Crystalline and Molecular Forces.

A LECTURE, Delivered in the Free Trade Hall, Manchester, on Wednesday, October 28th, 1874.

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A FEW years ago I paid a visit to a large school in the country, and was asked by the principal to give a lesson to one of his classes. I agreed to do so provided he would let me have the youngest boys in his school. To this he willingly assented; and, after casting about in my mind as to what could be said to the little fellows, I went to a village hard by and bought a quantity of sugar-candy. This was my only teaching apparatus. When the time for assembling the class had arrived I began by describing the way in which sugar-candy and other artificial crystals were formed, and tried to place vividly before their young minds the architecural process by which the crystals were built up. They listened to me with the most eager interest. I examined the crystal before them, and when they found that in a certain direction it could be split into thin laminæ with shining surfaces of cleavage, their joy was at its height. They had no notion that the thing they had been crunching and sucking all their lives embraced so many hidden points of beauty. At the end of the lesson I emptied my pockets among the class, and permitted them to experiment upon the sugar-candy in the usual way.

When asked to come here and lend a helping hand in what I believe to be a truly good work (though hard pressed by other duties), I could not refuse the invitation.

I know not whether this great assembly will deem it an impertinence on my part if I seek to instruct them for an hour or so on the subject chosen for my little boys. In doing so I run the imminent risk of being wearisome as well as impertinent, while labouring under the further disadvantage of not being able to make matters pleasant at the conclusion of the lecture by the process adopted at the end of my lesson to the boys.

We are to consider this evening the phenomena of crystallisation; but in order to trace back the genesis of the notions now entertained upon the subject, we have to go a long way back.

In the drawing of a bow, the darting of a javelin, the throwing of a stone, in the lifting of burdens, and in personal combats, even savage man became acquainted with the operation of *force.* His first efforts were directed towards securing food and shelter; but ages of discipline—during which his force was directed against nature, against his prey, and against his fellow-man—taught him foresight. He laid by at the proper season stores of food, and thus obtained time to look about him, and become an observer and inquirer. He discovered two things, which now more specially interest us, and sent down to us the knowledge of his discovery. He found that a certain resin dropped from the amber-tree possessed, when rubbed, the power of drawing light bodies to itself, and of causing them to cling to it; and he also found that a particular kind of stone exerted a similar power over a particular kind of metal. I allude, of course, to the loadstone, or natural magnet, and its power to attract particles of iron. Previous experience had enabled our early inquirer to distinguish between a push and a pull. In fact, muscular efforts might be divided into pushes and pulls. Augmented experience showed him that in the case of the magnet, pulls and pushes—attractions and repulsions—were also exerted; and, by a kind of poetic transfer, he applied to things external to himself the conceptions derived from the exercise of his own muscular power. The pushes and pulls of the magnet and of the rubbed amber were to him also force.

In the time of the great Lord Bacon the margin of these pushes and pulls was vastly extended by Dr. Gilbert, a man probably of firmer fibre, and of finer insight, than Bacon himself; who, moreover, was one of the earliest to enter upon that career of severe experimental research which has rendered our science almost as stable as the system of nature which it professes to explain. Gilbert proved that a multitude of other bodies, when rubbed, exerted the power which thousands of years previously had been observed in amber. In this way the notion of attraction and repulsion in external nature was rendered familiar. It was a matter of experience that bodies between which no visible link or connection existed, possessed the power of acting upon each other; and the action came to be technically called "action at a distance."

But out of experience in science there always grows something finer than mere experience. Experience, in fact, only furnishes the soil for plants of higher growth; and this observation of action at a distance furnished material for speculation upon the largest of all problems. Bodies were observed to fall to the earth. Why should they do so? The earth was proved to roll round the sun; and the moon to roll round the earth. Why should they do so? What prevents them from flying straight off into space? Supposing it to be ascertained that from a part of the earth's rocky crust a firmly-fixed and tightly-stretched chain started towards the sun, we might be inclined to conclude that the earth is held in its orbit by the chain—that the sun twirls the earth around him as a boy twirls a bullet at the end of a string round his head. But why should the chain be needed? asks the speculative mind. It is a fact of experience that bodies can attract each other at a distance, and without the intervention of any chain. Why should not the sun and earth so attract each other? and why should not the fall of bodies from a height be the result of their attraction by the earth? Here then we have one of those higher thoughts of speculation which grow out of the fruitful soil of observation. Having started with the savage and his sensations of muscular force, we pass on to the observation of force exerted between a magnet and rubbed amber, and the bodies which they attract, and rise by an unbroken growth of ideas to a conception of the force by which sun and planets are held together.

