ON THE

PHYSIOLOGY OF WINGS.

BY

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"On the Arrangement of the Muscular Fibres in the Ventricles of the Vertebrate Heart, with Physiological Remarks," Phil. Trans. 1864. "On the Relations, Structure, and Function of the Valves of the Vascular System in Vertebrata," Trans. Roy. Soc. Edin. 1864. "On the Ganglia and Nerves of the Heart and their connection with the Cerebro-spinal and Sympathetic Systems in Mammalia," Proc. Roy. Soc. Edin. 1865. "On the Presumption of Survivorship," Med.-Chir. Trans. 1865. "On the Muscular Arrangements of the Bladder and Prostate, and the manner in which the Ureters and Urethra are closed," Phil. Trans. 1867. "On the various Modes of Flight in relation to Aëronautics," Proc. Roy. Inst. Great Britain, 1867. "On the Muscular Tunics of the Stomach in Man and other Mammalia," Proc. Roy. Soc. Lond. 1867. "On the Mechanical Appliances by which Flight is attained in the Animal Kingdom," Trans. Linn. Soc. 1868. &c. &c. &c.

FROM THE
TRANSACTIONS OF THE ROYAL SOCIETY OF EDINBURGH, VOL. XXVI.

EDINBURGH:
PRINTED FOR THE SOCIETY BY NEILL AND COMPANY.
MDCCCLXXI.

Herrn Professor W. Preyer
with the Authors Complts.

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(Received 2d August 1870. Read 16th January 1871.)

INTRODUCTORY REMARKS.

In order to determine with exactitude the movements made by the wings in flight, and the part which the air plays in modifying them, I was induced several years ago to collect a large number of facts, and to undertake an extensive series of experiments with natural and artificial wings. My observations and experiments, I may remark, were not wholly confined to flight. On the contrary, I traced the analogy between flying, swimming, and walking; a circumstance which compelled me to pay particular attention to the size, shape, and movements, not only of wings, but also of the travelling surfaces of quadrupeds, amphibia, and fishes. By adopting this method, I obtained suggestions which have proved of the utmost importance to me in my attempts at elucidating the very intricate problem of flight.

As there are, strictly speaking, only three highways in nature (the land, the water, and the air), so there are three principal varieties of locomotion. There are, however, a limited number of mixed forms, the animal in such cases being furnished with travelling surfaces, modified in such a manner as to enable it to progress upon, or in, two essentially different media. The mixed movements are alike interesting and instructive, as they prove that movements apparently very dissimilar are in reality only links of a great chain of motion, which drags its weary length over the land, through the water, and extends skyward. That, therefore, is not wanting which connects the motions peculiar to walking animals with those peculiar to swimming and flying animals. Thus the seal furnishes the link between the land and water, and the galeopithecus between the land and air; while the flying fish supplies the link between the water and the air.

On making a careful examination of the structure and movements of the great pectoral fins or pseudo-wings of the flying fish, I felt persuaded that a close analogy existed between the flippers, fins, and tails of sea mammals and fishes on the one hand, and the wings of insects, bats, and birds on the other; in fact, that theoretically and practically these organs one and all formed flexible helices or screws, which, in virtue of their rapid reciprocating action, operated upon the water and air after the manner of double inclined planes.

Guided by these indications, I especially directed my attention to the twisting flail-like movements of the wings of insects; of the flippers and tails of sea mammals, and of the fins and tails of fishes. These I found all acted upon the air and water by curved surfaces, the curved surfaces reversing, reciprocating, and engendering a wave pressure, which could be continued indefinitely at the will of the animal.

In order to prove that sea-mammals and fishes swim, and insects, bats, and birds fly, by the aid of curved figure of 8 surfaces, which exert an intermittent wave pressure, I constructed artificial fins, flippers, and wings, which curved and tapered in every direction, and which were flexible and elastic, particularly towards the tips and posterior margins. These fins, flippers, and wings were slightly twisted upon themselves, and when applied to the water and air by a sculling or figure of 8 motion, curiously enough not only reproduced the curved surfaces referred to, but all the other movements peculiar to the fins and tail of the fish when swimming, and to the wings of the insect, bat, and bird when flying.

HISTORY OF THE FIGURE OF 8 OR WAVE THEORY OF FLYING.

The Wing a Twisted Lever or Helix.—I announced this view in a lecture delivered at the Royal Institution of Great Britain in the early part of 1867. An abstract of the lecture appeared in the Proceedings of the Institution under date the 22d of March 1867.* At pages 99, 100, and 101 of the abstract in question, the spiral conformation of the wing in the insect and bird is adverted to at length, and there described as a twisted lever or helix, which owes its peculiar elevating and propelling power in a great measure to its shape. Particular emphasis is also placed upon the partial rotation of the wing on its long axis during extension and flexion, and to its screwing and unscrewing action during the down and up strokes, this being a "*sine qua non*" in flight. In the pages alluded to, the subjoined passages occur:—"The wings of insects and birds are, as a rule, more or less triangular in shape, the base of the triangle being directed towards the body, the sides anteriorly and posteriorly. They are also conical on section from within outwards and from before backwards; this shape converting the pinion into a delicately graduated instrument, balanced with the utmost nicety to satisfy the requirements of the muscular system on

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* On the Various Modes of Flight in relation to Aëronautics.

the one hand, and the resistance and resiliency of the air on the other. . . . . The neuræ or nervures in the insect's wing are arranged at the axis or root of the pinion, after the manner of a fan or spiral stair; the anterior one occupying a higher position than that farther back, and so of the others. As this arrangement extends also to the margins, the wings are more or less twisted upon themselves, and present a certain degree of convexity on their superior or upper surface, and a corresponding concavity on their inferior or under surface; their free edges supplying those fine curves which act with such efficacy upon the air, in obtaining the maximum of resistance and the minimum of displacement; or what is the same thing, the maximum of support with the minimum of slip. . . . . All wings obtain their leverage by presenting oblique surfaces to the air, the degree of obliquity gradually increasing in a direction from behind forwards and downwards during extension, when the sudden or effective stroke is being given, and gradually decreasing in an opposite direction during flexion, or when the wing is being more slowly recovered preparatory to making a second stroke. The effective stroke in insects, and this holds true also of birds, is therefore delivered downwards and forwards, and not as the majority of writers believe, vertically, or even slightly backwards. . . . . To confer on the wing the multiplicity of movement which it requires, it is supplied at its root with a double hinge or compound joint, which enables it to move not only in an upward, downward, forward, and backward direction, but also at various intermediate degrees of obliquity. . . . The wing of the bird, like that of the insect, is concavo-convex, and more or less twisted upon itself. The twisting is in a great measure owing to the manner in which the bones of the wing are twisted upon themselves, and the spiral nature of their articular surfaces, the long axes of the joints always intersecting each other at nearly right angles. As a result of this disposition of the articular surfaces, the wing may be shot out or extended, and retracted or flexed in nearly the same plane, the bones of the wing rotating in the direction of their length during either movement. This secondary action, or the revolving of the component bones upon their own axes, is of the greatest importance in the movements of the wing, as it communicates to the hand and forearm, and consequently to the primary and secondary feathers which they bear, the precise angles necessary for flight. It, in fact, insures that the wing, and the curtain or fringe of the wing, which the primary and secondary feathers form, shall be screwed into and down upon the wind in extension, and unscrewed or withdrawn from the wind during flexion. The wing of the bird may therefore be compared to a huge gimlet or auger, the axis of the gimlet representing the bones of the wing; the flanges or spiral thread of the gimlet the primary and secondary feathers."

The lecture referred to formed part of a memoir which was communicated by Professor HUXLEY to the Linnean Society, and read before that body on the 6th and 20th of June 1867. It is published *in extenso* in the 26th volume of the Transactions of the Society, with upwards of eighty illustrations.*

The principal object of the memoir is to establish an analogy between the walking surfaces of quadrupeds, the swimming surfaces of fishes, and the flying surfaces of insects, bats, and birds. These are all described† and figured‡ as twisted levers or screws in an anatomical sense (pages 361 and 362, figures 37, 38, 39, and 40), and as flexible reversing screws in a functional or physiological sense (pages 336 and 362, figures 2, 41, 42, and 43).§ As a consequence, the quadruped and biped|| are represented as walking,¶ and the seal and

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* On the Mechanical Appliances by which Flight is attained in the Animal Kingdom, &c.

† *Op. cit.*, from page 199 to page 267 inclusive.

‡ *Op. cit.*, Plate XV. figs. 49, 51, 57, 68, 69, 70. Likewise Diagram 18 A $d'e'f'$, $a'b'$, page 253.

§ *Op. cit.*, Plate XV. figs. 58, 59, 61, 73, 74, and 75.

|| *Op. cit.*, Plate XV. fig. 78.

¶ I think it proper to state that various anatomists have carefully examined the form of the articular surfaces of the joints in the limbs, more especially in man. The researches of the brothers WEBER and Professor MEYER of Zurich are so well known, that it may suffice simply to refer to them. I would also direct attention to the writings of LANGER, HENKE, MEISSNER, and the late Professor GOODSIR. LANGER, HENKE, and MEISSNER succeeded in demonstrating the "screw configuration" of the articular surfaces of the elbow, ankle, and calcaneo-astragaloid joints, and GOODSIR showed that the articular surfaces of the knee-joint consist of "a double conical screw combination." The last-named observer also expressed his belief, "that articular combinations, with opposite windings on opposite sides of the body, similar to those in the knee-joint, exist in the ankle and tarsal, and in the elbow and carpal joints; and that the hip and shoulder joints consist of single-threaded couples, but also with opposite windings on opposite sides of the body." The following are the views of LANGER as interpreted by GOODSIR:—(Proc. Roy. Soc. Edin., Jan. 18, 1858, and Anatomical Memoirs, vol. ii. p. 231.) "LANGER, acting on the happy idea of prolonging the screw by uniting, in one direction, a number of plaster casts of the same articular surface, succeeded in forming continued screws from the upper articular surface of the astragalus in the horse, panther, and human subject. LANGER concludes that the 'go line' (a line obtained from the scratch of a steel point fixed on one of the articular surfaces, and which marks the opposite surface when the joint is moved) of the ankle-joint in all the mammalia is a portion of a helix, and that therefore the astragaloid surface is a segment of a cylindrical or conical male screw, while the tibio-fibular surface is a segment of the corresponding female screw. The right ankle-joint is a left-handed screw combination; the left ankle-joint a right-handed. When therefore the foot is conceived to be fixed, the leg, in passing from a position of extension to flexion, moves laterally outwards along the axis of rotation, and the sine of the angle of inclination of the thread—that is, in proportion to the extent of flexion and the rapidity of the screw." GOODSIR, in attempting by LANGER's method to develop those articular screw-models, found that when two casts were united, an apparently satisfactory helix was produced; but in adding to the series, the spire diminished, and the helix closed upon itself; so that it appeared that not only the angle of inclination of the thread, but also the radius of rotation, diminished. He was, therefore, of opinion, that the tibio-astragaloid articular surfaces could not be regarded as segments of a cylindrical series, and thought it extremely probable that, abstracting the terminal facets, the acting areas on each surface consist each of a segment of a conical screw—the convex portions of these two screws being on the astragaloid; the concave on the tibial articular surface; the one screw coming into action in flexion, the other in extension. GOODSIR's experiments on the knee and ankle-joints, conducted with extreme care, by the aid of fresh specimens, casts, and models, led him to conclude that both joints were 'spiral in their nature'—that in fact they were 'screwed structures,' and that the movements of the knee-joint are combined gliding and rolling movements of conical screwed surfaces upon one another. The following are his own words:—"The general character of the curves observed, and the corresponding movements and structure of the joint (knee-joint) leave little doubt in my mind that the flexion and extension, combined gliding and rolling movements of the knee, are performed between two conical double-threaded screw-combinations, an anterior and a posterior—the anterior being a left-handed screw, and the posterior fish* as swimming in figure of 8, or looped curves. The wings of the insect, bat, and bird, are also described and figured as executing figure of 8 movements when the animals are hovering before an object, or when their bodies are artificially fixed (page 336, figure 2);† the figure of 8, as I explained, being opened out or unravelled when the animals are flying at a high horizontal speed to form a looped and then a waved track (pages 341, 342, 344, and 345, figures 10, 13, 14, and 15).‡

The following brief passages from my memoir in the Transactions of the Linnean Society§ will, I hope, serve to elucidate the peculiar figure of 8 movements made by the wings in flight :—

The Wing Twists and Untwists during its action.—"That the wing twists upon itself structurally, not only in the insect, but also in the bat and bird, any one may readily satisfy himself by a careful examination,|| and that it twists upon itself during its action I have had the most convincing and repeated proofs.¶ The twisting in question is most marked in the posterior or thin margin of the wing, the anterior and thicker margin performing more the part of an axis. As a result of this arrangement, the anterior or thick margin cuts into the air quietly, and as it were by stealth, the posterior one producing on all occasions a violent commotion, especially perceptible if a flame be exposed behind the insect. Indeed, it is matter for surprise that the spiral conformation of the pinion, and its spiral mode of action, should have eluded observation so long; and I shall be pardoned for dilating upon the subject when I state my conviction that it forms the fundamental and distinguishing feature in flight, and must be taken into account by all those who seek to solve this most involved and interesting problem by artificial means." The importance of the twisted configuration or screw-like form of the wing cannot be over-estimated. That this shape is intimately associated with flight is apparent from the fact that the rowing feathers of the wing of the bird are every one of them distinctly spiral in their nature; in fact, one entire rowing feather is equivalent—morphologically and physiologically—to one entire insect wing. In the wing of the martin, where the bones of the pinion are short and in some respects rudimentary, the primary and secondary feathers are greatly developed, and banked up in such a

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a right-handed screw in the right knee-joint; the anterior a right-handed, and the posterior a left-handed screw in the left knee-joint. The movements which take place round these two combinations are alternate, those round the anterior completing extension and commencing flexion, those round the posterior completing flexion and commencing extension of the joint."

[*] *Op. cit.*, Diag. 2, page 204; Plate XV. fig. 76.

[†] *Op. cit.*, page 233, Diag. 5; Plate XV. fig. 61.

[‡] *Op. cit.*, page 233, Diag. 6; Plate XV. fig. 59.

[§] *Op. cit.*, pages 231, 232, 233, and 234.

[||] *Op. cit.*, Plate XV. figs. 68, 69, and 70.

[¶] *Op. cit.*, Plate XV. figs. 58, 61, 73, and 74.

manner that the wing as a whole presents the same curves as those displayed by the insect's wing, or by the wing of the eagle where the bones, muscles, and feathers have attained a maximum development. The conformation of the wing is such that it presents a waved appearance in every direction—the waves running longitudinally, transversely, and obliquely. The greater portion of the pinion may consequently be removed without essentially altering either its form or its functions. This is proved by making sections in various directions, and by finding that in some instances as much as two-thirds of the wing may be lopped off without materially impairing the power of flight. Thus, in the summer of 1866,[*] I removed the posterior two-thirds from either wing of a blow-fly, and still the insect flew, and flew well. The only difference I could perceive amounted to this, that the fly, while it could elevate itself perfectly, flew in circles, and had less of a forward motion than before the mutilation. It had in fact lost propelling or driving power, the elevating or buoying power remaining the same. I took another blow-fly and removed the tip or outer-third of either wing, and found that the driving-power was the same as before the mutilation, while the elevating or buoying power was slightly diminished. These experiments prove that the posterior or thin elastic margin of the wing is more especially engaged in propelling, the tip in elevating.[†] "The spiral nature of the pinion is most readily recognised when the wing is seen from behind and from beneath,[‡] and when it is foreshortened.[§] It is also well marked in some of the long winged oceanic birds when viewed from before,[||] and cannot escape detection under any circumstances, if sought for,—the wing being essentially composed of a congeries of curves, remarkable alike for their apparent simplicity and the subtlety of their detail."

The Wing during its action Reverses its Planes, and describes a Figure of 8 *track in space.*—"The twisting or rotating of the wing on its long axis is particularly observable during extension and flexion in the bat and bird, and likewise in the insect, especially the beetles, cockroaches, and others which fold their wings during repose. In these in extreme flexion the anterior or thick margin of the wing is directed downwards, and the posterior or thin one upwards. In the act of extension, however, the margins, in virtue of the wing rotating upon its long axis, reverse their positions, the anterior or thick margins describing a spiral course from below upwards, the posterior or thin margin describing a similar but opposite course from above downwards. These conditions, I need scarcely observe, are reversed during flexion. The movements of the margins during flexion and extension may be represented

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[*] *Op. cit.*, pages 219, 220, 221, 222.

[†] For further experiments in this direction, see footnote to pages 361 and 362.

[‡] *Op. cit.*, Plate XV. figs. 68, 69, 70, 73, and 74.

[§] *Op. cit.*, Plate XV. figs 61 and 62.

[||] *Op. cit.*, page 253; Diagram 18 A, *a'b'*, *d'e'f.'*

with a considerable degree of accuracy by a figure of 8 laid horizontally.[*] . . . . It may likewise happen, though more rarely, that the anterior or thick margin of the pinion may be directed upwards and backwards during the return or up stroke. I infer this from having observed that the anterior margin of the wing of the wasp (when the insect is fixed and the wings are being driven briskly) is not unfrequently directed upwards and forwards at the beginning of the down stroke, and upwards and backwards at the commencement of the up or return stroke. A figure of 8, compressed laterally and placed obliquely with its long axis running from left to right of the spectator, represents the movement in question. The down and up strokes, as will be seen from this account, cross each other, the wing smiting the air during its descent from above, as in the bird and bat, and during its ascent from below, as in the flying fish and boys' kite. The pinion thus acts as a helix or screw in a more or less horizontal direction from behind forwards, and from before backwards ; but it has a third function—it likewise acts as a screw in a nearly vertical direction from below upwards. . . . . If the wing (of the larger domestic fly) be viewed during its vibrations from above, it will be found that the blur or impression produced on the eye by its action is more or less concave. This is due to the fact that the wing is spiral in its nature,[†] and because during its action it twists upon itself in such a manner as to describe a double curve,[‡]—the one curve being directed upwards, the other downwards. The double curve referred to is particularly evident in the flight of birds from the greater size of their wings.[§] The wing, both when at rest and in motion, may not inaptly be compared to the blade of an ordinary screw propellor as employed in navigation.[||] Thus the general outline of the wing corresponds closely with the outline of the propellor, and the track described by the wing in space is twisted upon itself propellor fashion. The great velocity with which the wing is driven converts the impression or blur[¶] into what is equivalent to a solid for the time being, in the same way that the spokes of a wheel in violent motion, as is well understood, completely occupy the space contained within the rim or circumference of the wheel. . . . . From these remarks it will appear that not only the margins, but also the direction of the planes of the wing, are more or less completely reversed at each complete flexion and extension ; and it is this reversing, or screwing and unscrewing, which enables the wing to lay hold of the air with such avidity during extension, and to disentangle itself with such facility during flexion,—to present, in fact, a more or less concave, oblique, and

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[*] *Op. cit.*, page 233, Diagram 5. Compare this diagram with figs. 59 and 61 of Plate XV.

