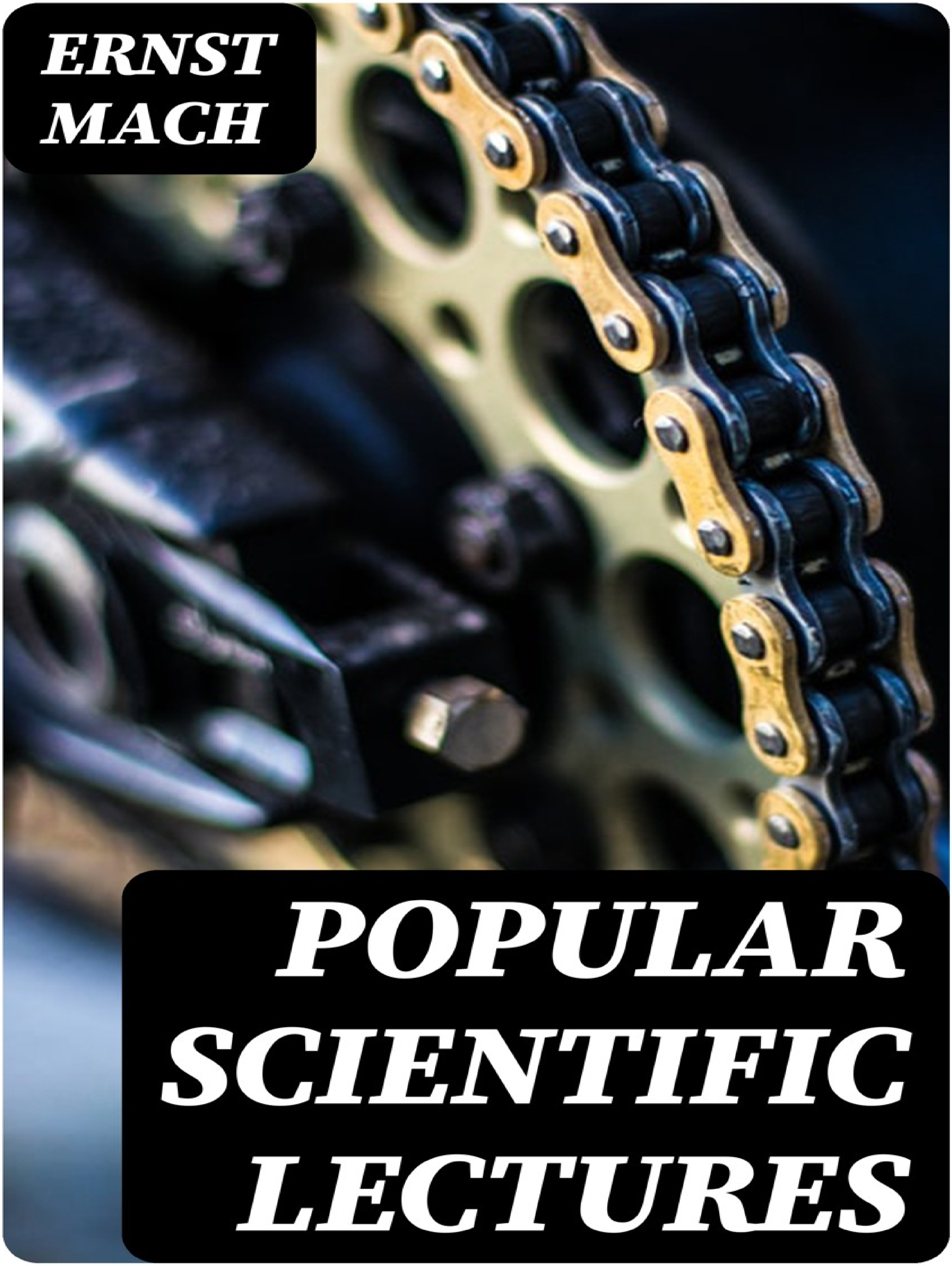

ERNST MACH

POPULAR SCIENTIFIC LECTURES

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THE FORMS OF LIQUIDS.

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What thinkest thou, dear Euthyphron, that the holy is, and the just, and the good? Is the holy holy because the gods love it, or are the gods holy because they love the holy? By such easy questions did the wise Socrates make the market-place of Athens unsafe and relieve presumptuous young statesmen of the burden of imaginary knowledge, by showing them how confused, unclear, and self-contradictory their ideas were.

You know the fate of the importunate questioner. So called good society avoided him on the promenade. Only the ignorant accompanied him. And finally he drank the cup of hemlock—a lot which we ofttimes wish would fall to modern critics of his stamp.

What we have learned from Socrates, however—our inheritance from him—is scientific criticism. Every one who busies himself with science recognises how unsettled and indefinite the notions are which he has brought with him from common life, and how, on a minute examination of things, old differences are effaced and new ones introduced. The history of science is full of examples of this constant change, development, and clarification of ideas.