This idea of attraction between sun and planets had become a familiar one in the time of Newton. He set himself to examine the attraction, and here, as elsewhere, we find the speculative mind falling back for its materials upon experience. It had been observed, in the case of magnetic and electric bodies, that the nearer they were brought together the stronger was the force exerted between them; while, by increasing the distance, the force diminished until it became insensible. Hence the inference that the assumed pull between the earth and the sun would be influenced by their distance asunder. Guesses had been made as to the exact manner in which the force varied with the distance; but, in the case of Newton, the guess was supplemented by being brought to the severe test of experiment and calculation. Comparing the pull of the earth upon a body close to its surface, with its pull upon the moon, 240,000 miles away, Newton rigidly established the law of variation with the distance, thus placing in our hands a principle which enables us to determine the date of astronomical events in the far historic past or in the distant future.

But on his way to this great result Newton found room in his ample mind for other conceptions, some of which, indeed, constituted the necessary stepping-stones to his result. The one which here concerns us most is this: Newton proved that not only did the sun attract the earth, and the earth attract the sun, *as a whole*, but that every particle of the sun attracts every particle of the earth, and the reverse. His conclusion was, that the attraction of the masses was simply the sum of the attractions of their constituent particles.

This result seems so obvious that you will perhaps wonder at my dwelling upon it; but it really marks a turning point in our notions of force. You have probably heard of late of certain disturbers of the public peace named Democritus, Epicurus, and Lucretius. These men adopted, developed, and diffused the dangerous doctrine of atoms and molecules which found its consummation in this city of Manchester at the hands of the immortal John Dalton. Now, the grand old pagans whom I have named, and their followers up to the time of Newton, had pictured their atoms as falling and flying through space, hitting each other, and clinging together by imaginary claws and hooks. They entirely missed the central idea that the atoms and molecules could come together, not by being fortuitously knocked against each other, but by their own mutual attractions. This is one of the great steps taken by Newton. He familiarised the world with the conception of *molecular force.*

But the matter does not end here; experience had given us the key to further mysteries. In the case of electricity and magnetism a double exercise of force had been observed—repulsion had been always seen to accompany attraction. Electricity and magnetism were examples of what are called *polar forces;* and in the case of magnetism, experience itself pushed the mind irresistibly beyond the bounds of experience, compelling it to conclude that the polarity of the magnet was resident in its molecules. I hold a strip of steel by its centre, between my finger and thumb. One half of the strip attracts, and the other half repels the north end of a magnetic needle. I break the strip in the middle, and what occurs? The middle point or equator of the magnetism has shifted to the centre of the new strip. This half, which a moment ago attracted throughout its entire length the north pole of a magnetic needle, is now divided into two new halves, one of which wholly attracts, and the other of which wholly repels, the north pole of the needle. Thus the half when broken off proves to be as perfect a magnet as the whole. You may break this half, and go on breaking till further breaking becomes impossible through the very smallness of the fragments; still you find at the end that the smallest fragment is endowed with two poles, and is, therefore, a perfect magnet. But you cannot stop here: you *imagine* where you cannot *experiment*; and reach the conclusion entertained by all scientific men, that the magnet which you can see and feel is an assemblage of molecular magnets which you cannot see and feel, but which must be intellectually discerned.

I shall endeavour to show you some of the actions of this polar force, at the same time asking you to remember that my main object here to-night is to show you the growth of scientific ideas, and to illustrate the manner in which the scientific investigator uses his thoughts and his hands in the investigation of nature.