[†] *Op. cit.*, Plate XV. fig. 68.

[‡] *Op. cit.*, Plate XV. figs. 58 and 59 *a a'*. Compare with *a a'* of fig. 52.

[§] *Op. cit.*, Plate XV. figs. 73 and 75 *b a c*.

[||] *Op. cit.*, Plate XV. fig. 52 *a a'*.

[¶] *Op. cit.*, Plate XV. figs. 58 and 59.

strongly resisting surface the one instant, and a comparatively narrow, non-resisting cutting edge the next. The figure of 8 action of the wing explains how an insect or bird may fix itself in the air, the backward and forward reciprocating action of the pinion affording support, but no propulsion. In these instances, the backward and forward strokes are made to counterbalance each other."

The Wing, when advancing with the body, Describes a Waved Track.—"Although the figure of 8 represents with considerable fidelity the twisting of the wing upon its axis during extension and flexion, when the insect is playing its wings before an object, or still better, when it is artificially fixed, it is otherwise when the down-stroke is added, and the insect is fairly on the wing, and progressing rapidly. In this case the wing, in virtue of its being carried forwards by the body in motion, describes an undulating or spiral course.[*] . . . . The down and up strokes are compound movements,—the termination of the down-stroke embracing the beginning of the up-stroke, the termination of the up-stroke, on the other hand, including the beginning of the down-stroke. This is necessary in order that the down and up strokes may glide into each other in such a manner as to prevent jerking and unnecessary retardation,—the angle made by the under surface of the wing with the horizon during the first part of the down-stroke being increased to support and propel the insect, and decreased during the second part to prepare it for making the up-stroke, and to diminish the friction caused by the wing itself, while it does not interfere with its sustaining power." . . . .

The Margins of the Wings thrown into Opposite Curves during Extension and Flexion.—"The anterior or thick margin of the wing and the posterior or thin margin present different degrees of curvature, so that under certain conditions the two margins cross each other, and form a true helix (page 361, fig. 37).[†] The anterior margin (*r*, *s*) presents two well-marked curves, a corresponding number being found on the posterior margin (*t*, *u*). These curves may, for the sake of clearness, be divided into axillary curves and distal curves, the former occurring towards the root of the wing, the latter towards its extremity. The curves (axillary and distal) found on the anterior margin of the wing are always the reverse of those met with on the posterior margin, *i.e.*, if the convexity of the anterior axillary curve be directed downwards (*r*),[‡] that of the posterior axillary curve (*t*) is directed upwards,[§] and so of the anterior and posterior distal curves (*s*, *u*). The two curves, axillary and distal, occurring on the anterior margin of the wing, are likewise antagonistic, the convexity of the axillary curve (*r*) being always directed downwards,[||] when the convexity of the

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[*] *Op. cit.*, page 233, Diagram. 6.

[†] *Op. cit.*. Plate XV. figs. 70, 73, and 74.

[‡] *Op. cit.*, Plate XV. fig. 73, *e*.

[§] *Op. cit.*, Plate XV. fig. 73, *a*, *c*.

[||] *Op. cit.*, Plate XV. fig. 73, *c*.

distal one (*s*) is directed upwards,[*] and *vice versa*. The same holds true of the axillary and distal curves occurring on the posterior margin of the wing (*t. u*).[†] . . . . The anterior axillary and distal curves completely reverse themselves during the acts of extension and flexion, and so of the posterior axillary and distal curves. This reversal of the curves is seen to most advantage in the posterior margin of the wing, formed in the bird, by the primary, secondary, and tertiary feathers.[‡] When the wing is partially flexed the convexity of the distal curve (occurring on the posterior margin of the wing) is directed downwards (page 362, figure 41 *a, b*),[§] that of the axillary curve upwards (*a, c*).[||] When the wing is rather more than half extended the curves are obliterated, the posterior margin of the wing becoming straight (page 362, figure 42 *b, c*).[¶] It is at this stage of extension that the axillary and distal curves reverse. When the wing is fully extended the convexity of the axillary curve is directed downwards (page 362, figure 43 *a, c*),[**] that of the distal one upwards (*a, b*),[††] which is just the opposite of what happens in flexion. This antagonism in the axillary and distal curves observed in the posterior margin of the wing of the bird is referrible to changes induced in the anterior margin of the pinion, as the subjoined paragraph will show." . . . .

The Tip of the Bird's Wing describes an Ellipse.—"The movements of the wrist are always the reverse of those occurring at the elbow joint. Thus, during extension, the elbow and bones of the forearm are elevated, and describe one side of an ellipse; while the wrist and bones of the hand are depressed, and describe the side of another and opposite ellipse.[‡‡] These movements are reversed during flexion,[§§] so that when the elbow is raised and carried backwards, the wrist is lowered and carried forwards, and *vice versa*."[||||] . . . .

The Wing capable of Change of Form in all its Parts.—"From this description it follows that when the different portions of the anterior margin are ele-

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[*] *Op. cit.*, Plate XV. fig. 73, *f*.

[†] *Op. cit.*, Plate XV. fig. 73, *a, b, c*.

[‡] *Op. cit.*, Plate XV. figs. 73, 74, 75.

[§] *Op. cit.*, Plate XV. fig. 73, *b*.

[||] *Op. cit.*, Plate XV. fig. 73, *a, c*.

[¶] *Op. cit.*, Plate XV. fig. 74, *b, c*.

[**] *Op. cit.*, Plate XV. fig. 75, *c*.

[††] *Op. cit.*, Plate XV. fig. 75, *a, b*.

[‡‡] *Op. cit.*, p. 249, Diagram 14.

[§§] *Op. cit.*, p. 249, Diagram 15.

[||||] Similar movements occur in the body and tail of the fish in the act of swimming. "The double curve or spiral into which the fish throws itself when swimming may be conveniently divided into an upper or cephalic curve,[*] and a lower or caudal one.[†] When the concavity of the caudal curve is biting or laying hold of the water, and when the concave surface of the tail is being forced during extension with great violence in the direction of the axis of motion,[‡] where the concave surface is suddenly converted into a convex one, the concavity of the cephalic curve, *i.e.*, the concave surface of the upper half of the fish, is being urged, with less vigour, in the direction of the same line from the opposite side of it. As the caudal and cephalic curves are obliterated when the line in question is reached, there is, consequently, a period (momentary it must be), between the effective and non-effective strokes, in which the body of the fish is comparatively straight, and, consequently, in a position to advance almost without impediment."[§]

[*] *Op. cit.*, Diag. 2, *d*, p. 204.

[†] *Op. cit.*, Diag. 2, *c*, p. 204.

[‡] *Op. cit.*, Diag. 2, *a, b*, p. 204

[§] *Op. cit.*, p. 205.

vated, corresponding portions of the posterior margin are depressed, the different parts of the wing moving in opposite directions, and playing, as it were, at cross purposes for a common good—the object being to rotate or screw the wing down upon the wind at a gradually increasing angle during extension, and to rotate it in an opposite direction and withdraw it at a gradually decreasing angle during flexion. It also happens that the axillary and distal curves co-ordinate each other and bite alternately, the distal curve posteriorly seizing the air in extreme extension with its concave surface (while the axillary curve relieves itself by presenting its convex surface), the axillary curve, on the other hand, biting during flexion with its concave surface (while the distal one relieves itself by presenting its convex one). The wing may, therefore, be regarded as exercising a fourfold function, the pinion in the bird being made to move from within outwards, and from above downwards during extension, in the effective or down stroke; and from without inwards, and from below upwards, during flexion in the up or return stroke."

The Wing during its Vibration produces a Cross Pulsation.—"This oscillation of the wing on two separate axes—the one running parallel with the body of the bird, the other at right angles to it—is well worthy of attention, as showing that the wing attacks the air on which it operates in every direction, and at almost the same moment, viz., from within outwards, and from above downwards, during the down or effective stroke; and from without inwards, and from below upwards, during the up or return stroke. As a corollary to the foregoing, the wing may be said to agitate the air in two principal directions, viz., from within outwards, or the reverse, and from behind forwards, or the reverse, the agitation in question producing two powerful pulsations—a longitudinal and a lateral; the longitudinal running in the direction of the *length* of the wing, the lateral in the direction of its *breadth*. As, however, the curves of the wing glide into each other when the wing is in motion, so the one pulsation merges into the other by a series of intermediate and lesser pulsations.

The longitudinal and lateral pulsations occasioned by the wing in action may be fitly represented by wave-tracks running at right angles to each other, the longitudinal wave track being the more distinct."

Analogy between the Wing in Motion and the Sounding of Sonorous Bodies.—"It is a remarkable circumstance that the undulation or wave made by the wing when the insect and bird are fixed or hovering before an object, and when they are progressing, corresponds in a marked manner with the track described by the stationary and progressive waves in fluids,* and likewise with the waves of sound.† This coincidence would seem to argue an intimate relation between

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* Handbook of Natural Phil. (vol. on Electricity, Magnetism, and Acoustics), by Dr LARDNER (Lond. 1863), pp. 366–7.

† *Op. cit.*, pp. 378, 379, 380.

the instrument and the medium on which it is destined to operate—the wing acting in those very curves into which the atmosphere is naturally thrown in the transmission of sound, in order, as appears to me, to secure the maximum of progression with the minimum of slip. Can it be that the animate and inanimate world reciprocate, and that animal bodies are made to impress the inanimate in precisely the same manner as the inanimate impress each other? This much seems certain:—The wind communicates to the water similar impulses to those communicated to it by the fish in swimming; and the wing in its vibrations impinges upon the air as an ordinary sound would. The extremities of quadrupeds, moreover, describe spiral tracks on the land when walking and running; so that one great law would seem to determine the course of the insect in the air, the fish in the water, and the quadruped on the land."

Various other passages might be adduced in elucidation and support of the curve, wave, or figure of 8 theory of flying, as originally propounded by me, but a sufficient number have, I trust, been cited to prove that the theory owes its origin and development to no hasty generalisation from a few scattered and imperfectly known facts, but that it rests upon a broad basis, such, in reality, as nature herself supplies.

In order that the reader may form his own conclusions on this point, I propose to lay before him in the course of my subsequent remarks the observations and experiments on which the theory was originally founded. The present memoir is illustrated by upwards of ninety original diagrams and drawings, the intricacy of the subject being such as to necessitate a free use of the pencil. The drawings have been made by myself from the life. I have gone into the origin and development of the figure of 8 theory of flying somewhat in detail; first, because the passages selected have an obvious bearing on the subject of the present communication; and second, because nearly two years after I had made my views known, Professor E. J. MAREY (College of France, Paris), published a series of lectures and papers in the "Revue des Cours Scientifiques de la France et de L'Etranger,"* and in the "Comptes Rendus hebdomadaires des Séances de L'Académie des Sciences,"† in which the figure of 8 theory of wing movements is put forth as a new discovery. Professor MAREY made no allusion to my researches, which was the more remarkable, as an abstract of my lecture, already referred to (p. 322), as published in the Proceedings of the Royal Institution of Great Britain in March 1867, was translated into French, and

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* Les mouvements de l'aile chéz les insectes, p. 171, 13th Février 1869. Mécanisme du vol chez les insectes—comment se fait la propulsion, p. 252, 20th Mars 1869. Du vol des oiseaux, p. 578, 14 Aout 1869. Du vol des oiseaux (suite), p. 601, 21 Aout 1869. Du vol des oiseaux (suite), p. 646, 11 Septembre 1869. Du vol des oiseaux (fin), p. 700, 2 October 1869.

† Determination expérimentale du mouvement des ailes des insectes pendant le vol. Par M. E. J. MAREY. Tome LXVII. p. 1341, Tome LXVIII. p. 667.

appeared on the 21st of September of that year in the same Journal* in which Professor MAREY's lectures were originally published. Having had my attention directed to this circumstance, I addressed a letter to the French Academy on the 28th of March 1870, which appeared in the "Comptes Rendus" (p. 875) on the 18th of April 1870. In it I claim to have been the first to describe and illustrate the following points, viz:—

That quadrupeds walk, and fishes swim, and insects, bats, and birds fly by figure of 8 movements.

That the flipper of the sea bear, the swimming wing of the penguin, and the wing of the insect, bat, and bird, are screws *structurally*, and resemble the blade of an ordinary screw propellor.

That those organs are screws *functionally*, from their twisting and untwisting, and from their rotating in the direction of their length, when they are made to oscillate.

That they have a reciprocating action, and reverse their planes more or less completely at every stroke.

That the wing describes *a figure of* 8 *track* in space when the flying animal is artificially fixed.

That the wing, when the flying animal is progressing at a high speed in a horizontal direction, describes *a looped* and then *a waved track*, from the fact that the figure of 8 is gradually opened out or unravelled as the animal advances.

That the wing acts after the manner of a kite.

Previous to replying to the foregoing, Professor MAREY wrote me, to inquire how he could respond to my "juste reclamation," without entering into a discussion which would needlessly complicate the question. I thereupon asked him to admit in a letter addressed to the French Academy my claim to have described and illustrated before him the figure of 8 movements made by the wings of insects, bats, and birds, when those animals are artificially fixed, and of the spiral and undulatory wave tracks made by the wings of said insects, bats, and birds, when the animals are flying at a high horizontal speed. This he has done, as the subjoined extract from his letter, printed in the "Comptes Rendus" for May 16, 1870 (p. 1093), will show:—"J'ai constaté qu' effectivement M. Pettigrew a vu avant moi, et représenté dans son Mémoire, la forme en 8 du parcours, de l'aile de l'insecte: que la méthode optique à laquelle j'avais recours est à peu près identique à la sienne . . . . je m' empresse de satisfaire à cette demande légitime, et je laisse entièrement la priorité sur moi, à M. Pettigrew relativement à la question ainsi restreinte."

Mode of Investigation pursued by the Author.—I obtained my results by

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* Revue des Cours Scientifiques de la France et de l'Etranger.

transfixing the abdomen of insects with a fine needle, and watching the wings vibrate against a dark background; by causing dragon-flies, butterflies, blow-flies, wasps, bees, beetles, &c., to fly in a large bell jar, one side of which was turned to the light, the other side being rendered opaque by dark pigment; by throwing young pigeons and birds from the hand into the air for the first time; by repeated observation of the flight of tame and wild birds; by stiffening, by tying up, and by removing portions of the wings of insects and birds; by an analysis of the movements of the travelling surfaces of quadrupeds, amphibia, and fishes; by the application of artificial fins, flippers, tails, and wings to the water and air; and by repeated dissections of all the parts directly and indirectly connected with flight.

Professor MAREY obtained his results by gilding the extremities and margins of the wings of the insect with minute portions of gold leaf; by the application of the different parts (tip and anterior margin) of the wing of the insect to a smoked cylinder rotating at a given speed, the wing being made to record its own movements; by the captive and free flight of birds, which carried on and between their wings an apparatus which, by the aid of electricity, registered the movements of the wings on a smoked surface, travelling at a known speed in a horizontal direction; and by the employment of an artificial wing, constructed on the plan recommended by BORELLI, CHABRIER, STRAUS-DURCKHEIM, GIRARD, and others.

Professor MAREY describes and figures a captive insect (the wasp) with its wings forming figure of 8 loops,* and a free insect, with its wings describing a waved track,† precisely similar to what I described and figured in a variety of ways in my memoir.‡ He also shows that the tip of the wing of the bird, because of its alternately darting out and in during extension and flexion, describes an ellipse. This, curiously enough, is another of the many points in which I have anticipated this author, and one which I took special pains to establish,§ having in my memoir devoted no less than ten figures || to its illustration. Professor MAREY's views may therefore be regarded as confirmatory of my own, as the following brief passage, selected from one of his papers, will show. He writes:—"But if the frequency of the movements of the wing vary, the form does not. It is invariably the same—*it is always a double loop—a*

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* Revue des Cours Scientifiques de la France et de l'Etranger, 13 Février 1869, page 175, figure 5. Professor MAREY represents the wing of the wasp as fanning the air in a vertical direction. In reality, the wing of the wasp and of most insects is made to vibrate very obliquely, and in a more or less horizontal direction.

† Revue des Cours Scientifiques et de la France et de l'Etranger, 13 Février 1869, pages 173, 174, and 176.

‡ Trans. Linn. Society, Vol. XXVI, page 233, Diagrams 5 and 6; page 249, Diagrams 14, 15, and 16; Plate XV. figures 59 and 61. *Vide* introduction to present memoir.

§ *Op. cit.*, pages 247, 248, 249, and 250.

|| *Op. cit.*, pages 248 and 249, Diagrams 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16.

figure of 8. Whether this figure be more or less apparent, whether its branches be more or less equal, matters little; it exists, and an attentive examination will not fail to reveal it."*

Professor MAREY's experiments, I may add, have been repeated and verified in England by Mr SENECAL. This investigator also represents and describes the *double loop* and *figure of* 8 *movements.*† These two sets of experiments conducted independently, and after a considerable interval, by M. MAREY and Mr SENECAL respectively, will, I hope, suffice to establish the absolute correctness of the "Figure of 8 or Wave theory of Flight."

NATURAL FLIGHT.‡

Method of Testing the Accuracy of the Figure of 8 *Theory of Wing Movements.*—The correctness of the figure of 8 theory of flying may be readily established by a careful study of the rapidly vibrating wing of the wasp or common blow-fly.

If the body of the former be held, and the wing made to vibrate in front of a dark screen, it will be found that not only the tip but also the margins of the wing describe a figure of 8 track in space.

It will further be observed that the planes of the wing are as a rule reversed during the down and up strokes; nay, more, that the angles of inclination made by the surfaces of the wing with the horizon vary at every stage of the wing's progress, this variation in the angles being accompanied by a variation in the curves occurring on the anterior and posterior margins, as already explained. As a consequence, the wing is moving in all its parts at the same time—a somewhat remarkable occurrence, and calculated, it appears to me, to excite the curiosity, if it does not rivet the attention of physiologists. The wing of the insect is, with few exceptions, more flattened than that of the bat and bird, a circumstance which enables it, when it is made to vibrate in a more or less horizontal direction, and when its planes are reversed at the end of each stroke, to apply its under or ventral surface to the air when it is urged from behind forwards, and its upper or dorsal one when urged from before backwards (figures 3 and 4, page 338). It sometimes happens that the posterior margin of the wing is rotated in an upward direction at the end of the forward stroke, and in this case it is the under surface of the wing which is effective during the backward stroke (*vide g h i j k l* of figure 19, page 351).