But we will not linger by this general consideration of the fluctuating character of ideas, which becomes a source of real uncomfortableness, when we reflect that it applies to almost every notion of life. Rather shall we observe by the study of a physical example how much a thing changes when it is closely examined, and how it assumes, when thus considered, increasing definiteness of form.

The majority of you think, perhaps, you know quite well the distinction between a liquid and a solid. And precisely persons who have never busied themselves with physics will consider this question one of the easiest that can be put. But the physicist knows that it is one of the most difficult. I shall mention here only the experiments of Tresca, which show that solids subjected to high pressures behave exactly as liquids do; for example, may be made to flow out in the form of jets from orifices in the bottoms of vessels. The supposed difference of kind between liquids and solids is thus shown to be a mere difference of degree.

The common inference that because the earth is oblate in form, it was originally fluid, is an error, in the light of these facts. True, a rotating sphere, a few inches in diameter will assume an oblate form only if it is very soft, for example, is composed of freshly kneaded clay or some viscous stuff. But the earth, even if it consisted of the rigidest stone, could not help being crushed by its tremendous weight, and must perforce behave as a fluid. Even our mountains could not extend beyond a certain height without crumbling. The earth *may* once have been fluid, but this by no means follows from its oblateness.

The particles of a liquid are displaced on the application of the slightest pressure; a liquid conforms exactly to the shapes of the vessels in which it is contained; it possesses no form of its own, as you have all learned in the schools. Accommodating itself in the most trifling respects to the conditions of the vessel in which it is placed, and showing, even on its surface, where one would suppose it had the freest play, nothing but a polished, smiling, expressionless countenance, it is the courtier *par excellence* of the natural bodies.

Liquids have no form of their own! No, not for the superficial observer. But persons who have observed that a raindrop is round and never angular, will not be disposed to accept this dogma so unconditionally.

It is fair to suppose that every man, even the weakest, would possess a character, if it were not too difficult in this world to keep it. So, too, we must suppose that liquids would possess forms of their own, if the pressure of the circumstances permitted it—if they were not crushed by their own weights.

An astronomer once calculated that human beings could not exist on the sun, apart from its great heat, because they would be crushed to pieces there by their own weight. The greater mass of this body would also make the weight of the human body there much greater. But on the moon, because here we should be much lighter, we could jump as high as the church-steeples without any difficulty, with the same muscular power which we now possess. Statues and "plaster" casts of syrup are undoubtedly things of fancy, even on the moon, but maple-syrup would flow so slowly there that we could easily build a maple-syrup man on the moon, for the fun of the thing, just as our children here build snow-men.

Accordingly, if liquids have no form of their own with us on earth, they have, perhaps, a form of their own on the moon, or on some smaller and lighter heavenly body. The problem, then, simply is to get rid of the effects of gravity; and, this done, we shall be able to find out what the peculiar forms of liquids are.

The problem was solved by Plateau of Ghent, whose method was to immerse the liquid in another of the same specific gravity.[1] He employed for his experiments oil and a mixture of alcohol and water. By Archimedes's well-known principle, the oil in this mixture loses its entire weight. It no longer sinks beneath its weight; its formative forces, be they ever so weak, are now in full play.

As a fact, we now see, to our surprise, that the oil, instead of spreading out into a layer, or lying in a formless mass, assumes the shape of a beautiful and perfect sphere, freely suspended in the mixture, as the moon is in space. We can construct in this way a sphere of oil several inches in diameter.

If, now, we affix a thin plate to a wire and insert the plate in the oil sphere, we can, by twisting the wire between our fingers, set the whole ball in rotation. Doing this, the ball assumes an oblate shape, and we can, if we are skilful enough, separate by such rotation a ring from the ball, like that which surrounds Saturn. This ring is finally rent asunder, and, breaking up into a number of smaller balls, exhibits to us a kind of model of the origin of the planetary system according to the hypothesis of Kant and Laplace.

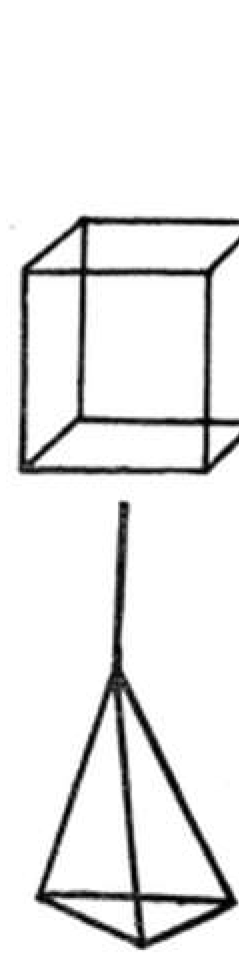

Fig. 1.

