THE MECHANISM OF THE FLIGHT OF BIRDS.

THE following is a translation of an article in *La Nature* (December 3, 1887), on the mechanism of the flight of birds, by Prof. E. H. J. Marey. Through the courtesy of the editor of our French contemporary we are able to reproduce the figures illustrating M. Marey's interesting paper.

In a preceding article [see NATURE, vol. xxvi. p. 84], I showed that photography could represent the successive positions of a bird's wing, at different moments in its flight; that there might be obtained at the same time the positions of the bird in space at equal and known intervals of time; and I expressed the hope of solving by this method the obscure problem of the mechanism of flight.

FIG. 1.—Sea-gull. Transverse flight. Ten images per second.

Since that time, the photographic method has been perfected, and the number of species of birds to which my researches have extended has been multiplied.

From the comparison of the several species which I have had at my disposal, the results show that, except in certain differences in details, they all execute movements of the same nature; in all, the wings bend up at the moment of ascension, spread out quickly when at the wished for height, are then lowered, carried in front, and approached to the body; at the close of the descent, the ioints anew bend up, and the ascent recommences.

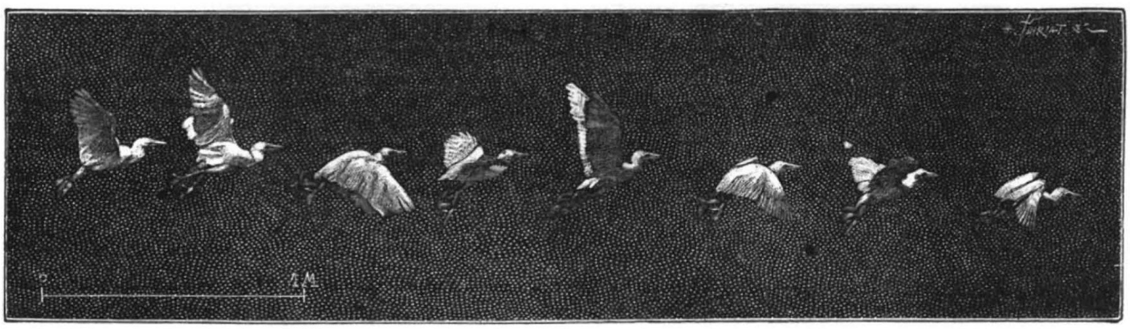

FIG. 2.—Small heron. Transverse flight. Ten images per second.

The illustrations 1, 2, 3, 4, and 5 represent the flight of the sea-gull, the heron, the pigeon, and the pelican.

These illustrations reveal curious attitudes which the eye has not time to seize, and with which we are not familiarized in the artistic interpretations of birds. According to a just remark of Mr. Muybridge, the European painters almost always represent birds flying with their wings elevated; the Chinese and Japanese, on the contrary, represent them indifferently with wings both raised and lowered. That does not, however, mean that the artists of the extreme East have faithfully reproduced the different attitudes of birds: the comparison of their representations with those of instantaneous photography shows clearly that no more in China than here does the eye perceive actions which last only for a very brief moment.