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* Méchanisme du vol des insectes—comment se fait la propulsion. Revue des Cours Scientifiques de la France et de l'Etranger, 20th March 1869.

† Fifth Annual Report of the Aëronautical Society of Great Britain for 1870, pages 42–47. Figures 1, 2; Diagrams 1–4.

‡ Artificial flight is described at page 402.

When the wing acts in this manner, it is the under or ventral surface which is effective both during the forward and backward strokes. The wing, during the back stroke occasions very little friction, from its being placed in a more or less horizontal position—this position being favourable to its affording a maximum of support. The upper and under surfaces of the wing are applied to the air alternately, more particularly when the insect is fixed, or when it is hovering in one spot. When it is flying at a high horizontal speed, and when the wing is made to oscillate in a slightly vertical direction, as in the butterfly (figures 29, 30, 31, 32, 33, and 34, page 360) and dragon-fly (figures 35, 36, 37, and 38, page 361), it is the under or concave surface of the pinion which does the principal part of the work, this attacking the air both during the down or forward stroke and the up or backward stroke, like a boy's kite, as explained at pages 349 and 350, figures 16 and 17. The direction of the stroke varies slightly according to circumstances, but it will be quite proper to assume that the wing of the insect is made to vibrate in a more or less *horizontal direction*, and that of the bird and bat in a more or less *vertical direction*. By a slight alteration in the position of the body, or by a rotation of the wing in the direction of its length, the vertical direction of the stroke is converted into a horizontal direction, and *vice versa*. The facility with which the direction of the stroke is changed is greatest in insects; it is not uncommon to see them elevate themselves by a figure of 8 *horizontal* screwing motion, and then, suddenly changing the horizontal screwing into a more *vertical* one, to dart rapidly forward in a curved line. The horizontal screwing movement is represented at figures 2, 3, 4, 5, 6, 7, and 10, pages 336, 338, 340, and 341; and the vertical screwing at figures 12 and 13, page 342. The horizontal action of the insect's wing is described at pages from 336 to 341 inclusive, and the vertical action at pages from 347 to 355 inclusive. The vertical action of the bat and bird's wing is described at page 342, and at pages from 366 to 397 inclusive. Whether the wing is made to vibrate vertically or horizontally, it, practically speaking, in *progressive flight*, strikes *downwards and forwards* during the down stroke, and *upwards and forwards* during the up stroke, as fully explained at pages 344 and 345.

Compound Rotation of the Wing.—The wing during its vibration rotates upon two separate centres, the tip rotating around the root of the wing as an axis (short axis of wing), the posterior margin rotating around the anterior margin (long axis of wing). This compound rotation goes on throughout the entire down and up strokes, and is intimately associated with the power which the wing enjoys of alternately seizing and evading the air.

The Wing inclined Forwards at the End of the Down Stroke and Backwards at the End of the Up Stroke.—I had my attention first strongly directed to the screwing figure of 8 action of the wing by closely observing the twisting figure of 8 movements made by the pectoral fins and tails of fishes, and from finding that in the beetle, blow-fly, and wasp (anterior wings), the posterior margin and body of the wing were inclined *forwards* (fig. 1 *a*) with reference to the head of the insect, at the end of the down stroke, and *backwards* (fig. 1 *b*) at the end of the up stroke.

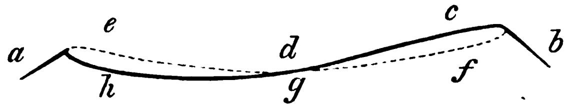

Fig. 1.

The Wing Rotates upon its Long Axis.—This at once suggested a rotation of the wing upon its long axis along its anterior margin, or, what is practically the same thing, a folding and plaiting of the posterior or thin yielding margin of the wing around the anterior semi-rigid and comparatively unyielding margin—a certain amount of rotation, or what is equivalent thereto, being necessary to reverse and change the planes of the wing at each stroke.

The Wing Twists and Untwists during its action.—I further observed that the planes of the wing were not only changed at the end of each stroke, but that the wing at this juncture was twisted upon itself, the outer portion of the posterior margin of the wing at the end of the down or forward stroke being inclined *forwards* (*g* of fig. 2), while the inner portion was inclined *backwards* (*r* of fig. 2); whereas at the termination of the up or backward stroke, the outer portion of the posterior margin was inclined *backwards* (*a* of fig. 2), while the inner portion was inclined *forwards* (*s* of fig. 2).

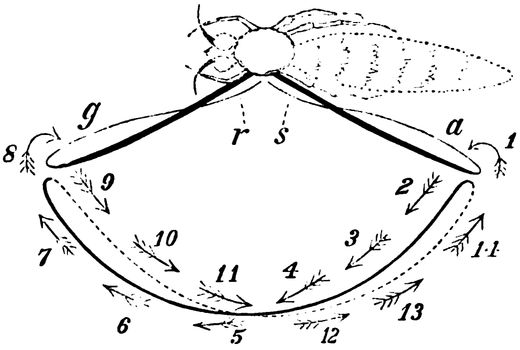

Fig. 2.

The Image produced on the Eye by the Wing in Motion is Concavo-Convex, and Twisted.—I likewise discovered that the blur or impression produced on the eye by the rapidly oscillating wing was *twisted upon itself* (fig. 1 *c d h*, *e g f*), and more or less *concave* above (*c d e* fig. 1), and *convex* below (*f g h* fig. 1), a circumstance which, while it strongly corroborated the opinion that the wing rotated upon its long axis during its vibration indicated that the twisting and reversal of the planes of the wing occurred more especially at the end of the down and up strokes. I inferred this from observing that the angle made by the wing with the horizon is greater towards the termination than towards the middle of the strokes. This could readily be ascertained by looking at the blur produced by the oscillating wing edgewise, and this view revealed what is perhaps the most important feature in wing movements, viz., that the tip of the wing during its vibrations describes a scooped out (*c d e* fig. 1) figure of 8 track as represented at 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14 of fig. 2.

The Direction of the Stroke of the Wing in the Insect—what Effective and what Non-effective—the Kite-like Action of the Wing.—This view also showed that the wing of the insect is made to vibrate in a more or less horizontal direction (figs. 3 and 5, page 338, Plate XI. fig. 4), in which respect it differs somewhat from the wing of the bat and bird, these being worked more or less vertically (Plate XI. figs. 5 and 6, and Plate XIV. figs. 18 and 19). The oblique action of the pinion is necessary to avoid the resistance of the air during the up stroke, the wing of the insect being in one piece, and having in many cases no adequate apparatus for diminishing its area during its ascent. One great advantage gained by the wing of the insect reversing its planes at the end of each stroke consists in the great length of the effective stroke—the wing flying backwards and forwards like a true kite, and tacking upon the air so suddenly as to occupy very little either of time or space.* The period occupied by the wing in reversing does not apparently amount to more than one-eighth of the time taken up by one entire stroke, so that something like seven-eighths of the area mapped out by the rapidly vibrating wing represents buoying area—the remaining eighth slip. This, put in other words, simply means that in one passage of the wing from behind forwards (down stroke) the pinion is effective in seven-eighths of its course and non-effective in one-eighth, the same remark being applicable to the passage of the wing from before backwards (up stroke).

The Wing Attacks the Air at various Angles.—It is just possible that even less than one-eighth is devoted to slip, from the fact that the wing when it is being reversed is slowed and applied to the air at an increased angle—a surface which makes a large angle with the horizon, giving, when forced against the air at a low speed, as much support as a similar surface whose inclination is less, but whose speed is higher. As the wing attacks the air during the down and up strokes at various angles, those angles being greatest when the wing travels slowest, and least when the wing travels most rapidly, it follows that the wing adapts itself to the resistance opposed to its passage by the air, and always extracts the maximum of support from it. The wing, in this respect, differs

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* The movements of the wing somewhat resemble those of a sailing ship. The wing and ship both tack upon the wind, and both change their tack or reverse abruptly. The changing of the tack is moreover always accompanied by a slowing or diminution of the speed.

widely from the screw propellors at present in use—the blades of these propellors always striking at a given angle and in the same direction. The advantage in favour of the wing as compared with the screw as employed in navigation is very great, and not at present understood.* The area mapped out by the wing during the effective stroke and while reversing; the various angles made by the surfaces of the wing with the horizon in its passage to and fro; the rotating and twisting of the posterior or thin margin of the wing round the anterior or thick margin; and the figure of 8 track made by the tip of the wing during its action, as seen in the wasp, are shown at figs. 3, 4, 5, and 6.

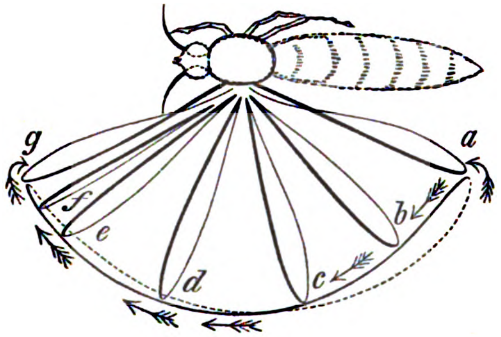

Fig. 3.

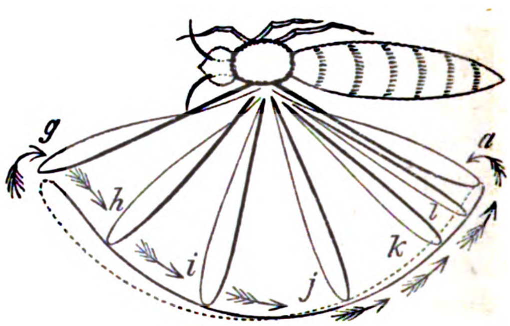

Fig. 4.

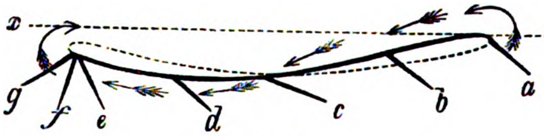

Fig. 5.

Fig. 6.

Analysis of the Movements of the Wing of the Wasp, Reversal of the Planes of the Wing, Reciprocating Action, &c.—In the wasp the wing commences the down or forward stroke at *a* of figures 3 and 5; and it will be observed that the angle which it makes with the horizon (*x* of fig. 5) is something like 45°. At *b* (figures 3 and 5) the angle is slightly diminished, partly because of a rotation of the wing along its anterior margin (long axis of wing), partly from increased speed, and partly from the posterior margin of the wing yielding to a greater or less extent.

At *c* the angle is still more diminished from the same causes.

At *d* the wing is slowed slightly, preparatory to reversing, and the angle made with the horizon (*x*) increased.

At *e* the angle, for the same reason, is still more increased; while at *f* the wing is at right angles with the horizon. It is, in fact, in the act of reversing.

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* For specific differences between the screws formed by the wings and the propellors employed in navigation, see memoir by the author, Trans. Linn. Society, vol. xxvi. pages 228, 229, 230, and 231.

At *g* the wing is reversed, and the up or back stroke commenced.

The angle made at *g* is, consequently, the same as that made at *a* (45°), with this difference, that the anterior margin and outer portion of the wing, instead of being directed *forwards*, with reference to the head of the insect, are now directed *backwards*.

During the up or backward stroke all the phenomena are reversed, as shown at *g h i j k l* of figures 4 and 6; the only difference being that the angles made by the wing with the horizon are somewhat less than during the down or forward stroke—a circumstance which facilitates the forward travel of the body, while it enables the wing during the back stroke still to afford a considerable amount of support. This arrangement permits the wing to travel backwards when the body is travelling forwards; the diminution of the angles made by the wing in the back stroke giving very much the same result as if the wing were striking in the direction of the travel of the body. The slight upward inclination of the wing during the back stroke permits the body to fall downwards and forwards to a slight extent at this peculiar juncture, the fall of the body, as will be more fully explained hereafter, contributing to the elevation of the wing.

If figure 5, representing the down or forward stroke, be placed upon figure 6, representing the up or backward stroke, it will be seen that the wing crosses its own track more or less completely at every stage of the down and up strokes. As, moreover, the wing draws a current after it, and is pursued in its passage from above downwards by a stream of air which it meets in its passage from below upwards, it follows that the pinion, during the down or *forward stroke*, creates a current on which it operates during the up or *backward stroke*, and *vice versa;* hence the *reciprocating action* of the wing.

The wing reciprocates most perfectly, and the figure of 8 is most distinct when the insect is fixed artificially, or when it is hovering of its own accord in a given spot, as is well shown at *a b c d e f g h i j k l m n o p* of fig. 8, p. 340, where the wing is represented as screwing steadily downwards.

Points wherein the Wing differs from the Scull of the Boatman.—The downward screwing movement of the wing somewhat resembles the action of an oar in sculling, as represented at *a b, c d, x s,* of fig. 7, the cross movement occasioned by the rotation of the wing on its long axis as it darts to and fro being shown at *m n, o p, q r*. There is, however, this marked difference. It is the *upper* surface of the oar which is effective in sculling, whereas it is the *under* surface of the wing which is effective in flying.* This is accounted for by the fact that the oar simply propels—the boat being buoyant, the wing propelling and

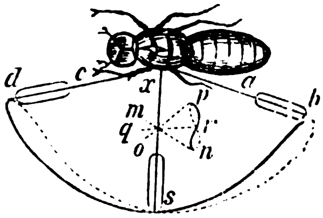

Fig. 7.

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[*] A precisely similar difference is found to exist between the aërial or flying wing and the subaquatic

likewise elevating. There is this further difference. The margins of the blades of the oar are of the same thickness, the axis of rotation running midway between the two; the anterior margin of the wing, on the contrary, is much thicker than the posterior one, the axis of rotation corresponding to the former. The oar, as far as the margins of its blade are concerned, is as it were *concentric*, the wing *eccentric*. As the downward screwing movement of the wing, in virtue of the action and reaction of the wing and air upon each other, is at once converted into an upward screwing movement, as shown at *a' b' c' d' e' f' g' h' i' j' k' l' m' n' o' p'* of fig. 9, it follows that the body of the insect is rapidly but steadily elevated in an almost vertical wave-line. The impulse is communicated to the wing at points corresponding to the heavy portions of the line in figure 8, and the corresponding upward recoil is indicated at similar points in figure 9.

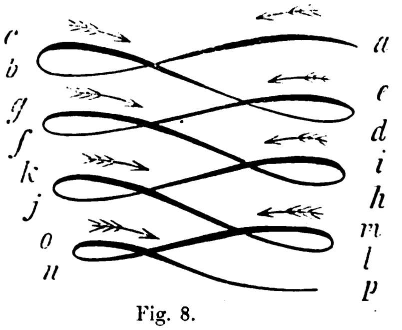

Fig. 8.

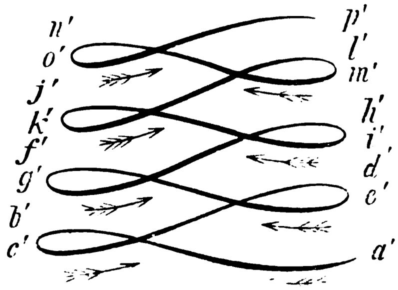

Fig. 9.

How the Figure of 8 *is Unravelled, and becomes a Waved-Track.*—When the insect flies in a horizontal direction, and the speed attained increases with the duration of flight, the wing reciprocates less and less perfectly, because the figure of 8 sweeps described by it are converted into a looped and then a waved track, as represented at *a b c d e f g h i j k l m n o p q r s t* of figure 10 (p. 341); the corresponding looped and waved track due to recoil being shown at similar letters of figure 11 (p. 341). When the horizontal speed attained by the insect is high,

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or diving wing. In the gannet, cormorant, merganser, grebe, &c., which fly under the water, it is the upper or dorsal surface of the pinion which gives the effective stroke, whereas in aërial flight it is the under or ventral surface. This is proved by the fact that in the penguin and great auk, which are incapable of flying out of the water, and confine their efforts to diving or swimming under it, the wing is actually twisted round, so that the dorsal surface of the pinion occupies the position normally occupied by the ventral surfaces in all other birds. This is necessitated by the fact that a diving bird, seeing it is of lighter specific gravity than the water, must always fly downwards; in other words, it must counteract buoyancy as the flying bird counteracts gravity—buoyancy forcing the diving bird to the surface of the water in the same way that gravity drags the flying bird to the surface of the earth. Levity and weight are therefore separate forces, and act under diametrically opposite conditions, levity being quite as useful to the diving bird as weight to the flying one. The wings of diving birds are applied to the water precisely in the same manner as the flippers of the seal, sea bear, walrus, turtle, porpoise, whale, manatee, &c. All these animals are lighter than the water, and, as a consequence, their travelling surfaces to be effective must act *from below* as in the case of the scull. It is the reverse in the air, the travelling surfaces acting invariably *from above.* For further development of this view see footnote to page 371.

the wing is successively and rapidly brought into contact with innumerable columns of undisturbed air. It consequently is a matter of indifference whether the wing is carried at a high speed against undisturbed air, or whether it operates upon air travelling at a high speed (as, *e.g.*, the artificial currents produced by the rapidly reciprocating action of the wing). The result is the same in both cases, inasmuch as a certain quantity of air is worked up under the wing, and the necessary degree of support and progression extracted from it. It is, therefore, quite correct to state, that as the horizontal speed of the body increases the reciprocating action of the wing decreases, and *vice versa*. In fact, the reciprocating and non-reciprocating function of the wing in such cases is purely a matter of speed. If the travel of the wing is greater than the horizontal travel of the body, then the figure of 8 and the reciprocating power of the wing will be more or less perfectly developed, according to circumstances. If, however, the horizontal travel of the body is greater than that of the wing, then it follows that no figure of 8 will be described by the wing, that the wing will not reciprocate to any marked extent, and that the organ will describe a waved track, the curves of which will become less and less abrupt, *i.e.*, longer and longer in proportion to the speed attained. The downward looped track represented at fig. 10, is at once converted into an upward looped track, as shown at figure 11, in virtue of the action and reaction of the wing and air upon each

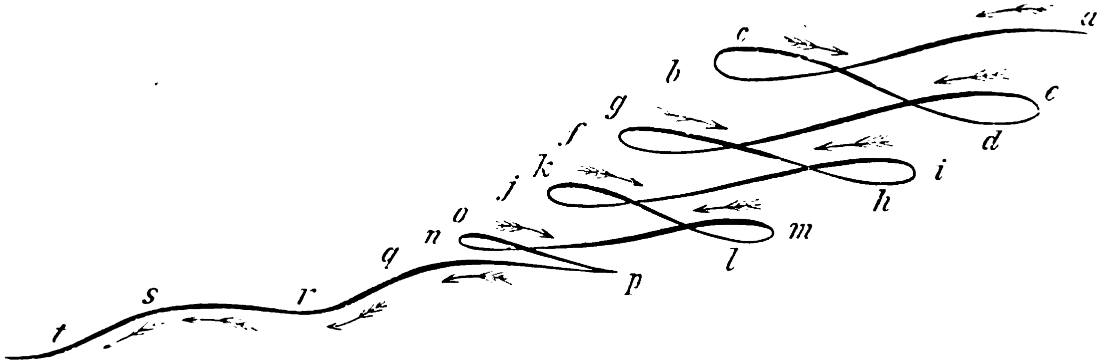

Fig. 10.