Still more curious are the phenomena exhibited when the formative forces of the liquid are partly disturbed by putting in contact with the liquid's surface some rigid body. If we immerse, for example, the wire framework of a cube in our mass of oil, the oil will everywhere stick to the wire framework. If the quantity of oil is exactly sufficient we shall obtain an oil cube with perfectly smooth walls. If there is too much or too little oil, the walls of the cube will bulge out or cave in. In this manner we can produce all kinds of geometrical figures of oil, for example, a three-sided pyramid, a cylinder (by bringing the oil between two wire rings), and so on. Interesting is the change of form that occurs when we gradually suck out the oil by means of a glass tube from the cube or pyramid. The wire holds the oil fast. The figure grows smaller and smaller, until it is at last quite thin. Ultimately it consists simply of a number of thin, smooth plates of oil, which extend from the edges of the cube to the centre, where they meet in a small drop. The same is true of the pyramid.

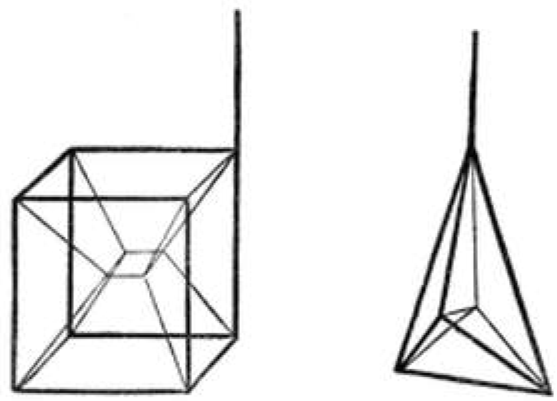

Fig. 2.

The idea now suggests itself that liquid figures as thin as this, and possessing, therefore, so slight a weight, cannot be crushed or deformed by their weight; just as a small, soft ball of clay is not affected in this respect by its weight. This being the case, we no longer need our mixture of alcohol and water for the production of figures, but can construct them in the open air. And Plateau, in fact, found that these thin figures, or at least very similar ones, could be produced in the air, by dipping the wire nets described in a solution of soap and water and quickly drawing them out again. The experiment is not difficult. The figure is formed of itself. The preceding drawing represents to the eye the forms obtained with cubical and pyramidal nets. In the cube, thin, smooth films of soap-suds proceed from the edges to a small, quadratic film in the centre. In the pyramid, a film proceeds from each edge to the centre.

These figures are so beautiful that they hardly admit of appropriate description. Their great regularity and geometrical exactness evokes surprise from all who see them for the first time. Unfortunately, they are of only short duration. They burst, on the drying of the solution in the air, but only after exhibiting to us the most brilliant play of colors, such as is often seen in soap-bubbles. Partly their beauty of form and partly our desire to examine them more minutely induces us to conceive of methods of endowing them with permanent form. This is very simply done.[2] Instead of dipping the wire nets in solutions of soap, we dip them in pure melted colophonium (resin). When drawn out the figure at once forms and solidifies by contact with the air.

It is to be remarked that also solid fluid-figures can be constructed in the open air, if their weight be light enough, or the wire nets of very small dimensions. If we make, for example, of very fine wire a cubical net whose sides measure about one-eighth of an inch in length, we need simply to dip this net in water to obtain a small solid cube of water. With a piece of blotting paper the superfluous water may be easily removed and the sides of the cube made smooth.

Yet another simple method may be devised for observing these figures. A drop of water on a greased glass plate will not run if it is small enough, but will be flattened by its weight, which presses it against its support. The smaller the drop the less the flattening. The smaller the drop the nearer it approaches the form of a sphere. On the other hand, a drop suspended from a stick is elongated by its weight. The undermost parts of a drop of water on a support are pressed against the support, and the upper parts are pressed against the lower parts because the latter cannot yield. But when a drop falls freely downward all its parts move equally fast; no part is impeded by another; no part presses against another. A freely falling drop, accordingly, is not affected by its weight; it acts as if it were weightless; it assumes a spherical form.

A moment's glance at the soap-film figures produced by our various wire models, reveals to us a great multiplicity of form. But great as this multiplicity is, the common features of the figures also are easily discernible.

> "All forms of Nature are allied, though none is
> the same as the other;
> Thus, their common chorus points to a hidden
> law."

This hidden law Plateau discovered. It may be expressed, somewhat prosily, as follows:

1) If several plane liquid films meet in a figure they are always three in number, and, taken in pairs, form, each with another, nearly equal angles.

2) If several liquid edges meet in a figure they are always four in number, and, taken in pairs, form, each with another, nearly equal angles.

This is a strange law, and its reason is not evident. But we might apply this criticism to almost all laws. It is not always that the motives of a law-maker are discernible in the form of the law he constructs. But our law admits of analysis into very simple elements or reasons. If we closely examine the paragraphs which state it, we shall find that their meaning is simply this, that the surface of the liquid assumes the shape of smallest area that is possible under the circumstances.