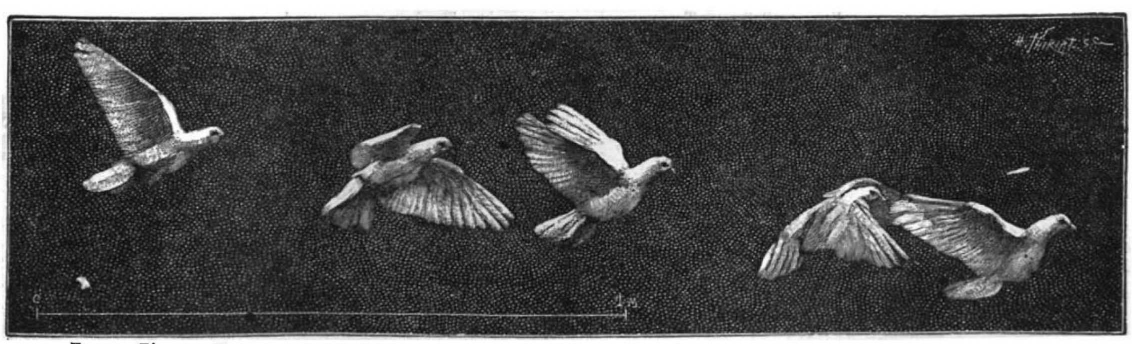

FIG. 3.—Pigeon. Transverse flight. Ten images per second. (Fac-simile of instantaneous photographs taken by the author.)

Seen only under one aspect, representations of a bird on the wing do not give us correct ideas or the movements of the wings; we must photograph the bird under several aspects in order thoroughly to comprehend this mechanism. We have made several arrangements in order to procure this effect. One of these, placed at a height of 12 metres (nearly $13\frac{1}{2}$ yards), gave representa-

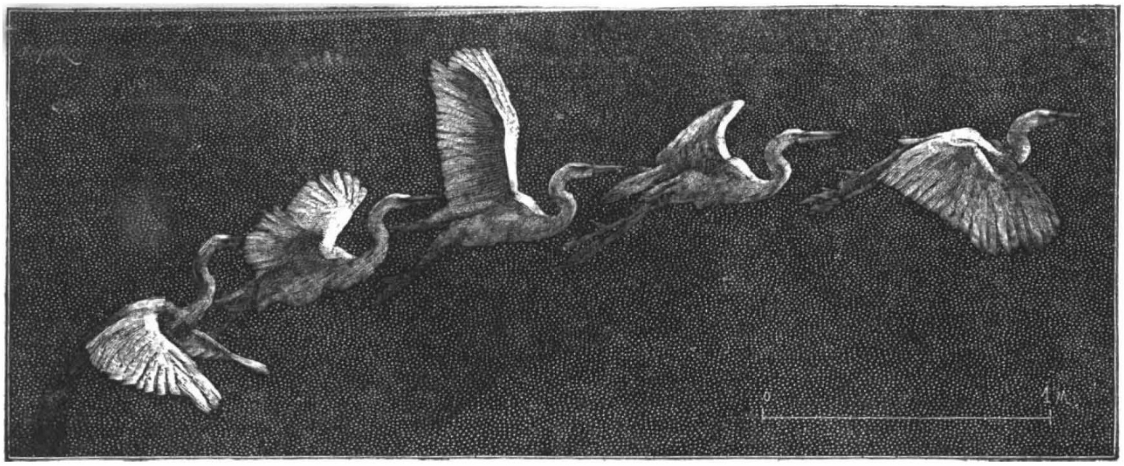

FIG. 4.—Crested heron. Transverse flight. Ten images per second.