Scientific ideas, as already stated, spring out of experience, but they extend beyond the boundary of experience. And, indeed, in this power of ideal extension consists for the most part the differences between scientific men. The man who cannot break the bounds of experience, but holds on to the region of sensible facts, may be an excellent observer, but he is no philosopher, and can never reach those principles which bind the facts of science together. True, the speculative faculty may be abused like all good things, but it is not men of science that are most likely to abuse it. When he accounted for the heat of chemical combination by referring it to the clash of atoms *falling* together, a townsman of your own described an image presented to his mind but entirely beyond the reach of his senses. It was, however, an image out of which grew memorable consequences; among others this one of a personal nature. The walls of this Free Trade Hall, or rather its predecessor, have rung with the speeches of Cobden, and Bright, and Wilson. But at the time when their words rolled round the world a scientific worker was silently and studiously engaged in your city grappling with the problem, how out of heat is extracted mechanical force, and by implication with far higher problems. He grappled with it successfully, bringing it into the full light of experimental demonstration. And I venture to affirm that in the coming time, not even the great orators and politicians just named, not even the greatest of your manufacturing princes, will enjoy a purer, a more permanent or enviable fame—there is not a man amongst them of whom Manchester will be more justly proud than of her modest brewer, but renowned scientific worker, James Prescott Joule.

You will pardon this momentary deflection from my subject. We have now to track still further the growth of our notions of force. We have learned that magnetism is a polar force; and experience also hints that a force of this kind may exert a certain structural power. It is known, for example, that iron filings strewn round a magnet arrange themselves in definite lines, called, by some, "magnetic curves," and, by Faraday, "lines of magnetic force." In these observed results of magnetic polarity we find the material for speculation, in an apparently distant field. You can readily make an experiment or two for yourselves with any magnet. My excellent assistant, Mr. Cottrell, places two magnets before me, and over them a sheet of paper. Scattering iron filings over the paper and tapping it, the filings arrange themselves in a singular manner. There is a polar force here in action, and every particle of iron on the paper responds to that polar force, and the consequence is a certain structural arrangement—if I may use the term—of the iron filings. Here is a fact of experience which, as you will see immediately, furnishes further material for the mind to operate upon, rendering it possible to attain intellectual repose and satisfaction while speculating upon apparently remote phenomena.

You cannot enter a quarry and scrutinise the texture of the rocks without seeing that it is not perfectly homogeneous. If the quarry be of granite, you find the rocks to be an agglomeration of crystals, of quartz, mica, and felspar. If the rocks be sedimentary, you find them, for the most part, composed of crystalline particles derived from older rocks. If the quarry be marble, you find the fracture of the rocks to be what is called crystalline fracture. These crystals are, in fact, everywhere. If you break a sugar-loaf, you find the surface of fracture to be composed of small, shining, crystalline surfaces. In the fracture of cast iron you notice the same thing; and next to his great object of squeezing out the entangled gas from his molten metal, another object of your celebrated townsman, Sir Joseph Whitworth, when he subsequently kneads his masses of white-hot iron as if they were so much dough, is to abolish this crystalline structure. The shining surfaces observed in the case of crystalline fracture are surfaces of weak cohesion; and when you come to examine large and well-developed crystals, you soon learn why they are so. I try the crystal of sugar referred to at the beginning of this lecture in various directions with the edge of my knife and find it obdurate; but I at length come upon a direction in which it splits clearly before the knife, revealing two shining surfaces of cleavage. Such surfaces are seen when you break cast iron, and the metal is strengthened by their abolition. Other crystals split far more easily than the sugar.

In the course of scientific investigation, then, as I have tried to impress upon you, we make continual incursions from a physical world where we observe facts, into a super or sub-physical world, where the facts elude all observation, and we are thrown back upon the picturing power of the mind. By the agreement or disagreement of our picture with subsequent observation it must stand or fall. If it represent a reality, it abides with us; if not, it fades like an unfixed photograph in the presence of subsequent light. Let me illustrate this. You know how very easy it is to cleave slate rock. You know that Snowdon, Honister Crag, and other hills of Wales and Cumberland, may be thus cloven from crown to base. How was the cleavage produced? By simple bedding or stratification, you may answer. But the answer would not be correct; for, as Henslow and Sedgwick showed, the cleavage often cuts the bedding at a high angle. Well, here, as in other cases, the mind endeavouring to find a cause passed from the world of fact to the world of imagination, and it was assumed that slaty cleavage, like crystalline cleavage, was produced by polar forces. And, indeed, an interesting experiment of Mr. Justice Grove could be called upon to support this view. I have here, in a cylinder with glass ends, a fine magnetic mud, consisting of small particles of oxide of iron suspended in water. You can render those suspended particles polar by sending round the cylinder an electric current; and their subsequent action may be rendered evident. At present they are promiscuously strewn in the liquid. But the moment the current passes they all set their lengths parallel to a common direction. Before the current passes, the strongest beam of light can hardly struggle through the turbid medium. But the moment it passes, light is seen to flash out upon the screen. Now, if you imagine the mud of slate rocks to have been thus acted on, so as to place its particles with their lengths in a common direction, such elongated and flat particles would, when solidified, certainly produce a cleavage.

