THREE LECTURES

ON

THE PRINCIPLE OF LEAST ACTION IN NATURE,
ILLUSTRATED BY ANIMAL MECHANICS.*Delivered at the Royal Institution of Great Britain.*

BY THE

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LECTURE III.—Tuesday, June 6th, 1871. (Concluded.)

Application of the principle of Least Action to the Heart and other involuntary Muscles.—The Mechanism of the Heart explained, and the amount of work done by it.—“Experimentum crucis” of the entire Theory, derived from the measurements of the Fibres of the Heart of Man and the Ox.—General conclusions as to the future progress of Animal Mechanics and Comparative Anatomy, when subject to the Rule of Geometry, the Queen and Mistress of all the Sciences.

WE have now discussed, and I hope satisfactorily solved, the question how much work is done by the heart; but a question remains unanswered which no intelligent mind can avoid asking: How does the heart do that work? I cannot pretend to tell you how ultimately it does that work, for that depends upon the problem of nerve-supply—a subject with which we are totally unacquainted. But I believe I have succeeded in making one step further in advance and getting at a slight knowledge of the arrangement of the fibres of the heart by which this enormous amount of work is possible, and have arrived at it by a strict and rigorous application of the principle of least action. I have applied the principle of least action to the construction of the heart, so as to ascertain, if possible, some law that must be fulfilled by the arrangement of the fibres which will allow of this principle being carried out. The law of muscular contraction which must be complied with is this: Let l represent the length of a muscular fibre; an order comes from the brain or some other part of the nervous system to this fibre to contract; it is immediately shortened to an extent that leaves it about eight-ninths of its original length. Now, when a group of fibres are so arranged, as in the example I showed you before of the triangular muscle, that each fibre in the system is not at liberty to contract to eight-ninths of its entire length, there is a necessary loss of force. Therefore, if the principle of least action applied to the heart be true, we must find such an arrangement of the fibres in the heart as will allow of every individual fibre contracting to eight-ninths of its length. The fibres of the heart have been compared by Borelli to a ball of twine; and this has been more correctly explained by subsequent writers as two balls of twine contained in a third. There are two cavities in a heart; we call them the right and left ventricles; the whole heart surrounds these. Certain groups of fibres run round one cavity, certain groups run round another, and certain other groups run round both. The fibres that run round the entire heart are called common fibres, because they are fibres which are common to both cavities, while the fibres that run round each cavity separately are called proper fibres. In these diagrams, which I have taken from Dr. Sibson's excellent work on Medical Anatomy, a general view of the arrangement of these fibres is shown. You see here represented what is called the tendinous zone or tendinous ring. The fibres start from this tendinous ring, wind round the heart in a spiral manner, and, having come to the apex of the heart, enter it and run straight back again towards the ring. In this model I endeavour to show you what I cannot show by a diagram. Supposing this to represent the heart, here is the tendinous ring which surrounds the great vessels that issue from the heart. In order to avoid confusion, I have only placed four muscular fibres on the model. Following the red one, you see it starts from this zone, twines round the heart spirally, and, as you see in the diagram, makes a complete revolution and comes back directly towards the spot from which it started. It now leaves the outside surface of the heart and enters the heart, and you may see it running almost in a straight line up the inner side of the heart. The outer fibres, therefore, wind spirally round the heart, enter it at the apex, and form, as they return to the tendinous ring or zone from which they started, the lining of the internal portion of the cavities of the heart. Imagine millions of such fibres arranged in this spiral orbicular manner, as it was called by Borelli, and you will have an idea of the complexity of the arrangements of the heart. There is a necessary space left between these outer spiral fibres and the returning fibres which you see running through the interior. This space is filled in the heart with the proper fibres. The proper

fibres wind each in a spiral manner round their respective cavities and go back again, so that we have three distinct groups of spiral fibres arranged apparently in the most hopeless intricacy, but in reality according to extremely simple and beautiful geometrical laws. The law which regulates the arrangement of these fibres, so far as I have succeeded in discovering it, is this: the spiral fibre which goes round the entire of the two cavities of the heart describes a complete circumference of 180° before its return, whereas the spiral fibres that surround the right and left ventricles of the heart respectively describe an entire circumference and one-fifth over before they come back. This extra fifth of a turn I believe is for the purpose of giving a twisting motion to the cavity, just as you would wring a cloth, so that it should be completely emptied at the close of the stroke and no blood left remaining in the cavity, or even the least loss of force occasioned.