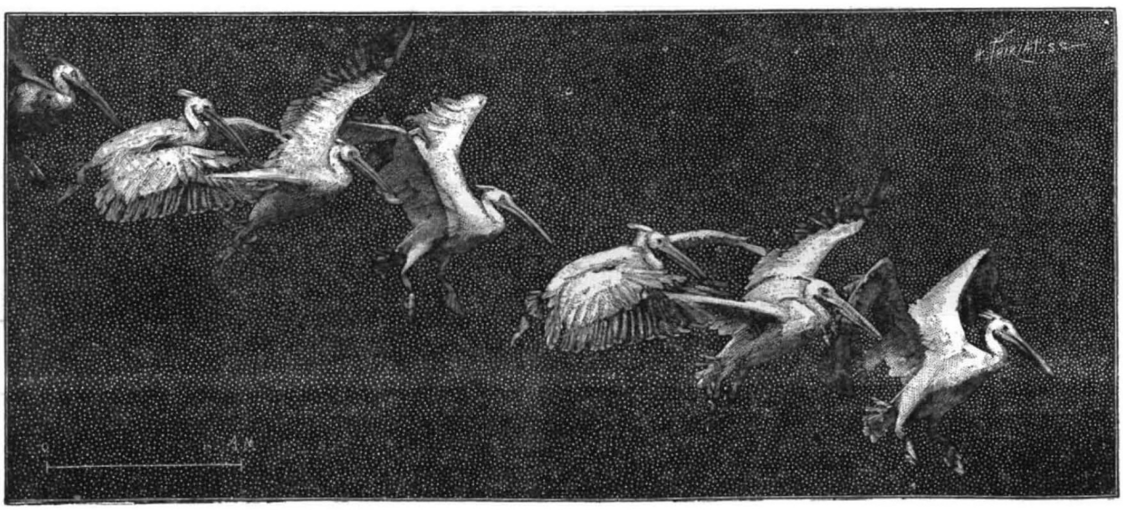

FIG. 5.—Pelican. Transverse descending flight. Ten images per second.

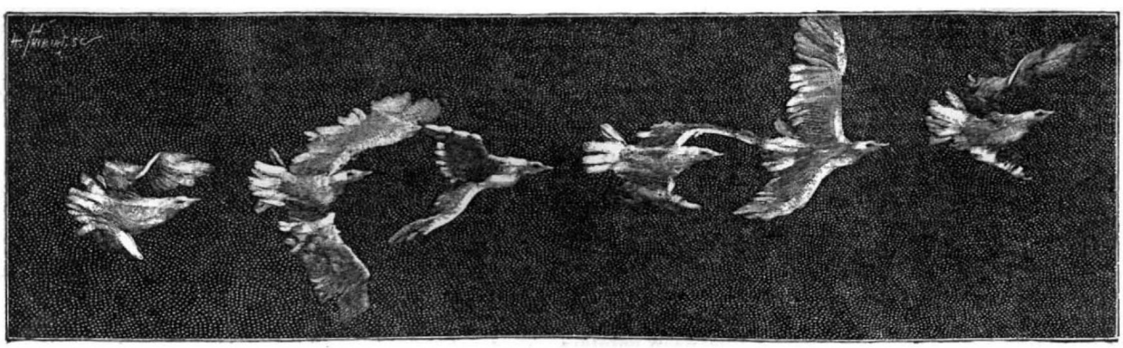

FIG. 6.—Sea-gull seen from above. Ten images per second. (Fac-simile of instantaneous photographs taken by the author.)

tions of the bird as seen from above (Fig. 6); others, variously placed, showed it from the side, or flying in the direction of the photographic apparatus (Fig. 7) These representations, taken under different conditions, complement each other. Thus, the birds seen from above show a singular curvature in the flat surface of the wing, the existence of which one would not suspect from the profile representations. This curvature appears at the end of the depression of the wing, at the moment in which the joints begin to bend upwards in order to prepare for an ascent. Hence results a spiral aspect of the wing, recalling the form which Mr. Pettigrew considers the essential element in a bird's propulsion. But we must observe that this form is only produced at the very close of the act of descent, at the "*point mort*" of the wing's action, as we say in mechanics, and at a moment in which it, having become passive, is about to remount by the resistance of the air. These figures also show a fact wholly unforeseen—namely, that the movements in flying are not symmetrical. It had been previously supposed that the bird, when desirous of turning laterally the direction of its flight, executes movements more extended from the side which is to progress most rapidly; that is to say, that it gives more amplitude to the movements of the right wing if it wishes to turn to the left, and reciprocally. It is scarcely needful to say that photochronography condemns entirely the hypothesis in which it was supposed that one of the wings of the bird could bend more frequently than the other; the movements of the two wings are perfectly synchronous, if not equal, in extent. It is seen, in short, from these representations, that the body of the bird inclines and moves in different ways, so as to carry its centre of gravity to one side or the other, according to the necessities of the equilibrium. The bird whose attitudes are portrayed in Fig. 6 seemed careful to bear the weight of its body to the left on account of the smaller surface of its right wing, from which some feathers were missing.