Plausible as this is, it is not the proper explanation, the cleavage of the slate rocks being demonstrably not crystalline, but, as shown by Sharpe, Sorby, Haughton, and myself, due to pressure.

The outward forms of these crystals are various and beautiful. A quartz-crystal, for example, is a six-sided prism, capped at each end by six-sided pyramids. Rock salt, with which your neighbours in Cheshire are so well acquainted, crystallises in cubes; and it can be cloven into cubes until you cease to be able to cleave further for the very smallness of the masses. Rock salt is thus proved to have three planes of cleavage at right angles to each other. Iceland spar has also three planes of cleavage, but they are oblique instead of rectangular, the crystal being, therefore, a rhomb instead of a cube. Various crystals, moreover, cleave with different facilities in different directions. A plane of principal cleavage exists in these crystals, and is accompanied by other planes, sometimes of equal, sometimes of unequal value as regards ease of cleavage. Heavy spar, for example, cleaves into prisms, with a rhombus or diamond-shaped figure for a base. It cleaves with greatest ease across the axis of the prism, the other two cleavages having equal values in this respect. Selenite cleaves with extreme facility in one direction, and with unequal facilities in two other directions.

Looking at these beautiful edifices and their internal structure, the pondering mind has submitted to it the question, How have these crystals been built up? What is the origin of this crystalline architecture? Without crossing the boundary of experience we can make no attempt to answer this question. We have obtained clear conceptions of polar force: we know that polar force may be resident in the molecules or smallest particles of matter—we know that by the play of this force structural arrangement is possible. What, in relation to our present question, is the natural action of a mind furnished with this knowledge? Why, it is compelled by its bias towards unity of principle to transcend experience, and endow the atoms and molecules of which these crystals are built with definite poles, whence issue attractions and repulsions for other poles. In virtue of this attraction and repulsion some poles are drawn together, some retreat from each other; atom is thus added to atom, and molecule to molecule, not boisterously or fortuitously, but silently and symmetrically, and in accordance with laws more rigid than those which guide a human builder when he places his bricks and stones together. From this play of invisible particles we see finally growing up before our eyes these exquisite structures, to which we give the name of crystals.

In the specimens hitherto placed before you the work of the atomic architect has been completed; but you shall see him at work. In the first place, however, I will take one of his most familiar edifices, and try to pull it to pieces before your eyes. For this purpose I choose ordinary ice, which is our commonest crystalline body. The agent to be employed in taking down the molecules of the ice is a beam of heat. Sent skilfully through the crystal, the beam selects certain points for attack; round about those points it works silently, taking down the crystalline edifice, and reducing to the freedom of liquidity molecules which had been previously locked in a firm, solid embrace. The liquefied spaces are rendered visible by strong illumination, and throwing their magnified images on a screen. Starting from numerous points in the ice we have expanding flowers, each with six petals, growing larger and larger, and assuming, as they do so, beautifully crimped borders; showing, if I might use such terms, the pains, and skill, and exquisite sense of the beautiful, displayed by nature in the formation of a common block of ice.