If, therefore, some extraordinarily intelligent tailor, possessing a knowledge of all the artifices of the higher mathematics, should set himself the task of so covering the wire frame of a cube with cloth that every piece of cloth should be connected with the wire and joined with the remaining cloth, and should seek to accomplish this feat with the greatest saving of material, he would construct no other figure than that which is here formed on the wire frame in our solution of soap and water. Nature acts in the construction of liquid figures on the principle of a covetous tailor, and gives no thought in her work to the fashions. But, strange to say, in this work, the most beautiful fashions are of themselves produced.

The two paragraphs which state our law apply primarily only to soap-film figures, and are not applicable, of course, to solid oil-figures. But the principle that the superficial area of the liquid shall be the least possible under the circumstances, is applicable to all fluid figures. He who understands not only the letter but also the reason of the law will not be at a loss when confronted with cases to which the letter does not accurately apply. And this is the case with the principle of least superficial area. It is a sure guide for us even in cases in which the above-stated paragraphs are not applicable.

Our first task will now be, to show by a palpable illustration the mode of formation of liquid figures by the principle of least superficial area. The oil on the wire pyramid in our mixture of alcohol and water, being unable to leave the wire edges, clings to them, and the given mass of oil strives so to shape itself that its surface shall have the least possible area. Suppose we attempt to imitate this phenomenon. We take a wire pyramid, draw over it a stout film of rubber, and in place of the wire handle insert a small tube leading into the interior of the space enclosed by the rubber (Fig. 3). Through this tube we can blow in or suck out air. The quantity of air in the enclosure represents the quantity of oil. The stretched rubber film, which, clinging to the wire edges, does its utmost to contract, represents the surface of the oil endeavoring to decrease its area. By blowing in, and drawing out the air, now, we actually obtain all the oil pyramidal figures, from those bulged out to those hollowed in. Finally, when all the air is pumped or sucked out, the soap-film figure is exhibited. The rubber films strike together, assume the form of planes, and meet at four sharp edges in the centre of the pyramid.

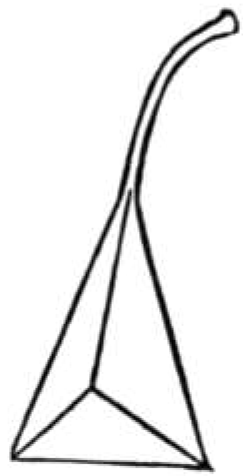

Fig. 3.

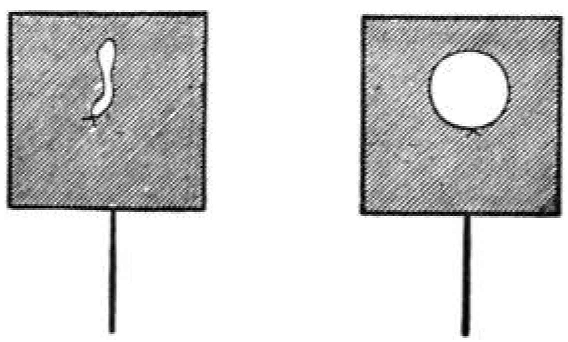

Fig. 4.

The tendency of soap-films to assume smaller forms may be directly demonstrated by a method of Van der Mensbrugghe. If we dip a square wire frame to which a handle is attached into a solution of soap and water, we shall obtain on the frame a beautiful, plane film of soap-suds. (Fig. 4.) On this we lay a thread having its two ends tied together. If, now, we puncture the part enclosed by the thread, we shall obtain a soap-film having a circular hole in it, whose circumference is the thread. The remainder of the film decreasing in area as much as it can, the hole assumes the largest area that it can. But the figure of largest area, with a given periphery, is the circle.

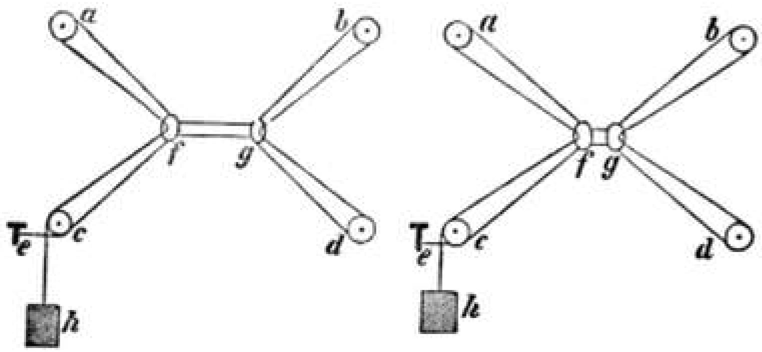

Fig. 5.