The representations taken in front and a little obliquely, as in Fig. 7, give also useful information. They show that the extremity of the wing—a part of the organism in full activity, since it strikes the air with greater speed—presents, at the time of lowering, changes of surface which the secondary *rémiges* extending from the carpus to the shoulder do not offer. There exists in the wing feathers of the different orders a species of separation, showing that the carpal articulations are the seat of a light twisting movement favourable to the bending of the surface of the carpal *rémiges*. In these representations may also be readily seen the bending and convergence of the wings at the close of their lowering, the depression which the anterior side of the wing presents at this moment from the effect of a flexion beginning at the elbow. In order to follow in all their details the changes of movement in the wings, it has been necessary to make many experiments, so as to obtain, during a single stroke of the wing, ten or twelve successive views of the bird seen under each of these different aspects.

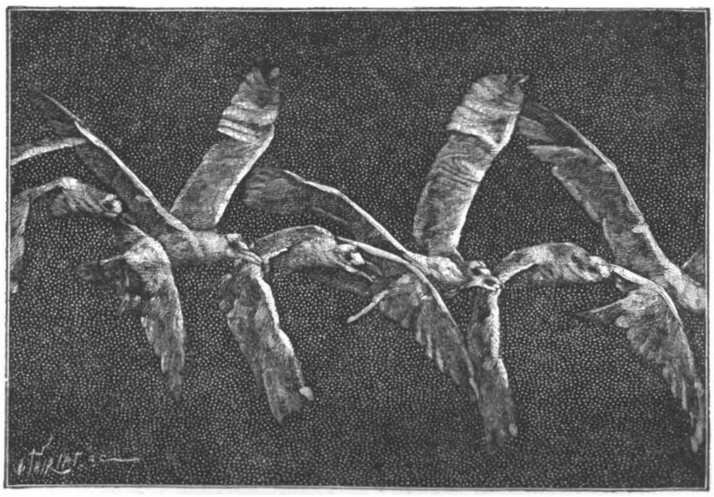

Fig. 7.—Sea-gull flying obliquely in the direction of the photochronographic apparatus. (Fac-simile of instantaneous photograph taken by the author.)

These representations having once been obtained, I was in possession of all the elements necessary to understand completely the motions of the wings according to the three dimensions of space. But in order to represent them, figures in relief were necessary; and circumstances were favourable to this. At Naples, where I then was, the almost lost industry of casting bronze in wax has been preserved from the most remote antiquity. I modelled in wax a series of figures representing the successive attitudes in a single revolution of the wing, ten for the sea-gull, eleven for the pigeon: these models, when given to a skilful moulder, were reproduced in bronze with perfect fidelity.

Fig. 8 represents, disposed in a series, and following each other in their order of succession, at intervals of 1/88 of a second, the phases of one stroke of a pigeon's wing.

These bronze figures were made white, in order to render more apparent the effects of light and shade. Thanks to the multiplicity of the attitudes represented in this series, all the phases of the motion of the wings are easily followed: it is seen how they fold, rise, expand, and sink.

In order the better to understand how the movements of the bird's wing follow each other, of which photochronography gives an analysis, I have had recourse to the use of the zootrope, which recomposes them, and gives to the sight the impression of a bird flying.

The zootrope, represented in Fig. 9, offers this speciality, that it is formed by figures in relief. This is a great advantage from the point of view of the impression which it gives; in fact, these small figures of birds, arranged in a circle in the apparatus, present themselves to the observer under various aspects.

At the beginning of the movement the bird's backs are seen; then, in their circular course, they present their sides, pass across in full view, and at last return to the observer. Besides, the movements of the wings, which in nature are extremely rapid, and consequently imperfectly seen, are here much slower, so that the phases may be easily followed, and in an instant, more may be perceived than the most attentive observer of the flight of birds could discover by the most careful observation.

Fig. 9 shows the arrangement of the zootrope; it cannot unfortunately give an idea of the effect produced by the apparatus in motion.