Here we have a process of demolition, which, however, clearly reveals the reverse process of erection. I wish, however, to show you the molecules in the act of following their architectural instincts, and building themselves together. You know how alum, and nitre, and sugar crystals are formed. The substance to be crystallised is dissolved in a liquid, and the liquid is permitted to evaporate. The solution soon becomes supersaturated, for none of the solid is carried away by evaporation; and then the molecules, no longer able to enjoy the freedom of liquidity, close together and form crystals. My object now is to make this process rapid enough to enable you to see it, and still not too rapid to be followed by the eye. For this purpose a powerful solar microscope and an intense source of light are needed. They are both here. Pouring over a clean plate of glass a solution of sal ammonia, and placing the glass on its edge, the excess of the liquid flows away, but a film clings to the glass. The beam employed to illuminate this film hastens its evaporation, and brings it rapidly into a state of supersaturation; and now you see the orderly progress of the crystallisation over the entire screen. You may produce something similar to this if you breathe upon the frost ferns which overspread your window-panes in the winter, and permit the liquid to recrystallise. It runs, as if alive, into the most beautiful forms.

In this case the crystallising force is hampered by the adhesion of the liquid to the glass; nevertheless the play of power is strikingly beautiful. In the next example our liquid will not be so much troubled by its adhesion, for we shall liberate our atoms at a distance from the surface of the glass. Sending an electric current through water, we decompose the liquid, and the bubbles of the constituent gases rise before your eyes. Sending the same current through a solution of acetate of lead, the lead is liberated and its free atoms build themselves together to crystals of marvellous beauty. They grow before you like sprouting ferns, exhibiting forms as wonderful as if they had been produced by the play of vitality itself. I have seen these things hundreds of times, but I never look at them without wonder. And, if you allow me a moment's diversion, I would say that I have stood in the spring-time and looked upon the sprouting foliage, the grass, and the flowers, and the general joy of opening life. And in my ignorance of it all I have asked myself whether there is no power, being, or thing, in the universe whose knowledge of that of which I am so ignorant is greater than mine. I have asked myself, Can it be possible that man's knowledge is the greatest knowledge—that man's life is the highest life? My friends, the profession of that Atheism with which I am sometimes so lightly charged would, in my case, be an impossible answer to this question: only slightly preferable to that fierce and distorted Theism which I have had lately reason to know still reigns rampant in some minds as the survival of a more ferocious age.

Everywhere throughout our planet we notice this tendency of the ultimate particles of matter to run into symmetric forms. The very molecules seem instinct with a desire for union and growth. How far does this play of molecular power depend? Does it give us the movement of the sap in trees? Assuredly it does. Does it give us in ourselves the warmth of the body and the circulation of the blood, and all that thereon depend? We are here upon the edge of a battlefield which I do not intend to enter to night; from which, indeed, I have just escaped bespattered and begrimed, but without much loss of heart or hope. It only remains for me to briefly indicate the positions of the opposing hosts. From the processes of crystallisation which you have just seen you pass by almost imperceptible gradations to the lowest vegetable organisms, and from these through higher ones up to the highest. The opposition to which I have referred is: that whereas one class of thinkers regard the observed advance from the crystalline through the vegetable and animal worlds as an unbroken process of natural growth, thus grasping the world, inorganic and organic, as one vast and indissolubly connected whole, the other class suppose that the passage from the inorganic to the organic required a distinct creative act, and that to produce the different forms, both in the world of fossils and in the world of living things, creative acts were also needed. If you look abroad you will find men of equal honesty, earnestness, and intelligence, taking opposite sides as regards this question. Which are right and which are wrong is, I submit, a problem for reasonable and grave discussion, and not for anger and hard names. The question cannot be solved—it cannot even be shelved—by angry abuse. Nor can it be solved by appeals to hopes and fears—to what we lose or gain here or hereafter by joining the one or the other side. The bribe of eternity itself, were it possible to offer it, could not prevent the human mind from closing with the truth. Scepticism is at the root of our fears. I mean that scepticism which holds that human nature, being essentially corrupt and vile, will go to ruin if the props of our conventional theology are not maintained. When I see an able, and in many respects courageous man, running to and fro upon the earth, and wringing his hands over the threatened loss of his ideals, I feel disposed to exhort him to cast out this scepticism, and to believe undoubtingly that in the mind of man we have the substratum of all ideals. We have there capacity which will as surely and infallibly respond to the utterances of a really living soul as string responds to string when the proper note is sounded. It is the function of the teacher of humanity to call forth this resonance of the human heart, and the possibility of doing so depends wholly and solely upon the fact that the conditions for its production are already there.