Similarly, by the principle of least superficial area, a freely suspended mass of oil assumes the shape of a sphere. The sphere is the form of least surface for a given content. This is evident. The more we put into a travelling-bag, the nearer its shape approaches the spherical form.

The connexion of the two above-mentioned paragraphs with the principle of least superficial area may be shown by a yet simpler example. Picture to yourselves four fixed pulleys, *a*, *b*, *c*, *d*, and two movable rings *f*, *g* (Fig. 5); about the pulleys and through the rings imagine a smooth cord passed, fastened at one extremity to a nail *e*, and loaded at the other with a weight *h*. Now this weight always tends to sink, or, what is the same thing, always tends to make the portion of the string *e h* as long as possible, and consequently the remainder of the string, wound round the pulleys, as short as possible. The strings must remain connected with the pulleys, and on account of the rings also with each other. The conditions of the case, accordingly, are similar to those of the liquid figures discussed. The result also is a similar one. When, as in the right hand figure of the cut, four pairs of strings meet, a different configuration must be established. The consequence of the endeavor of the string to shorten itself is that the rings separate from each other, and that now at all points only three pairs of strings meet, every two at equal angles of one hundred and twenty degrees. As a fact, by this arrangement the greatest possible shortening of the string is attained; as can be easily proved by geometry.

This will help us to some extent to understand the creation of beautiful and complicated figures by the simple tendency of liquids to assume surfaces of least superficial area. But the question arises, *Why* do liquids seek surfaces of least superficial area?

The particles of a liquid cling together. Drops brought into contact coalesce. We can say, liquid particles attract each other. If so, they seek to come as close as they can to each other. The particles at the surface will endeavor to penetrate as far as they can into the interior. This process will not stop, cannot stop, until the surface has become as small as under the circumstances it possibly can become, until as few particles as possible remain at the surface, until as many particles as possible have penetrated into the interior, until the forces of attraction have no more work to perform.[3]

The root of the principle of least surface is to be sought, accordingly, in another and much simpler principle, which may be illustrated by some such analogy as this. We can *conceive* of the natural forces of attraction and repulsion as purposes or intentions of nature. As a matter of fact, that interior pressure which we feel before an act and which we call an intention or purpose, is not, in a final analysis, so essentially different from the pressure of a stone on its support, or the pressure of a magnet on another, that it is necessarily unallowable to use for both the same term—at least for well-defined purposes.[4] It is the purpose of nature, accordingly, to bring the iron nearer the magnet, the stone nearer the centre of the earth, and so forth. If such a purpose can be realised, it is carried out. But where she cannot realise her purposes, nature does nothing. In this respect she acts exactly as a good man of business does.

It is a constant purpose of nature to bring weights lower. We can raise a weight by causing another, larger weight to sink; that is, by satisfying another, more powerful, purpose of nature. If we fancy we are making nature serve our purposes in this, it will be found, upon closer examination, that the contrary is true, and that nature has employed us to attain her purposes.

Equilibrium, rest, exists only, but then always, when nature is brought to a halt in her purposes, when the forces of nature are as fully satisfied as, under the circumstances, they can be. Thus, for example, heavy bodies are in equilibrium, when their so-called centre of gravity lies as low as it possibly can, or when as much weight as the circumstances admit of has sunk as low as it can.

The idea forcibly suggests itself that perhaps this principle also holds good in other realms. Equilibrium exists also in the state when the purposes of the parties are as fully satisfied as for the time being they can be, or, as we may say, jestingly, in the language of physics, when the social potential is a maximum.[5]

You see, our miserly mercantile principle is replete with consequences.[6] The result of sober research, it has become as fruitful for physics as the dry questions of Socrates for science generally. If the principle seems to lack in ideality, the more ideal are the fruits which it bears.

But why, tell me, should science be ashamed of such a principle? Is science[7] itself anything more than—a business? Is not its task to acquire with the least possible work, in the least possible time, with the least possible thought, the greatest possible part of eternal truth?

THE FIBRES OF CORTI.

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Whoever has roamed through a beautiful country knows that the tourist's delights increase with his progress. How pretty that wooded dell must look from yonder hill! Whither does that clear brook flow, that hides itself in yonder sedge? If I only knew how the landscape looked behind that mountain! Thus even the child thinks in his first rambles. It is also true of the natural philosopher.

The first questions are forced upon the attention of the inquirer by practical considerations; the subsequent ones are not. An irresistible attraction draws him to these; a nobler interest which far transcends the mere needs of life. Let us look at a special case.

For a long time the structure of the organ of hearing has actively engaged the attention of anatomists. A considerable number of brilliant discoveries has been brought to light by their labors, and a splendid array of facts and truths established. But with these facts a host of new enigmas has been presented.