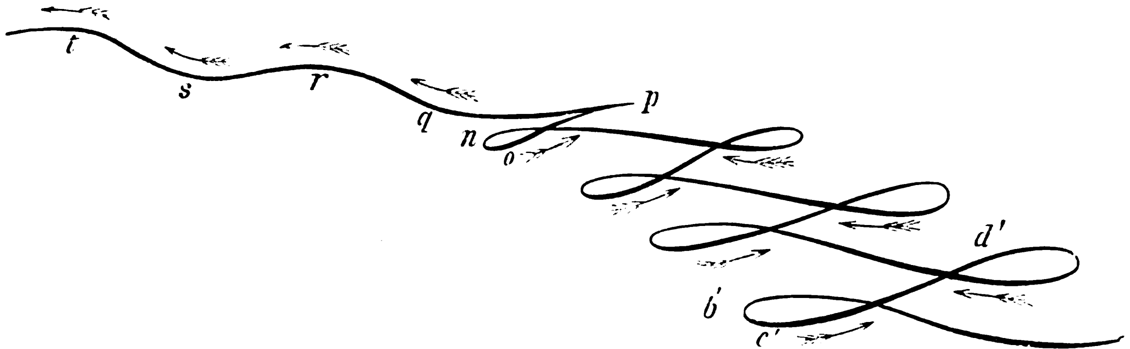

Fig. 11.

other, the body of the insect being carried along a waved line obliquely upwards and forwards (*q r s t*, fig. 11, p. 341). The waved track made by the wing is generated by the figure of 8 loops being gradually opened out, these becoming less and less distinct as the insect advances, as is more especially shown at *n o p q r s t* of both figures (10 and 11, p. 341). The impulse is communicated to the wing at *a c e g i k m o q s* of fig. 10, and the upward recoil at corresponding letters of fig. 11.

The waved track formed by the ascent and descent of the wing of the bat and bird is originated in a similar manner, but in this case the figure of 8 loops are disposed more vertically, because of the more vertical direction of the stroke, as shown at *e f g h i j k l* of figure 12. (*Vide* also Plate XI. figures 5 and 6). In this figure (12) the oar, as seen at *a b*, *x s*, and *c d*, represents the wing of the bat and bird at the beginning, middle, and termination of the down stroke—the little oar, *m n o p q r*, indicating the cross action of the wing. The large oar is more especially engaged in elevating, the little one in propelling. The manner in which the figure of 8 loops made by the wing of the bat and bird during its ascent and descent are opened out or unravelled by the horizontal travel of the body is shown at *a b c d e f g h i j k l m n o p* of figure 13; the completed waved track being seen at *s t u v w* of the same figure.

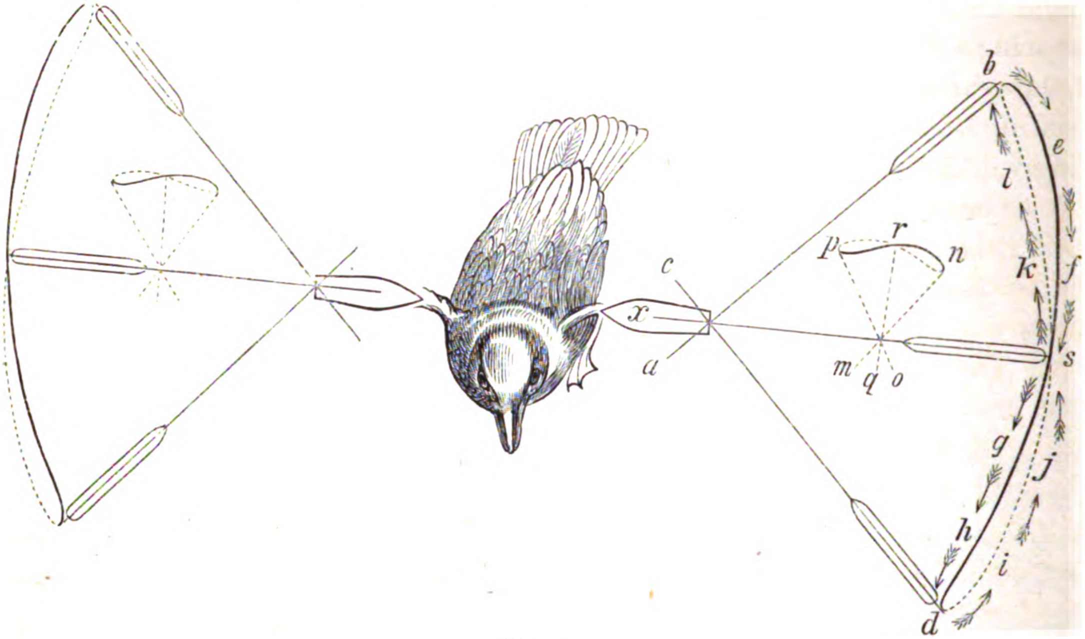

Fig. 12.

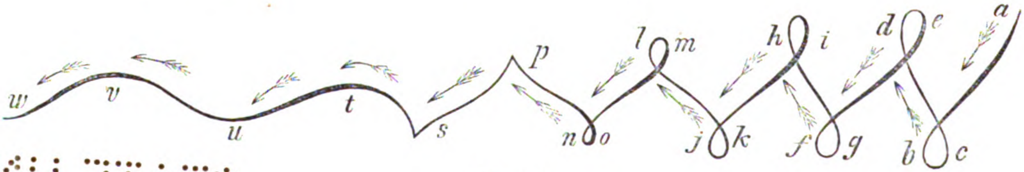

Fig. 13.

When the Wing Ascends the Body Descends, and vice versa.—As the body of the insect, bat, and bird falls forwards in a curve when the wing ascends, and is elevated in a curve when the wing descends, it follows that the trunk of the animal is urged along a waved line, as represented at 1, 2, 3, 4, 5 of figure 14, p. 344, the waved line *a c e g i* of the same figure giving the track made by the wing. I have distinctly seen the alternate rise and fall of the body and wing when watching the flight of the gull from the stern of a steam-boat.

The direction of the stroke in the insect (figs. 3, 5, and 8, pp. 338, 340), as I have already explained, is much more horizontal than in the bat or bird (figs. 12 and 13, p. 342). In either case, however, the down stroke must be delivered in a more or less forward direction. This is necessary for support and propulsion. A horizontal to and fro movement will elevate, and an up and down vertical movement propel, but an oblique forward motion is requisite for progressive upward flight.*

The Wing during its Vibrations moves on the Surface of an Imaginary Sphere.—All wings are convex above and concave below. This shape is necessary to enable the wing to evade the air during the up stroke, and to seize it during the down one. The concave surface is presented during the up stroke, and the concave one during the down stroke—the resistance experienced by a concave surface when compared with a convex one being something like two to one. The resistance is further increased by the wing being made to descend with greater rapidity than it ascends. In whatever direction the wing turns during the up stroke its movements are calculated to evade the air, and in whatever direction it turns during the down stroke they are calculated to seize it. This arises alike from the shape of the wing and the manner in which it is applied to the air. Thus, in the insect in progressive flight the wing during the up stroke describes a curve which is directed upwards and forwards. In the bat and bird, where the wing is drawn towards the body during the up stroke, the wing describes a second curve, this curve being directed upwards and inwards with reference to the body. The under or concave surface of the wing may, therefore, be said to be moving on the surface of an imaginary sphere during the up stroke—an arrangement which enables it to avoid the superincumbent air by its upper or convex surface, while it affords a certain amount of support and ascensional power by its under or concave surface, this latter acting partly as a kite and partly as a parachute. The wing may, in fact, be said to climb during the up stroke; and this climbing is so adroitly performed that two objects are served by it—the superimposed air being avoided, and the body bearing the wing being supported. In the climbing movement the anterior margin of the wing cleaves a passage from behind upwards and forwards for the body

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* On the Mechanism of Flight, by the Author, Trans. Linn. Society, vol. xxvi. pages 214, 255, and 256.

and posterior margin, the root in like manner cleaving a passage from without inwards and upwards for the body and tip. It is in this way that the wing presents a sharp cutting edge during the up stroke, a remark which applies even to the rowing feathers (quill feathers) of the wing of the bird. The ascent of the wing, as will be subsequently explained, is favoured by the reaction of the air on its under surface, and by the downward and forward fall of the body. If the wing was not concavo-convex in form, and made to oscillate on the surface of an imaginary sphere, it would be impossible for it alternately to avoid and seize the air while it is rising and falling. When the wing descends or makes the down stroke, as it is termed, it also rotates on the surface of the imaginary sphere in question. In this case, however, it is the concave or under surface of the wing which is active, and the rolling takes place in such a manner (it is outwards, downwards, and forwards) as actually greatly to increase the support afforded—the air, which was dispersed and avoided during the up stroke, being now collected together and seized with avidity. It would be difficult to conceive a more simple or effective arrangement.

The Natural Wing, when Elevated and Depressed, must move Forwards.—It is a condition of natural wings, and of artificial wings constructed on the principle of living wings, that when forcibly elevated or depressed, even in a strictly vertical direction, they inevitably dart forward. This is well shown in figure 14.

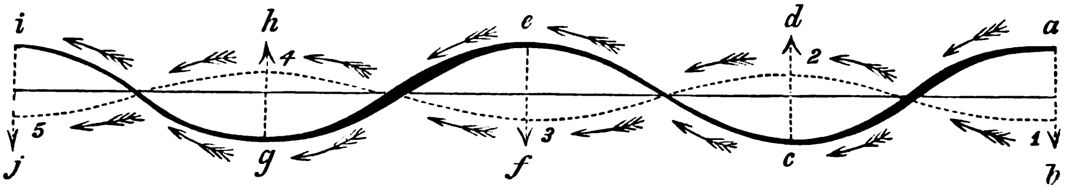

Fig. 14.

If, for example, the wing is suddenly depressed in *a vertical direction,* as represented at *a b,* it at once darts downwards and forwards in a curve to *c,* thus converting the vertical down stroke into *a down oblique forward stroke.* If, again, the wing be suddenly elevated in a strictly vertical direction, as at *c d,* the wing as certainly darts upwards and forwards in a curve to *e,* thus converting the vertical up stroke into an *upward oblique forward stroke.* The same thing happens when the wing is depressed from *e* to *f,* and elevated from *g* to *h.* In both cases the wing describes a waved track, as shown at *e g, g i,* which clearly shows that the wing strikes *downwards and forwards* during the down stroke, and *upwards and forwards* during the up stroke. The wing, in fact, is always advancing, its under surface attacking the air like a boy's kite. If, on the other hand, the wing be forcibly depressed, as indicated by the heavy waved line *a c,* and left to itself, it will as surely rise again, and describe a waved track, as shown at *c e.* This it does, in virtue of its flexibility and elasticity, aided by the recoil obtained from the air. In other words, it is not necessary to elevate the wing forcibly in the direction *c d* to obtain the upward and forward movement *c e*. One single impulse communicated at *a*, causes the wing to travel to *e*, and a second impulse communicated at *e*, causes it to travel to *i*. It follows from this that a series of vigorous down impulses would, *if a certain interval was allowed to elapse between them*, beget a corresponding series of up impulses, in accordance with the law of action and reaction, the wing and the air under these circumstances being alternately active and passive. I say if a certain interval was allowed to elapse between every two down strokes, but this is practically impossible, as the wing is driven with such velocity that there is positively no time to waste in waiting for the purely mechanical ascent of the wing. That the ascent of the pinion is not, and ought not to be, entirely due to the reaction of the air, is proved by the fact that in flying creatures (certainly in the bat and bird) there are distinct elevator muscles and elastic ligaments, delegated to the performance of this function. The reaction of the air is therefore only one of the forces employed in elevating the wing; the others, as I shall show presently, are vital and vito mechanical in their nature. The falling downwards and forwards of the body when the wings are ascending also contribute to this result.

The Wing acts as a true Kite both during the Down and Up Strokes.—If, as I have endeavoured to explain, the wing, even when elevated and depressed in a strictly vertical direction, inevitably and invariably darts forward (figure 14, p. 344), it follows as a consequence that the wing, as already partly explained, flies forwards as a true kite, both during the down and up strokes, as shown at *c d e f g h i j k l m* of fig. 15, and that its under concave or biting surface, in virtue of the forward travel communicated to it by the body in motion, is closely applied to the air, both during its ascent and descent, a fact hitherto overlooked, but one of considerable importance, as showing how the wing furnishes a persistent buoyancy, alike when it rises and falls.

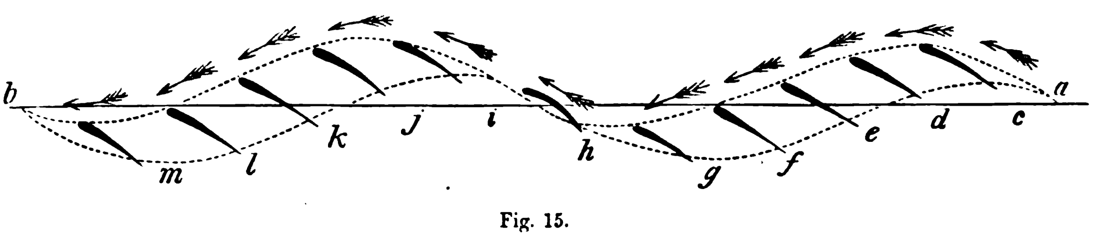

Fig. 15.

In figure 15 the greater impulse communicated during the down stroke is indicated by the double dotted lines. The angle made by the wing of the bat and bird with the horizon (*a b* of figure 15) is constantly varying, as in the insect wing, as a comparison of *c* with *d*, *d* with *e*, *e* with *f*, and *f* with *g* of figure 15 will show, these letters having reference to supposed transverse sections of the wing. Figure 15 also shows that the *convex* or non-biting surface of the wing is always directed upwards, so as to avoid unnecessary resistance on the part of the air to the wing during its ascent, whereas the *concave* or biting surface is always directed downwards, so as to enable the wing to contend successfully with gravity.

On comparing *c d e f g* of figure 15, p. 345, with *a b c d* of figures 3 and 5, p. 338, it will be seen that the principle involved in the flight of the wing of the insect, bat, and bird is essentially the same. The wing is, in short, in every instance, a true kite, and flies forward in accordance with natural laws.

Where the Kite formed by the Wing differs from the Boy's Kite.—The natural kite formed by the wing differs from the artificial kite only in this, that the former is capable of being moved in all its parts, and is more or less flexible and elastic, the latter being comparatively rigid. The flexibility and elasticity of the kite formed by the natural wing is rendered necessary by the fact that the wing is articulated or hinged at its root; its different parts travelling at various degrees of speed in proportion as they are removed from the axis of rotation. Thus the tip of the wing travels through a much greater space in a given time than a portion nearer the root. If the wing was not flexible and elastic, it would be impossible to reverse it at the end of the up and down strokes, so as to produce a continuous vibration. The wing is also practically hinged along its anterior margin, so that the posterior margin of the wing travels through a much greater space in a given time than a portion nearer the anterior margin. The compound rotation of the wing is greatly facilitated by the flexible and elastic properties of the pinion. It causes the pinion to twist upon its long axis during its vibration, as already fully explained (see *g*, *r* and *a*, *s* of fig. 2, p. 336). The twisting referred to is partly a vital and partly a mechanical act; that is, it is occasioned in part by the action of the muscles, and in part by the greater momentum acquired by the tip and posterior margin of the wing, as compared with the root and anterior margin; the speed acquired by the tip and posterior margin causing them to reverse always subsequently to the root and anterior margin, which has the effect of throwing the anterior and posterior margins of the wing into figure of 8 curves. It is in this way that the posterior margin of the outer portion of the wing is made to incline forwards at the end of the down stroke (fig. 2 *g*, p. 336), when the anterior margin is inclined backwards, and that the posterior margin of the outer portion of the wing is made to incline backwards at the end of the up stroke (fig. 2 *a*, p. 336), when a corresponding portion of the anterior margin is inclined forwards.

The Angles formed by the Wing in Action.—Not the least interesting feature of the compound rotation of the wing, of the varying degrees of speed attained by its different parts, and of the twisting or plaiting of the posterior margin around the anterior, is the great variety of kite-like surfaces developed upon its dorsal and ventral aspects. Thus the tip of the wing forms a kite which is inclined upwards, forwards, and outwards, while the root forms a kite which is inclined upwards, forwards, and inwards. The angles made by the tip and outer portions of the wing with the horizon are less than those made by the body, and those made by the body less than those made by the root and inner portions. The inclined surfaces peculiar to any portion of the wing become more inclined as the speed peculiar to said portion decreases, and *vice versa.* The wing is consequently mechanically perfect, the angles made by its several parts with the horizon being accurately adjusted to the speed attained by its different portions during its travel to and fro. From this it follows that the air set in motion by one part of the wing is seized upon and utilised by another, the inner and anterior portions of the wing supplying, as it were, currents for the outer and posterior portions. This results from the wing always forcing the air outwards and backwards. These statements admit of direct proof, and I have frequently satisfied myself of their exactitude by experiments made with natural and artificial wings.

In the bat and bird the twisting of the wing upon its long axis is more of a vital and less of a mechanical act than in the insect, the muscles which regulate the vibration of the pinion in the former (bat and bird), extending quite to the tip of the wing.

The Body and Wings move in Opposite Curves.—I have stated that the wing advances in a waved line, as shown at *a c e g i* of figure 14, p. 344; and the same remark holds true, within certain limits, of the body as indicated at 1, 2, 3, 4, and 5 of the same figure. Thus, when the wing descends in the curved line *a c,* it elevates the body in a corresponding but minor curved line, as shown at 1, 2; when, on the other hand, the wing ascends in the curved line *c e,* the body descends in a corresponding but smaller curved line (2, 3), and so on *ad infinitum.* The undulations made by the body are so trifling when compared with those made by the wing that they are apt to be overlooked. They are, however, deserving of attention, as they exercise an important influence on the undulations made by the wing, the body and wing swinging forward alternately, the one rising when the other is falling, and *vice versa.* Flight may be regarded as the resultant of three forces:—the *muscular and elastic force,* residing in the wing, which causes the pinion to act as a true kite, both during the down and up strokes; the *weight of the body,* which becomes a force the instant the trunk is lifted from the ground, from its tendency to fall downwards and forwards; and *the recoil obtained from the air* by the rapid action of the wing. These three forces may be said to be active and passive by turns.