But it may be said that this rotatory method interprets the movements of the bird without indicating the forces which produces them. While it would be well to know that force, it is better still to measure the mechanical labour expended in order to sustain and transport itself in the air.

Let us see whether our photographic images reveal to us anything in regard to this.

When one knows the mass of a body, and the speed with which it moves, one can calculate the force

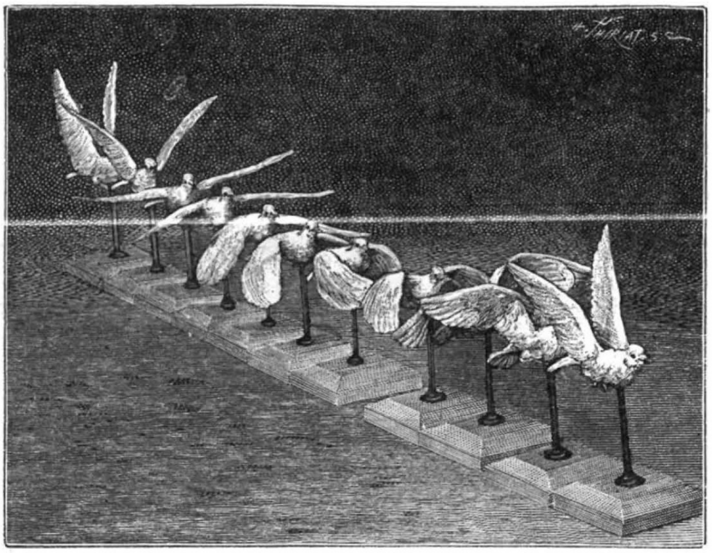

FIG. 8.—Bronze figures representing eleven successive positions at successive moments in the stroke of a pigeon's wing.

which has set this body in motion, and the labour expended by this force. If we take a projectile of a certain weight, and throw it before the photochronographic apparatus, and take a series of images of this projectile at intervals of 1/100 of a second, Fig. 10 shows the trajectory curve followed, and the space which separates the images from each other shows the space traversed by the projectile in each of the hundredth parts of a second during which its movement has lasted. From ten to ten a more brilliant image has been produced by an aperture in the diaphragm larger than the others: these marks are useful in order to facilitate the numbering of the images,

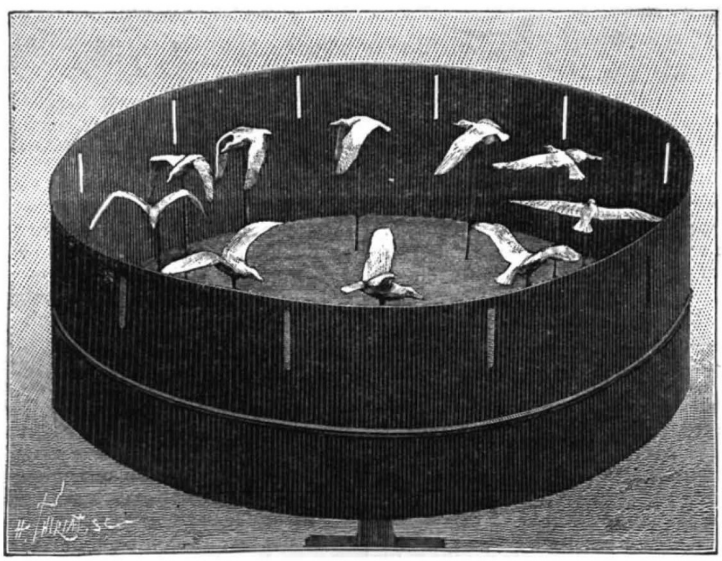

FIG. 9.—Zootrope, in which are placed ten figures, in relief, of a sea-gull in the successive positions of flight.

a fixed metrical scale, photographed at the same time as the object in motion, serves to measure the spaces traversed at each moment; then it is a problem in dynamics, whose solution may be readily obtained by the usual methods of calculation.