Whilst in the theory of the organisation and functions of the eye comparative clearness has been attained; whilst, hand in hand with this, ophthalmology has reached a degree of perfection which the preceding century could hardly have dreamed of, and by the help of the ophthalmoscope the observing physician penetrates into the profoundest recesses of the eye, the theory of the ear is still much shrouded in mysterious darkness, full of attraction for the investigator.

Look at this model of the ear. Even at that familiar part by whose extent we measure the quantity of people's intelligence, even at the external ear, the problems begin. You see here a succession of helixes or spiral windings, at times very pretty, whose significance we cannot accurately state, yet for which there must certainly be some reason.

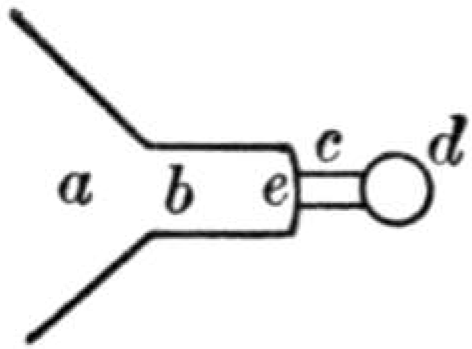

Fig. 6.

The shell or concha of the ear, *a* in the annexed diagram, conducts the sound into the curved auditory passage *b*, which is terminated by a thin membrane, the so-called tympanic membrane, *e*. This membrane is set in motion by the sound, and in its turn sets in motion a series of little bones of very peculiar formation, *c*. At the end of all is the labyrinth *d*. The labyrinth consists of a group of cavities filled with a liquid, in which the innumerable fibres of the nerve of hearing are imbedded. By the vibration of the chain of bones *c*, the liquid of the labyrinth is shaken, and the auditory nerve excited. Here the process of hearing begins. So much is certain. But the details of the process are one and all unanswered questions.

To these old puzzles, the Marchese Corti, as late as 1851, added a new enigma. And, strange to say, it is this last enigma, which, perhaps, has first received its correct solution. This will be the subject of our remarks to-day.

Corti found in the cochlea, or snail-shell of the labyrinth, a large number of microscopic fibres placed side by side in geometrically graduated order. According to Kölliker their number is three thousand. They were also the subject of investigation at the hands of Max Schultze and Deiters.

A description of the details of this organ would only weary you, besides not rendering the matter much clearer. I prefer, therefore, to state briefly what in the opinion of prominent investigators like Helmholtz and Fechner is the peculiar function of Corti's fibres. The cochlea, it seems, contains a large number of elastic fibres of graduated lengths (Fig. 7), to which the branches of the auditory nerve are attached. These fibres, called the fibres, pillars, or rods of Corti, being of unequal length, must also be of unequal elasticity, and, consequently, pitched to different notes. The cochlea, therefore, is a species of pianoforte.

Fig. 7.

What, now, may be the office of this structure, which is found in no other organ of sense? May it not be connected with some special property of the ear? It is quite probable; for the ear possesses a very similar power. You know that it is possible to follow the individual voices of a symphony.

Indeed, the feat is possible even in a fugue of Bach, where it is certainly no inconsiderable achievement. The ear can pick out the single constituent tonal parts, not only of a harmony, but of the wildest clash of music imaginable. The musical ear analyses every agglomeration of tones.

The eye does not possess this ability. Who, for example, could tell from the mere sight of white, without a previous experimental knowledge of the fact, that white is composed of a mixture of other colors? Could it be, now, that these two facts, the property of the ear just mentioned, and the structure discovered by Corti, are really connected? It is very probable. The enigma is solved if we assume that every note of definite pitch has its special string in this pianoforte of Corti, and, therefore, its special branch of the auditory nerve attached to that string. But before I can make this point perfectly plain to you, I must ask you to follow me a few steps into the dry domain of physics.

Look at this pendulum. Forced from its position of equilibrium by an impulse, it begins to swing with a definite time of oscillation, dependent upon its length. Longer pendulums swing more slowly, shorter ones more quickly. We will suppose our pendulum to execute one to-and-fro movement in a second.

This pendulum, now, can be thrown into violent vibration in two ways; either by a *single* heavy impulse, or by a *number* of properly communicated slight impulses. For example, we impart to the pendulum, while at rest in its position of equilibrium, a very slight impulse. It will execute a very small vibration. As it passes a third time its position of equilibrium, a second having elapsed, we impart to it again a slight shock, in the same direction with the first. Again after the lapse of a second, on its fifth passage through the position of equilibrium, we strike it again in the same manner; and so continue. You see, by this process the shocks imparted augment continually the motion of the pendulum. After each slight impulse, the pendulum reaches out a little further in its swing, and finally acquires a considerable motion.[8]

But this is not the case under all circumstances. It is possible only when the impulses imparted synchronise with the swings of the pendulum. If we should communicate the second impulse at the end of half a second and in the same direction with the first impulse, its effects would counteract the motion of the pendulum. It is easily seen that our little impulses help the motion of the pendulum more and more, according as their time accords with the time of the pendulum. If we strike the pendulum in any other time than in that of its vibration, in some instances, it is true, we shall augment its vibration, but in others again, we shall obstruct it. Our impulses will be less effective the more the motion of our own hand departs from the motion of the pendulum.

