water to get from the inside to the outside. One of the materials used for this purpose is sawdust; in the case of bricks made of London clay, the danger of cracking is so great that quantities of ashes and clinker are added. The Israelites, we may remember, mixed straw with their bricks, for, I am told, the same reason.

During firing, further shrinkages occur which are very complicated in nature, so that pottery must always be designed in anticipation of the fact. A bad design will crack when a good design will not.

One or two figures will help us to visualise the firing processes. In the first (Plate XXXIII, *c*), the workmen are seen placing the ware in the oven. The ware would be injured if the flame were allowed to play over it, or if the heating were irregular. The ware is therefore placed in open earthenware vessels called saggars, which, as the illustration shows, are piled up on top of one another, from the floor to the roof. Sections of an ancient and a modern oven are shown in figs.

42 and 43, from which we can grasp the method of distribution of the heat. The progress of the firing is indicated to the watcher by the state of certain little cones, made of a mixture of clay and felspar, which are placed in the furnace at the beginning of the firing (Plate XXXIV, *a*). After

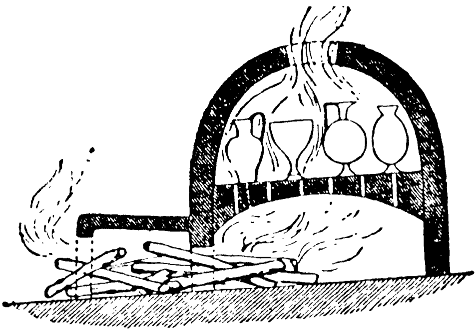
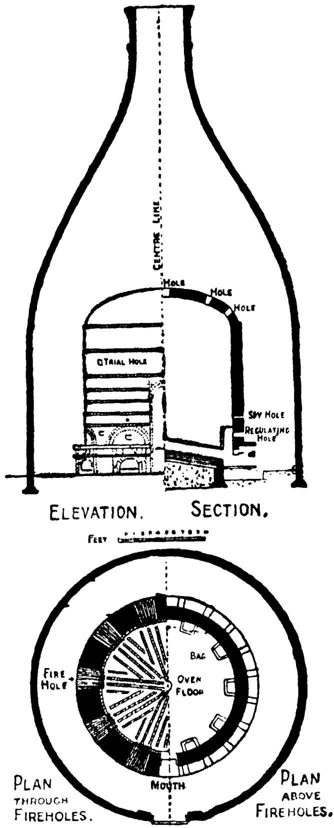


FIG. 42.—An Early Greek Pottery Kiln. (*By courtesy of the publishers of the "Encyclopædia Britannica."*)

the firing has reached a certain stage, the cones begin to "squat," to use the technical expression, and they are so graded by variations in composition that the squatting of each cone indicates the completion of a definite amount of firing. In the illustration one of the cones has squatted altogether, a second is well down, and the third has just begun to fall over. From the state of the three cones it is possible to obtain the information wanted. It is interesting that this method is in some respects better than that of measuring temperature by any form of thermometer or pyrometer, because the latter instruments record the temperature at a particular moment, whereas what is really wanted is information as to how much the ware has been fired.



BISCUIT OVEN.

FIG. 43.

Sometimes one firing is all that the ware receives; this is always the case with common objects — bricks, flower-pots, roof tiles, and the like. On the other hand, many objects are fired twice. After the first firing the object is dipped into or painted with a slip, or decorated with other clays which the second firing forms into glazes and patterns. The process of dipping is illustrated in Plate XXXIV, *b*. Many kinds of ware have more than two firings, if the system of decoration is complicated.

Let us go back to this casting process, for it brings us at once into touch with some of the most interesting of all the clay problems. One curious aspect of it appears when we find that the potter adds a very small amount of an alkali—sodium silicate—to his slip before he uses it. A slip which was much too stiff to run, and would require the addition of a considerable amount of water to bring it to a creamy state, is brought at once to the proper condition. The operation of casting requires that untreated clay shall contain about 40 per cent. of water, while treated clay needs 30 per cent. only. In the first drying process part of the water is removed, but the use of the alkali reduces that portion greatly, so that the risks incurred during the drying process are materially lessened. This improvement is of the highest importance to the manufacturer.

If we now ask the explanation of this strange action, we find that we are in face of the whole question of the nature of clay, of which we have already noticed both the importance and the mystery. In certain respects this behaviour of clay is very similar to a host of actions which are found to take place when one substance, finely divided, is dispersed through another substance. Of recent years it has been found necessary to consider so many cases of this sort that they are sometimes grouped together into a class. We speak of colloidal substances, or substances of glue-like behaviour. But derivation means little now, although it was thought to be good when first it was used, and it is simpler to begin with the facts themselves.

Think for the moment of a cloud hung in the sky. It consists of multitudes of fine water-drops, all about the same in size. Because a drop is so small, its rate of fall through the air is exceedingly slow, and because this is true of every drop, the whole cloud is almost stationary in the air in which it floats. The cloud does not cling together because there is any mutual attraction between the drops, but simply because the drops were all made about the same time and in the same region, and they have not drifted apart. They came into being, perhaps, when there was an expansion of the air, due to wind movements, and the consequent chilling slowed down the motions of the water molecules already in the air, so that they were inclined to gather into tiny groups, particularly if any minute dust particles were wandering about to serve as nuclei. If they gathered round many centres, each drop would be small; if the number of dust particles was small, the drops would be larger. Once the drops are formed they can be singularly persistent; and the cloud may last a long time without much change. Under other conditions, as when the temperature falls, or an electric storm occurs, the small drops may gather into larger and the water comes down in a heavy shower. So also the smoke cloud consists of particles of carbon which remain in suspension in the air because their minuteness makes their rate of fall imperceptible. At the same time their numbers give the smoke the appearance of an associated mass, though really the particles are quite independent and merely happen to be all in the same region. So, too, the clay particles, or any other set of fine particles may be suspended in water, each quite independent, with not even the herding instinct of a shoal of fish; and they may remain so for a long time. The smaller they are, the less the rate at which they fall through the liquid; larger particles may fall and finally form a layer on the bottom of the containing vessel. The point, so far, is that a crowd of fine particles dispersed in some medium, such as air or water, may quite naturally stay as a crowd, changing very little in course of time.

Moreover, such conditions occur very often indeed, and they can readily be brought about. Indian ink, for example, consists of fine particles of carbon dispersed in water. Many metals can be dispersed in water in a fine state of subdivision. Faraday made many experiments with gold and silver. I shall refer to some of them later.

The next point is that a material so dispersed presents a very large surface to the liquid which contains it. The surface of a cube of gold weighing one gramme has an area of nearly five-sixths of a square centimetre. If the gramme is divided into a million parts, the total area of all the parts, still supposed to be cubes, is increased a hundred times; if the subdivision is repeated, the whole area is ten thousand times what it was; and after another similar subdivision, it is a million times its original value. It is then equal to the floor space of a large room. Now, if a solid is exposed to a liquid which can act upon it, the action can only take place at the surface of the solid; so that the larger the surface, the quicker the action. We take advantage of this whenever we crush the sugar in our tea so that it may dissolve more quickly.

But now another point presents itself. When an action takes place of the kind we are talking about, it is a series of minor actions between molecules of the solid and molecules of the liquid. When, for example, the sugar crystal dissolves in the water, we should see, if we could look closely enough into what is going on, a crystal with its outside molecules all more or less arranged as they were when they formed part of the inside of the crystal and other molecules were on the outside of them. They are probably a little shaken from their places because the stream of moving water molecules is always knocking against them. And sooner or later the water molecules, which have all the time a tendency to associate with the sugar molecules, at last break them away one by one and carry them off. A reverse process occurs if the number of sugar molecules in the water is very great and if the solution is cooling down; then the forces that draw the sugar molecules together may make the crystals grow rather than melt away. Everything depends on a balance of opposing tendencies.

Sometimes a tendency for actions of this sort to take place can be checked by spreading a layer of atoms or molecules over the surfaces of the solid particles. There may be some substance in the solution which has a considerable attraction for the solid molecules, so that the atoms or molecules of the substance settle quickly all over the solid surfaces and protect them from the actions of the molecules of the liquid. It is remarkable how small a quantity is wanted for such a purpose. If we take the case of the gramme of gold which is so subdivided that its whole area is as large as that of the floor of a room, and spread over all its many surfaces a layer of some substance, one molecule thick, the quantity required would not be more than about a hundredth of a cubic centimetre, taking an average value for the size of a molecule. This helps one to realise how small a quantity of some foreign substance, if of the right nature of course, can either hasten or hinder an action between a liquid and a finely divided substance suspended in it. We can take a curious example of the effect of a thin coating of this kind from an important research by Bone on combustion. Two dry gases, carbon monoxide and oxygen, when mixed together will combine if encouraged to do so; in fact they may be made to combine so quickly as to form an explosion. They combine very slowly if made to stream together through metal gauze in a glass tube, on account of a curious action of the gauze surface. In particular, when the surface is what we ordinarily call dry, the action is small; when it is carefully dried in the usual laboratory manner, it is active; but when it is dried with extreme care, the process taking days or weeks it may be, then this action ceases altogether. It is clear that the uniting of the two gases is promoted by the presence of a thin film of water on the metal surface, but it must be extremely thin, something that is left even after the surface has been thoroughly dried in the ordinary sense. Again, a freshly-cleaned piece of steel is acted on by copper nitrate; if drops of the latter in solution are placed on a clean steel surface, the chemical action results in the deposit of dark patches of copper where the drops have rested. But if the steel is left in the open air for a day, the steel is no longer affected by the nitrate. This is because a layer of molecules, taken from the air, has been slowly deposited over the steel and protects it. Yet there is nothing to be seen on the steel.

When we find that the presence of small quantities of various substances added to the clay suspension can produce great changes in its properties, when, to take a particular example, we find that china clay and ball clay differ so entirely in their plasticity, though so very much alike in constitution, we cannot but be reminded of those many other cases when small quantities applied to a surface can completely alter its behaviour. Yet we do not know exactly what is happening to the clay. Sometimes the picture is a little clearer, as when we think of what must happen when a substance such as salt is added to the clay slip. It is known that the molecules of the salt will break up in the water into two parts, sodium atoms carrying a positive charge, and chlorine atoms each carrying a negative charge. Now, the clay particles are from some cause slightly charged with negative electricity. The positive sodiums gather the negative clay particles round them, and these in turn other positives, and so on; and so the clay particles grow together and finally sink to the bottom of the vessel. So, it is said, the clay carried down by the rivers is deposited when it meets the salt water of the sea. The action of hydrochloric acid is similar, but more forcible; in this case it is the hydrogen atom that is positively charged. When we pour some of the acid into our creamy slip, the latter becomes so stiff after a little while that our stirrer stands upright in it. But when we put in an alkali, such as caustic soda, which also breaks up into parts, each molecule dividing into a positively charged atom of sodium and a negatively charged group consisting of one oxygen and one hydrogen, the latter easily takes up the hydrogen atoms to make water molecules, and the material becomes fluid once more. The positive sodium atoms are there, but their action is probably too slow.

There is another aspect of the properties of clay which resembles similar well-known properties of ordinary substances. Clay can be dried, shrinking somewhat as it does so; if water is then added to it, the clay will take up a certain volume and expand again. In this it resembles gelatine. If sand is mixed with water it can be moulded like clay and acquire a sort of plasticity, but if the sand is dried, then, unlike clay, it falls to a powder. There is, therefore, something of a gelatinous behaviour about clay, which has to be explained. Now gelatine and many similar substances have this curious power of "setting" when the amount of the substance is quite small in comparison with the amount of the liquid into which it is placed. A 2 per cent. solution of gelatine in water is a solid. Castor-oil soap is an almost solid jelly at a concentration of a tenth of 1 per cent., if a certain amount of alkali is present. The properties of a jelly are peculiar, of course; it is weak in texture and its shape is easily altered. One cannot help thinking that the jelly must consist of long fibres, perhaps of long molecules which are laced together in a somewhat irregular way. There would naturally be many empty spaces, through which other atoms or molecules could move in the way that we find does actually happen. In a well-known experiment a test-tube is half filled with a jelly on which a liquid containing fine particles in suspension is poured. If the particles are molecules, and not too big molecules, they will gradually wander into the jelly, otherwise the jelly remains quite clear (Plate XXXV, *b*). For instance, copper sulphate molecules pass into a jelly out of a solution placed upon it, but particles of gold suspended in water do not.

When, therefore, a jelly is dried we can imagine the water driven out of its pores and the long molecules or fibres falling together into a matted condition, ready to open up again if water is supplied. Clay behaves much in the same way. But, then, are there fibres in the clay or anything corresponding to them? I believe that at present no exact answer can be given to the question; we are again brought to realise how little is known about the clay molecule and its relations to external water. Perhaps we can go so far as to say that each particle is a crystal or an assemblage of crystals, and that it is surrounded by a jelly-like envelope. The envelope might be some structure composed of an alliance between the atoms found in clay and the atoms found in water; perhaps, on the other hand, it might be mainly some arrangement in the water itself brought about and maintained by forces due to the clay molecules.

If clay is heated to a temperature of 400° to 600° it loses its power of absorbing water and is no longer plastic; in fact, at about the latter temperature the clay molecule breaks down altogether and a new substance is formed; it may be that the molecule is first broken up into separate molecules of alumina (Al_2O_3) and silica (SiO_2). This change may be observed by means of the X-rays. No amount of mixing with water will make the substance into clay again. There is a new crystalline structure, probably built on a combination of the substance of one molecule of alumina and two molecules of silicon dioxide; but the water molecules of the clay have gone. At a high temperature there is again a further change and a crystal is formed which is built on a combination between three alumina molecules and two of silicon dioxide (Plate XXXV, *a*).

The properties of any substance are profoundly affected by any change in its crystalline structure or arrangement; indeed one may justly say that such a change converts one substance into another. It therefore becomes very interesting to study the properties of china ware in relation to its structure, and in this the X-rays have begun to help us.

When we think that these important changes of crystalline structure are brought about gradually during the firing in the furnace, that their progress is dependent on the constitution and the composition of the materials of which they are moulded, because different substances will melt or flow or change at different temperatures and at different rates, that the shape of the vessel, and the way it is placed in the furnace, and the distribution of the furnace heat, will all influence the result, we can form some idea of the complexity of the craft. We can well understand how it has been a matter of traditional rule and blind formula, and can marvel even more at the beauty of the results because we realise the cost of their attainment. If only we could learn more of the actual form, structure, and properties of the clay molecule on which the whole craft depends—and very skilled observers are straining to get that knowledge—we should understand so much better the mysteries that have baffled the potter and hindered his work. Indeed, we may well expect that there would be a new development of the trade, as has happened in parallel cases.

I have given the briefest sketch of the subject.

I might have tried to give some account of the glazes which are so essential both to the use of pottery and to its beauty; which just as much as pottery itself have been the subject of infinite pains, which have a history of their own, and a science that is full of interest.

But this subject is itself a very large one, and I must refer only to one point. We have all admired the gorgeous colours that the glazes can show. These colours are often due to the fine dispersion of metals in the body of the glaze; a state of division which we have already seen to be a common occurrence in nature and to be the cause of many curious effects. One of the possible effects of dispersion is an intense coloration. Finely divided gold suspended in water gives a beautiful red, which interested Faraday greatly, and there are still in the Royal Institution some of his preparations in which the colour persists; and, therefore, the gold must still be in a state of suspension.