I shall take this opportunity of publicly thanking Dr. Sibson for his kindness in having placed at my disposal his unrivalled collection of dissected hearts. He allowed me to take them with me to Dublin and retain them for twelve months for study; and he placed not only his preparations but all his stores of knowledge at my disposal. As he is not present, and therefore cannot blush at what I have to say, I will add that his great knowledge of the pathology of the heart is fully equalled by the kindness with which he places that knowledge at the disposal of the humblest searcher after truth. Jealousy is so often the characteristic of scientific men, that it is pleasant to meet a man who is entirely free from it. I suppose that this quality of jealousy which men of science possess entitles them to be considered as rising to the level of the better and the gentler sex. In the first place, each of these fibres is so arranged that it is capable of contracting to eight-ninths of its length, because I find that each of these fibres is the same length: the length of the common fibres is the same, and the length of each group of proper fibres is the same, but of course the two groups differ from each other in length. Now, since each of these fibres is so arranged spirally and is of the same length, and is capable of contracting to its full extent when ordered to do so by the brain, you will see that, as far as they are concerned, the principle of least action has been fulfilled. But there is a remarkable opportunity of applying to this case a crucial test of whether the principle of least action is or is not the great principle in muscular mechanics that I assert it to be. I have two groups of fibres, one surrounding the two cavities and another group of fibres surrounding one cavity, and by the application of a little geometrical manipulation I was able to arrive at a very remarkable result.

If I call L the length of one of these spiral fibres going round the entire heart, the volume of the whole heart will be proportional to the cube of L being a linear symmetrical dimension, the volume of the whole heart will be proportional to its cube; so that $L^3 - L'^3$ will be proportional to the difference in the volume of the heart before and after contraction. But the difference in the volume of the heart before and after contraction is the sum of the volumes of the two cavities.

I will call λ and ρ the left and right ventricles. If we take the fibres that go round a single cavity, I find that if l and l' represent their lengths before and after contraction, that in like manner $l^3 - l'^3$ will be proportional to the volume of the left ventricle.

Therefore, if the principle of least action be true, I can predict a thing that at first sight appears very strange. I can find the ratio which the volumes of the two cavities bear to each other by the measurement of the lengths of the fibres that surround them. On measuring these fibres it comes simply to this. Let L be the length of the fibres that go round the entire heart; let l be the length of the fibres that go round the left ventricle. Find those lengths and cube them. The ratio of those cubes will be proportional to the sum of the right and left ventricles divided by the left. There are theoretical grounds which I believe are almost of themselves sufficient to entitle us to believe that these two cavities are of equal volume, and therefore that this fraction will come out equal to 2. I have taken, however, a more certain mode of determining this by collecting together all the observations of direct measurement of these volumes that I can find, and I find that the mean is 2.125. From theoretical grounds I believe that more accurate experiments and observations will prove that the decimal fraction of an eighth must be struck off, and that the true proportion is represented by 2. Certainly 2 is the number given by the most accurate of the ten observers. But now to my verifications. I measured the lengths of the common fibres in the heart of a great number of oxen, and I find it to be 10.875 inches. I measured the length of the fibres that go round the left ventricles in the same hearts, and I find as the mean of many measurements 8.625. Well, I suppose there is no one present here who is a good enough arithmetician to tell me at sight what the ratio of the cubes of those numbers would be. I have cubed the numbers, and their ratio comes out 2.004. I believe that to be a remarkable result, and to entitle us to assert that the

principle of least action applied to the problem of the heart is capable of solving it a step beyond what it has been solved, and bringing us within reach of the knowledge of one more of the wonderful laws of the Creator. How it would rejoice the soul of the great Kepler if he had known that the ratio of the length of the fibres in his own heart was in the proportion of cube root of 2 to 1! Divine Geometry! Queen and mistress of philosophy, thy right to rule the sciences shall never be disputed!