Analysis of the Down and Up Strokes in the Insect—the Terms Extension and Flexion defined.—As considerable confusion exists in the minds of most investigators as to the precise changes induced in the wing during the *down* and *up* strokes respectively, and in especial as to the manner in which the wing is elevated, so as to avoid the resistance of the air and yet afford support, I have felt it incumbent upon me carefully to analyse the movements as observed in progressive flight. In insects the wings are variously arranged during the period of repose. In some they are elevated above the body, as in the butterfly; in others, they are disposed on the same level with the body, and rest upon the dorsal surface of the abdomen, as in the common fly; in a third, the wings are arranged partly on the sides and partly upon the dorsal aspect of the body, the anterior or thick margin of the wing being in such cases directed downwards, as in the cicada. This is also the position occupied by the wings of the bat and bird, the pinions, when not employed in flying, being folded upon themselves to economise space. In some insects, as the ephemera or mayfly, the beetles, locusts, &c., the wings are also folded upon themselves during the intervals of rest. The power which some wings possess of alternately folding, flexing, or crushing their component parts together, and of extending and widely separating them, has introduced the terms *extension* and *flexion:* extension, strictly speaking, signifying the opening out or spreading of the pinion, and the carrying of it away from the body in the direction of the head of the animal; flexion signifying the folding of the pinion, and the drawing of it towards the body in a direction from before backwards. The terms extension and flexion, when applied to insect wings, which are in one piece, and which consequently do not admit of being alternately opened and closed to any great extent, are only partly correct,—extension in the insect, signifying the carrying of the wing away from the body in a plane nearly on the same level with it in the direction of the head; flexion the drawing back or recovering of the wing until it regains its original position.

The terms extension and flexion have, unfortunately, got mixed up with the expressions the *down* and *up* strokes, from the fact that the wings of bats, birds, and some insects are always extended towards the termination of the up strokes, and flexed towards the termination of the down ones. This confusion is the more natural as all wings when extended rotate upon their long axes in such a manner that their posterior margins are screwed *downwards* and *forwards.*

In all wings, whatever their position during the intervals of rest, and whether in one piece or in many, this feature is to be observed in flight. The wings are slewed downwards and forwards, *i.e.*, they are carried more or less in the direction of the head during their descent, and reversed or carried in an opposite direction during their ascent. In stating that the wings are carried away from the head during the back stroke, I wish it to be understood that they do not therefore necessarily travel backwards in space when the insect is flying forwards. On the contrary, the wings, as a rule, move forward in curves, both during the down and up strokes. The fact is, that the wings at their roots are hinged and geared to the body so loosely that the body is free to oscillate in a forward or backward direction, or in an up, down, or oblique direction. As a consequence of this freedom of movement, and as a consequence likewise of the speed at which the insect is travelling, the wings during the back stroke are for the most part actually travelling forwards. This is accounted for by the fact that the body falls downwards and forwards in a curve during the up or return stroke of the wings, and because the horizontal speed attained by the body is as a rule so much greater than that attained by the wings, that the latter are never allowed time to travel backward, the lesser movement being as it were swallowed up by the greater. For a similar reason the passenger of a steamship may travel rapidly in the direction of the stern of the vessel, and yet be carried forward in space,—the ship sailing much quicker than he can walk. While the wing is descending, it is rotating upon its root as a centre (short axis). It is also, and this is a most important point, rotating upon its anterior margin (long axis), in such a manner as to cause the several parts of the wing to assume various angles of inclination with the horizon.

Figures 16 and 17 will supply the necessary illustration.

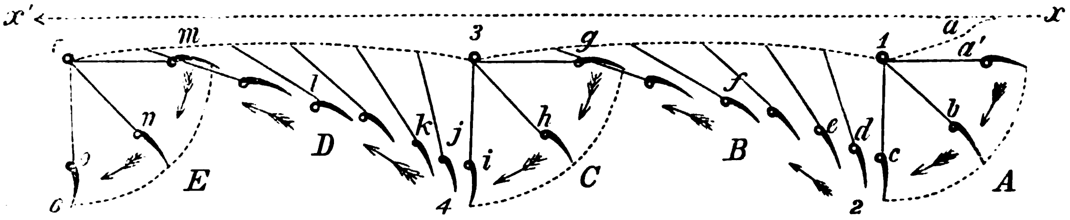

Fig. 16.

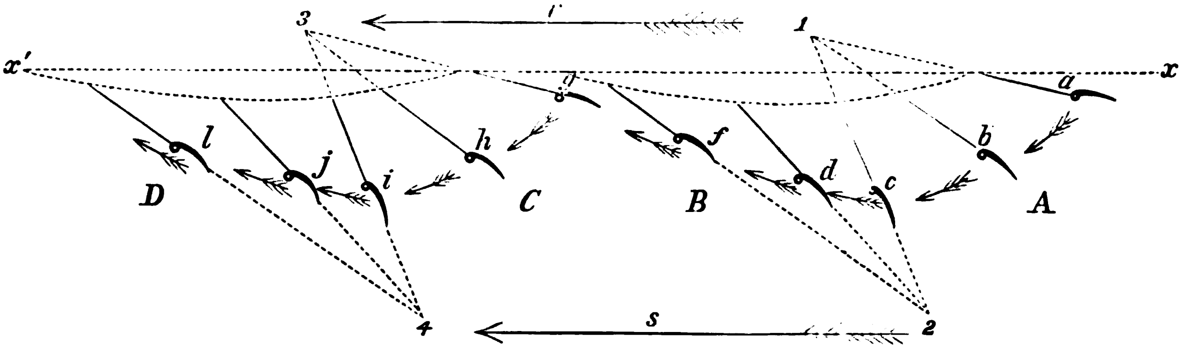

Fig. 17.

If, for example, we take the common blow-fly when reposing we will find that the plane of the wing (fig. 16 *a'*) is arranged in the same plane with the body, and that both are in a line with the horizon (*x x'*).* When, however, the

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* It happens occasionally in insects that the posterior margin of the wing is on a higher level than the anterior one towards the termination of the up stroke as shown at *a* (dotted line) of fig. 16. In such cases the posterior margin is suddenly rotated in a downward and forward direction at the

wing is made to descend, it gradually, in virtue of its simultaneously rotating upon its long and short axes, makes a certain angle with the horizon as represented at *b*. The angle is increased at the termination of the down stroke as shown at *c*, so that the wing, particularly its posterior margin, during its descent (*A*), is screwed or crushed down upon the air with its concavity or biting surface directed forwards and towards the earth. The same phenomena are indicated at *a b c* of fig. 17, p. 349, but in this figure the wing is represented as travelling more decidedly forwards during its descent, and this is characteristic of the down stroke of the insect's wing—the stroke in the insect being delivered in a very oblique and more or less horizontal direction, as shown at Plate XI. fig. 4. The forward travel of the wing during its descent has the effect of diminishing the angles made by the under surface of the wing with the horizon. Compare *b c d* of fig. 17 with the same letters of fig. 16. At fig. 15, page 345, the angles for a similar reason are still further diminished, and this latter figure gives a very accurate idea of the kite-like action of the wing both during its descent and ascent. The downward screwing of the posterior margin of the wing during the down stroke is well seen in the dragon-fly at page 361, fig. 38. (In this figure the arrows *r s* give the range of the wing.) At the beginning of the down stroke (dragon-fly) the upper or dorsal surface of the wing (*i d f*) is inclined *downwards and backwards*, the under or ventral surface *downwards and forwards*. In other words, the anterior margin (*i d*) of the pinion is directed slightly upwards and forwards, the posterior margin (*f*) slightly downwards and backwards. As the wing descends, which it does in a *downward and forward direction*, the posterior margin (*f*) is screwed downwards and forwards until it assumes the position indicated by *j*; the anterior margin (*i d*) inclining more and more upwards and backwards, as shown at *g h*. This rotation of the posterior margin (*j*) round the anterior margin (*g h*) has the effect of causing the different portions of the under surface of the wing to assume various angles of inclination with the horizon, the wing attacking the air like a boy's kite. The angles are greatest towards the root of the wing and least towards the tip. They accommodate themselves to the speed at which the different portions of the wing travel—a small angle with a high speed giving the same amount of buoying power as a larger angle with a diminished speed. The screwing of the under surface of the wing (particularly the posterior margin) in a downward direction during the down stroke is necessary to insure a sufficient upward recoil, the wing being made to swing downwards and forwards pendulum fashion, for the purpose of elevating the body, which it does by acting upon the air as a long lever, and after the manner of a kite. During the down stroke the wing

beginning of the down stroke—the downward and forward rotation securing additional elevating power for the wing. The posterior margin of the wing in bats and birds, unless they are flying downwards, never rises above the anterior one, either during the up or down stroke.

is active—the air passive. In other words, the wing is depressed by a purely vital act. This is proved by taking a living or dead blow-fly, and forcibly depressing its wing in the direction of the head by the aid of a slender rod. This act causes the wing to make various angles of inclination with the horizon, as shown at *a b c d e f g* of fig. 18 ; but the instant the rod is removed the wing obliterates the angles in question, and flies in an upward and backward direction to its original position as indicated at *g h i j k l m* of fig. 19.

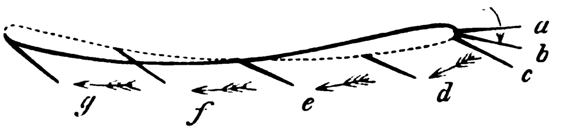

Fig. 18.

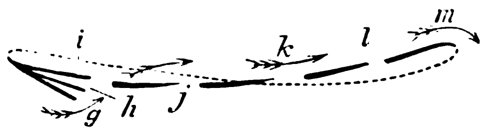

Fig. 19.

This shows very satisfactorily that while a voluntary effort is required to depress the wing, it is in some measure elevated, and the various inclined surfaces which it makes with the horizon changed by the aid of an elastic ligament or spring common to all wings. The down stroke is readily explained, and its results upon the body obvious. The real difficulty begins with the up or return stroke. If the wing was simply to travel in an upward and backward direction from *c* to *a'* of fig. 16, page 349, it is evident that it would experience much resistance from the superimposed air, and undo or negative the advantages secured by the descent of the wing. What really happens is this. The wing does not travel upwards and *backwards* in the direction *c b a'* of fig. 16 (the body be it remembered is advancing), but upwards and *forwards* in the direction *c d e f g*. This is brought about in the following manner. The wing is at right angles to the horizon (xx') at *c*. It is therefore caught by the air because of the more or less horizontal travel of the body at 2, the elastic ligaments and other structures rotating the posterior or thin margin of the pinion in an upward direction, as shown at *g h i* of figure 19, page 351, and *d e f g* of figure 16, page 349. The wing by this partly vital and partly mechanical arrangement is rotated off the wind in such a manner as to keep its dorsal or non-biting surface directed upwards, while its concave or biting surface is directed downwards. The wing, in short, has its planes so arranged, and its angles so adjusted to the speed at which it is travelling, that it darts up a gradient like a true kite, as shown at *c d e f g* of figures 16 and 17, page 349. The wing consequently elevates and propels during its *ascent* as well as during its *descent*. It is, in fact, a kite during both the down and up strokes. The ascent of the wing is greatly assisted by the *forward* travel of the body. It is further assisted by the downward and forward fall of the body. This view will be readily understood by supposing, what is really the case, that the wing is more or less fixed by the air in space at 2 of figure 16, page 349, and that the body, the instant the wing is fixed, falls downwards and forwards in a curve, which, of course, is equivalent to placing the wing above, and, so to speak, behind the insect—in other words, to elevating the wing preparatory to a second down stroke, as seen at *g* of figures 16 and 17, page 349.*

The Body ascends when the Wing descends, and vice versa.—The manner in which the body falls downwards and forwards in progressive flight is illustrated at figs. 20, 21, and 22.

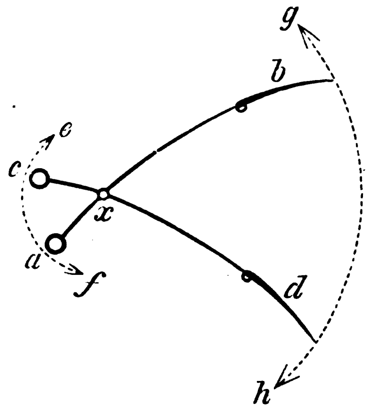

Fig. 20.

At fig. 20 the body is represented at *a* and *c*, the wing at *b* and *d*, *x* supplying the fulcrum or pivot on which the body and wing oscillate.

If the body (*a*) is elevated in the direction *e*, the wing (*b*) of necessity descends in the direction *h*. If, on the other hand, the body (*c*) descends in the direction *f*, the wing (*d*) ascends in the direction *g*. The ascent or descent of the wing is always very much greater than that of the body, from the fact of the pinion acting as a long lever. The remarks just made are true more especially of the body

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* When a bird rises from the ground it runs for a short distance, or throws its body into the air by a sudden leap, the wings being simultaneously elevated. When the body is fairly off the ground, the wings are made to descend with great vigour, and by their action to continue the upward impulse secured by the preliminary run or leap. The body then falls in a curve downwards and forwards, the wings, partly by the fall of the body, partly by the reaction of the air, on their under surface, and partly by the contraction of the elevator muscles and elastic ligaments being placed above, and to some extent behind the bird—in other words, elevated. The second down stroke is now given, and the wings again elevated as explained, and so on " ad infinitum," the body falling when the wings are being elevated, and *vice versa*, as shown at fig. 14, p. 344. When a long-winged oceanic bird rises from the sea, it uses the tips of its wings as levers for forcing the body up, the points of the pinions suffering no injury from being brought violently in contact with the water. A bird cannot be said to be flying until the trunk is swinging forward in space and taking part in the movement. The hawk, when fixed in the air over its quarry, is simply supporting itself. To fly, in the proper acceptation of the term, implies to support and propel. This constitutes the difference between a bird and a balloon. The bird can elevate *and carry itself forward*, the balloon can simply elevate itself, and must rise and fall in a straight line in the absence of currents. When the gannet throws itself from a cliff the inertia of the trunk at once comes into play, and relieves the bird from those herculean exertions required to raise it from the water when it is once fairly settled thereon. A swallow dropping from the eaves of a house, or a bat from a tower, afford illustrations of the same principle. Many insects launch themselves into space prior to flight. Some, however, do not. Thus the blow-fly can rise from a level surface when its legs are removed. This is accounted for by the greater amplitude and more horizontal play of the insect's wing as compared with that of the bat and bird, and likewise by the remarkable reciprocating power which it possesses when the body of the insect is not moving forwards. (*Vide* figs. 3, 4, 5, and 6, page 338). When a beetle attempts to fly from the hand it extends its front legs and flexes the back ones, and tilts its head and thorax upwards so as exactly to resemble a horse in the act of rising from the ground. This preliminary over, whirr go its wings with immense velocity, and in an almost horizontal direction, the body being inclined more or less vertically. The insect rises very slowly, and often requires to make several attempts before it succeeds in launching itself into the air. I could never detect any pressure communicated to the hand when the insect was leaving it, from which I infer that it does not leap into the air. The bees, I am disposed to believe, also rise without anything in the form of a leap or spring. I have often watched them leaving the petals of flowers, and they always appeared to me to elevate themselves by the steady play of their

and wing when oscillating on either side of the fixed point *x*, this furnishing the fulcrum on which the body and the wing alternately act. The peculiarity, however, of the wing consists in the fact that it is a flexible lever and acts upon yielding fulcra (the air), the body participating in, and to a certain extent perpetuating the movements originally produced by the pinion. The part which the body performs in flight is illustrated at fig. 21. At *a* the body is depressed, the wing being elevated and ready to make the down stroke at *b*. The wing descends in the direction *c d*, but the moment it begins to descend the body moves *upwards and forwards* (see arrows) in a curved line to *e*. As the wing is attached to the body it is made gradually to assume the position *f*. The body is now elevated and the wing depressed, the under surface of the latter being so adjusted that it strikes upwards and forwards as a kite would. The body now falls *downwards and forwards* in a curved line to *g*, and in doing this it elevates or assists in elevating the wing to *j*. The pinion is a second time depressed in the direction *k l*, which has the effect of forcing the body along a waved track and in *an upward direction* until it reaches the point *m*. The ascent of the body necessitates the descent of the wing as at *n*. The body and wing, as will be seen from this figure, are alternately above and beneath a given line *x x′*. The same points are shown at fig. 22, the only difference being that the sweep of the wing is greater and the undulation made by the body less abrupt, as seen in vigorous flight. At *a* the body is depressed, and the wing (*b*) elevated high above the body. The pinion (*b*) descends in the direction *c d*, and forces the body in *an upward curve* to *e*. The body (*e*) is now elevated and the wing (*f*) depressed. The body (*e*) *falls downwards and*

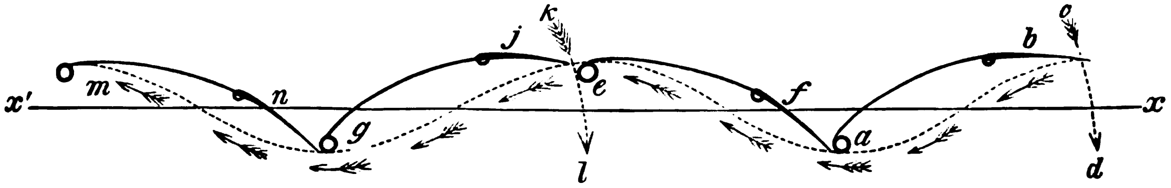

Fig. 21.

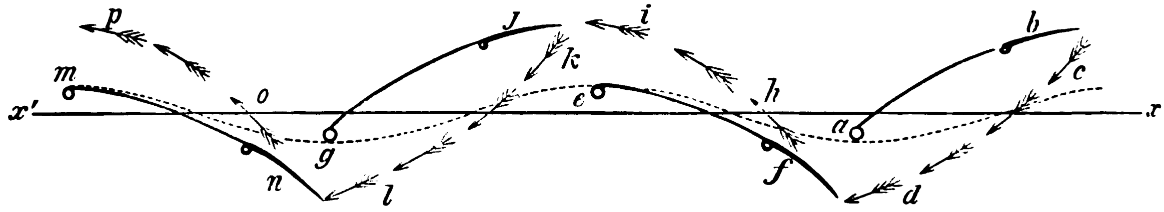

Fig. 22.