The tint changes with the size of the particles, and by a considerable alteration a blue can be obtained. So the effect is in some ways analogous to the colours of mother of pearl, or to the blue of the sky; that is to say, it depends upon the size of the particles. But it may also depend on the presence of some molecular resonator, such as we saw was the cause of colour in stains and dyes.

It was no doubt an accidental discovery that glass and enamels could be coloured in this way; indeed, there were all sorts of secret and jealously guarded recipes for the process in the Middle Ages. Cassius, who wrote a book on gold in 1685, was the first to describe a method of preparing a substance which, when mixed with the glaze to be fired, would give the colour of ruby. The substance is a compound of gold and an oxide of tin, called the purple of Cassius. It is supposed that it consists of fine particles, perhaps atoms, of gold, each of which is surrounded by a protective film of the tin oxide. When this is fired the gold collects into tiny globules to the existence of which the colour is due. The pink known as Rose du Barry is produced in this way, and various maroons and crimsons. Chromium can be used in place of gold and gives a crimson; while copper gives a famous red known as rouge flambé, or *sang-de-bœuf*; this is the much prized red of Chinese vases. Rubies themselves owe their colour to the presence of finely divided chromium.

It is extraordinary what a small quantity of the metal is required; one part of gold in 100,000 parts of glass gives a fine rose-red.

Finally, I must be content to hope that what I have found time to say, will give some idea of the intricacy of a splendid craft which happens in these times to be of extraordinary interest. For it seems as if new knowledge and illumination might result at any moment from the labours of those who are engaged in the study of the foundations on which it is built.

LECTURE VI

The Trade of the Miner

THE story of the miner's trade is more like that of the sailor's than is the case with any of the other trades which we have been considering. He is not a handicraft man, making some object such as a sword, or a pot, or a piece of cloth. His work is to bring out from the earth the raw materials which others are going to use and fashion in various ways. When he enters the cage that is to take him down the shaft, he is like a sailor embarking on a voyage, counting on the returns to repay him for the labour and for the dangers he must undergo. He is on an adventure every time he enters the mine; it is not without reason that one talks of "winning coal." In the famous book *De Re Metallica*—of Metallurgy—which Agricola wrote in the middle of the sixteenth century, he speaks of the evils and dangers of the miner's life, of the very cold water which is harmful to the sinews, and of the dust which produces asthma and consumption, of the ores containing arsenical cobalt which cause wounds and ulcers that eat to the bone, of poisonous gases and landslides, and of the occurrence in some mines, fortunately few in number, of demons of ferocious aspect which can only be put to flight by prayer and fasting. Of this last belief we have still a memory in the word "cobalt," which is supposed to be connected with "kobbold," the name given to the little underground gnome of many German stories and pictures.

There is a second point of resemblance between the sailor's and the miner's trades. Both have made constant use of new knowledge as it became available in order to help them over their difficulties, and in doing so have enriched knowledge in return and laid the foundation of great scientific developments. Perhaps the second resemblance is a consequence of the first. Astronomy and its instruments, clocks, telescopes, and the rest; magnetic theories, the laws of moving fluids, and the lines of ships; these and many more have been studied because of the necessities of navigation and the need to overcome the difficulties of the seas. In the development of mining it has been just the same; perhaps mining can count even more influences on the science and industry of the world. The steam-engine was called into existence to overcome the floodings of the mines, the laws of gases were studied in order to help the miner with his poisonous damps, the safety lamp was invented to give him light in dangerous places; railways and lifts began with him their service to industry.

Indeed, if we begin at the beginning and think of the prospector searching over the earth for minerals, usually for some particular mineral, we can see that he must gradually acquire a store of knowledge relating to the characteristics of the places where his search is likely to be rewarded. The ores that are wanted are not scattered indiscriminately, but are associated with definite strata in the earth; coal, for example, is, in the main, found under certain layers of rock well marked in their constitution and the fossils which they contain. Other strata are not associated with coal. So the science of the geologist helps in the search, and indeed has very largely grown from it. The sinkings and cuttings and borings of the mine are a large part of the geologist's library. Even the plants that grow on the surface can help, for they change, as we all know, with the nature of the soil. Chestnuts and broom and heath grow where there is silica, box and gentian and larkspur where there is chalk; some plants like the sand and some like clay. There is a kind of viola which grows best where there is zinc in the soil, and in Queensland a certain plant gives a strong indication of the places where copper may be found. In mining districts it sometimes happens that the presence of ore below the surface is indicated by a general effect on vegetation due to the soil's excessive holding, or rejection of heat and moisture. Agricola advised miners to watch the hoar frost which "whitens all the herbage except that growing over the veins." He wrote especially of mining for metallic ores, making no mention of coal, which was not then an important mineral, at any rate on the Continent. Agricola's book is extraordinarily interesting, because it gives us a full account of all mining as carried on in Europe in his day; the book was published in 1556. It is much easier, I think, to form an idea of the main processes of mining from his descriptions and drawings, than from pictures of the complicated machinery of modern times.

His numerous illustrations are delightfully clear and explanatory; he has a charming way of surrounding his principal drawing of a machine, or a process, with separate drawings of all the important parts, scattered about on the ground, somewhat regardless of perspective when it would interfere with clearness. One of his pictures is shown in fig. 44; it shows the preliminary operations of the miner. We see the ground being opened up and

FIG. 44.—Preliminary operations of the miner. Two men have divining rods (A). Others are turning up the ground. The two on the left are evidently discussing the plan of operations.

trenched, and men with divining rods busily engaged in the search for metallic veins. Not that Agricola believes in the rods himself, he only describes what he has seen. In a very clear discussion which might have been written to-day, he discusses the theory and practice of the rod, and comes to the conclusion that the miner had better leave it alone.

In all such early steps of mining, the indications on which the prospector relies must be such as we have described. Sometimes, it may be, he may make a chance discovery of fragments of ore broken from the main body. But in operations on a large scale, the more comprehensive principles of the trained geologist and mineralogist are required, and that is why the science of geology itself has developed so greatly from the problems of the mine.

As long as the mine is no more than a surface quarry, the operations are simple; but when the miner gets well underground his special difficulties present themselves. The galleries are below the level of the surrounding country, so that water accumulates in them; it may be that rain soaks through the strata above them, or flows in by underground channels that are cut across during the sinking of the shaft or the driving of the galleries. The water problem has been very serious indeed. Let us again appeal to an illustration from Agricola's book, in order that we may see one of the ways in which the problem was attacked in his time. We may take it that the figure represents accurately the general practice of the period in the more advanced mining centres

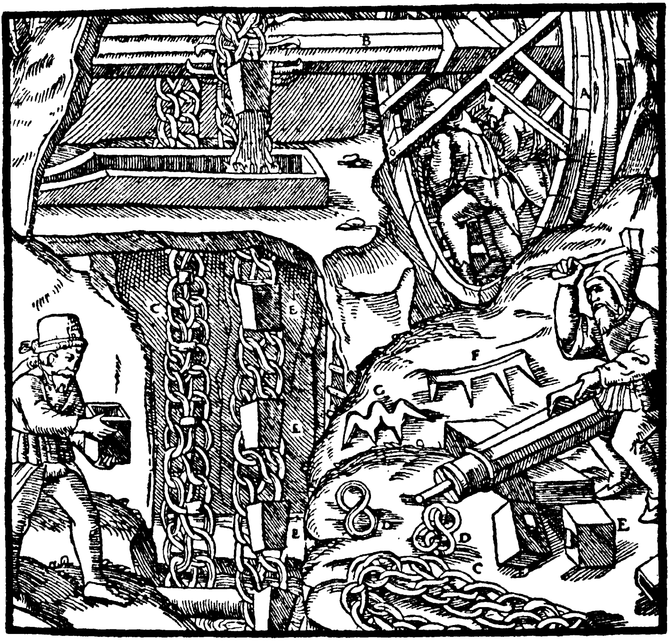


FIG. 45.—Raising water by a chain of buckets, worked by a treadmill. Details are shown in the foreground, where one man is bringing a fresh bucket, and another is driving clamps (like F and G) into a barrel (like B).

of Europe. England at that time was a long way behind; our coal mines were still little more than open pits. It was much later, when the coal-mining industry became so important, that England took a lead in mining developments. Agricola's picture shows the bucket-and-chain system, worked by two men in a treadmill. We can see the full buckets emptying their water into the trough near the top of the picture, and we see also all the parts laid out for our inspection. It seems to me that the men are turning the wheel the wrong way round, but the intention is clear. When water power was available, a water-wheel replaced the treadmill.

Now it will be clear that the labour of lifting water in this way from a deep mine must have been very severe. In our own country's coal mines the difficulty did not arise at first, or could be easily overcome, because the coal which was first worked lay near the surface. In the very early days of the use of coal, it was simply picked up from the Northumberland beaches when the tides had washed it from outcrops under the sea; for that reason, so it is said, it was called sea coal to distinguish it, presumably, from wood charcoal, which also was called coal. When it was first taken from the earth it was dug out of the seams that here and there lay open to the sky, or could be dug into with little trouble. If the digging could be so arranged that the water ran away naturally, then so much the better; the sketch marked A in fig. 46 shows how such a simple method of mining could be carried on. But if the outcrop of the seam was its highest point, as in the second sketch B of the same figure, a different arrangement became necessary. A long channel or adit could be driven from a lower level in some

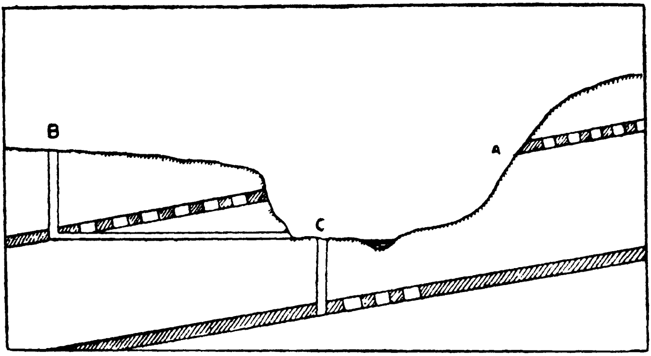


FIG. 46.—(*From Galloway's "Annals of Coal Mining," p. 74.*)

neighbouring valley and a shaft sunk from above to meet it where it struck the coal. The adit sloped slightly and the water from the workings was drained away under gravity. The adits were narrow, sometimes only 18 in. wide; but they might be a mile or even two miles along, so that they would be costly to make. Obviously, the method can only be applied in districts where deep valleys cut through the coal seams, as in the Forest of Dene and the Pennant country of South

Wales; and even in these places the shafts and galleries have now been driven so deep that the method can no longer be employed. In all districts there must come a time when the water has to be lifted by mechanical means; the picture from Agricola shows that in his country and time such means were regularly employed. The picture is doubtless a fair representation of the usual practice in England even in later times; the horse-gin of fig. 47 is a later improvement thereon which was in general use by the end of the seventeenth century. However, the difficulties of drainage were then becoming greater than any known system could grapple with, for even horses could not supply the necessary power. Mines had to be abandoned when, but for the water, they might still have been worked profitably. The problem became one of the great industrial prob-

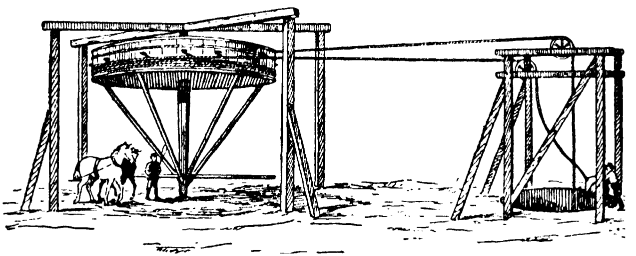


FIG. 47.—A horse-gin. (*Redrawn from Galloway's "Annals of Coal Mining,"* p. 178.)

lems of the time, and many ingenious people laboured to find a solution.

Now it happened that during that period, the latter half of the seventeenth century, the problems of the atmosphere and its pressure were much to the fore. Torricelli had, in the earlier part of the century, made the barometer, and had shown the astonishing fact that the pressure of the air could support a mercury column 76 cm. high more or less. Pascal, in the middle of the century, carried out his famous experiment on the difference in the height of the barometer at the top and the bottom of the Puy-de-Dôme, a high mountain in Auvergne. There was a difference of 3 in. in the height of the mercury, "which ravished us with admiration and astonishment." So the old idea that "Nature abhorred a vacuum" disappeared, and was replaced by the recognition of the fact that air exerted a pressure, which was the true cause of various phenomena that had puzzled the philosophers. It was an idea that fascinated the men of the time; all over scientific Europe experiments were made to test it. Guericke of Magdeburg constructed a copper globe to which a pump had been attached; the globe was filled with water and then closed up except at its point of attachment to the pump. At first the piston moved easily, but later the strength of two men could hardly move it, when "suddenly with a loud clap and to the terror of all," the sphere collapsed. He also made a larger pair of hemispheres which not even teams of horses could separate when the air had been removed from within them.

In England the new knowledge excited equal interest. Pepys tells us in his Diary (1st February 1663) that he went to Whitehall, and there came in the King "laughing mightily at Gresham College" —meaning the Royal Society—"for spending time only in weighing of ayre." Hooke, one of the founders of the Royal Society, worked at the subject and wrote about it; so did Robert Boyle, who first demonstrated the exact relation between the pressure and the volume of a gas, so that his name is always given to the law which this relation fulfils.

It was sure to occur to someone, sooner or later, that there might be a way of applying the new discoveries to the raising of water. One of the earliest to do so was Savery, whose method was very simple and direct. The fundamental principle of his engine is illustrated simply in the accompanying figure. Suppose that a vessel, A, can be filled with steam, either by passing steam into it, or by boiling some water in it; let it have communication by means of the pipe, P, with the water at a lower level, and let the steam in A be condensed by chilling the vessel. A vacuum will then be formed in A, and the pressure of the air on the water surface will force water up the pipe into the vessel. A tap, T, at the bottom of the vessel can be closed and the water therefore trapped. The vessel can be drained and made ready for a repetition of the process. Savery was granted a patent for his new invention for raising water "by the impellent force of fire" on 25th July 1698.

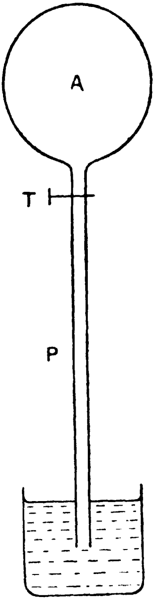


FIG. 48.—To illustrate the principle of Savery's engine for raising water.

But, of course, water cannot, even if the machine is perfectly efficient, be lifted by this method to a greater height than the pressure of the air can force it; that is to say, about 34 feet. Savery's engine, based on the principle which is illustrated in the figure in an elementary way, was similarly limited. It is true that Savery actually tried to make the lift a little greater by using the pressure of the steam to force the water higher;

but he could not do much in this way, because the boiler which he used was not strong enough. In actual practice, the useful lift of Savery's pump was only about 15 ft.

The only way of using Savery's engine to draw water from pits, that even then were hundreds of feet deep, would have been to instal several engines at different levels in the mine, each lifting water within reach of the one above. For that reason the engines were never employed for the purpose for which they were intended. Not only would they have been cumbersome and expensive, but they would have been dangerous, because their fires might have set alight inflammable gases.