What is true of the pendulum holds true of every vibrating body. A tuning-fork when it sounds, also vibrates. It vibrates more rapidly when its sound is higher; more slowly when it is deeper. The standard *A* of our musical scale is produced by about four hundred and fifty vibrations in a second.

I place by the side of each other on this table two tuning-forks, exactly alike, resting on resonant cases. I strike the first one a sharp blow, so that it emits a loud note, and immediately grasp it again with my hand to quench its note. Nevertheless, you still hear the note distinctly sounded, and by feeling it you may convince yourselves that the other fork which was not struck now vibrates.

I now attach a small bit of wax to one of the forks. It is thrown thus out of tune; its note is made a little deeper. I now repeat the same experiment with the two forks, now of unequal pitch, by striking one of them and again grasping it with my hand; but in the present case the note ceases the very instant I touch the fork.

What has happened here in these two experiments? Simply this. The vibrating fork imparts to the air and to the table four hundred and fifty shocks a second, which are carried over to the other fork. If the other fork is pitched to the same note, that is to say, if it vibrates when struck in the same time with the first, then the shocks first emitted, no matter how slight they may be, are sufficient to throw the second fork into rapid sympathetic vibration. But when the time of vibration of the two forks is slightly different, this does not take place. We may strike as many forks as we will, the fork tuned to *A* is perfectly indifferent to their notes; is deaf, in fact, to all except its own; and if you strike three, or four, or five, or any number whatsoever, of forks all at the same time, so as to make the shocks which come from them ever so great, the *A* fork will not join in with their vibrations unless another fork *A* is found in the collection struck. It picks out, in other words, from all the notes sounded, that which accords with it.

The same is true of all bodies which can yield notes. Tumblers resound when a piano is played, on the striking of certain notes, and so do window panes. Nor is the phenomenon without analogy in other provinces. Take a dog that answers to the name "Nero." He lies under your table. You speak of Domitian, Vespasian, and Marcus Aurelius Antoninus, you call upon all the names of the Roman Emperors that occur to you, but the dog does not stir, although a slight tremor of his ear tells you of a faint response of his consciousness. But the moment you call "Nero" he jumps joyfully towards you. The tuning-fork is like your dog. It answers to the name *A*.

You smile, ladies. You shake your heads. The simile does not catch your fancy. But I have another, which is very near to you: and for punishment you shall hear it. You, too, are like tuning-forks. Many are the hearts that throb with ardor for you, of which you take no notice, but are cold. Yet what does it profit you! Soon the heart will come that beats in just the proper rhythm, and then your knell, too, has struck. Then your heart, too, will beat in unison, whether you will or no.

The law of sympathetic vibration, here propounded for sounding bodies, suffers some modification for bodies incompetent to yield notes. Bodies of this kind vibrate to almost every note. A high silk hat, we know, will not sound; but if you will hold your hat in your hand when attending your next concert you will not only hear the pieces played, but also feel them with your fingers. It is exactly so with men. People who are themselves able to give tone to their surroundings, bother little about the prattle of others. But the person without character tarries everywhere: in the temperance hall, and at the bar of the public-house—everywhere where a committee is formed. The high silk hat is among bells what the weakling is among men of conviction.

A sonorous body, therefore, always sounds when its special note, either alone or in company with others, is struck. We may now go a step further. What will be the behaviour of a group of sonorous bodies which in the pitch of their notes form a scale? Let us picture to ourselves, for example (Fig. 8), a series of rods or strings pitched to the notes *c d e f g*.... On a musical instrument the accord *c e g* is struck. Every one of the rods of Fig. 8 will see if its special note is contained in the accord, and if it finds it, it will respond. The rod *c* will give at once the note *c*, the rod *e* the note *e*, the rod *g* the note *g*. All the other rods will remain at rest, will not sound.

Fig. 8.

We need not look about us long for such an instrument. Every piano is an instrument of this kind, with which the experiment mentioned may be executed with splendid success. Two pianos stand here by the side of each other, both tuned alike. We will employ the first for exciting the notes, while we will allow the second to respond; after having first pressed upon the loud pedal, so as to render all the strings capable of motion.

Every harmony struck with vigor on the first piano is distinctly repeated on the second. To prove that it is the same strings that are sounded in both pianos, we repeat the experiment in a slightly changed form. We let go the loud pedal of the second piano and pressing on the keys *c e g* of that instrument vigorously strike the harmony *c e g* on the first piano. The harmony *c e g* is now also sounded on the second piano. But if we press only on one key *g* of one piano, while we strike *c e g* on the other, only *g* will be sounded on the second. It is thus always the like strings of the two pianos that excite each other.