This principle of least action applied to the heart consists, as you will see, simply in making every fibre and particle of the heart do the entire amount of work that it is capable of doing. In a somewhat analogous case, mechanical engineers have attempted to produce the same effect. If you take a fowling-piece, it is a matter of comparatively little consequence how the fibres are arranged if they be of ordinary strength. One fibre helps the other, and they all do their work; therefore, no one thinks of inquiring how the fibres of a fowling-piece are arranged; they are capable of resisting an explosion, because they all assist in doing it. But when you come to build up monster guns like Mr. Robert Mallet's great mortar, or Sir William Armstrong's six hundred pounder, you have to calculate with the utmost nicety what your contrivances and arrangements must be, so as to compel every fibre of steel or wrought iron in these great guns to bear its share in the work. Some few days ago, I went to the Woolwich Arsenal, to see the Armstrong six hundred pounder which exploded. It consists of eight rings; the first, sixth, and eighth rings were burst; the remaining five were not injured. Now, this gun, although a great attempt to solve the problem, was not a perfect gun, because a perfect gun would burst in such a manner that all the eight rings would give way together, each perishing in the effort to resist the explosion. That which human skill is not able to effect, is solved in the arrangement of the fibres of the heart of every person in this room.

I shall now apply the principle of least action to the case of ellipsoidal muscles. We call an ellipsoidal muscle a muscle that surrounds a cavity—a muscular bag surrounding a cavity which generally contains fluids. In attempting the solution of the problem of an ellipsoidal muscle, I found myself brought into contact with a problem in architecture which has baffled architects for many years: I mean the problem of the equilibrium of an elliptical dome. Every portion of a curved ellipsoidal muscle forms a portion of a small flat dome; and to determine the equilibrium of tensions and strains amongst the muscular fibres of such an animal structure, is the same thing as solving the problem in architecture of what are the strains in various directions in an elliptical dome. I believe I have succeeded completely in solving the problem; and I have done so by an application of pure geometry, in which I have not used a single letter of analysis. The difficulty of constructing equilibrated domes may be illustrated when I tell you that, with the exception of the Pantheon in Paris (fortunately saved from destruction), there is not a truly equilibrated dome in existence. The dome of St. Paul's, in our own city, is propped up with double chains of iron, and other chains of timber and lead put on to cover the defects in the original structure of the dome. Even Sir Christopher Wren was not able, from his want of knowledge of the solution of this problem, to apply the principles of architecture to make the dome of St. Paul's stand by its own intrinsic strength without support. In the great dome of St. Peter's, at Rome, many hoops of iron are employed which were never intended by the great mind of Michael Angelo, who conceived it. They are confessedly failures. Brunelleschi's octagonal dome at Florence is perfectly equilibrated; but then it is octagonal. No case exists, I believe, of a self-supporting perfectly equilibrated spherical dome but that of the Pantheon at Paris. An attempt has been made in the construction of the roof of the Albert Hall, to make an elliptical dome, but whether that construction has been successfully carried out on the principle of least action, I cannot say. The principle of least action applied to the building of a dome would require that not a single pound of material more than was sufficient was used in any part of it. The solution of the problem is so simple that I will venture to give you the result of it. Here is an ellipse that represents a section of the elliptical dome of the Hall of Albert the Good, the father of our future king. I draw a line in any direction from the centre, and I require a construction which shall give me the strain which the structure must be capable of bearing in that direction. The problem requires me to draw a line in every possible direction, radiating from the top of the dome, and to assign what amount of strength I must give the materials in that direction. In the required direction draw a radius, and draw a tangent where the radius meets the ellipse, and let fall a perpendicular on that tangent. The strain along this radius must be made proportional to the square of the perpendicular dropped on the corresponding tangent. That construction is so simple that a stonemason or a carpenter could apply it. For example, if he has an elliptical dome in which the major

axis is double the minor axis, the squares of the perpendiculars will give him that the strength in the direction of the long axis must be four times the strength in the lesser axis.