At the same time that Savery was trying to solve the water problem in this way, Thomas Newcomen of Dartmouth, aided by John Cawley of the same town, was making independent attempts. His engine was designed to employ the same fundamental principle, but he made a different application of it. Perhaps his mind ran on the familiar picture of a man using a hand pump, and was intent on the idea of replacing the man at the end of the pump handle by a machine which would work the handle up and down in the ordinary way. He proposed to himself to use the principle of the condensation of steam in order to create a vacuum which the air pressure would try to fill; in this he was on the same road as Savery. We do not know exactly how the idea came to him, but certainly he must have been aware of the discussions concerning the atmosphere which were in full force at that time. It is known that he was in correspondence with Hooke, already mentioned; and, indeed, it is said that there used to be, among the papers of the Royal Society, a set of notes on the pressures of air and vapours which Hooke made for Newcomen at his request.

No one appears to have seen these notes for more than a century. They were described by Robison in the *Encyclopædia Britannica* of 1797, and again in his *Mechanical Philosophy*, vol. ii, p. 57. Hooke would be able to tell Newcomen of the experiments of Papin, a French scientist, who was a Fellow of the Royal Society of London and read papers on methods of transmitting energy to a distance by means of a pipe in which a partial vacuum was to be made. There was to be a cylinder with a piston at each end of the pipe. When the piston belonging to one of these cylinders, A, was pulled out, the pressure of the air in the cylinder would be reduced and the piston in B would be drawn in. Hooke argued that this would make a very ineffective means, in practice, of transmitting power. Robison quotes from Hooke's notes the passage: "Could he (meaning Papin) make a speedy vacuum under your second piston, your work is done." As the quotation is in inverted commas, it would seem likely that Robison had actually seen this note, or obtained it from someone who had done so. The meaning appears to be that Papin's method would not make a vacuum in B of sufficient completeness, or with sufficient rapidity. He knew

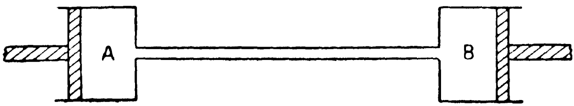


FIG. 49.

at that time, as others did, the great force which the pressure of the atmosphere would exert on the piston in B, if a good vacuum were produced in B, and that this might be done by filling the cylinder with steam and condensing it. There is a simple experiment which is still used to demonstrate the magnitude of this force; it was shown at the Christmas Lectures given in this place two years ago, and is illustrated in Plate XXXVI, *b*.

The fundamental idea of Newcomen's engine is illustrated in the diagram of fig. 50, and a picture of one of his earliest engines in fig. 51.

The man at the pump handle is replaced by the cylinder in which the piston can move up and down, and the top of the piston rod is connected

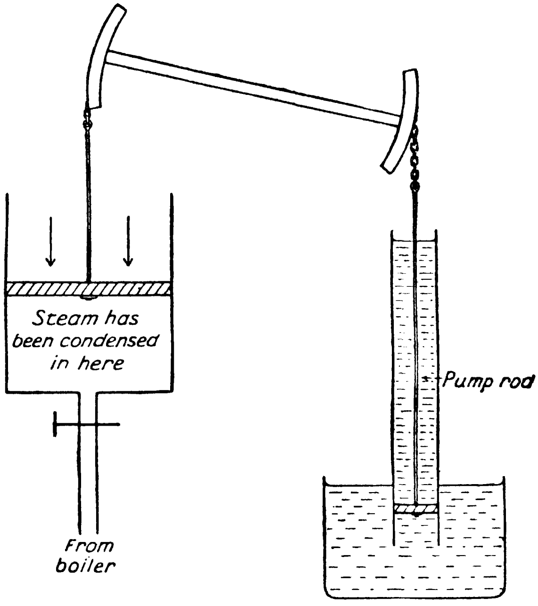


FIG. 50.—To illustrate the principle of Newcomen's engine for raising water.

with one end of the handle which now has become a beam of great strength. Steam is admitted to the cylinder below the piston, at a pressure just enough to lift the piston against the pressure of the atmosphere; at the same time the pump rod descends. The steam in the cylinder is then condensed by injecting cold water; the air pressure

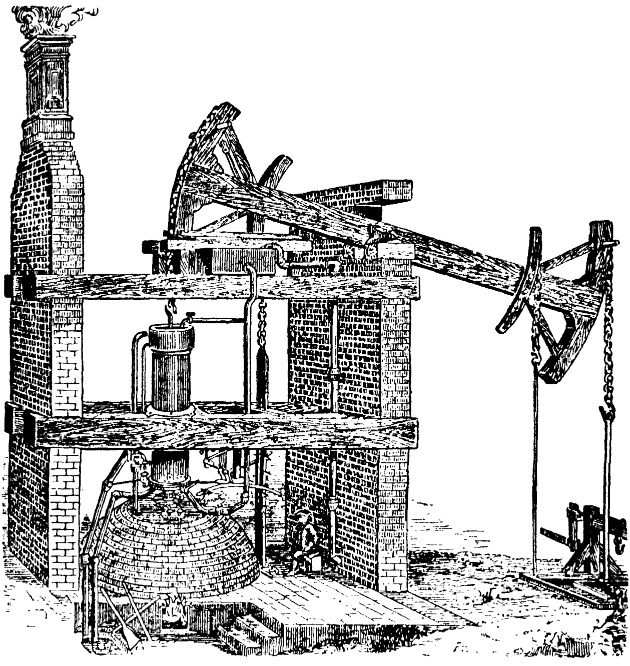


FIG. 51.—Newcomen's engine, probably his second, erected at Griff Colliery, Warwickshire. (*From Galloway's "Annals of Coal Mining,"* p. 241.)

on the top of the piston forces the latter down, and the pump rod is raised.

You see what a difference is made by adopting this method of working the engine. The pump rod can be as long as is wished although the engine is on the surface, so that there is no need to take the boiler and fire into the depths of the mine. Also the lift can be far more than 30 ft., because the area of the steam cylinder can be made correspondingly greater than the area of the cylinder of the pump. If, for instance, the diameter of the steam cylinder is 21 in., as it actually was in the earliest known picture of one of Newcomen's pumps, one of the first that he made, and if the diameter of the pump itself is, let us say, 7 in. (there is no record of this figure), then the area of the steam cylinder is nine times the area of the pump, and therefore a pressure of 34 ft. of water on the piston—the pressure of the atmosphere—can support a column of water $9 \times 34 = 306$ ft. high in the pump. Thus any desired lift can be obtained, but, of course, the higher the lift, the smaller the amount lifted. It was often arranged that a long lift should be divided into smaller lifts by a series of separate pumps. The engine of fig. 51 was erected at a coal pit in Warwickshire in 1712, and made ten strokes a minute, each stroke lifting 10 gallons of water 153 ft. Newcomen's engines were immediately successful, and for more than half a century were the only steam-engines in general use for any purpose.

The interesting point is that his engine was a direct application of the new knowledge of the properties of air and gases to a great and urgent practical problem, and knowledge came from a number of men who were interested in understanding and extending it—Torricelli, and Pascal, Papin, and Hooke, and Boyle. None of these philosophers made practical use of the knowledge; most of them were not sufficiently in touch with industry to think of it. But Savery and Newcomen and others like them were well aware of the great problem that must be solved if the flooded mines were to go on working, and when Newcomen appealed to Hooke, the latter was obviously delighted to help as far as he could.

Newcomen's steam engine was adapted only to push and pull at the end of a pump handle; but there must have been many who wondered if the new machine could not be used for other purposes than that of raising water. Could it, for example, be adapted to the task of raising and lowering the cage which carried men and coal? It seems to have been an extraordinarily long time before this was achieved. It was sometimes used indirectly; water was raised to a height and then made to work water-wheels. A double water-wheel worked by a natural stream is illustrated in Agricola's book (fig. 52), and such wheels were afterwards used in England as an intermediate agent between the Newcomen engine and the winding gear. The double wheel had two sets of buckets pointing opposite ways, so that the engineman could, by directing the water to one or other of the wheels, raise or lower the cage.

There was another purpose for which the power of the steam-engine must have seemed most desirable, namely, for hauling the trucks along the galleries of the mine, or from outside the mine to the place of shipment. But that was more difficult still.

The first great advances in the direction of the improvements which made these further uses possible were due to James Watt. One of them consisted in the removal of the steam from the cylinder before condensing it. In Newcomen's engine a jet of cold water was squirted into the cylinder; but Watt saw that the cylinder must lose so much heat in this way that some of the next lot of steam would be condensed also. The cylinder ought to be kept as hot as possible. So he added the separate vessel called the condenser. He also closed the top of the cylinder completely, and admitted steam alternately above and below

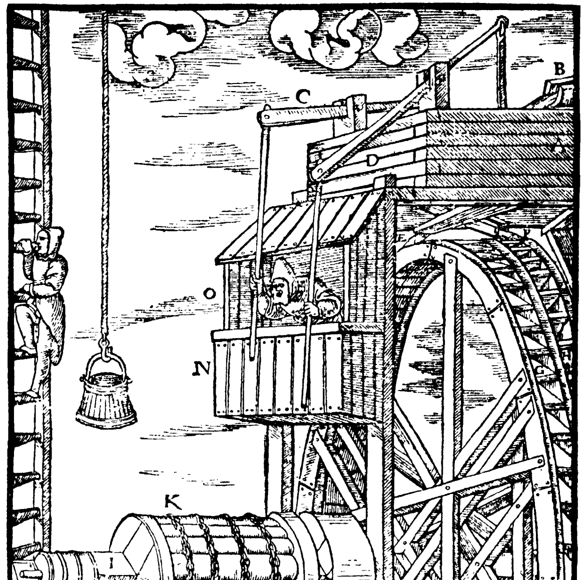


Fig. 52.—Illustration of the double water-wheel taken from Agricola. The letters refer to the Latin description in the original: but the latter is omitted since the figure is quite clear.

the piston, which had the effect of making the engine do twice as much work in the same time, since two lots of steam were used in each stroke instead of one. We have to remember that the steam did all the work in either form of engine, or, as we should now put it, the work done by the engine came from the burning of the coal. Even in Newcomen's engine the air did no work on the whole; it was left in the same condition after a stroke as it was before.

Watt also used the crank to convert the to-and-fro motion to a rotary motion, and when someone else patented the idea he invented a substitute called the "sun and planet" gear, and he made many other improvements.

Later Trevithick showed that the engine was far more efficient if high-pressure steam was used instead of low; in Newcomen's engine the steam pressure was very little more than that of the atmosphere. And when all these changes had been made, the steam-engine became adaptable to all those purposes for which the miners had wanted it, and to the purposes of many other trades as well. But the further development of the steam-engine is outside our subject.

Not only the steam-engine, but the railway also had its origin in the mine. In some mines, even in comparatively recent times, the coal was carried by men, even by women and children, on their backs. But an obviously better way was to drag the coal on sledges, or, much better still, to provide

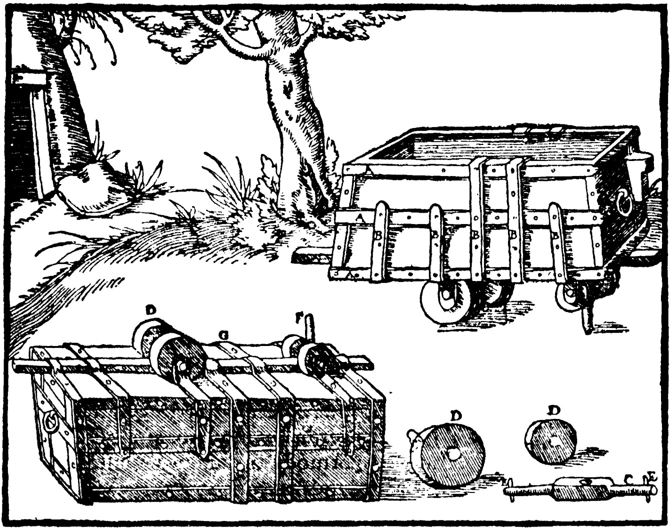


FIG. 53.—Agricola's drawing of a truck. The pin F ran down the groove in the middle of the plank on which the truck ran.

the "tubs" with four wheels and run them along rails, whence the name "railways." At first the rails were of wood; it was only when iron came into more general use that iron plates were attached to the wood. An illustration from Agricola's book (fig. 53) shows how the ore was transported in his day. The truck is on wooden rollers; at F in the figure is a blunt iron pin which, according to the text, ran in a groove of a plank in such a way that the truck did not leave the track. In later times, when "railways" for these trucks were first introduced into England, the wheels of the wagons were provided with flanges, and the rails were carefully spaced so that the action of the flanges kept the wheels from leaving the rails. So in this also the miner led the way.

The problem of ventilation became serious even in the early days of the mines, and increased in importance as the shafts became deeper and the galleries longer. When mines were shallow, a shoot to catch the wind and direct it down the shaft might be enough; Agricola (fig. 54) shows how such an arrangement was carried out in his day. We actually see the wind coming in from the side and entering the hole in the barrel, whence it is conveyed down the shaft by a pipe which also serves as an axle for the barrel. A vane sets the barrel so as to catch the wind. In the other illustration taken from the same writer's book, three separate kinds of blower are shown, two worked by horses, the other by a man. Notice how in the second of these pictures the horse is induced to climb the treadmill by the position of the rack that holds the hay. Notice also the great bellows and the pipes that conduct the air away to the recesses of the mine.