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wings, which was the more necessary, as the surface from which they rose was in many cases a yielding surface. The falling forward of the body during flight was indicated in my Memoir "On the Mechanism of Flight," Trans. Linn. Society, vol. xxvi. p. 226.

forwards in a curve to *g*, the pinion (*f*) by this act being made to describe the segment of a circle *h i j*, its under concave surface being applied to the air like a kite all the time. (It is thus that the wing elevates and sustains during the up stroke.) The wing (*j*) is made to descend in the direction *k l*, and forces the body (*g*) along *an upward curve* until it arrives at *m*, its subsequent fall elevating the wing (*n*) in the direction *o p*. Here again, the body and wing play alternately on either side of a given line *x x'*.

A careful study of figs. 20, 21, and 22 (pages 352, 353) shows the great importance of the twisted configuration and curves peculiar to the natural wing. If the wing was not curved in every direction it could not be rolled on and off the wind during the down and up strokes, as seen more particularly at fig. 22. This, however, is a vital point in progressive flight. The wing (*b*) is rolled on to the wind in the direction *c d*, its under concave or biting surface being crushed hard down with the effect of elevating the body to *e*. The body falls to *g*, and the wing (*f*) is rolled off the wind in the direction *h i*, and elevated partly by the action of the elevator muscles and elastic ligaments, and partly by the reaction of the air, operating on its under or concave biting surface, until it assumes the position *j*. The wing is therefore to a certain extent resting during the up stroke. The concavo-convex form of the wing is admirably adapted for the purposes of flight. In fact, the power which the wing possesses of always keeping its concave or under surface directed *downwards* and more or less *forwards* enables it to seize the air at every stage of both the up and down strokes so as to supply a persistent buoyancy. The action of the natural wing is accompanied by remarkably little slip—the elasticity of the organ, the resiliency of the air, and the contraction and relaxation of the elastic ligaments and muscles all co-operating and reciprocating in such a manner that the descent of the wing elevates the body, the descent of the body aided by the reaction of the air and the contraction of the elastic ligaments and muscles elevating the wing. The wing during the up stroke *arches above the body* after the manner of a parachute, and in turn prevents the body from falling. The sympathy which exists between the parts of a flying animal and the air on which it depends for support and progress is consequently of the most intimate character.

The up stroke (B of figures 16 and 17, page 349), as will be seen from the foregoing account, is a compound movement due in some measure to recoil or resistance on the part of the air—to the contraction of the muscles, elastic ligaments, and other vital structures, to the elasticity of the wing, and to the falling of the body in a downward and forward direction. The wing may be regarded as rotating during the down stroke upon 1 of figure 16, page 349, which may be taken to represent the long and short axes of the wing, and during the up stroke upon 2, which may be taken to represent the yielding fulcrum furnished by the air.

The same points are illustrated at 1 and 2 of figure 17, page 349, allowance being made in this case for the greater horizontal travel of the body during the down (A C) and up (B D) strokes, the increased horizontal travel of the body, as already pointed out, having the effect of diminishing the angles made by the under surface of the wing with the horizon during its vibrations.

The Wing acts upon Yielding Fulcra.—The chief peculiarity of the wing, as has been stated, consists in the fact that it is a twisted flexible lever specially constructed to act upon yielding fulcra (the air). The points of contact of the wing with the air are represented at *a b c d e f g h i j k l* respectively of figures 16 and 17, page 349, and the imaginary points of rotation of the wing upon its long and short axes at 1, 2, 3, and 4 of the same figures. The assumed points of rotation advance from 1 to 3, and from 2 to 4 (*vide* arrows marked *r* and *s*, fig. 17). The actual points of rotation correspond to the little loops *a b c d e f g h i j k l* of same figure; the descents of the wing to A and C, and the ascents to B and D. When the wing is in the position represented at *g* of figures 16 and 17, page 349, it is ready to begin a second down stroke, that is, it is screwed in a downward and forward direction. At *i* the second down stroke (C) is completed; at *i* the second up stroke is begun, the posterior margin of the wing being gradually rotated in an upward direction to prepare it for making the return or up stroke (D), as shown at *j k l m*. A third down stroke (E, fig. 16) is commenced at *m* and completed at *o*.

Weight contributes to Horizontal Flight.—That the weight of the body plays an important part in the production of flight may be proved by a very simple experiment. If two quill feathers are fixed into an ordinary cork, as represented at fig. 23, p. 356, and the apparatus is allowed to drop from a height, the cork does not fall vertically downwards, but *downwards* and *forwards* in a curve, and for the following reasons. The feathers *a b* are twisted flexible inclined planes, which arch in an upward direction. They are, in fact, true wings in the sense that an insect wing in one piece is a true wing. When dragged downwards by the cork (*c*), which would, if left to itself, fall vertically, they have what is virtually a down stroke communicated to them. Under these circumstances they inevitably dart forward; a struggle ensuing between the cork tending to fall vertically and the feathers tending to travel in a horizontal direction. As a consequence, the apparatus describes the curve *d e f g* before reaching the earth, *h i*. This is due to the action and reaction of the feathers and air upon each other, and to the influence which gravity exerts upon the cork. The forward travel of the cork and feathers, as compared with the space through which they fall, is very great. Thus, in some instances, they advanced as much as a yard and a half in a descent of three yards.

When artificial wings constructed on the principle of natural ones (*vide* fig. 24, p. 357), with stiff roots (*c*, *a*), tapering semi-rigid anterior margins (*a b*, *c d*), and thin yielding posterior margins (*e f*, *g h*), are allowed to drop from a height (*r*), they describe double curves in falling, as shown at *m n o l*, *i j k l*, the roots of the wings (*c*, *a*) reaching the ground first, a circumstance which proves the greater buoying power of the tips of the wings. I might refer to many other experiments made in this direction, but sufficient have been adduced to show that weight, when acting upon wings, or, what is the same thing, upon elastic twisted inclined planes, must be regarded as an independent moving power. But for this circumstance flight would be at once the most awkward and laborious form of locomotion, whereas in reality it is incomparably the easiest and most graceful.* The power which rapidly vibrating wings have of sustaining a body which tends to fall vertically downwards, is much greater than one would naturally imagine, from the fact that the body, which is always beginning to fall, is never permitted actually to do so. Thus, when it has fallen sufficiently far to assist in elevating the wings, it is at once elevated by the vigorous descent of those organs. The body consequently never acquires the downward momentum which it would do if permitted to fall through a considerable space uninterruptedly. It is easy to restrain even a heavy body when beginning to fall, while it is next to impossible to check its progress when it is once fairly launched into space and travelling rapidly in a downward direction (see footnote to page 371).

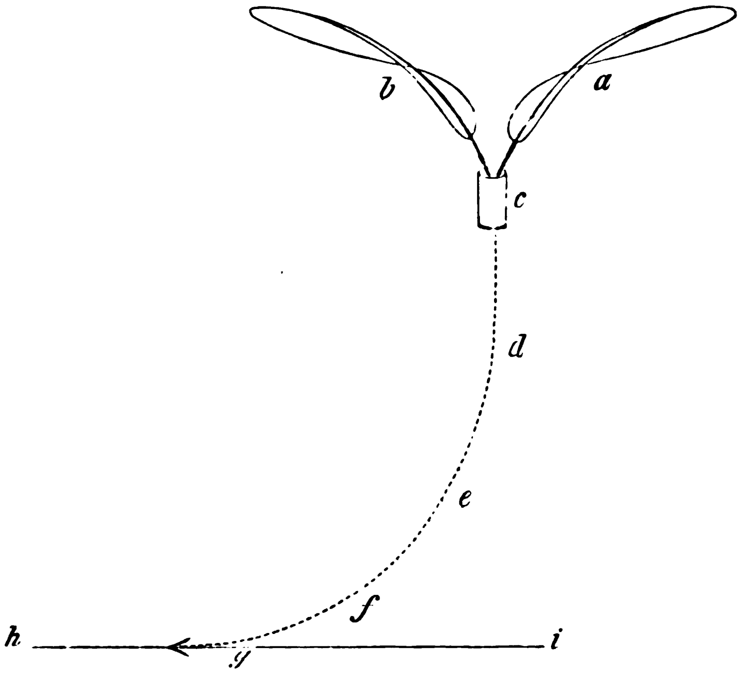

Fig. 23.

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* The importance to be attached to weight in flight is variously explained in my Memoir on the subject, Trans. Linn. Society, vol. xxvi. pages 218, 219, 246, 260, and 261.

Mechanical Theory of the Action of the Insect's Wing as stated by CHABRIER.—In one instance only, according to CHABRIER,* are the muscles of flight in insects inserted directly into the root of the wing. This solitary example is the dragon-fly. CHABRIER regards the action of the insect's wing as purely mechanical. His argument may be stated in a few words. He observes, that whereas the muscles which propel the wings of the insect are, with one exception (the dragon-fly), confined to the interior of the thorax, that therefore they exert no direct influence upon the wings. He further gives it as his opinion, that the wings are actuated by the muscles *only during the down stroke,* and that the up stroke is entirely due to the reaction of the air—in fact, that if the wings only be depressed rythmically, the air will do the remainder of the work. Unfortunately for this theory there is no time to wait for the reaction of the air, the wings being driven with such velocity as necessitates their being partly elevated either by elastic ligaments or elevator muscles, in addition to the reaction of the air (*vide* page 345). CHABRIER, as will be seen, delegates to the air the task of reversing the planes of the wing, and of conferring upon it *those peculiar curves* which, overlooked by him, I have

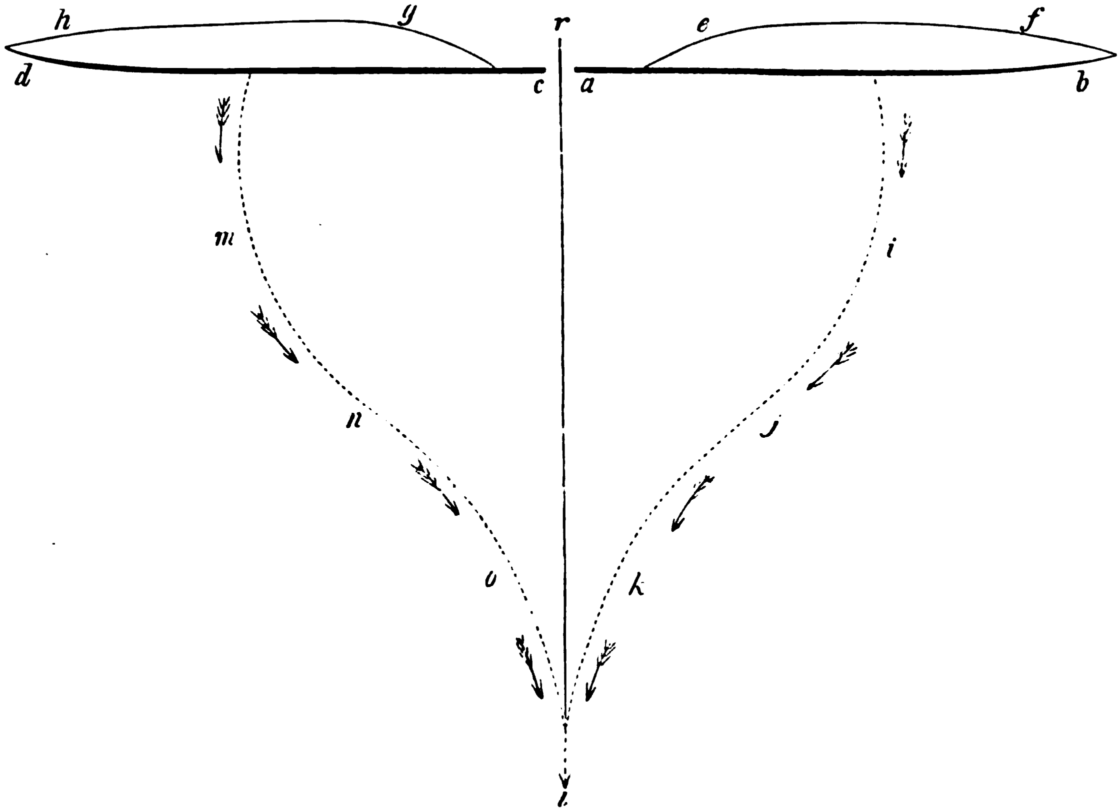

Fig 24.

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* Mémoires du Muséum d'Histoire Naturelle. Tome septième. Paris, 1821. Essai sur le vol des Insectes, par I. CHABRIER, p. 297. Plates x. xi. and xii.

endeavoured to show are indispensable in flight. In short, he confides to the air the delicate task of arranging the details of flight—those details constituting in reality the most difficult part of the problem.

Objections to the Mechanical Theory of Wing Movements.—There are many facts which militate against CHABRIER's mechanical theory of the movements of the insect's wing. I find, for example, that if the wing of the wasp, fly, humble bee, or butterfly be depressed by a delicate rod, its posterior margin is made to curve downwards, and to make various angles with the horizon (fig. 18, *a b c d e f g*, page 351); the wing, the instant the rod is removed, being flexed and elevated by the action of elastic ligaments which obliterate the angles formed during the depression (fig. 19, *g h i j k l m*, page 351). This implies the existence of a muscular system for depressing the wing, and a fibro-elastic system for elevating it, similar to what is found in the bat and bird, to be described presently. It also proves that the wing is jointed to the body in such a manner that it cannot either descend or ascend without changing the direction of its planes—the air taking no part in the change of plane referred to.

I find, secondly, that insects have the power of vibrating either wing by itself in any part of a radius not exceeding a half circle, and that the wing may be played above the body or on a level with or beneath it, as circumstances demand. These facts argue a much more intimate relation between the muscular system and the wings than CHABRIER is inclined to admit.

Thirdly, The wing in most insects is composed of two distinct portions at its root (figure 25, *a b*, p. 359), those portions being endowed with independent movements, which enable the insect to incline the anterior or thick margin (*a c f e*) of the wing in one direction, and the posterior or thin margin in another—to twist, in fact, the wing upon its long axis. This twisting of the wing upon its long axis exerts upon the organ precisely the same influence which the extending and flexing of the pinion does upon the wing of the bird and bat (figures 39, 40, 41, 42, and 43, p. 362). *It in short developes double figure of* 8 *curves along the anterior and posterior margins, and converts the wing into a screw capable of change of form.*

Fourthly, In the humble bee and other insects supplied with two pairs of wings geared to each other by hooklets, the posterior or thin margin of the first wing glides along the anterior or thick margin of the alula or second wing, which latter, acting as a long lever, has the power of adjusting the posterior or thin margin of the first wing.

Fifthly, In the wasp the first wing can be distinctly folded upon itself in the direction of its length, the alula or second wing folding upon the first wing previously folded, so that the area of the two wings is reduced to about one-third of what it was before the folding took place. When the wing is so folded it is very compact, and presents a well-defined cutting edge, which points in a backward direction.

I am induced to believe that the wing is folded after this fashion in certain cases during the back or return stroke, although the action of the pinion is so rapid that I have hitherto failed to make it out. The folding of the first wing upon itself in the wasp occurs in the line *g s* of fig. 25; the folding of the first wing upon itself and of the second upon the first, being seen at fig. 26 (*h d*); and the two wings, when folded and ready to make the return stroke, at fig. 27 (*d s*). The course pursued by the folded wings during the back stroke is indicated at *g h i j k l m* of fig. 19, page 351. Figure 28 represents the wing of the crane-fly, which has, I believe, a similar action, the thin posterior margin, *f g h i*, being folded during the back or return stroke, and opened out during the forward stroke.

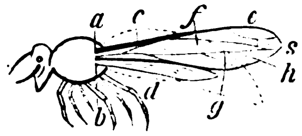

Fig. 25.

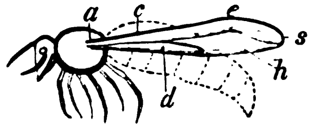

Fig. 26.

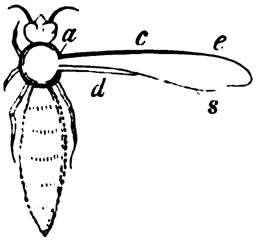

Fig. 27.

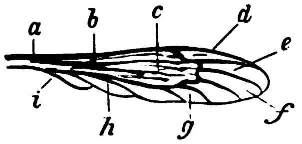

Fig. 28.

Sixthly, Many insects, such as the ephemera, beetles, locusts, &c., have assuredly the power of more or less completely crushing their wings together, and of alternately increasing and diminishing the wing area during the down and up strokes. The wings of most insects, moreover, are during the up stroke thrown into rugæ, which are flattened or altogether disappear during the down stroke. They further have the power of arching their wings during the up stroke, and of opening them out so as to increase their area during the down one. The butterfly affords an admirable example.

The Down and Up Stroke of the Wing of the Butterfly; Increase and Diminution of the Wing Area; Development of Figure of 8 *Curves on the Margins of the Wing.*—In the butterfly, as I have sufficiently satisfied myself, the first wing is made to pass above or over the second wing towards the termination of the down stroke, the convexity of both wings increasing meanwhile. This reduction in the wing area is necessary to destroy the momentum acquired by the wings during their descent, and to prepare them for making the up or return stroke. In the butterfly the wings strike downwards and forwards, and have a more vertical play than in almost any other insect. The wings are elevated in the overlapped arched condition, and towards the end of the up stroke they are gradually separated to increase the area and prepare them for making the down stroke in a manner precisely analogous to what happens in bats and birds. They are then made to descend in their flattened condition, the first wing passing over the second towards the termination of the down stroke as just stated. Nor is this all. While the wings are being depressed and made to overlap more or less completely, and while they are being elevated and spread out, *double and opposite curves are being developed along their anterior, posterior, and outer margins.* This is a somewhat remarkable circumstance, as the butterfly is perhaps the most awkward flying creature that exists. It seems to prove that the presence of *double or figure of* 8 *curves,* is indispensable to flight. These points are illustrated at figs. 29, 30, 31, 32, 33, and 34. At *a,* of fig. 29, the concavity of the first wing is directed downwards, the concavity of the second wing being directed slightly upwards as at *b.* The two curves taken together give a double or wave curve. In this figure the two wings are separated or spread out and ready to give the down stroke. At fig. 30 the two wings are separated to the utmost, and in the act of making the down stroke. Here the concavity of both wings is directed downwards as at *a,* a very small portion of the second wing only curving upwards (*b*). At fig. 31 the down stroke is completed, the first wing overlapping the second, and both being deeply concave on their under surfaces, as shown at *a.* They are now in a condition to make the up stroke, which is the reverse of the down one, and need not be described. The curves produced along the anterior and posterior margins of the wings of the butterfly during the up and down strokes are seen at figs. 32, 33, and 34. At fig. 32, the curves formed along the anterior (*c d*) and posterior (*e f*) margins of the first wing at the beginning of the down stroke, are represented. At fig. 33 the wing is represented, as seen at the middle of the down stroke, and the

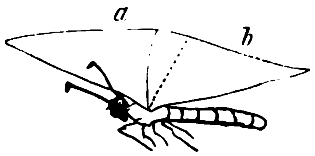

Fig. 29.