I applied this principle of equilibrium to the case of the muscle which is used in placental animals for causing the birth of the young. This muscle is produced by Nature for a special purpose. As soon as it has accomplished that purpose, it is carefully removed; and therefore, if we could find in any part of Nature a test for the principle of least action, we ought to find it here. If the muscle be made by Nature too strong for the purpose intended, there is a waste of material, a waste of force; if it be made too weak, the life of the animal is risked. It is not the case of a muscle which has to overcome a resistance which it tries from day to day. If I go into a gymnasium and exercise every muscle in my body, there will be growth of the muscles of my limbs, because there is a growing resistance day by day; but the muscle that causes the birth of the young animal never tries its strength against the resistance it is required to overcome until the moment of actual exercise arrives. By measuring the curvatures and thickness of the muscles, I ascertained that inside the ellipsoidal uterine muscle a hydrostatic pressure of 3.4 lbs. per square inch can be produced by its contraction. Dr. Matthews Duncan of Edinburgh, and Professor Tait of the same University, have made a number of valuable experiments on the strength of the membranes which this muscle has to rupture. They have tabled them; and in no case do they find that the resistance exceeds 3.1 lbs. per square inch. I am entitled to regard this as a remarkable example of the principle of least action in Nature. There is an adaptation of force to resistance—the force produced in order to overcome resistance for months not exercised against it, and found exactly of the right degree of strength, not too strong or too weak, when the time of trial comes. Here we see Nature attaining perfection at a single bound, by a process of foresight. There is no evidence whatever of the supposed necessity of an endless succession of previous blunders.

I have now to take my leave of you. I have to thank you, as I do sincerely, for the kindness with which you have listened to me; and I sincerely hope that you will make some allowance for the difficulties of my subject, as well as for its novelty, in the task which I have undertaken of laying it before you. I come amongst you bringing you new facts on subjects which your minds are not familiar with, and I labour under the disadvantage of having to place these facts before you in the minimum of time. In fact, I have myself solved, in these lectures, the problem of least effort. I appear as a traveller from a strange country, where I have seen strange things. The pleasantest part of my life has been spent in making these researches. The pleasure of making them—the novelty of the facts which they disclose—encouraged me to come before an audience like this, in the hope of interesting others in taking up similar pursuits. I am but an humble craftsman, collecting a few stones together for the great building of Nature; but after us there must arise some great master-builder, who will perfect the task. The science of Animal Mechanics is only commencing; a vast future is before it. It would be impossible to describe all the results that must come from the careful conscientious combination of geometry and mechanics with the science of comparative anatomy. All these results must come in time. Amongst other applications, I may mention that we are even now in a position to lend valuable aid to the science of geology. You see the fossil skeletons; you see the points or processes on their bones where certain muscles were attached. We now can calculate with precision, as, I believe, within a few ounces, what the weights, the forms and sizes, of the muscles that supplied those extinct animals, must have been: therefore, if it were worth the trouble, we could reclothe with flesh the fossil megatherium, and restore the perfect form of outline which its body would have when covered with its muscles.