Fresh air has to be driven into the mine for more

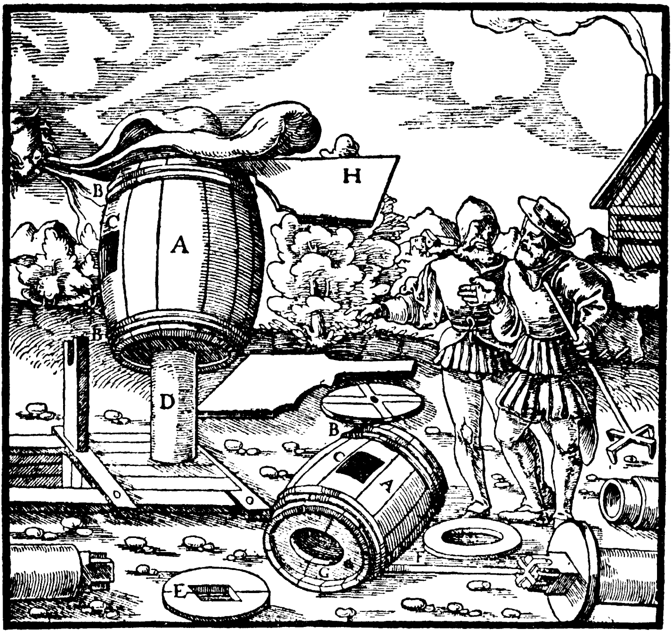


FIG. 54.—A ventilator according to Agricola. Notice the wind on the left.

than one purpose. It is not only required for replenishing the air used up in breathing, but also and more urgently for driving out the noxious gases that are apt to accumulate. In the early days when mines were shallow, the only gas that

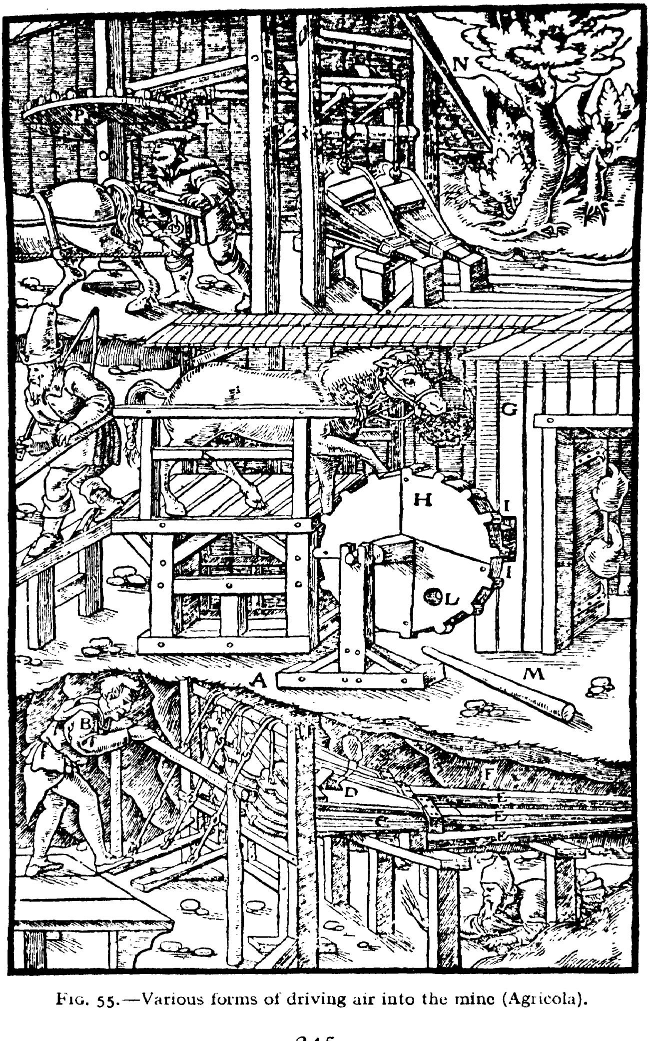


FIG. 55.—Various forms of driving air into the mine (Agricola).

gave much trouble was "stythe" or chokedamp. It was a mixture of carbon dioxide and nitrogen, incapable of supporting life. We must remember that a certain combustion is going on in a coal mine the whole time. The carbon of the coal tends to combine with the oxygen of the air; if the temperature is raised sufficiently it will do so very rapidly, as we see when we put a piece of coal on the fire. But even at low temperatures the process is taking place at a slow rate. Consequently carbon dioxide, the result of the combination, tends to accumulate, and, being heavier than air, to collect in pools in the deep parts of the mine; if men descend into it, they fall insensible and die. When the coal is broken, gases, including carbon dioxide which has already been formed, are let loose; the supply is further increased by the breathing of men and horses, which is also a combustion though occurring in a different way; there is also the burning of lamps, and there are certain chemical actions which are set going during mining operations, and particularly the action of acid pit water (formed by the oxidation of iron pyrites) upon minerals containing carbonates (*Historical Review of Coal-mining*, Wembley Exhibition, p. 109). Nitrogen is, of course, always present in the air, and further quantities of it are evolved during the decay of timbers and other chemical changes that are always in progress. Chokedamp is the gas that so often accumulates in wells and other deep recesses; for which reason a lighted candle is lowered before anyone enters them, since the gas will put the candle out.

In the latter half of the seventeenth century these gases were also a subject of interest to the members of the newly-formed Royal Society, who did much to collect information about them. In their *Proceedings* for 1675 they publish an extract from a letter written by a certain Dr Jessop of Yorkshire, which contains the following:—"There are four sorts common in these parts. The first is the *Ordinary Sort*, of which I need not say much being known everywhere; the external signs of its approach are the Candles burning orbicular and the flames lessening by degrees, until it quite extinguish; the internal, shortness of breath. I never heard of any great inconvenience which anyone suffered by it, who escaped swooning. Those that swoon away and escape an absolute suffocation are, at their first recovery, tormented with violent Convulsions; the pain whereof, when they begin to recover their senses, causeth them to roar exceedingly. The ordinary remedy is to dig a hole in the earth and lay them on their bellies, with their mouths in it; if that fail they tun them full of good Ale; but if that fail they conclude them desperate. I have known some, who have been recovered after this manner (when some of their Companions, at the same time, have died), that told me they found themselves very well within a little time after they had recovered their senses, and never after found themselves the worse for it.

"They called the second sort the *Pease-bloom Damp*, because, as they say, it smells like Pease-bloom. They tell me it always comes in the Summer time, and those Groves are not free which are never troubled with any sorts of Damps. I never heard that it was mortal, the scent, perhaps, freeing them from the danger of a surprise; But by reason of it many good groves lie idle at the best and most profitable time of the year, when the subterraneous waters are at the lowest. They fancy it proceeds from the multitude of red *Trifoil-flowers*, by them called Honeysuckles, with which the Lime-stone Meadows in the Peake do much abound. . . .

"The third is the strangest and most Pestilential of any, if all be true which is said concerning it. Those who pretend to have seen it (for it is visible) describe it thus: In the highest part of the roof of those passages which branch out from the main

Grove, they often see a round thing hanging, about the bigness of a Football, covered with a skin of the thickness and colour of a *Cobweb*; this, they say, if by any accident, as the splinter of a Stone or the like, it be broken, immediately disperseth itself and suffocates all the company. Therefore, to prevent casualties, as soon as they have espied it, they say they have a way, by the help of a stick and a long roap, of breaking it at a distance; which done, they purifie the place well by fire before they dare enter it again. . . .

"The fourth, which they also call a Damp (although how proper I will not now argue), is that vapour which, being touched by their Candle, presently takes fire; and giving a crack like a Gun, produceth the like effects, or rather those of Lightning. A fellow they commonly call *Dobby Leech* is, at this day, a sad example of the force of one of those blasts in *Hasleberg hills*, having his arms and legs broken and his body strangely distorted."

The first of these four gases is clearly the choke-damp; what the second and third were is a matter of conjecture; the last is the gas known as fire-damp, which, when the above was written, was just beginning to appear as one of the miner's enemies. In later years it became a terrible curse.

The miners penetrated deeper and deeper into the earth, and, having passed through the wet strata which were the cause of the water difficulty, came to the drier strata below where the firedamp lay in wait for them. One of the earliest references to it occurs in a paper sent in to the Royal Society in 1667 by Dr Thomas Shirley, who describes the mysterious burning of water in a spring near Wigan, and tells how he found that the mystery was due to nothing more than the discharge of firedamp in bubbles at the surface of the water, which took fire upon the application of a light. Firedamp is known to the chemist as methane, a gas having the composition of CH_4; that is to say, one atom of carbon to four of hydrogen; it has an extreme tendency to enter into combination with oxygen, so that it is not merely inflammable but explosive. It is formed during the decay of vegetable matter and is the origin of the "will-o'-the-wisp" that floats over marshes and gives a feeble light during its slow combustion. It is most explosive when mixed with a certain proportion of air, about one of gas to nine of air; with much more or much less it will not explode at all.

To remove all these gases from a mine of any extent, a thorough form of ventilation was necessary, but it was long before the necessity was realised and met. The effective way was first indicated when mines were big enough to have two shafts, and it was observed that air might, in certain states of the wind at any rate, pass down one and up the other. If this could be encouraged, so much the better, and an efficient method was devised in which a fire was lit at the bottom or at some point in one of the shafts. This produced a draught up that shaft, which was for that reason called the upcast; the downcast shaft was used for working the mine because it was full of fresh air, and the coal was brought to the bottom of it by roads which kept fresh in the same way. One of the papers read in the Royal Society in 1665 described this method practised at Liège; the illustration in Plate XXXVI, *a*, taken from the paper. Of course, it was necessary that firedamp should not be drawn through the flame, for which reason it was often conducted into the upcast shaft at a point much higher than the furnace. Men learnt much about the problems of ventilation during this struggle with the accumulating vapours. They had, for example, to solve the difficulty of covering an immense area with flowing air; the total length of the ways might amount to ten, even twenty or thirty miles, so that the air had to be divided into sections feeding separate districts, and all this had to be worked out. Fires were not in the end sufficiently strong to compete with the

FIG. 56.—Splitting the rocks by applying fire and water in succession. The workman on the top is making a bunch of shavings on each faggot. The man below has lit the fire and is hurrying away from the fumes. (*An illustration from Agricola.*)

difficulty of clearing large mines, and the difficulty was finally met, as it is still, by the use of great fans driven by steam. Fans were used even in Agricola's time; but it has been an engineering problem to bring them to their present state of efficiency.

No system of ventilation can, however, remove all the dangers of explosion. Methane is continually bursting out from the coal where it exists in pockets at high pressure, sometimes many times greater than the pressure of the air. No doubt it has accumulated during changes in the coal spread over millions of years, changes which are a slow continuation of the process of vegetable decay. Sometimes there are continuous outpourings of the gas which may continue for years.

When it first appeared in comparatively small quantities it might be removed without a forbidding amount of danger by setting it alight. The first record of the practice of getting rid of it by deliberate firing comes from the end of the seventeenth century. It was the practice in some places for a man, told off for the purpose, to push a candle up into the recesses of the roof; he used a long stick and lay on the floor, so that the discharge might go overhead. Not inappropriately the man who carried the candle was called the "penitent," and there are said to be "penitents" still living. Sometimes again a pulley was fixed in the roof, a wire was fastened to the candlestick, passed over the pulley and carried a long distance away. The workers barricaded themselves into a convenient room and hauled on the wire so that the lighted candle was raised to the roof and exploded the gas there.

At the beginning of the nineteenth century there was a series of disastrous explosions which was a spur to several independent efforts to overcome the increasing danger. It was necessary to find some sort of light which could with safety be taken into fiery mines. Some mines were free from gas

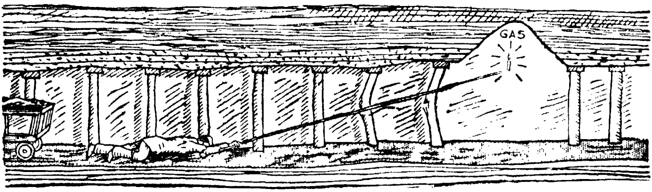


FIG. 57.—"The Penitent."

and safe, so that naked lights could be used; but in others gas appeared continuously, and even the improved methods of ventilation could not carry it away. An appeal was made to Humphry Davy, who was at that time the Director of the Royal Institution. Davy undertook at once a series of experiments on the explosive properties of methane, and quickly discovered two facts which he recognised to be of great importance. The first of these was that mixtures of methane and air exploded only when they were raised to a high temperature; the second, that they gave out a comparatively small amount of heat when burning. He argued that it might be made possible to carry away the heat of the lamp before the temperature rose to such a point that the gas could be exploded, and that so the difficulty of providing light without risk might be removed. He therefore enclosed the candle in a vessel to which air could be admitted only by a series of fine metal tubes; in the hope that flame would not pass down such tubes because their power of conducting heat would keep the mixture from acquiring the requisite temperature. Davy found that his hopes could be realised if the tubes were long enough and narrow enough, and that the finer they were, the shorter they might be. Finally, he found that a metal gauze was sufficient to screen a flame on one side of the gauze from igniting an explosive mixture on the other, provided that the gauze was fine enough and was not allowed to become red hot. The meshes in the gauze might be looked on as a collection of short very narrow tubes.

Davy's original models are all preserved at the Royal Institution (Plate XXXVIII). On 9th November 1815 he described his experiments to the Royal Society, related the conclusions to which they had led him, and showed the lamp which embodied them.

Davy was by no means the only worker in the field. Dr Clanny devised a lamp in which the air on its way to the flame had to bubble through a water seal; the products of combustion were taken out through water in the same way. But it was too cumbersome. George Stephenson also devised a lamp in which the air was admitted through holes in a perforated plate; his lamp was known as the "Geordie," and came into fairly general use. It is difficult to compare the contributions of Clanny, Stephenson, and Davy to the solution of the great problem. It seems to be generally agreed that all three deserve credit for their work. Davy's lamp very quickly became popular. "To my astonishment and delight, it is impossible for me to express my feelings at the time when I first suspended the lamp in the mine, and saw it red hot; if it had been a monster destroyed, I could not have felt more exultation than I did. I said to those around me: 'We have at last subdued this monster.'" This was the enthusiastic outburst of Mr Buddle, who gave devoted service to the question of safety in mines. In the little book which Davy wrote about his work, he tells us of the letters he received from managers and men thanking him gratefully for what he had done; we can be sure he was a happy man when he received them. He is said to have often spoken in after life of his work on the safety lamp as that which, of all he had done, gave him the greatest satisfaction. Perhaps the most remarkable thing about his work was that he knew nothing of the problem when he started, and found a solution within a few months. He never asked for any reward; neither did Stephenson nor Clanny. It is told by Mr Buddle that he spoke to Davy on the subject. Davy replied: "No, my good friend, I never thought of such a thing; my sole object was to serve the cause of humanity and, if I have succeeded, I am amply rewarded in the gratifying reflection of having done so."

An experiment will illustrate for us the action of gauze in stopping the progress of a flame. Here is a combination of glass tubes (fig. 58). An explosive mixture of methane and air is introduced at A; it fills the large tube and pours out at C. When a light is put to the issuing gas, it burns with a blue flame. The flame does not strike back into the tube because the gas is pouring out too fast; but if we remove the plug at A, and let air in instead of the mixture, the gas at C will pour out more and more slowly, and we see that the flame at C gradually dwindles. The only thing which makes the gas continue to come out at C is the chimney action of the tubes: the mixture within them is lighter than the air, and all the more so if the tubes are a little warmed by the flame. As air enters at A, the chimney action fades away. Now, if we watch the flame at C we observe that when it becomes quite small it suddenly enters the tube and travels down towards B, where it arrives in one or two seconds. The gas is burning but

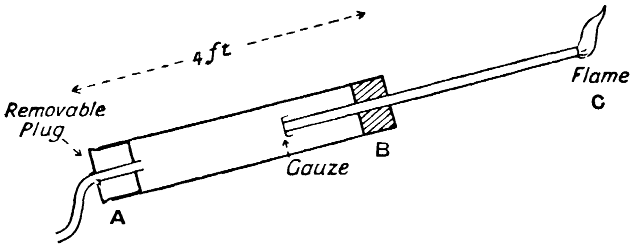


FIG. 58.

not exploding; where it is burning heat is developed and this affects the mixture on one side of the burning spot, raising its temperature so that it is set on fire in its turn, and so the flame passes down the tube. The flame travels more slowly if the tube is narrow, or if the mixture is less explosive. If the tube is too wide, and the flow is not even, the movement of the flame may develop into an explosion. The reason is that if the gas once begins to burn too fast at any one spot, the heat generated accumulates too rapidly;

and since all additional heat starts more gas burning, the evil becomes rapidly worse. Finally, the flame-wave runs along the tube very quickly; much gas is burned at once and the tremendous pressures of an explosion are developed.

We watch the flame running down CB; it travels quietly because the combustion is not too fast. A little cap of Davy's gauze has been put over the end of the narrow tube, and we see that the flame stops there and goes out. It does not pass into the wide tube AB.

Now let us repeat the experiment having first made a hole in the gauze with a bradawl. This time, when the flame wave reaches the gauze it is not arrested; it passes through into the big tube, and, at the place of issue, where the flow is disturbed, some local over-rapid development of heat takes place. At once, as we see, an explosion is developed.