The successive images of the flying bird lend themselves to the same dynamical analysis. The balance indicates to us the weight of the bird; we know its size; and in order that photochronography may give us to perfection the trajectory of this mass, it only requires manifold multiplication of the images obtained (a hundred may be taken in a second if need be). But those images will be partially confused, because the bird, in the hundredth part of a second, only traverses a space equal to the length of its body: the image of the second will therefore partly cover that of the first, the third that of the second, and so on. In this confusion one can scarcely distinguish the moment in which the wing lowers itself, or that in which it is raised. But this is of no importance: we fix on the head of the bird a small but very brilliant metallic point, and the image of this point, clearly seen in the series of figures, reveals the trajectory of the bird, together with its speed, and the accelerations and slackening of speed produced by the movements of the wings. One may then face the dynamic problem of flight. It is granted first that the bird does not oscillate sensibly in the vertical sense, whence one must conclude that the resistance of the air under its wings is precisely equal to its weight. On the other hand, it is to be observed that the motion of the animal presents alternations of speed and slowness, showing that the propelling force and the resistance of the air predominate by turns. From the value of these accelerations there must be deducted the value of the horizontal component of the bird's motion, and that of the resistance of the air.

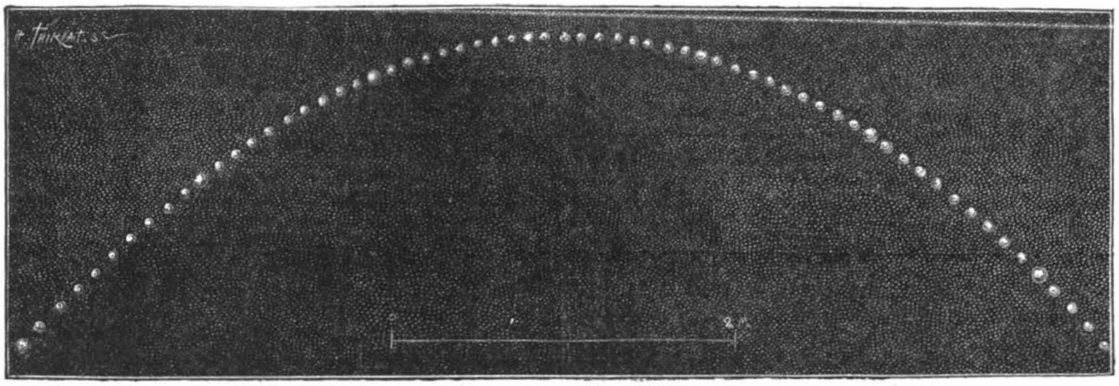

FIG. 10.—Trajectory of a white ball thrown in front of a black screen. The interval between two successive images is measured on the metrical scale. The time taken to travel over this interval is 1/100 of a second.

The calculations based on these experiments have given the following results for the forces which act during the flight of the sea-gull:—

Vertical component	0·623	kilogramme
Horizontal component	0·898	,,
Total ...	1·521	,,

These forces develop themselves during the act of lowering the wings; the ascent is passive, and is due to the pressure of the air upon the lower surface of the wings, which act then for the support of the bird, as in a paper kite.

As the resistance of the air under the wings acts at a point a considerable distance from the articulation of the shoulder, and as the pectoral muscles, by which the wings are lowered, act very near the articulation—that is to say, on the arm of a very unfavourable lever—it results that the effort of the muscles is much greater than the resistance of the air which they surmount. For the pectorals of the sea-gull, the effort developed would be 19 kilogrammes.