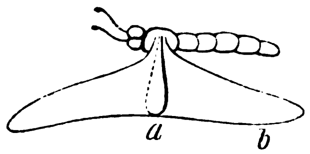

Fig. 30.

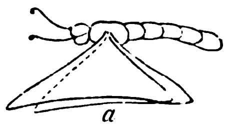

Fig. 31.

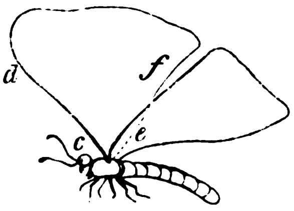

Fig. 32.

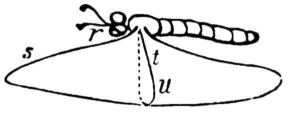

Fig. 33.

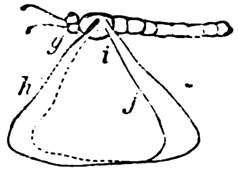

Fig. 34.

curves referred to are nearly obliterated (*vide r s, t u*). At fig. 34 the wing is shown at the end of the down stroke, and the curves are reversed, as a comparison of *c d, e f* of fig. 32 with *g h, i j* of fig. 34 will satisfactorily prove.

In the dragon-fly *similar figure of* 8 *curves are developed along the anterior and posterior margins of the wings* at the beginning, middle, and termination of the down stroke, as an examination of figs. 35, 36, 37, and 38 will show. If the letters *c d, e f* of fig. 35 (dragon-fly) be compared with corresponding letters of fig. 32 (butterfly); the letters *r s, t u* of fig. 37 (dragon-fly) with similar letters of fig. 33 (butterfly), and the letters *g h, i j* of fig. 36 (dragon-fly) with the same letters of fig. 34 (butterfly), it will at once be perceived that the curves which these letters represent are identical in both cases. At fig. 38 the wings are represented as seen at the beginning and end of the down stroke, the arrows *r, s* giving the range or play of the wings. The letters *d f* of this figure (anterior wing at beginning of down stroke) correspond with *d f* of fig. 35; the letters *g h i j* (anterior wing at end of down stroke) corresponding with similar letters in fig. 36. Fig. 38 shows how the posterior margin of the wing (*f*) is screwed *downwards and forwards* (*j*) during the down stroke (compare with *a, b, c* of figs. 16 and 17, page 349, and read remarks on the dragon-fly's wing at pages 335 and 350).*

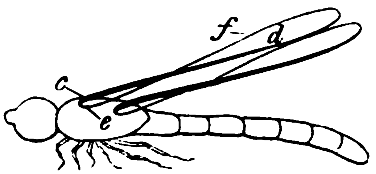

Fig. 35.

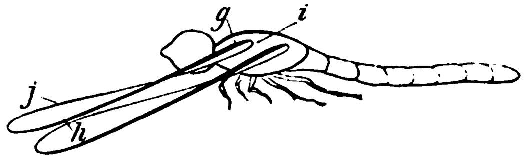

Fig. 36.

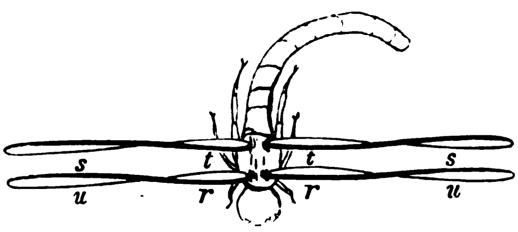

Fig. 37.

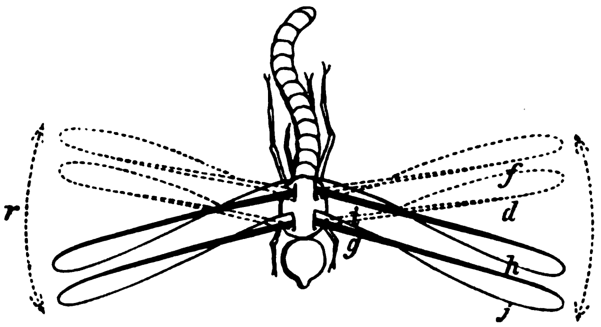

Fig. 38.

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* The wing area in insects is usually greatly in excess of what is absolutely required for flight, as the following experiments made with the common white and brown butterfly and dragon-fly will show :—

1. Removed posterior halves of first pair of wings of white butterfly. Flight perfect.

2. Removed posterior halves of first and second pairs of wings. Flight not strong but still perfect. If additional portions of the posterior wings were removed, the insect could still fly, but with great effort, and came to the ground at no great distance.

3. When the tips (outer sixth) of the first and second pairs of wings were cut away, flight was in no wise impaired. When more was detached the insect could not fly.

Curves in all respects analogous to those occurring in the wing of the butterfly and dragon-fly are observed in the wing of the bat and bird, as a reference to figs. 39, 40, 41, 42, and 43 will satisfy. They are also found in the rowing feathers of the wing of the bird, as shown at fig. 50, page 379.

Fig. 39.*

Fig. 40.

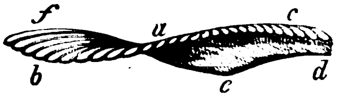

Fig. 41.

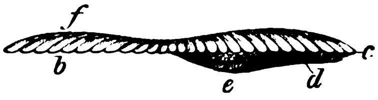

Fig. 42.

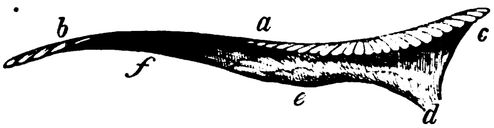

Fig. 43.

4. Removed the posterior wings of the brown butterfly. Flight unimpaired.

5. Removed in addition a small portion (one-sixth) from the tips of the anterior wings. Flight still perfect, as the insect flew upwards of ten yards.

6. Removed in addition a portion (one-eighth) of the posterior margins of anterior wings. The insect flew imperfectly, and came to the ground about a yard from the point where it commenced its flight.

7. In the dragon-fly either the first or second pair of wings may be removed without destroying the power of flight. The insect generally flies most steadily when the posterior pair of wings are detached, as it can balance better; but in either case flight is perfect and in no degree laboured.

8. Removed one-third from the posterior margin of the first and second pairs of wings. Flight in no wise impaired.

If more than a third of each wing be cut away from the posterior or thin margin, the insect can still fly, but with effort.

Experiment 8 shows that the posterior or thin flexible margin of the wing may be dispensed with in flight. It is more especially engaged in propelling.

9. The extremities or tips of the first and second pair of wings may be detached to the extent of one third, without diminishing the power of flight.

If the mutilation be carried further, flight is laboured, and in some cases destroyed.

10. When the front edges of the first and second pair of wings are notched, or when they are removed, flight is completely destroyed.

This shows that a certain degree of stiffness is required for the front edges of the wings, the front edges indirectly supporting the back edges It is, moreover, on the front edge of the wing that the pressure falls in flight, and by this edge the major portion of the wing is attached to the body. The principal movements of the wing are in addition communicated to this edge.

Note.—Some of my readers will probably infer from the foregoing experiments, that the figure of 8 curves formed along the anterior and posterior margins of the pinion are not necessary to flight, since the tip and posterior margin of the wing may be removed without destroying it. To such I reply, that the wing is flexible, elastic, and composed of a congeries of curved surfaces, and that so long as a portion of it remains, it forms, or tends to form, figure of 8 curves in every direction.

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* Figures 39, 40, 41, 42, and 43 show the double curves which occur on the anterior (*b a c*) and posterior (*d e f*) margins of the wing of the bat and bird.

Consideration of the Forces which Propel the Wings of Insects.—Proceeding now to a consideration of the forces which propel and regulate the wings of insects, I find that in the thorax of the insect the muscles are arranged in two principal sets in the form of a cross—*i.e.*, there is a powerful vertical set which runs from above downwards, and a powerful antero-posterior set which runs from before backwards. There are likewise a few slender muscles which proceed in a more or less oblique direction. The antero-posterior and vertical sets of muscles are quite distinct, as are likewise the oblique muscles. Portions, however, of the vertical and oblique muscles terminate at the root of the wing in jelly-looking points which greatly resemble rudimentary tendons, so that I am inclined to believe that the vertical and oblique muscles exercise a direct influence on the movements of the wing. The contraction of the antero-posterior set of muscles (indirectly assisted by the oblique ones) elevates the dorsum of the thorax by causing its anterior extremity to approach its posterior extremity, and by causing the thorax to bulge out or expand laterally. This change in the thorax necessitates the descent of the wing. The contraction of the vertical set (aided by the oblique ones) has a precisely opposite effect, and necessitates its ascent. While the wing is ascending and descending the oblique muscles cause it to rotate on its long axis, the bipartite division of the wing at its root, the spiral configuration of the joint, and the arrangement of the elastic and other structures which connect the pinion with the body, together with the resistance it experiences from the air, conferring on it the various angles which characterise the down and up strokes. The wing may therefore be said to be depressed by the contraction of the antero-posterior set of muscles, aided by the oblique muscles, and elevated by the contraction of the vertical and oblique muscles, aided by the elastic ligaments, and the reaction of the air. If we adopt this view we have a perfect physiological explanation of the phenomenon, as we have a complete circle or cycle of motion, the antero-posterior set of muscles contracting when the vertical set of muscles are relaxing, and *vice versa*, an arrangement which gives an equal period of activity and repose to both sets. This, I may add, is in conformity with all other muscular arrangements, where we have what are usually denominated extensors and flexors, but which, as I have shown elsewhere,* are simply the two halves of a circle of muscle and of motion, an arrangement for securing diametrically opposite results in limbs and the condition of activity and rest in muscles.

CHABRIER'S account, which I subjoin, virtually supports this hypothesis :—

"It is generally through the intervention of the proper motions of the dorsum, which are very considerable during flight, that the wings or the elytra are moved equally and simultaneously. Thus, when it is elevated, it carries

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* On the Mechanical Appliances by which Flight is attained in the Animal Kingdom, Trans. Linn. Society, vol. xxvi. pages 200, 201, and 262.

with it the internal side of the base of the wings with which it is articulated, from which ensues the depression of the external side of the wing; and when it approaches the sternal portion of the trunk, the contrary takes place. During the depression of the wings the dorsum is curved from before backwards, or in such a manner that its anterior extremity is brought nearer to its posterior, that its middle is elevated, and its lateral portions removed further from each other. The reverse takes place in the elevation of the wings; the anterior extremity of the dorsum being removed to a greater distance from the posterior, its middle being depressed, and its sides brought nearer to each other. Thus its bending in one direction produces a diminution of its curve in the direction normally opposed to it; and by the alternations of this motion, assisted by other means, the body is alternately compressed and dilated, and the wings are raised and depressed by turns." *

Objections to Mechanical Theory of Insect WingMovements specified.—The objections to CHABRIER's mechanical theory of the action of insects' wings may be briefly stated:—

First, The movements of the wings of insects are not necessarily absolutely synchronous. On the contrary, insects have the power of moving their wings independently.

Second, Insects can twist or plait their wings at the root—the butterfly having the power of causing the one wing to overlap the other when required.

Third, Insects can increase the convexity of their wings during the up stroke and decrease it during the down stroke.

Fourth, They can in some cases fold and diminish the area of the wing during the up stroke and increase it during the down one.

Fifth, In the dragon-flies we can without difficulty trace the muscles terminating in the roots of the wings—a presumptive proof that in other insects there is a direct connexion between the muscles of the thorax and the wings they are destined to move.

Sixth, All insects have the power of elevating their wings when dressing them, so that the reaction of the air is not necessary to the up stroke, although it certainly contributes to it in flight. They can, moreover, during the intervals of rest, develope figure of 8 curves along the anterior and posterior margins of the pinion independently of the air.

Seventh, There are muscles in the dragon-fly, and I believe in other insects also, delegated to elevate as well as depress the wing.

Eighth, There are elastic ligaments which recover or flex and *partly elevate the wing* when the organ is depressed artificially and not engaged in flight. In

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* "General Observations on the Anatomy of the Thorax in Insects, and on its Functions during Flight." By E. T. BENNETT, F.L.S., &c. (Extracted chiefly from the "Essai sur le vol des Insectes," par J. CHABRIER, Mém. du Muséum d'Histoire Naturelle. Zool. Journal, vol. i. art. xlvi. 1825.)

such cases the air can exert no influence whatever, as the wing is depressed gently, expressly to avoid recoil.

We have therefore the conditions of flight developed to nearly as great an extent in the insects as in the bats and birds. That distinct elevator and depressor muscles exist in the bat and bird, and that these act in conjunction with elastic ligaments there can be no doubt whatever, see pages 395, 396, and 397.

Wings Mobile and Flexible as well as Elastic—Elasticity, Flexibility, and Mobility not to be confounded—Mobility and Flexibility necessary to Flight.—Much importance has been attached by ancient and modern authors to the elastic properties of the wing, and not a few recent investigators are of opinion that flight is mainly due to the yielding of the wing to the impact of the air on its under surface during the down stroke. That, however, the mere elasticity of the pinion, if regarded apart from its mobility and flexibility, avails little may be proved in a variety of ways. By mobility I mean that power which the wing enjoys of moving at its root in an upward, downward, forward, backward, or oblique direction, and likewise the remarkable property which it possesses of rotating or twisting in the direction of its length. I also include under the term mobility the additional power possessed by bats and birds of opening and closing, *i.e.*, of flexing and extending the wings during the up and down strokes, as well as the power enjoyed by the bat of moving its fingers, and by the bird of moving its individual primary, secondary, and tertiary feathers at their roots. By the flexibility of the wing, I mean that power which the wing possesses of throwing itself into a great variety of curves during its action—these curves being formed, reversed, or obliterated at the will of the flying animal. It is necessary to distinguish between mobility, flexibility, and mere elasticity, because any rotation of the wing along its anterior or thick margin is at once followed by an elevation or depression of its posterior or thin margin, which elevation or depression is almost invariably and wrongly attributed to elasticity. That the wing is elastic throughout, and that its posterior or thin margin yields slightly (to prevent shock) when it attacks the air there can be no doubt. The yielding, however, is very slight, and it is always accompanied by a certain degree of rotation or torsion. If it were otherwise—if the posterior margin of the wing yielded to any marked extent in an upward direction when the wing descended, it is evident that the air on which the wing depended for support would escape from under it, and flight as a consequence be rendered abortive. It is the air more than the wing which yields or gives way in flight, and the yielding that occurs in the wings, is to be traced for the most part, to a rotation of the wing along its anterior margin—to movements occurring in the muscles and ligaments, and in the bones and feathers when present, particularly at the root of the feathers. These remarks are true of living wings. It is not, however, to be inferred from what is here stated that natural wings may not be successfully imitated, both in their structure and movements, by mechanical appliances in which elasticity plays a very prominent part. On the contrary, I am prepared to show further on, that flight may be regarded as a purely mechanical problem, and that it admits of a mechanical solution. I am, however, desirous of showing in the first place what movements are vital, what vito-mechanical, and what mechanical *in natural flight.* This done, we will then be in a position to enter upon a consideration of artificial flight. That elasticity of itself will not produce flight may be inferred from the following experiments. If, for instance, we lash light unyielding reeds to the anterior margins of a pigeon's wings so as to prevent flexion at the elbow-joints, we instantly destroy flight. In this experiment the *elasticity* of the wings, and particularly of the rowing feathers, is in no wise impaired; in reality the mobility and flexibility of the wings only are interfered with. A still more conclusive proof is to be found in the fact that in insects the most *elastic portions* of the wings can be *altogether removed* without destroying the power of flight. Thus I have cut away as much as two-thirds from the posterior margin of either wing of the blow-fly, and yet the insect flew with remarkable buoyancy. I have also removed portions of the tips of the wings with impunity. I made similar experiments with the dragon-fly, butterfly (pages 361 and 362), and sparrow, and with nearly uniform results.

Analysis of the Down and Up Strokes in the Wing of the Bird and Bat.—What was said of the movements of the wing of the insect holds equally true of those of the bat and bird, if allowance be made for the more vertical direction of the down and up strokes, and for the fact that the wings of the bat and bird are in several pieces and jointed.* The joints, like the muscles, extend in the direction of the length of the wing; thus, in addition to the shoulder-joint, we have the elbow, wrist, and finger joints. The insect, bat, and bird have the shoulder joint in common, and this joint is so constructed that the wing is free to move in an upward, downward, forward, backward, and oblique direction. It also admits of a certain amount of rotation or torsion in the direction of the length of the wing. The joint is in fact universal in its nature. Another feature possessed in common by insects, bats, and birds, is the elastic ligaments which recover and partly elevate the wing during the up stroke. Those ligaments in the bat and bird are not confined to the root of the wing, but extend along its margins even to its tip.

The presence of those ligaments shows that the wing is not elevated exclusively by the reaction of the air. There are, moreover, distinct elevator muscles in the wing of the bat and bird. The presence of voluntary muscles, and of elastic and other ligaments, afford important indications in the construction and

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* The beetles have also their wings jointed.

application of artificial wings, and I find that by employing a ball and socket joint, and a cross system of elastic bands at the root of the wing, I can imitate the movements of the natural wing with remarkable precision. By adopting the springs referred to—by making the wing elastic in all its parts, even along its anterior or thick margin (natural wings are elastic in this situation), and by applying a power which varies in intensity, I can communicate to an artificial wing a vibratory motion, completely devoid of *pauses or dead points.* The working of the wing in question is accompanied with very little slip. Indeed, the slip is so little that the wing may be said to supply a persistent buoying and propelling power. When the wing is made to vibrate briskly in a more or less vertical direction, it leaps forward in a series of curves, the down stroke running into the up one and *vice versa,* to form a continuous upward wave track. The power applied is greatest at the beginning of the down stroke. It is decreased at the end of the down stroke, slightly increased at the beginning of the up stroke, and again decreased towards the termination of that act. Those changes in the intensity of the driving power are necessary to allow the air time to react on the under surface of the wing, and to bring the elastic properties of the springs and of the wing into play. The springs should be arranged at right angles and obliquely, that is, there should be a superior, inferior, anterior, and posterior set running at right angles to each other, and between these as many oblique springs as are deemed necessary. The springs ought to vary as regards their length and their strength. Thus, the superior springs, which assist in elevating the wing, ought to be longer and stronger than the inferior ones; and the posterior springs, which restrain the wing from leaping forwards during its vibrations, should be longer and stronger than the anterior ones, the wing having no tendency to travel backwards. A detailed account of the structure and movements of artificial wings will be found at the end of the present memoir.

In the bat and bird the wing is extended or pushed away from the body prior to the down stroke, and folded or drawn towards the body prior to the up stroke. The unfolding or extending of the wing prior to the down stroke, as seen in the gull, is shown at Plate XI. figures 3, 2, 1, 5; Plate XIV. figure 18.