With the new lamp many mines that had been abandoned could now be worked. A milestone had been passed. Yet explosions did not cease entirely, and, indeed, some of later date were disastrous, and there was much disappointment because the new lamps seemed to be a failure. No doubt the use of gunpowder for blasting was occasionally responsible; it certainly seemed futile to enclose the candles carefully and at the same time expose the explosive mixture to the chances of being fired by the flames of a shot. But in truth there was a second cause of explosions which had not been detected; the dangers of fire-damp had been to some extent guarded against, those of coal dust still remained. In 1845 there was a serious explosion at the Haswell Colliery; Lyell, the geologist, and Faraday, who had succeeded Davy at the Royal Institution, were asked to report upon the cause. They agreed that the results of the disaster were mainly due to coal dust.

It seems remarkable at first sight that dust should be an explosive, even though coal is combustible. The fact is easily observed, however, when a little dust from the bottom of the coal-scuttle is thrown upon a hot fire; the *woof!* which results is an indication of what may happen on a larger scale. The effect is another example of the results of dispersion that were spoken of in the previous lecture on the trade of the dyer. Dust in suspension has a very large surface compared to its volume: the combination of carbon with oxygen can go on all over this surface as soon as the temperature is high enough. If, therefore, there is combustion of a portion of the dust, or if there is an explosion of fire-damp, or an ill-regulated shot during blasting, the combustion may be carried on from point to point in the air bearing the dust until it becomes an explosion. Flour dust, suspended in the air, can also be exploded; and so can magnesium dust on account of which special precautions have to be taken when forming articles of magnesium metal. And as each portion of the mixture burns it provides heat enough to start the combination in the neighbouring parts, so that as the flame spreads along the tube (fig. 58) in mixed air and methane, so also the flame spreads in the air charged with coal dust; in the same way, too, it is possible to start an explosion.

We can illustrate this by a simple experiment. A box of cubical form (fig. 59), 1 ft. each way, can be filled with a mixture of ordinary coal-gas and air. Connected with this box is a wooden gallery 6 ft. long and 9 in. square in section. We dust a quantity of lycopodium powder into the gallery: the powder—which is just fern seed—is inflammable, and therefore in its finely divided form is explosive. The whole arrangement represents a mine, in which a fire-damp explosion starts a dust explosion in a long gallery. When the gas has been running long enough, eight or nine seconds is just right in our case, the gas tube is withdrawn, the opening in the top of the box is closed, and the box is put into communication with the gallery by lifting a sliding partition which hitherto has separated the two. The gas mixture in the box is fired with the help of a burning taper; in this way we represent the fire-damp explosion which starts the more deadly dust explosion, and a sheet of flame issues from the open end of the gallery.

It is curious that it took so long to recognise

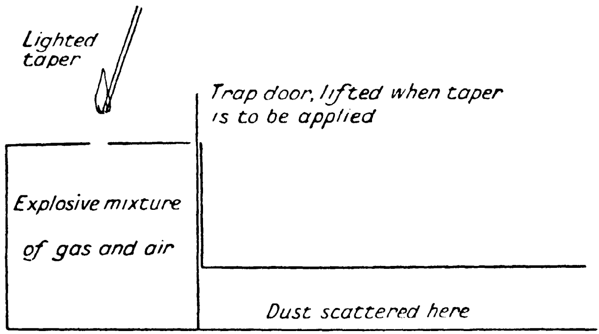


FIG. 59.

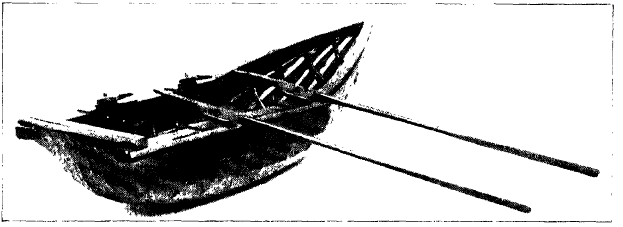
the part played by dust. The report of Faraday and Lyell was made thirty years after the introduction of the safety lamp. Thirty years more went by before the action of coal dust was generally accepted, and fifty years after that—quite recently in fact—the Research Board was still finding it necessary to organise demonstrations in order to convince miners of the appalling danger. These demonstrations were carried out at Eskmeals in Cumberland, where a gallery was constructed for the purpose on the moors so that no harm could be done (Plate XXXIX, *b*). The gallery is several hundred yards long and big enough for people to walk in; in fact, it represents very truthfully a gallery in an actual mine. Shelves are placed on its inside throughout its whole length, which shelves are covered with fine coal dust when an experiment has to be made. A small cannon is fired at some point in the gallery, and an explosion may or may not take place according to the arranged conditions of the experiment. Sometimes it is so violent that the end of the gallery is broken up and pieces are hurled away; the pictures in Plate XL are sufficient illustration. Sometimes the dust is not exploded, there is nothing more than the gas wave from the cannon which drives out the dusty air in black clouds. The Research Board is a body of men appointed by the Government years ago to consider all means by which the safety of mines may be increased. Many a disaster would have been avoided in the hundred and ten years that have gone by since the safety lamp made its first appearance if there had been a Research Board at the beginning of the period as there is now at the end.

Coal dust lies chiefly along the roads by which the coal is brought from the working face; the roads which carry all the traffic because the ventilation system passes the fresh air along them on its way to the workers. Explosions take place mostly along these roads; a fire-damp explosion is a local affair, but the scattered dust can carry the explosion for great distances.

An explosion is in itself terrible, smashing machinery and frame-work, and bringing down masses from the roof so that the passage-ways are blocked. But, worse than that, the coal dust has combined with oxygen and used it up, replacing the gas which supports life with gases that do not and are, in fact, deadly poisons. The most dangerous of these is a gas called carbon monoxide, the molecule of which contains one atom of carbon and one of oxygen; its outstanding characteristic is its tendency to absorb one more atom of oxygen so as to form carbon dioxide. It is absorbed into the blood of the person who breathes it, and destroys the capacity of the blood to carry oxygen to different parts of the body—one of its chief functions. A very small amount in the air, not more than 2 per cent. makes a fatal mixture. It is not perceptible by the senses, even death which is due to it is without pain; on account of which it is all the more difficult to fight. When fire-damp is present in a mine, a warning is given by the fact that a faint blue cap can be seen over the safety-lamp flame when it is turned down to a point; but no such warning is given by carbon monoxide. The most effective signal is given by the distress that it causes to small warm-blooded animals such as mice or canaries; their respiration is so much more rapid than ours that the gas acts on them more quickly. It is now the law that canaries or mice shall be kept at all coal mines. Of course, the miners become fond of their pets, and cases have been known when they would not take them down the mine when the presence of afterdamp was suspected, because they would sooner run the risk themselves.

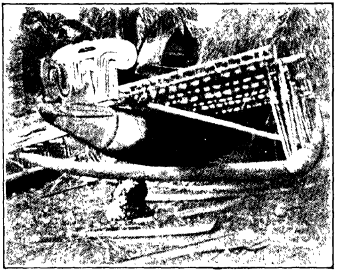
The dangers of coal-dust explosions can also be diminished by mixing the dust with stone dust, which, of course, is not inflammable. Not every sort of stone can be used for the purpose, because there are some kinds, such as quartz, which can cause injury to the lungs, but many are quite harmless. Even the coals vary among themselves, some being very fiery, others less so; and different amounts of dust are required to make them safe.

So there are very many problems to solve before the miner is able to bring his coal to the surface with safety to himself and health, and in such quantities as to repay him for his labour even when the mines are deep and difficult. He has constantly appealed for help to such new knowledge as has been available, and so has overcome the difficulties of the past one by one. It is a wonderful thing that in spite of all the obvious dangers and hindrances, the miner's life is now as healthy on the average as any other. Fifty years ago there was a very different state of things. The change is due to the scientific investigation of the causes of danger and of the right means to arrest them, and also to the legislation which has been formed in consequence. The work goes on still; there are laboratories, some private, some organised by the State, which are devoted to mining research. They are full of interesting things; perhaps what I have said to you will make you realise that it must be so, and that the same may be said of all those other laboratories of which I have spoken in the previous lectures, where new knowledge is brought to the service of old trades. Some of you will perhaps be engaged in one of those laboratories when you start your life's work; and I can promise you that whether you become rich or not, you will with ordinary good fortune, unless you have mistaken your aptitude, find your life full of interest and happy employment.

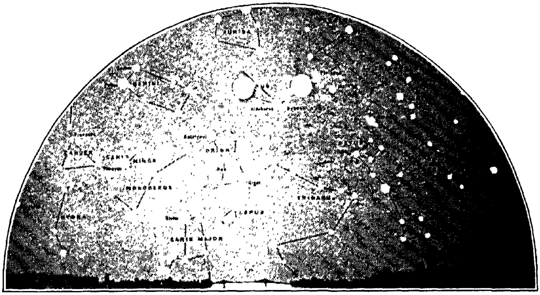


(a) A modern Irish curagh or coracle, probably resembling the ancient British coracle very closely. (*By courtesy of The Science Museum, South Kensington.*)

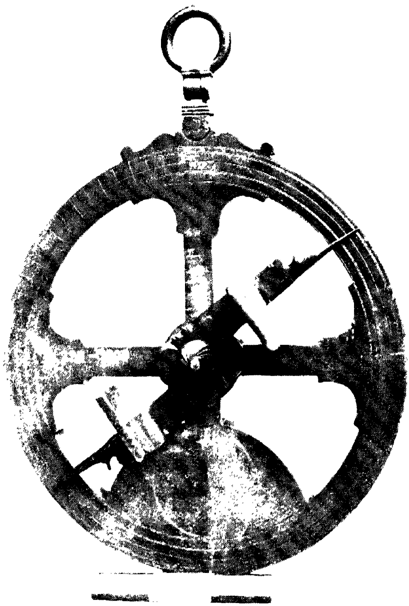
(b) Catamaran at sea. (*By courtesy of "The Illustrated London News."*)



(c) Catamaran on the beach. (*From Malinowski's "Argonauts of the Pacific."*) The outrigger rests on the ground on the right and is joined to the boat by a system of struts, the upper members forming a kind of deck.

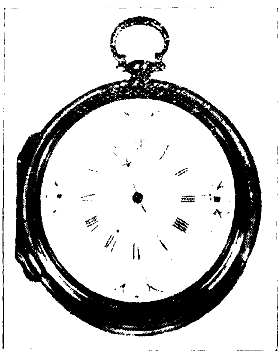


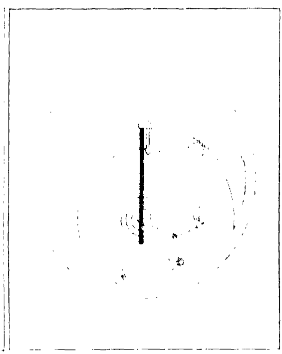
(*a*) The figure shows the movement of the moon across the sky in one day. The moon is represented by the disc in two positions at the top of the figure. (*By courtesy of The Astronomer Royal.*)



(*b*) An astrolabe believed to have belonged to the Spanish Armada. (*By courtesy of The Science Museum, South Kensington.*)

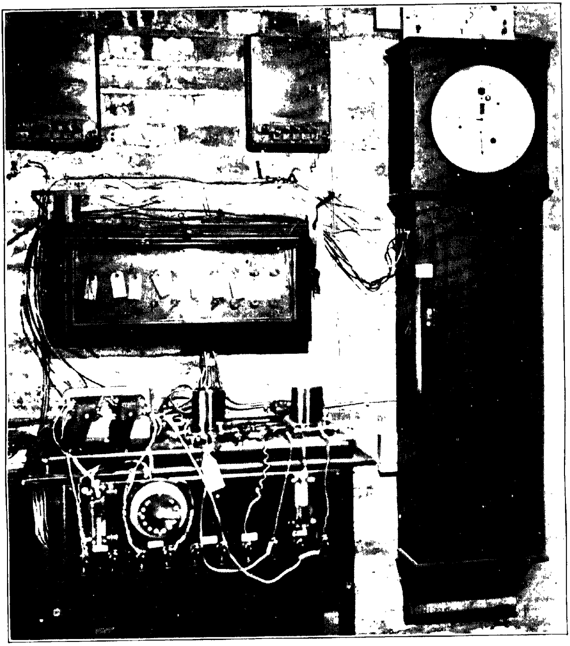
(a) Portrait of John Harrison, the designer of the chronometer which won the prize offered by Parliament.





(b) (On the left) Harrison's chronometer.

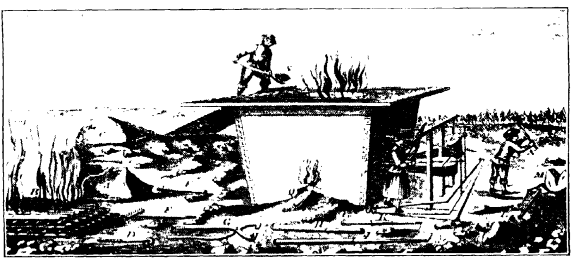
(c) (On the right) Diagram of the device for temperature compensation. The vertical bar is made of two strips of metal, cemented together, which do not expand equally with heat. The bar therefore bends when the temperature changes and, pressing on the balance spring, alters the latter's time of vibration.



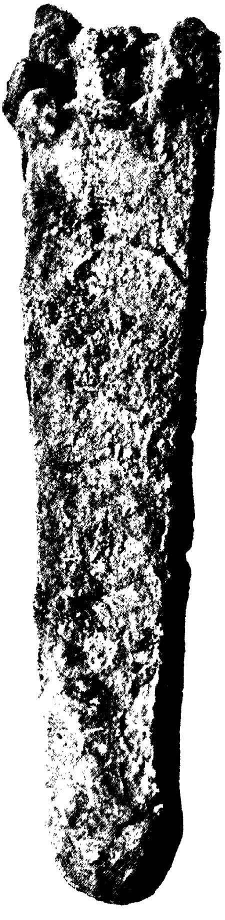
One of the master clocks at the Royal Observatory, Greenwich. The apparatus on the left compares, amongst other things, the electrical connection with the slave clock, which does all the work of driving the master clock, leaving the latter nothing to do but keep time.

(*a*) Roman mask of iron. (*By courtesy of Dr George Macdonald.*)

(*b*) Metal workers in Africa. Note the primitive form of bellows used by the man on the left

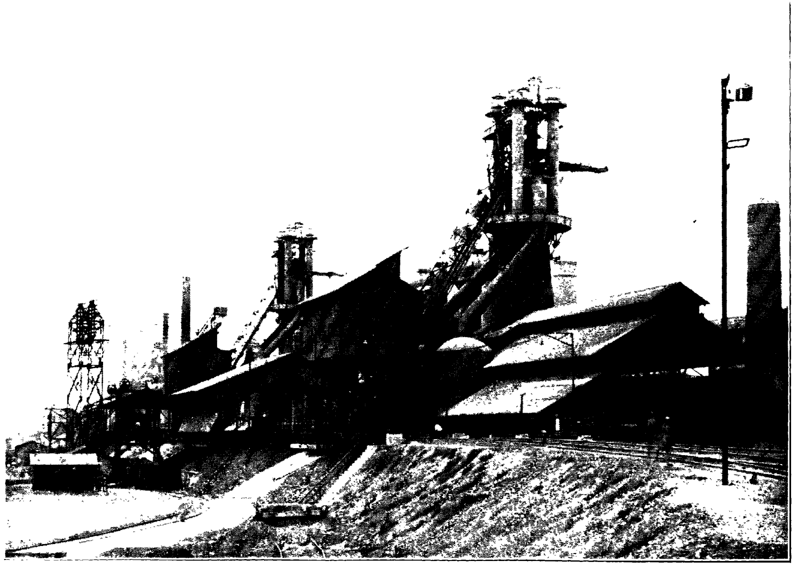


(*c*) Osmund furnace.