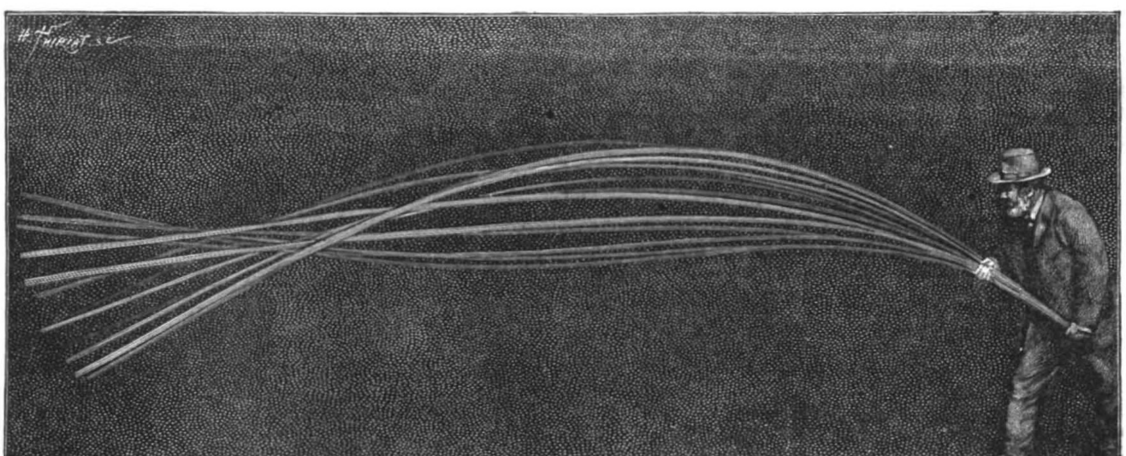

FIG. 11.—Curves and nodes produced by a vibrating stalk, one end of which is fixed. (Fac-simile of instantaneous photographs taken by the author.)

It is frequently asked whether the muscles of birds have not a specific strength greater than those of other animals—that is to say, whether two bundles of the same thickness of muscles belonging, one to a bird, the other to a mammal, would have different powers. In the sea-gull which served for my experiments, one transverse section of the pectoral muscles arranged perpendicularly to the direction of their fibres had about 11 centimetres square of surface, or about 1·600 kilogramme per square centimetre. Other birds had formerly given me nearly similar returns for their specific strength; thus, the buzzard developed 1200 grammes per square centimetre, the pigeon 1400 grammes.

Aëronauts hope that they will one day invent a machine capable of transporting man through the air, but many of them are troubled by a doubt; for they ask themselves whether the force of the bird does not exceed that of the known motors. The experiments on that subject may reassure them, for, if we compare the muscular force of the bird with that of steam, we see that one muscle would be comparable to an engine at very low pressure. In fact, the steam which would develop 1·600 kilogramme per square centimetre would scarcely have more than an atmosphere and a half of pressure. But the true comparison to establish between the animated motors and the engines consists in measuring the work which each of these motors can furnish, with equal weight, in the unity of time.

The measure of the work of a motor is obtained by multiplying the effort put forth, by the path which the point of application of that effort traverses. Photochronography expresses at each moment the spaces traversed by the mass of the bird and the displacement of the centre of pressure of its wings, giving thus the factor path in the measure of the work. In this way it is found that for the five strokes of its wing which the sea-gull gives every second, at the moment when it flies away, the labour done would be 3·668 kilogrammes. This calculation is very high; it corresponds to that which an engine would make in raising its own weight to a height of more than 5 metres in a second.

But that is only a maximum which the bird does not attain to except at the moment of flight, when it has not attained much speed. In fact, according as the passage of the bird is accelerated, the air under its wings presents a more resisting fulcrum. I have previously experimentally demonstrated this fact, announced by the brothers Planavergue, of Marseilles, and of which the following is the theory.