In conclusion, let us suppose that this and all the other branches of science which man can study have been carried to their utmost perfection; let us suppose that man has fully explored all the secrets of Nature he is capable of obtaining, and has found a key that unlocks all her mysteries: he will still find himself only a worshipper in the temple and before the altar of an unknown God, whose true nature and moral relations to himself must be sought from other sources than those which Nature furnishes. There are truths in the system of things as real and as certain as any laws of Nature, although we cannot perceive them with our senses. My eyes cannot see them; my ears may not hear them; nor can I touch them with my hands; but they are there. I know them to be true, and that they will endure when Nature and her laws have passed away like the memory of a troubled dream. I testify what I have seen. I have many a time seen an humble earnest faith in these unseen truths cause a smile of joy to play upon the pale face distorted with pain like a sunbeam dancing

on the bosom of the troubled ocean. I have seen those truths illumine with a light from heaven the dim eyes soon to be closed for ever by the cold hand of death. These truths are more dear to me than all that Nature can teach me, because they touch my inner life and consciousness. I learned those truths as a little child upon my mother's knee; I cherish them in my heart of hearts; and in defence of them, if opportunity should offer and God should count me worthy, I would gladly lay down my life.

DUST AND DISEASE:

BEING

Part of a Lecture delivered at the Royal Institution of Great Britain.*

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AFTER some preliminary experiments and observations on the polarisation of light by fine dust, by the sky, and the coarser particles of smoke, Professor Tyndall proceeded:

In looking at this illuminated dust, we may ask ourselves what it is. How does it act, not upon a beam of light, but upon our own lungs and stomachs? The question at once assumes a practical character. We find, on examination, that this dust is of organic matter—in part living, in part dead. There are among it particles of ground straw, torn rags, smoke, the pollen of flowers, the spores of fungi, and the germs of other things. But what have they to do with the animal economy? Let me give you an illustration to which my attention has been lately drawn by Mr. George Henry Lewes, who writes to me thus.

"I wish to direct your attention to the experiments of von Recklinghausen, should you happen not to know them. They are striking confirmations of what you say of dust and disease. Last spring, when I was at his laboratory in Würzburg, I examined with him blood that had been three weeks, a month, and five weeks, out of the body, preserved in little porcelain cups under glass-shades. This blood was living and growing. Not only were the amoeba-like movements of the white corpuscles present, but there were abundant evidences of the growth and development of the corpuscles. I also saw a frog's heart still pulsating which had been removed from the body (I forget how many days, but certainly more than a week). There were other examples of the same persistent vitality or absence of putrefaction. Von Recklinghausen did not attribute this to the absence of germs—germs were not mentioned by him; but when I asked him how he represented the thing to himself, he said the whole mystery of his operation consisted in keeping the blood *free from dirt*. The instruments employed were raised to a red heat just before use, the thread was silver-thread and was similarly treated, and the porcelain cups, though not kept free from air, were kept free from currents. He said that he often had failures, and these he attributed to particles of dust having escaped his precautions."

Professor Lister, who has founded upon the removal or destruction of this "dirt" great and numerous improvements in surgery, tells us of the effect of its introduction into the blood of wounds. He informs us what would happen with the extracted blood should the dust get at it. The blood would putrefy and become foetid; and when you examine more closely what putrefaction means, you find the putrefying substance swarming with organic life, the germs of which have been derived from the air.

Another note which I received a day or two ago has a bearing particularly significant at the present time upon this question of dust and dirt, and the wisdom of avoiding them. The note is from Mr. Ellis of Sloane Street, to whom I owe a debt of gratitude for advice given to me when sorely wounded in the Alps. "I do not know", writes Mr. Ellis, "whether you happened to see the letters, of which I enclose you a reprint, when they appeared in the *Times*. But I want to tell you this in reference to my method of vaccination as here described, because it has, as I think, a relation to the subject of the intake of organic particles from without into the body. Vaccination in the common way is done by scraping off the epidermis, and thrusting into the punctures made by the lancet the vaccine virus. By the method I use (and have used for more than twenty years) the epidermis is lifted by the effusion of serum from below, a result of the irritant cantharidine applied to the skin. The little bleb thus formed is pricked, a drop of fluid let out, and then a fine vaccine point is put into this spot, and after a

minute of delay it is withdrawn. The epidermis falls back on the skin and quite excludes the air—and not the air only, but what the air contains.