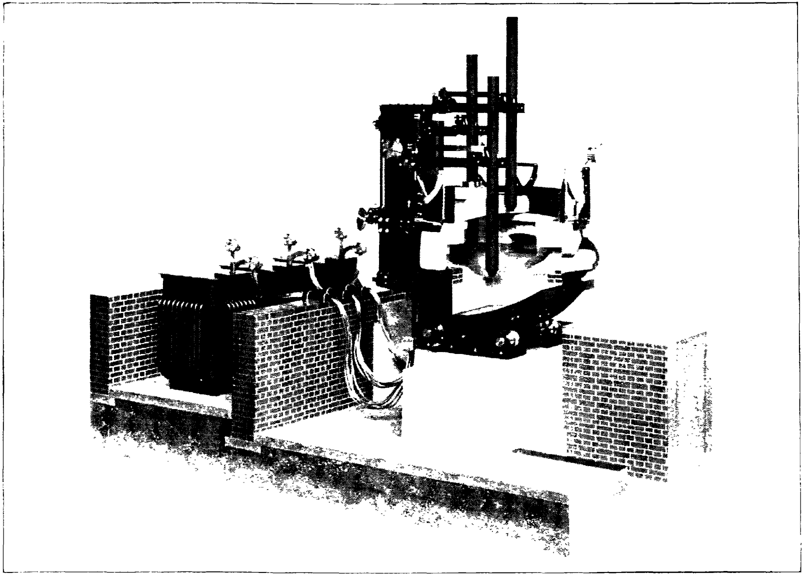


A bloom of Roman iron found at Corstopitum near Corbridge, on the Tyne: weight, [illegible] cwt. 8 lbs.

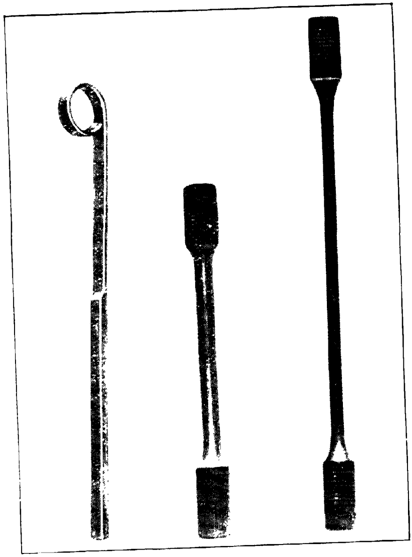
Photograph of drawing, showing how the Roman bloom was built up (one seventh natural size). J. E. Stead. (*From Newton Friend's "Iron in Antiquity."*)



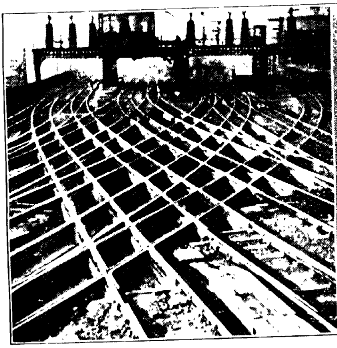
A modern blast-furnace, Tata Works, Jamshedpur, India. (By courtesy of Mr R. Mather.)

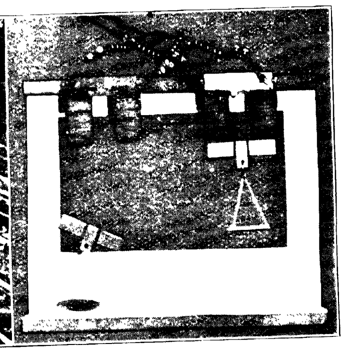


From a photograph of a model electric furnace. (*By courtesy of The Science Museum, South Kensington.*)



(*a*) Specimens of manganese steel. The upper part of the bar on the left is in the tough, non magnetic condition; part of it has been bent into a ring. The lower part is in the hard, brittle, magnetic condition. The bar on the right is of the tough modification and has been stretched: before stretching, it had the form shown in the centre. The extent of the stretching and its evenness are very remarkable.





(*b*) (On the left) Showing where a tough steel such as manganese steel is of great value. (On the right) The cores of the two electromagnets are of ordinary soft iron (right) and [illegible] (left) respectively. When the same electric current runs through both of them they [illegible] able to hold up a certain weight. But, when the current is turned off, the magnet [illegible] the left instantly drops its weight; that on the right still holds on to its weight by virtue of the residual magnetism in the iron. Permalloy acts like mumetal.

(a)

(*a*) Microphotograph of very pure iron (magnification 150 diameters), showing separate crystals.

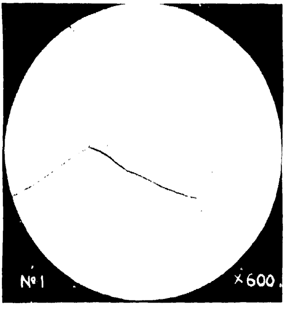
(b)

(*b*) Microphotograph of slowly cooled steel containing 0·2 per cent. carbon. The white portions are pure iron, or ferrite; the black, when examined under a higher power as in (*c*), show a curious laminated structure, known as pearlite. It consists of laminæ of cementite (see the text) embedded in ferrite. (*From Rosenhain's "Introduction to Physical Metallurgy."*)

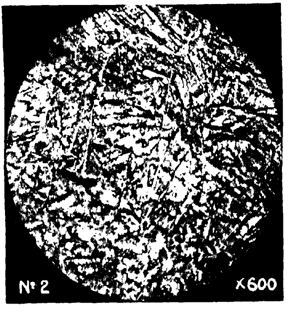
(a) Same as Plate XI (b), except that the carbon content of the steel has been increased from 0·2 to 0·6 per cent., so that there is now more pearlite and less ferrite.

(b) This steel has a high carbon content: separate crystals of cementite are now to be seen embedded in pearlite.

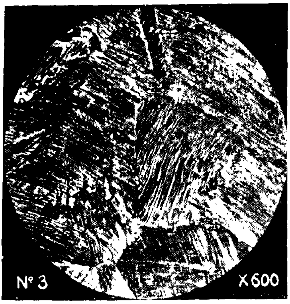
(From Rosenhain's "Introduction to Physical Metallurgy.")



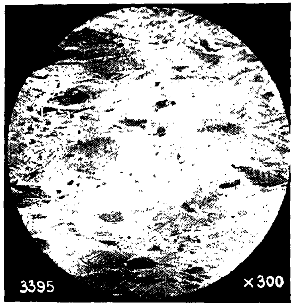
(c) Manganese steel quenched in water from 1000° C. It is tough, non-magnetic, and can be stretched (Plate X (a)).



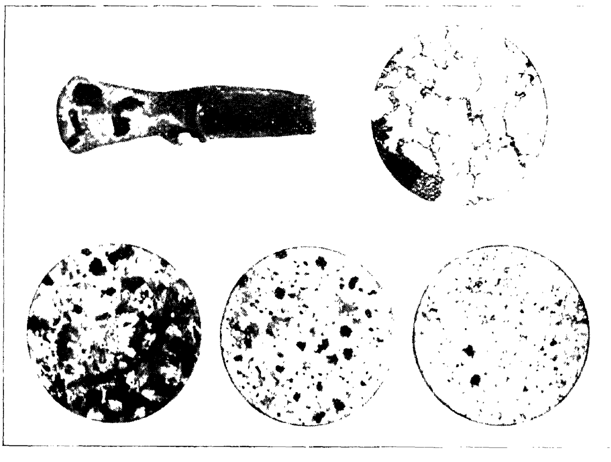
(d) Same steel reheated to 500° C. for 60 hours, and cooled slowly. The atoms of iron have now re-arranged themselves. The steel is hard and non-magnetic.



(a) Same originally as XII (c), but has been strained in the testing machine. The lines are edges of slip planes, which have different directions in the different crystals.

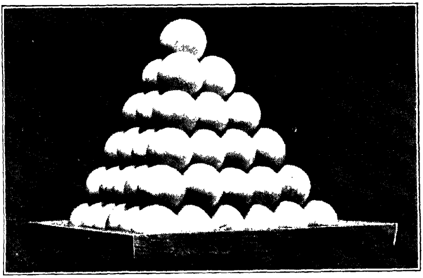


(b) Same originally as XII (c), but has been compressed. *(The four photomicrographs of manganese steel are due to Sir Robert Hadfield.)*

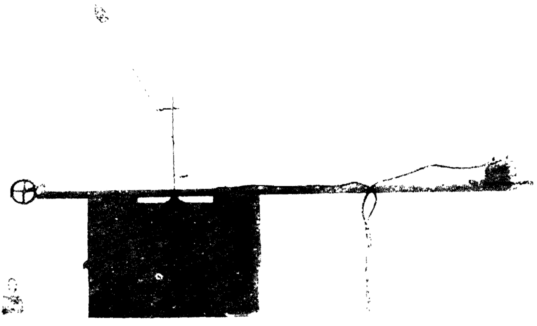


(c) The "celt" referred to in the text, and microphotographs showing the structure of various parts of it. *(By courtesy of Professor C. O. Bannister.)*

(*a*) Showing how the atoms of iron are arranged when the iron is at a low temperature: α iron.

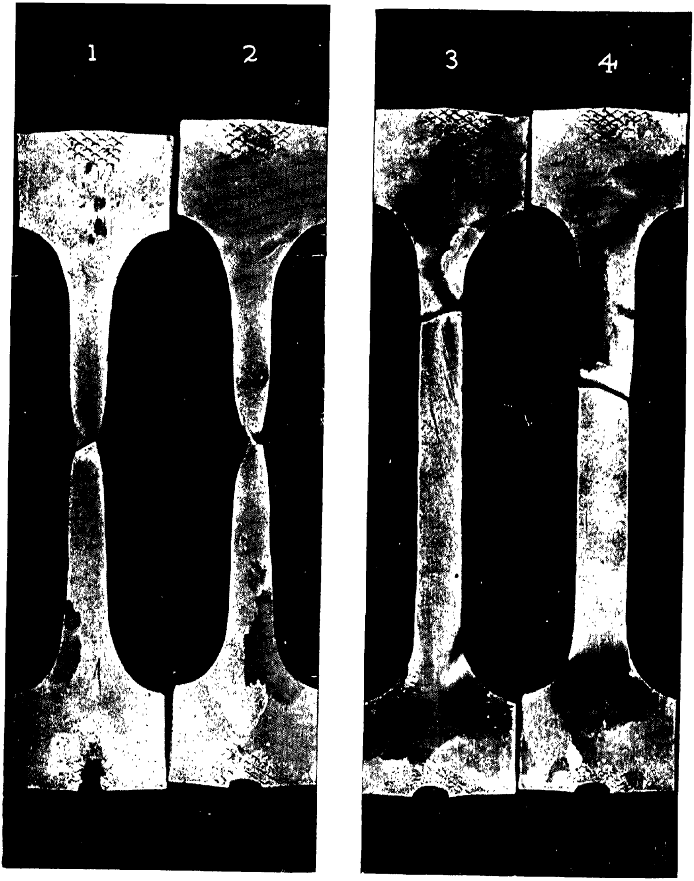


(*b*) Showing how the atoms are arranged at a high temperature: γ iron.

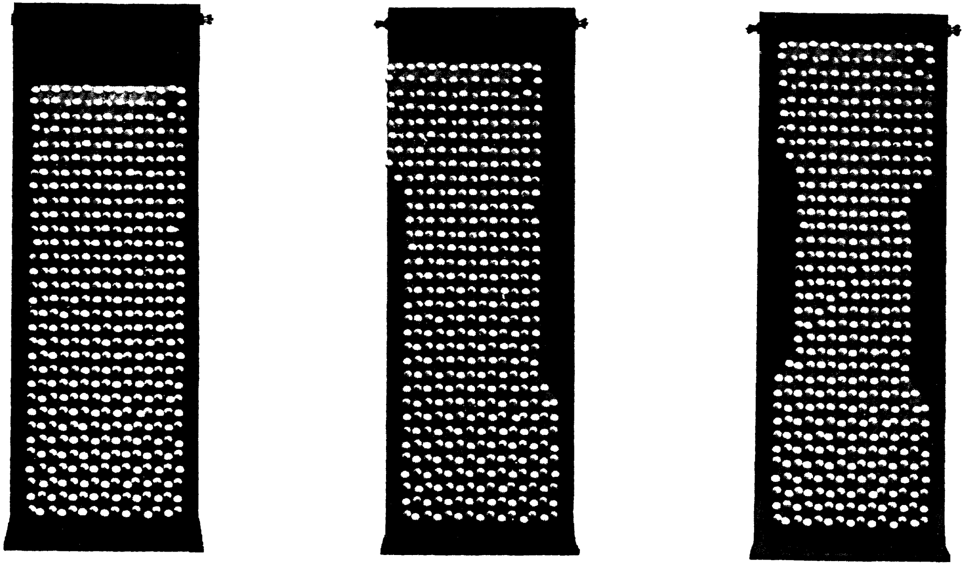


(*c*) Experiment described in the text, showing the alteration in length of an iron wire as it passes from the low to the high temperature state, and *vice versa*.

PLATE XV



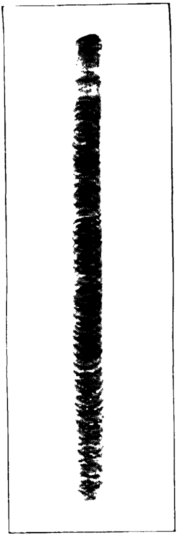
Test pieces of aluminium, stretched to breaking in the testing machine. Large portions consist of single crystals, and the nature of the rupture depends on the orientation of the crystal in which the straining and the rupture occur.



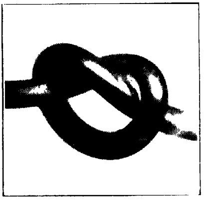
(a) (b) (c)

A model showing how the stretching of a metal crystal occurs by slipping first on one plane, (a) to (b), then on another, (b) to (c); while the arrangement of the atoms remains the same. (*By courtesy of Dr E. C. Goucher.*)

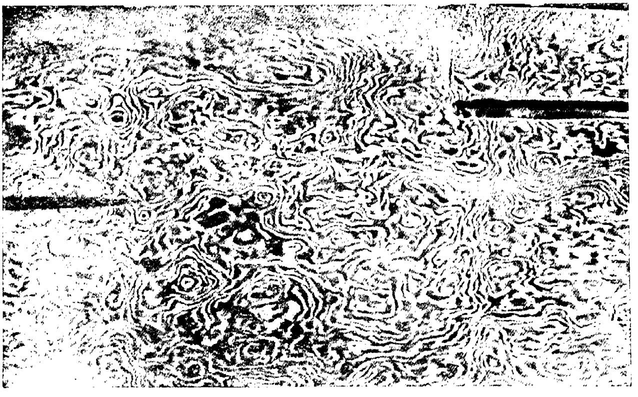
(*a*) (On the left) A soldier's helmet made of manganese steel. The soldier was not wearing the helmet when the bullets made the dents that are seen in it!