When the bird is not yet in motion, the air which is struck by its wings presents, in the first instance, a resistance due to its inertia, then enters into motion, and flies below the wing without furnishing to it any support. When the bird is at full speed, on the contrary, its wing is supported each moment upon new columns of air, each one of which offers to it the initial resistance due to its inertia. The sum of these resistances presents to the wing a much firmer basis. One might compare a flying bird to a pedestrian who makes great efforts to walk on shifting sand, and who, in proportion as he advances, finds a soil by degrees firmer, so that he progresses more swiftly and with less fatigue. The increase of the resistance of the air diminishes the expenditure of labour; the strokes of the bird's wing become, in fact, less frequent and less extended. In calm air, a sea-gull which has reached its swiftest, expends scarcely the fifth of the labour which it had to put forth at the beginning of its flight. The bird which flies against the wind finds itself in still more favourable conditions, since the masses of air, continually renewing themselves, bring under his wings their resistance of inertia. It is, then, the start which forms the most laborious phase of the flight. It has long been observed that birds employ all kinds of artifices in order to acquire speed prior to flapping their wings: some run on the ground before darting into the air, or dart rapidly in the direction they wish to take in flying; others let themselves fall from a height with extended wings, and glide in the air with accelerated speed before flapping their wings; all turn their bill to the wind at the moment of starting.

My experiments have, up to the present, only been able to apply to the flight of departure. In order to study the full flight there are conditions difficult to realize. With a courtesy for which I thank him, M. Eiffel has offered to me on the gigantic tower which he is erecting (at Paris) a post of observation which will leave nothing to be desired. From that enormous height, birds photographed during a long flight will give photochronographic images much more instructive than those which I have hitherto been able to obtain.

Without entering into the dry details of experiments and calculations made,[1] I have aimed at showing that the movements of birds, if they escape the sight, may be faithfully recorded by a new method which is applicable to the most varied problems of rotation and of mechanics.

Photochronography, in fact, gives experimentally the solution of problems often very difficult to solve by calculation.

Imagine a certain number of forces acting in different ways upon a known mass; the complicated way in which those forces are arranged sometimes renders long calculations needful in order to determine the positions which the moving object will occupy at successive moments; whilst if the body itself, submitted to those different forces, can be placed before the photochronographic apparatus, the path which it will follow expresses itself upon the sensitive plate.

Distinguished physicists disputed lately as to the form the free extremity of a vibrating stalk ought to present in which are produced curves and nodes: the greater number of them supposed that between the last node and its free extremity the stalk would present a bent form. Experiment has shown that it is not so, and that the last elements of the vibrating stalk are perfectly rectilinear (Fig. 11).

How many problems whose solution has formerly cost efforts of genius might be solved by a very simple experiment! Galileo in our day would not have needed to lessen the speed of the falling body in order to observe its motion. He would let fall a brilliant ball before a dark field, and would receive from it photographically successive images. Upon the sensitive plate he would have read, in the simplest way possible, the laws of space, of the speed and the accelerations which he has had the glory to discover.

To return to our subject, the laws of the resistance of the air to the living creatures of different forms which move in it ought to be searched into by photochronography. Already interesting results have been acquired: we have been able to determine the path of motion and the speed of small polished bodies (*petits appareils planeurs*) which move freely in the air, and which the eye has not time to follow in their rapid motions. Studies like these, undertaken and methodically carried out, will certainly lead to a comprehension of the still obscure mechanism of the hovering of birds.

TECHNICAL EDUCATION.

WHEN the time comes for the discussion of the new Technical Instruction Bill, attention will no doubt be given to an important series of resolutions (printed on the next page) which have just been passed by the Executive Committee of the North of England Branch of the National Association for the Promotion of Technical Education. The first six of these resolutions were unanimously adopted by the Committee, and the seventh was, on the motion of Mr. T. Burt, M.P., seconded by Mr. J. H. Girling (President of the Trades Council), adopted with one dissentient. The following are the advantages which the Committee desire to secure:—(1) For primary and secondary education a greater freedom of instruction under the existing code preparatory to technical education in the higher schools. (2) A direct or indirect pecuniary aid for superior education in science and art schools and in Colleges which afford technical education. (3) For all apprenticeship schools or trade classes a supervision by members of the trade, but no Government grant, thus to avoid any objections which might be raised by Trades Unions, or any jealousy arising from an apparent protection of one

[1] See the *Comptes rendus* of the Académie des Sciences 1886–37.