"Now mark the result: out of hundreds of cases of revaccination which I have performed, I have never had a single case of blood-poisoning or of abscess. By the ordinary way the occurrence of secondary abscess is by no means uncommon, and that of pyæmia is occasionally observed. I attribute the comparative safety of my method, first, to the exclusion of the air and what it contains; and, secondly, to the greater size of the apertures for the inlet of mischief made by the lancet."

I bring these facts forward that they may be sifted and challenged if they be not correct. If they be correct, it is needless to dwell upon their importance; nor is it necessary to say that, if Mr. Ellis resigned himself wholly to the guidance of the germ-theory, he could not have acted more in accordance with the requirements of that theory than he has actually done. It is what the air contains that does the mischief in vaccination. Mr. Ellis's results fall in with the general theory of putrefaction propounded by Schwann, and developed in this country with such striking success by Professor Lister. They point, if true, to a cause distinct from bad lymph for the failures and occasional mischief incidental to vaccination; and, if followed up, they may be the means of leaving the irrational opposition to vaccination no ground to stand upon, by removing even the isolated cases of injury on which the opponents of the practice rely.

We are now assuredly in the midst of practical matters. With your permission, I will recur once more to a question which has recently occupied a good deal of public attention. You know that as regards the lowest forms of life, the world is divided, and has for a long time been divided, into two parties, the one affirming that you have only to submit absolutely dead matter to certain physical conditions to evolve from it living things; the others, without wishing to set bounds to the power of matter, affirming that in our day no life has ever been found to arise independently of pre-existing life. Many of you are aware that I belong to the party which claims life as a derivative of life. The question has two factors: the evidence, and the mind that judges of the evidence; and you will not forget that it may be purely a mental state or bias on my part that causes me throughout this discussion, from beginning to end, to see on the one side dubious facts and defective logic, and, on the other side, firm reasoning and a knowledge of what rigid experimental inquiry demands. But, judged of practically, what, again, has the question of spontaneous generation to do with us? Let us see. There are numerous diseases of men and animals that are demonstrably the products of parasitic life, and such disease may take the most terrible epidemic forms, as in the case of silkworms of France in our day. Now, it is in the highest degree important to know whether the parasites in question are spontaneously developed, or are wafted from without to those afflicted with the disease. The means of prevention, if not of cure, would be widely different in two cases.

But this is by no means all. Besides these universally admitted cases, there is the broad theory now broached and daily growing in strength and clearness—daily, indeed, gaining more and more of assent from the most successful workers and profound thinkers of the medical profession itself—the theory, namely, that contagious disease generally is of this parasitic character. If I had heard or read anything since to cause me to regret having introduced this theory to your notice more than a year ago, I should here frankly express that regret. I would renounce in your presence whatever leaning towards the germ-theory my words might then have betrayed. Let me state in two sentences the grounds on which the supporters of the theory rely. From their respective viruses you may plant typhoid fever, scarlatina, or small-pox. What is the crop that arises from this husbandry? As surely as a thistle rises from a thistle-seed, as surely as the fig comes from the fig, the grape from the grape, the thorn from the thorn, so surely does the typhoid virus increase and multiply into typhoid fever, the scarlatina virus into scarlatina, the small-pox virus into small-pox. What is the conclusion that suggests itself here? It is this:—That the thing which we vaguely call a virus is to all intents and purposes a *seed*; that in the whole range of chemical science you cannot point to an action which illustrates this perfect parallelism with the phenomena of life—this demonstrated power of self-multiplication and reproduction. There is, therefore, no hypothesis to account for the phenomena but that which refers them to parasitic life.

And here you see the bearing of the doctrine of spontaneous generation upon the question. For if the doctrine continue to be discredited as it has hitherto been, it will follow that the epidemics which spread havoc amongst us from time to time are not spontaneously generated, but that they arise from an ancestral stock whose habitat is the human body itself. It is not on bad air or foul drains that the attention of the physician will primarily be fixed, but upon disease-germs which no bad

* For this report, we are indebted to our contemporary *Nature*.