(*b*) The picture on the right is a bar consisting of one crystal of sodium: the bar has been stretched and the planes of slipping are easily seen; the elliptical marks show how their edges lie. (*Dr Alex. Muller.*)



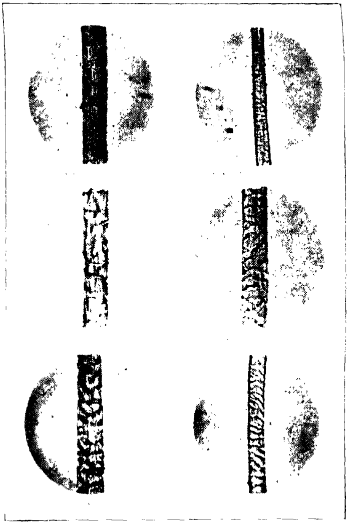
(*c*) (On the left) A wire, consisting of a single crystal of tungsten, bends so easily by slipping on certain planes that it can be tied into a knot. The picture is much magnified. (*Dr F. C. Goucher.*)

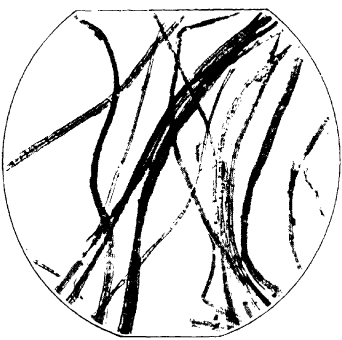


(*d*) The markings on a sword of Damascus steel. (*Belaiew.*)

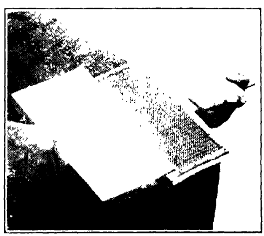
(*a*) Microphotographs of various woollen fibres, showing the scales that help the fibres to cling together.

1. (*Top left*) Mohair.
2. (*Middle left*) Leicester wool.
3. (*Bottom left*) New Zealand cross bred wool.
4. (*Top right*) Alpaca wool hair.
5. (*Middle right*) Down wool.
6. (*Bottom right*) Australian merino wool.

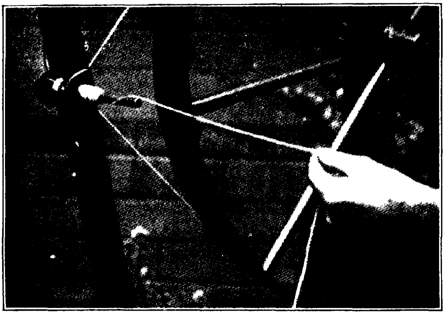




(*b*) Microphotograph of linen fibres.



(*c*) Showing how " carders " are held by the hands.

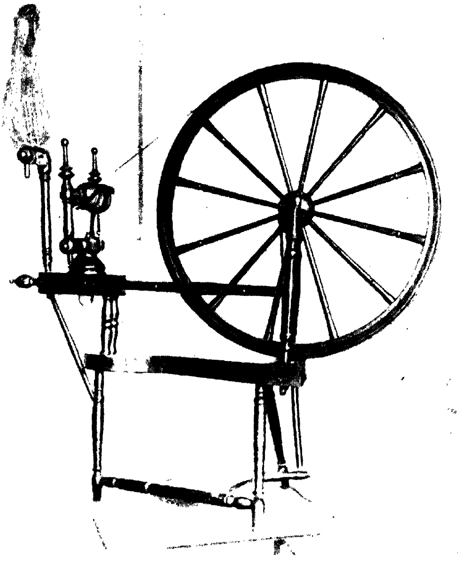


(*a*) Showing how the yarn is held so as to be twisted without winding.

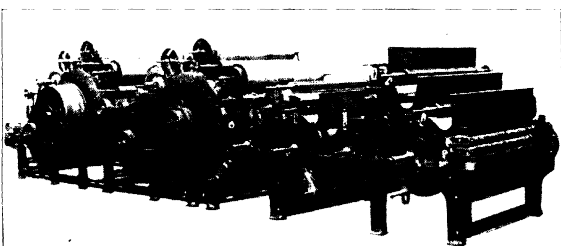
(*b*) Winding without twisting.

(*c*) A general vi

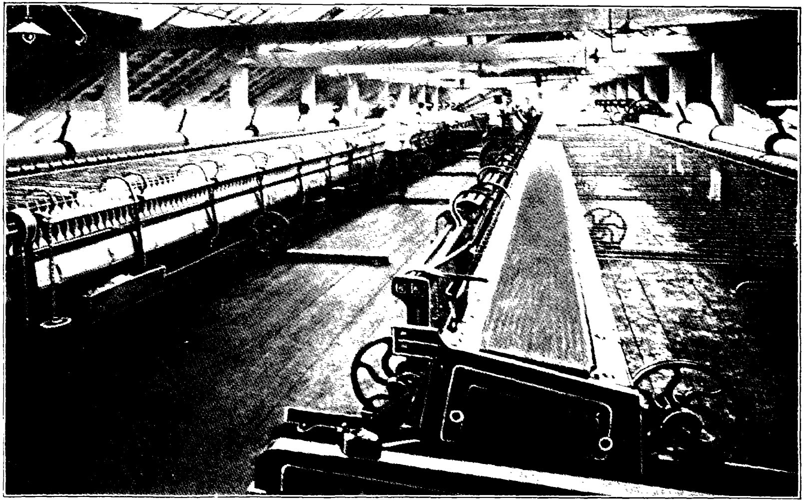
(*By courtesy of Professor* **Barker**, *Leeds University.*)



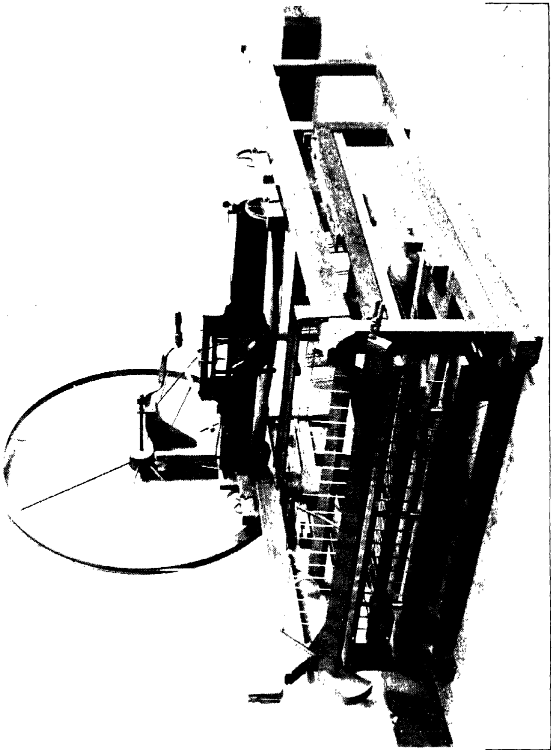
(a) An old spinning-wheel, with its flier.
(By courtesy of The London School of Weaving.)



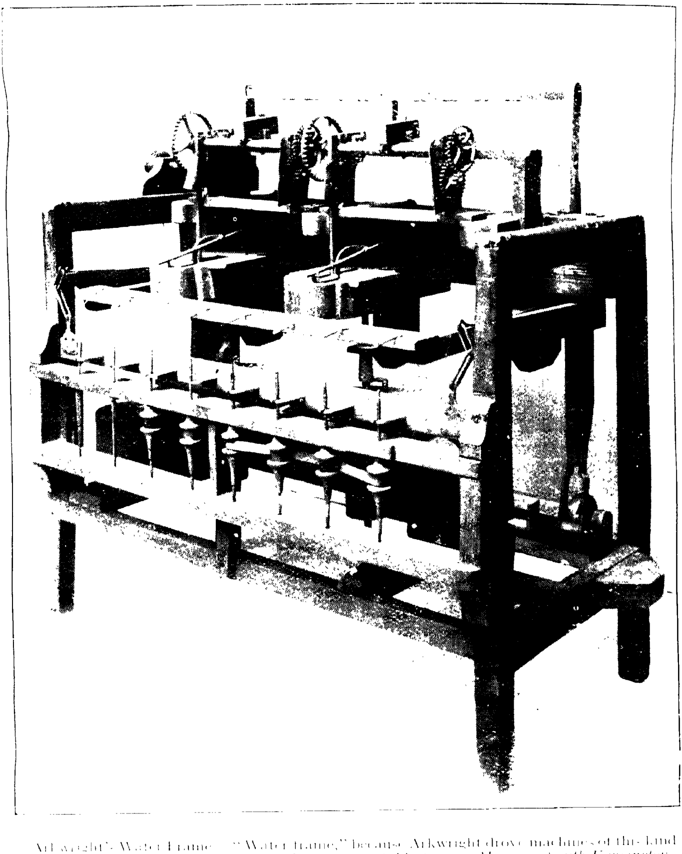
(b) A carding-machine.



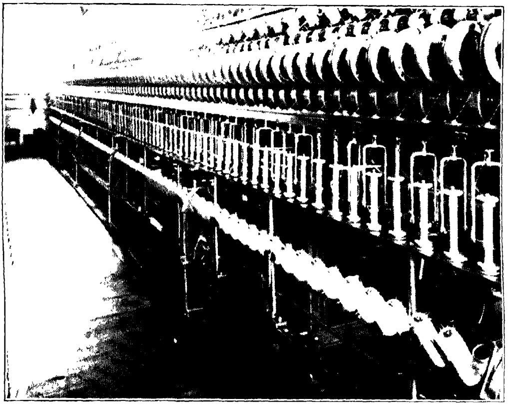
Mule-spinning. The central block runs on the wheels that are to be seen; in the position shown it is finishing the spinning and will presently run back to the frame on the right, to get more yarn to spin.



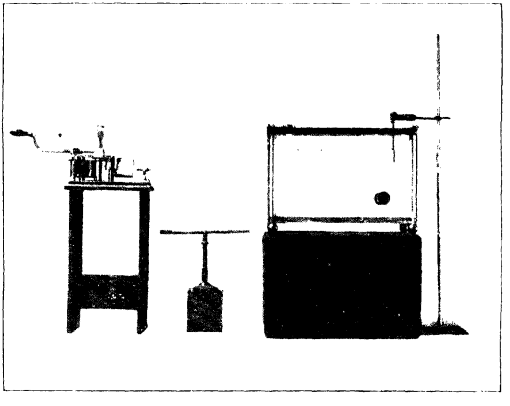
Hargreaves' Spinning-Jenny. (*By courtesy of The Science Museum, South Kensington.*)



Arkwright's Water Frame. "Water frame," because Arkwright drove machines of this kind by water at Cromford in Derbyshire. (*By courtesy of The Science Museum, South Kensington.*)

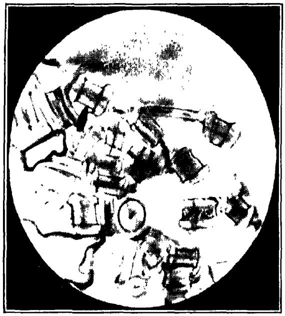


(a) Spinning machinery : the things like croquet hoops are the fliers.



(b) Spinning a thread of "artificial silk." The "viscose" is contained in a glass tube, held vertically on the right ; the thread drops into the hardening solution and is wound up by clockwork on the left.

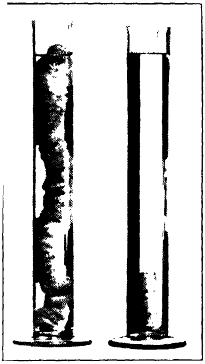
(a) Mercerisation of "tendered" cotton threads; there is no bulging of the material from the ends.



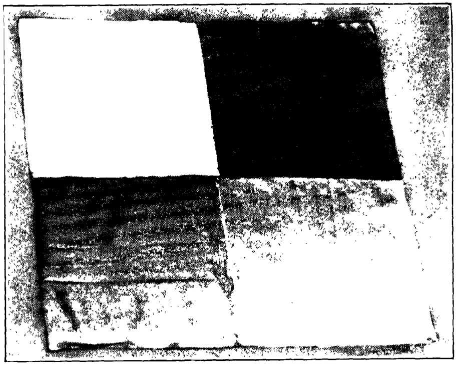
(b) Mercerisation of short sound pieces of cotton fibre. Observe the bulgings at the ends.

(c) Section of a yarn, showing the forms of the ends of the unmercerised fibres.

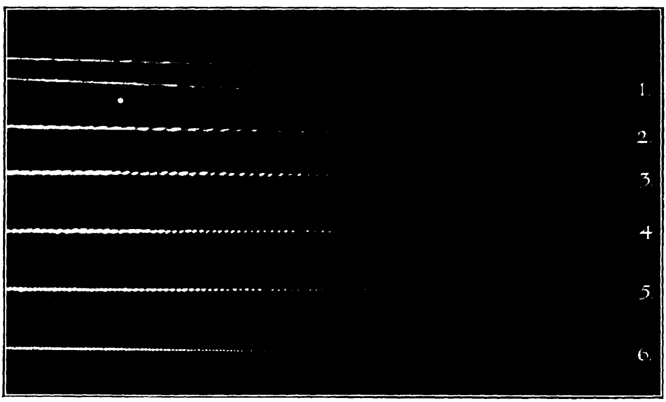
(d) The same as (c) when mercerised.



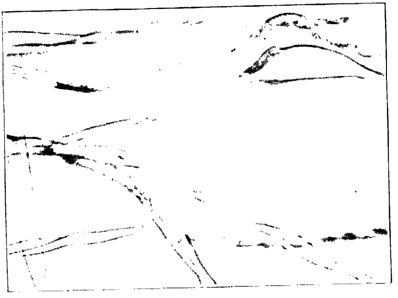
(*a*) A compressed plug of cotton is unaffected when dropped into the tall jar on the right, containing *benzene*, because cotton does not absorb benzene. But when dropped into the water in the jar on the left it expands notably.



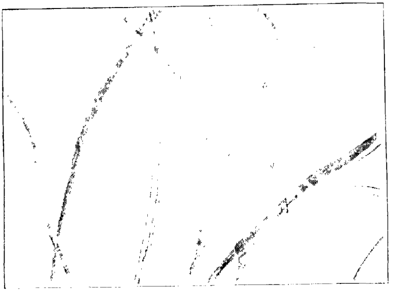
(*b*) Four pieces of the same schreinered material are pinned to a board: the top piece on the left is placed with the furrows running from left to right, so that their edges can reflect light to the observer's eye (or the camera) from a source of light behind the observer. In the top piece on the right the furrows run in the perpendicular direction and there is no reflection. In the other two the furrows run obliquely.



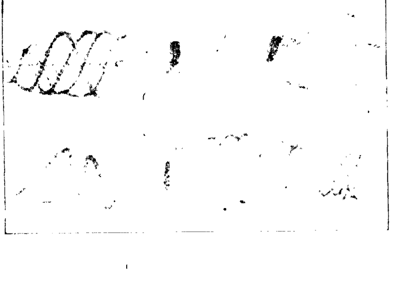
(*c*) Showing the improvement in lustre when the "doubled yarn" is correctly twisted, as explained in the text.