The piano can reproduce any sound that is composed of its musical notes. It will reproduce, for example, very distinctly, a vowel sound that is sung into it. And in truth physics has proved that the vowels may be regarded as composed of simple musical notes.

You see that by the exciting of definite tones in the air quite definite motions are set up with mechanical necessity in the piano. The idea might be made use of for the performance of some pretty pieces of wizardry. Imagine a box in which is a stretched string of definite pitch. This is thrown into motion as often as its note is sung or whistled. Now it would not be a very difficult task for a skilful mechanic to so construct the box that the vibrating cord would close a galvanic circuit and open the lock. And it would not be a much more difficult task to construct a box which would open at the whistling of a certain melody. Sesame! and the bolts fall. Truly, we should have here a veritable puzzle-lock. Still another fragment rescued from that old kingdom of fables, of which our day has realised so much, that world of fairy-stories to which the latest contributions are Casselli's telegraph, by which one can write at a distance in one's own hand, and Prof. Elisha Gray's telautograph. What would the good old Herodotus have said to these things who even in Egypt shook his head at much that he saw? ἐμοὶ μὲνε ού πιστα, just as simple-heartedly as then, when he heard of the circumnavigation of Africa.

A new puzzle-lock! But why invent one? Are not we human beings ourselves puzzle-locks? Think of the stupendous groups of thoughts, feelings, and emotions that can be aroused in us by a word! Are there not moments in all our lives when a mere name drives the blood to our hearts? Who that has attended a large mass-meeting has not experienced what tremendous quantities of energy and motion can be evolved by the innocent words, "Liberty, Equality, Fraternity."

But let us return to the subject proper of our discourse. Let us look again at our piano, or what will do just as well, at some other contrivance of the same character. What does this instrument do? Plainly, it decomposes, it analyses every agglomeration of sounds set up in the air into its individual component parts, each tone being taken up by a different string; it performs a real spectral analysis of sound. A person completely deaf, with the help of a piano, simply by touching the strings or examining their vibrations with a microscope, might investigate the sonorous motion of the air, and pick out the separate tones excited in it.

The ear has the same capacity as this piano. The ear performs for the mind what the piano performs for a person who is deaf. The mind without the ear is deaf. But a deaf person, with the piano, does hear after a fashion, though much less vividly, and more clumsily, than with the ear. The ear, thus, also decomposes sound into its component tonal parts. I shall now not be deceived, I think, if I assume that you already have a presentiment of what the function of Corti's fibres is. We can make the matter very plain to ourselves. We will use the one piano for exciting the sounds, and we shall imagine the second one in the ear of the observer in the place of Corti's fibres, which is a model of such an instrument. To every string of the piano in the ear we will suppose a special fibre of the auditory nerve attached, so that this fibre and this alone, is irritated when the string is thrown into vibration. If we strike now an accord on the external piano, for every tone of that accord a definite string of the internal piano will sound and as many different nervous fibres will be irritated as there are notes in the accord. The simultaneous sense-impressions due to different notes can thus be preserved unmingled and be separated by the attention. It is the same as with the five fingers of the hand. With each finger I can touch something different. Now the ear has three thousand such fingers, and each one is designed for the touching of a different tone.[9] Our ear is a puzzle-lock of the kind mentioned. It opens at the magic melody of a sound. But it is a stupendously ingenious lock. Not only one tone, but every tone makes it open; but each one differently. To each tone it replies with a different sensation.

More than once it has happened in the history of science that a phenomenon predicted by theory, has not been brought within the range of actual observation until long afterwards. Leverrier predicted the existence and the place of the planet Neptune, but it was not until sometime later that Galle actually found the planet at the predicted spot. Hamilton unfolded theoretically the phenomenon of the so-called conical refraction of light, but it was reserved for Lloyd some time subsequently to observe the fact. The fortunes of Helmholtz's theory of Corti's fibres have been somewhat similar. This theory, too, received its substantial confirmation from the subsequent observations of V. Hensen. On the free surface of the bodies of Crustacea, connected with the auditory nerves, rows of little hairy filaments of varying lengths and thicknesses are found, which to some extent are the analogues of Corti's fibres. Hensen saw these hairs vibrate when sounds were excited, and when different notes were struck different hairs were set in vibration.

I have compared the work of the physical inquirer to the journey of the tourist. When the tourist ascends a new hill he obtains of the whole district a different view. When the inquirer has found the solution of one enigma, the solution of a host of others falls into his hands.

Surely you have often felt the strange impression experienced when in singing through the scale the octave is reached, and nearly the same sensation is produced as by the fundamental tone. The phenomenon finds its