(*a*) Unmercerised cotton fibres. Observe the many kinks, and the tape like appearance.



(*b*) Mercerised cotton fibres. Observe that the fibres are more rounded than in (*a*).



(*c*) The spiral framework contained in the covering of the cotton fibre (in this case swollen to bursting).

(*a*) African natives treading clay in order to give it more uniform consistency and to free it from air holes.

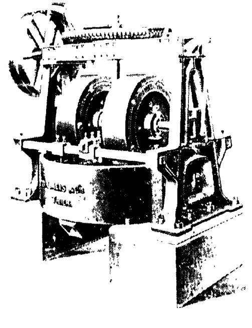
(*b*) An analogous process in a factory at the "Potteries," where it is called "wedging."

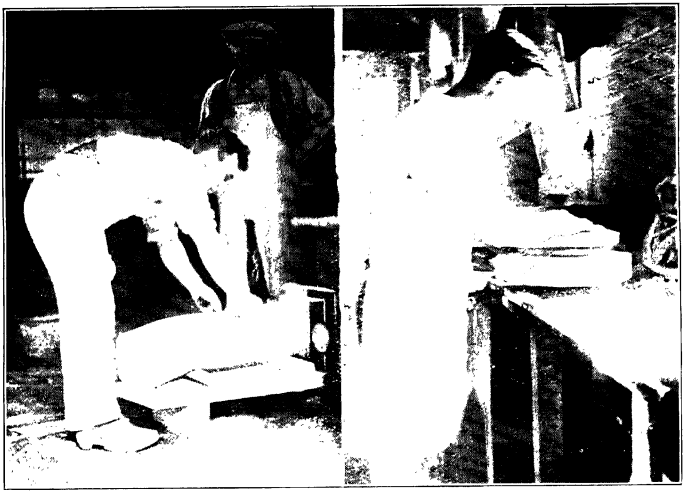
(a) Washing down the clay in the mine. (*By courtesy of Messrs H. D. Pochin & Co.*)

(b) Collecting flints on the shore at Boulogne.

(a) Settling pits.

(b) A grinding mill.

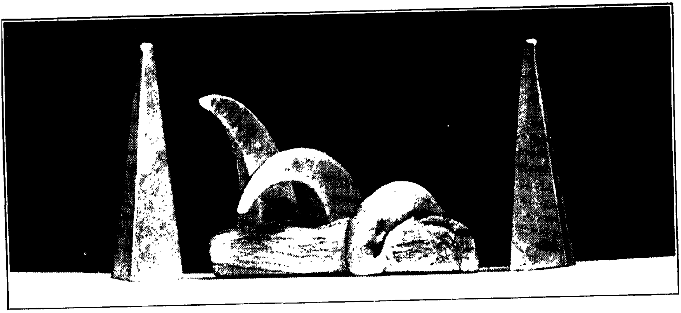




(*a*) (On the left) The "pug." The clay is now well mixed, of uniform consistency, and free from air holes. Only in this condition can clay be fired safely, because it shrinks greatly. If there were any irregularities in the composition the shrinkage would not be the same in different parts of the object, and cracks would certainly appear.

(*b*) (On the right) Forming a dinner plate on a small turntable or "potter's wheel."

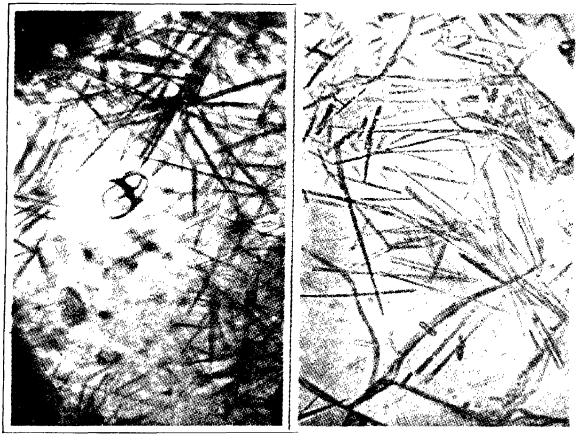
(*c*) The inside of the firing oven is seen through the opening. The men on the outside are packing the pots and dishes into the saggars (of rough earthenware): the men inside are piling the full saggars into position.



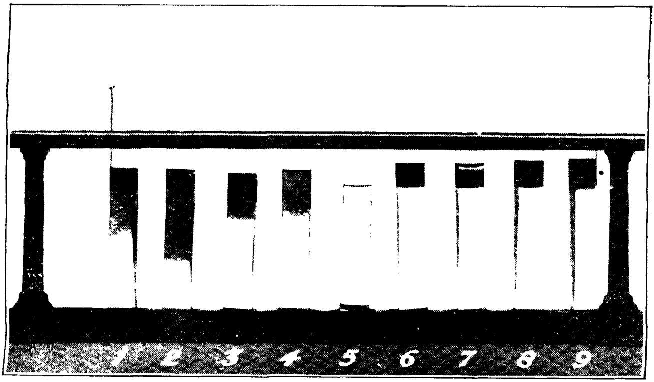
(*a*) Seger cones. These are made of clay of different compositions, so graded that cones numbered consecutively begin to run at different degrees of firing. The three in the centre have been in the furnace: the cone on the left has just begun to flow, that in the centre has bent well over, that on the right has collapsed altogether. From the state of these three, the firing has been judged to be completed in the case of the pots which were in the same furnace. The two cones on the left and right of the picture have not been in the furnace.

(*b*) (On the left) Dipping. The plates have already been fired, and are now being covered with a thin film of slip which will form the enamel after another firing. The dipper has two tubs, in one of which the slip is thicker than in the other. Plates vary in their capacity for absorbing, and the dipper is skilful in judging by their appearance the exact nature of the dip they ought each to have.

(*c*) (On the right) Pouring slip into the mould in the casting process.



(a) Microphotographs of fired china ware, showing the hard needle-like crystals which lace the structure together.



(b) The test tubes all contain gelatine. A solution of a "crystalloid" substance has been poured upon each of the first four, viz.:

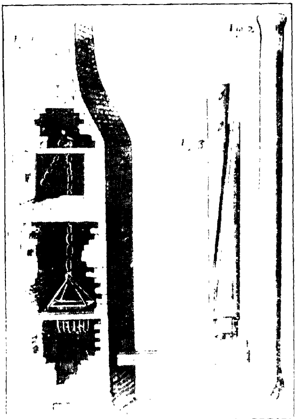
1. Picric acid.
2. *Bichromate of potash.*
3. Ferric chloride.
4. *Copper sulphate.*

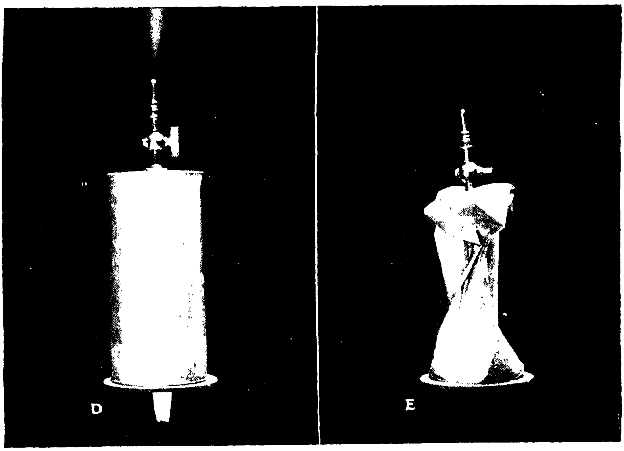
In these "crystalloid" substances the molecules move about as individuals and [illegible] through the [illegible] of the gelatine so that [illegible] slowly down the tube. The fifth tube is a blank, containing [illegible]. The test tubes on the right contain

[illegible] Prussian blue solution.
[illegible] Ferric hydroxide.
8. Colloidal silver.
9. Congo red.

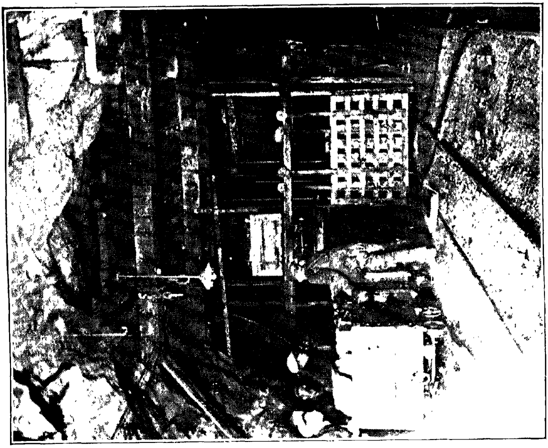
[illegible] colloidal substances the molecules have assembled into aggregates, [illegible] though very minute, cannot make their way into the gelat[illegible].

(a) A set of figures printed in the first volume of the *Transactions of the Royal Society*, illustrating a paper by Sir Robert Moray on "Mining at Liège." It shows the interest which the founders of the Royal Society took in the problems of mining. Fig. 1 shows the system of ventilation by a cage containing burning coal suspended in a chimney connected by a pipe (marked F) with the mine. Fig. 2 shows the tool for drilling holes in rock for blasting, and fig. 3 the form of double wedge used for closing the hole: the peculiar form of the wedges is intended to make the force of the gunpowder explosion close the hole still more tightly.

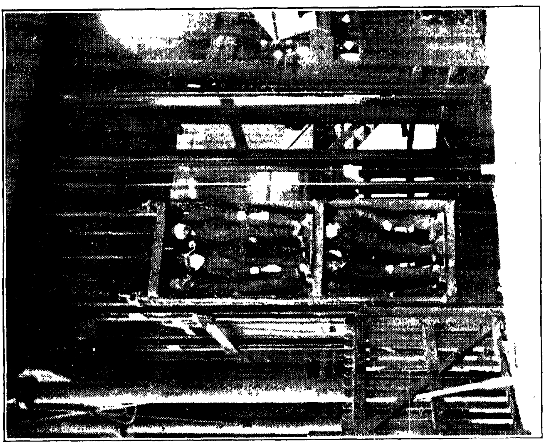




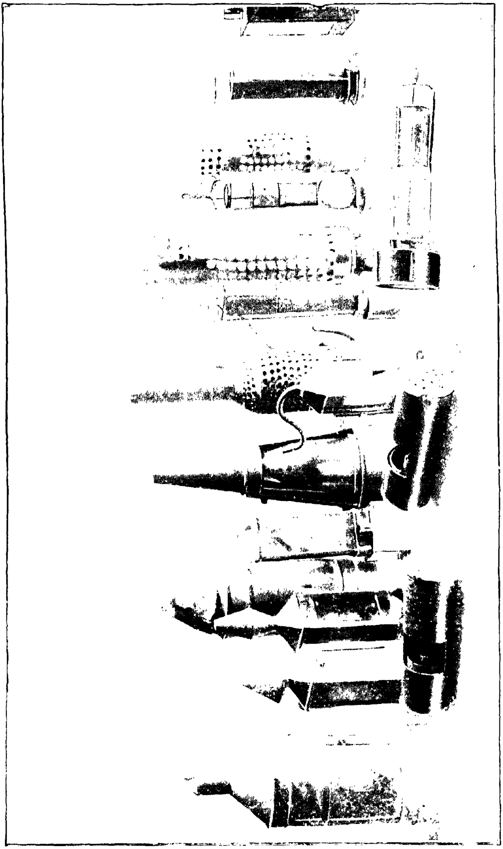
(b) A well known experiment to illustrate the great pressure of the atmosphere which Savery, Newcomen and others made use of in their engines. The cylinder on the left contains a little water boiling under the influence of the gas jet below. While the steam is issuing freely, the tap at the top is closed and the flame withdrawn. A little cold water is poured on the cylinder. The steam condenses and the pressure of the air from without crushes the cylinders together. James Watt records how one of his experiments failed from his under-estimating the strength of this effect.



At the bottom of the shaft. Coal being put into the cage for raising to the surface.

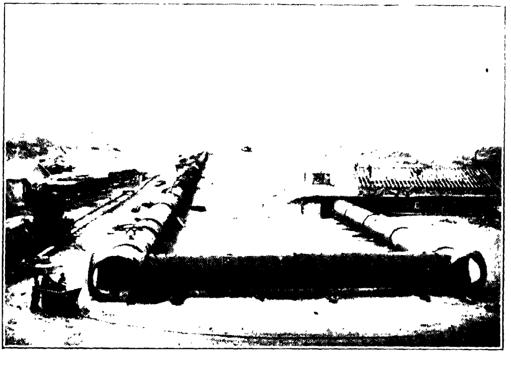


At the top of a shaft. Miners ready to be lowered.

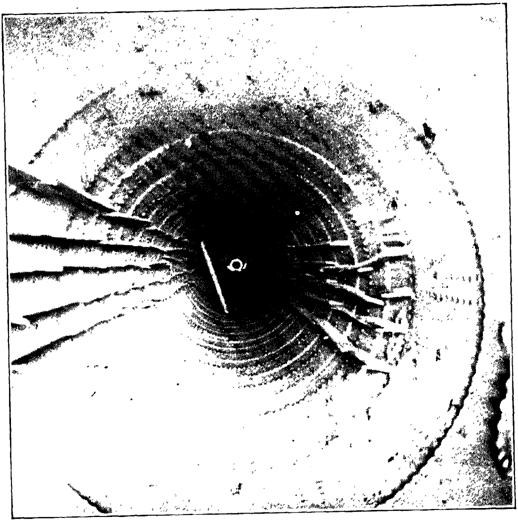


A collection of experimental safety-lamps, most of them Humphry Davy's, preserved at The Royal Institution.

(*a*) At the coal face. One man is hewing coal, the other is fixing props into their places.

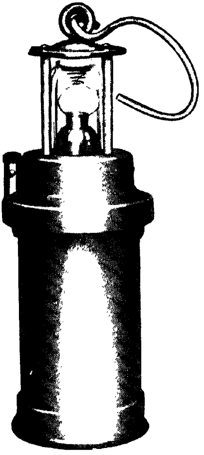


(*b*) The great pipe at Eskmeals in Cumberland which has been constructed to represent the gallery of a mine, so that the effect of explosions may be studied.

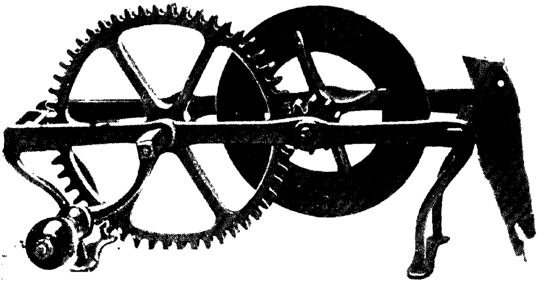


(a) Looking along the inside of the gallery. The small white patch in the centre is the opening at the other end. Note the shelves on the sides which are loaded with coal dust before an explosion.

(b) A cloud of smoke and coal dust issuing from the mouth of the experimental gallery after an explosion.



(a) A modern electric safety lamp. The battery is contained in the case in the lower part of the lamp. The bulb is at the top: note the spiral spring, which is arranged to cut out the light if the bulb is broken.



(b) The old miner's wheel. The miner's boy turned the wheel with one hand; with the other hand he held a piece of flint (a piece of flint is leaning against the frame on the right) so that the quickly moving edge of the steel wheel struck from it a shower of sparks. The wheel was thought to be less dangerous than a candle.