When the wing is being extended or opened out it is also being elevated, as shown at 1, 2, 3 of Plate XI. figure 5, and Plate XIV. figure 18. When the wing is flexed, as at *t p* of figure 3, Plate XI., the under surface of the wing (*s q*) is nearly on a level with the horizon (*b d*). When, however, the wing is partially extended, as at Plate XI. figure 2, the angle which its under surface makes with the horizon is considerable, *c b d* representing the angle, and *b d* the horizon. When the wing is fully extended, and ready to give the down stroke, the angle which the under surface of the wing makes with the horizon is still more increased, as shown at Plate XI. figure 1, *c b d* indicating the angle, and *b d* the horizon. The angle made by the under surface of the root of the wing with the horizon considerably exceeds that made by the tip, and is much greater than a casual observer would be inclined to admit. It is obscured by the curving downwards and forwards of the anterior margin of the wing towards the root, as seen at *a* of figure 7, Plate XII. In this figure the apparent angle made by the root of the wing with the horizon (*e f*) is *a b d*, the real angle being *c b d*. The wing of the bird rotates in opposite directions during extension and flexion. The various angles of inclination made by the wing of the gannet in extension and flexion is well shown at Plate XIII. figures 16 and 17.

In figure 17 (flexion) the posterior margin of the wing (*s q p o*) is on a level with the body of the bird; whereas in figure 16 (extension) the posterior margin (*q p o*) is directed downwards and forwards, as indicated by the arrows. The same thing is seen in the pea-wit, at Plate XII. figure 8. In this figure the wing to the right of the observer is flexed, and in the act of making the up stroke, the anterior margin of the pinion being slightly directed downwards (*vide* arrow). The wing to the left of the observer is, on the contrary, extended, and in the act of making the down stroke, the anterior margin of the pinion being directed upwards (*vide* arrow).

The rotation of the posterior margin around the anterior as an axis during extension, is occasioned by the points of insertion of the pectoralis major and other muscles, by the attachments and directions of the elastic and other ligaments, and by the spiral nature of the articular surfaces of the bones of the wing—the mere act of extension on all occasions involving the rotation in question.

The Wing of the Bird Descends as a Long Lever.—Let us imagine the wing fully extended and elevated, and making a certain angle with the horizon, as indicated at *c b d* of figure 1, Plate XI., at 3 of figure 5, Plate XI., and at 3′ of figure 18, Plate XIV. The wing is now prepared to make the down stroke, and descends in a spiral swoop, successively assuming the position 4 in figure 19, Plate XIV., and 4 in figure 6, Plate XI. It acts with extreme energy as a long lever (*vide c d* of figure 6, Plate XI.), the purchase which it has on the body being much greater than is usually anticipated.

During its descent the angle which the wing makes with the horizon is increased, as shown at *a b c* of figures 16 and 17 (page 349), the horizon in these figures being indicated by the straight line *x x′*.

In the bird, therefore, as in the insect, the posterior or thin flexible margin of the wing is screwed down upon the air while the wing is descending.

The Rotation of the Posterior Margin of the Wing in a Downward Direction increases the Elevating, but diminishes the Propelling Power of the Wing.—The additional hold which the bird can cause its wing to take of the air by resorting to a greater or less degree of rotation, is truly surprising. If the wing is depressed *minus* the rotation, it darts forward, but takes no very decided catch of the air. As a consequence, the recoil is feeble. If, however, the rotation is added, the wing seizes the air with such avidity as in all cases to produce a very violent reaction. The tendency of the wing to dart forward is diminished by the rotation, but the actual elevating power of the pinion is greatly augmented. This point can be readily ascertained by depressing and screwing, in the manner described, the wing of the swan or of any other large bird, previously dried, in the extended position. In preparing the wing for the experiment care should be taken not to destroy the curves peculiar to the natural extended wing. I mention this fact because, of many swans' wings prepared by me for this purpose, I found one had been inadvertently flattened, and gave quite an indifferent result.

The Importance to be attached to the Concavo-Convex Form of the Wing in Birds.—The downward screwing of the concave or under surface of the wing, which is so efficacious in securing a powerful hold of the air during the down stroke, is followed during the up stroke by an upward screwing of the convex or upper surface, which is not less effective in evading the air. In fact, when the wing ascends it is drawn towards the body, and deeply arched, so that it is literally made to roll upwards, its convex or dorsal surface being directed upwards throughout the entire up stroke. It is thus the wing evades the superincumbent air during the return stroke. This account will be readily understood by a reference to figures 13, 14, and 15, Plate XIII.

At figure 15, Plate XIII., the wing is represented as seen in the middle of the down stroke. It is widely spread out, and finely arched. At figure 14, Plate XIII., the wing is shown as observed towards the end of the down stroke—the wing being partly flexed or drawn towards the body, and the arch rendered more abrupt, particularly towards the root of the pinion. At figure 13, Plate XIII., the wing is seen quite at the termination of the down stroke. It is fully flexed, and drawn still closer to the body. It is, moreover, more deeply arched than in either of the other figures. It has, in fact, assumed the shape which offers least resistance in an upward direction, and is prepared to make the up stroke.

The Under or Concave Biting Surface of the Wing of the Bird effective both during the Down and Up Strokes.—If, instead of believing that *the wing is elevated*, we believe what, as I have already stated is actually the case, viz., that *the body of the bird falls downwards and forwards*, we at once transfer the resistance from the dorsal or convex non-biting surface of the wing to the ventral concave or biting surface—the body being supported while the wings are being elevated by a beautifully arched natural parachute formed by the wings. The elevation of the wings is, in short, in a great measure a consequence of the falling of the body. It is in this way that the air comes to assist in elevating the wings. The air, in short, caught under the wings is instrumental in elevating and extending them in proportion as the body falls (*vide* figures 13, 14, and 15, Plate XIII.) The small size of the elevator muscles of the wing of the bird and bat, as compared with the very powerful depressor muscles, is thus accounted for. The elevation of the wing, as will be inferred, is to a certain extent a mechanical act, and is due to the reaction of the air, the contraction of the elastic ligaments, and the downward and forward fall of the body. It is, however, not altogether mechanical, the wing, as I shall show subsequently, being perfectly under control both during the down and up strokes.

Lax Condition of the Shoulder Joint in Birds, &c.—The great laxity of the shoulder joint readily admits of the body falling downwards and forwards during the up stroke. This joint, as has been already stated, admits of movement in every direction, so that the body of the bird is like a compass set upon gimbals, *i.e.*, it swings and oscillates, and is equally balanced, whatever the position of the wings. The movements of the shoulder joint in the bird, bat, and insect, are restrained within certain limits by a system of check ligaments and prominences; but in each case the range of motion is very great, the wing being permitted to swing forwards, backwards, upwards, downwards, or at any degree of obliquity. It is also permitted to rotate along its anterior margin, or to twist in the direction of its length to the extent of nearly a quarter of a turn. This great freedom of movement at the shoulder joint enables the insect, bat, and bird, to rotate and balance upon two centres—the one running in the direction of the length of the body, the other at right angles, or in the direction of the length of the wings.

The Wings Elevated Indirectly by the Operation of Gravity.—I have explained that during the up stroke the body falls, and the wings are elevated. Let us now, for the sake of argument, advocate an opposite view. Let us take for granted that the body is fixed in space, and that the wings are elevated by a purely vital act. From this it follows that the wings during their ascent will of necessity experience much resistance from the superimposed air, the rounded form of the upper or dorsal surfaces of the pinions diminishing, but not removing the evil.

The resistance experienced by the wings during their ascent is obviated in the simplest manner possible, the movement, as has been explained, being dexterously transferred from the wings to the trunk in such a manner that the under or concave surfaces of the wings are made to act in lieu of the upper or convex surfaces. The body, in a word, is dragged downwards by the inexorable power of gravity; but the descent of the body involves the ascent of the wings. The body and wings, therefore, reciprocate, the body being elevated by the descent of the wings in conjunction with other means, while the wings are elevated to a great extent by the descent of the body, as shown at figures 20, 21, and 22, pages 352 and 353.* The wings are also partly elevated by the reaction elicited from the air—the contraction of the elevator muscles and elastic ligaments and the forward travel

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* The alternate ascent and descent of the wings and body during the down and up strokes are well seen in the butterfly and in all animals whose wings are large for their bodies.

of the body. The space through which the body descends when the wings ascend is very trifling, from the fact that the body is situated at the roots of the wings—a very slight movement at the roots of the pinions necessitating an extensive movement at the tips. This explains the very small waved track made by the body in progressive flight as compared with that made by the wings. (Contrast 1, 2, 3, 4, 5 of figure 14 page 344, with *a c e g i* of the same figure.)

The Wings of the Bird form a Natural Parachute from which the Body Depends both during the Down and Up Strokes.—The falling downwards of the body, and the gradual expansion and elevation of the wings during the up stroke, is seen at Plate XIII. figures 13, 14, and 15. At figure 13 the wings and the body are in the position peculiar to them at the end of the down stroke, *i.e.*, the body is elevated and the wings depressed. The up stroke is commenced, and the body falls, while the wings are somewhat expanded and elevated, as at Plate XIII. figure 14. The body falls still more, and the wings are further elevated and expanded, as seen at Plate XIII. figure 15. The wings are now on a level with the body of the bird, and mark how beautifully the latter is buoyed up. The body is attached to, and suspended from, a widespread finely arched parachute. The body goes on falling, and the wings rising, till the body is depressed and the wings elevated, as seen at 2, 2′ and 3, 3′ of figure 18, Plate XIV. This terminates the up stroke, and it will be observed that the position of the body is just the reverse of what it was at the beginning of the up stroke. At the beginning of the up stroke, the body was highest and the wings lowest (*vide* figure 13, Plate XIII.) At the end of the up stroke, the body is lowest and the wings highest (*vide* 3, 3′ of figure 18, Plate XIV.) That the body is supported and carried forward during the up stroke of the wings is proved beyond doubt by the experiment described at pages 355, 356, and illustrated by figure 23. If the quill feathers *a*, *b*, of figure 23 (p. 356) be compared with the two wings 3, 3′ of figure 18, Plate XIV., and the cork *c* of figure 23 with the body of the bird in figure 18, Plate XIV., it will be found that the conditions are the same in both, and that both are to a great extent sustained and carried forward in space, the one by the overarching feathers and the other by the overarching wings.* Perhaps the simplest illustration that can be given of

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* *Weight necessary to Flying Animals as at present constructed—Weight and Levity relatively considered with regard to Aërial and Subaquatic Flight* (Diving).—Captain W. F. Hutton, in a recent pamphlet (On the Sailing Flight of the Albatros, Phil. Mag., August 1869), contends, that whereas a bird lighter than the water can fly in it, so, in like manner, a bird lighter than the air could fly in this medium, and that therefore *weight* is not necessary to aërial flight. Captain Hutton, however, forgets that a bird destined to *fly above* the water is provided with travelling surfaces so fashioned and so applied (they strike from *above downwards and forwards*), that if it was lighter than the air, they would carry it off into space without the possibility of a return; in other words, the action of the wings would carry the bird obliquely upwards, and render it quite incapable of flying either in a horizontal or downward direction. In the same way a bird destined to *fly under* the water (auk and penguin), if it was not lighter than the water, such is the configuration and mode of applying its travelling surfaces (they strike *from below upwards and backwards*), they would carry it in the direction of the bottom

the mutual action and reaction of the body and wings during the up stroke is that furnished by a partly opened umbrella, whose handle has been intentionally weighted. If the umbrella thus prepared be dropped from a height, the

without any chance of return to the surface. In aërial flight, weight is the power which nature has placed at the disposal of the bird for regulating its altitude and horizontal flight, a cessation of the play of its wings, aided by the inertia of its trunk, enabling the bird to approach the earth. In subaquatic flight, levity is a power furnished for a similar but opposite purpose; this, combined with the partial slowing or stopping of the wings and feet, enabling the diving bird to regain the surface at any moment. Levity and weight are auxiliary forces, but they are necessary forces when the habits of the animals, and the form and mode of applying their travelling surfaces are taken into account. If the aërial flying bird was lighter than the air, its wings would requite *to be twisted round* to resemble the diving wings of the penguin and auk. If, on the other hand, the diving bird (penguin or auk) was heavier than water, its wings would require to resemble aërial wings, and they would require to strike in an opposite direction to that in which they strike normally. From this it follows that *weight* is necessary to the bird (as at present constructed) destined to navigate the air, and *levity* to that destined to navigate the water. If a bird was made very large and very light, it is obvious that the diving force at its disposal would be inadequate to submerge it. If, again, it was made very small and very heavy, it is equally plain that it could not fly. Nature, however, has struck the just balance; she has made the diving bird, which flies under the water, relatively much heavier than the bird which flies in the air, and has curtailed the travelling surfaces of the former, while she has increased those of the latter. For the same reason, she has furnished the diving bird with a certain degree of buoyancy, and the flying bird with a certain amount of weight—levity tending to bring the one to the surface of the water, weight the other to the surface of the earth, which is the normal position of rest for both. The action of the subaquatic or diving wing of the king penguin is well seen in the annexed woodcut (Fig. 44).

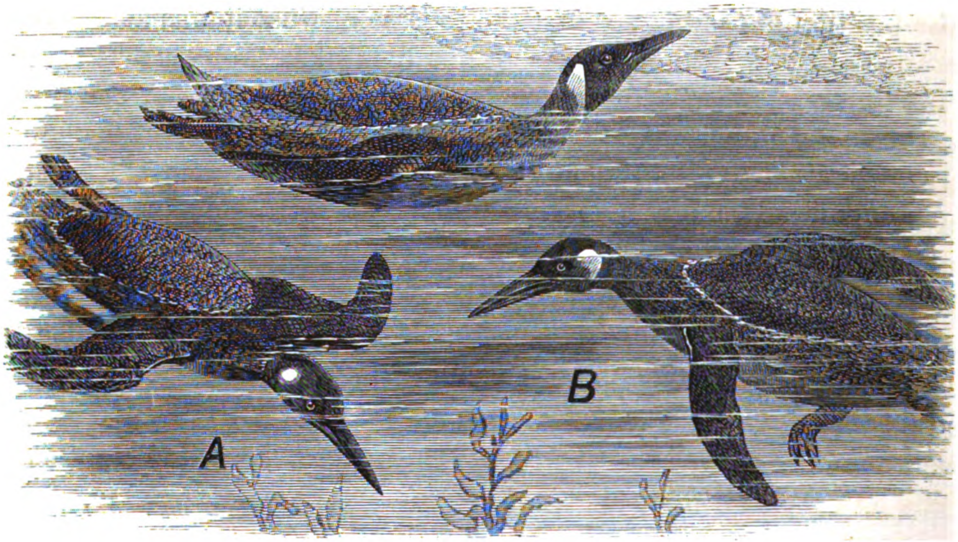

Fig. 44.

At A, the penguin is in the act of diving, and it will be observed that the anterior or thick margin of the wing is directed downwards and forwards, while the posterior margin is directed upwards and backwards. This has the effect of directing the under or ventral concave surface of the wing *upwards* and *backwards*, the effective stroke being delivered in this direction. The efficacy of the wing in counteracting *levity* is thus obvious. At B, the penguin is in the act of regaining the surface of the water, and in this case the wing is maintained in one position, or made to strike downwards and forwards like the aërial wing, the margins and under surface of the pinion being reversed for this purpose. The object now is not to depress but to elevate the body. Those movements are facilitated by the alterfalling of the weighted handle will have the effect, in conjunction with the resistance which the under concave surface of the umbrella experiences from the air, of opening it up, precisely as the wings are opened up and elevated at figures 13, 14, and 15, Plate XIII. And if it so happens that the steels of the umbrella are feeble, and the weight attached to the handle sufficiently great, the umbrella will be more or less everted, as shown at 2, $2'$ and 3, $3'$ of figure 18, Plate XIV. If the frame of the umbrella was endowed with vitality, and had the power of quickly regaining its original form, it would elevate the weighted handle, and so attain its original position. A repetition of those changes, if the proper degree and kind of power were added, would result in flight, particularly if one side of the umbrella was rendered more rigid than the other, as this would have the effect of conferring an eccentric action upon it. The parachute principle here advocated is corroborated to a certain extent by the flight of the beetles. In these, in some cases, the *elytra* or wing cases are deeply concavo-convex. The membranes or true wings strike in a downward, forward, and more or less horizontal direction, and in so doing they force the air forward under the ventral or concave surfaces of the elytra or false wings, which are thus converted into parachutes or tiny sustaining balloons. That the elytra perform a very important function in flight is proved by the fact that when they are removed the insect cannot fly. I had ocular demonstration of this at Somerton, Wexford, in the summer of 1868. When I amputated the elytra close to the roots, the insects could not rise, although they made frequent attempts to do so. The elytra or false wings and the membranous or true wings form, when extended, deeply concave or umbrella shaped surfaces, the peculiarity in such instances being that the umbrellas formed by the true wings move and are active; whereas those formed by the elytra are fixed or immobile, and consequently passive.

The Wing of the Bird elevated as a Short Lever.—In birds with short rounded wings, and in others with longer wings, in forced flight the wing is usually elevated as a short lever, as shown at 6 of figures 6 and 19, Plates XI. and XIV., and 1 of figures 5 and 18, Plates XI. and XIV.; it being extended or spread out quite towards the end of the up stroke, as represented at 1, 2, 3 of figures 5 and 18, Plates XI. and XIV. In birds with long pointed wings, when flying leisurely, the wing is not unfrequently expanded at the middle of the up

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nate play of the feet. What strikes one in the present woodcut is the comparatively small size of the diving or swimming wing, which resembles the flipper of the turtle, seal, sea bear, and walrus. At Plate XIII. figure 15, the aërial wing, as seen in the gull, is represented, and the large size of the flying pinion, as compared with the diving subaquatic one, is at once apparent. Here the anterior margin (x s t v w) of the wing is directed upwards and forwards, the posterior one (o p q) downwards and backwards. This causes the under or ventral concave surface of the pinion to look *downwards and forwards*, the direction in which the effective or down stroke is delivered. The aërial wing, like the subaquatic wing, *is twisted upon itself*. It strikes *downwards and forwards*, because this is the direction in which a body in motion would naturally fall.

stroke, as seen at 4 of figure 19, Plate XIV., and at figure 15, Plate XIII.; and it is no doubt this circumstance which has induced hasty generalisers to deny that the wing is flexed during the up stroke. This is a pardonable mistake, as the wing in such cases may be actually extended for two-thirds of the up stroke. When the wing is fully flexed and elevated as a short lever, its rowing feathers are separated and opened up, and the bird draws largely upon its vital resources. When, on the other hand, the wing is elevated as a long lever, and is wielded in one piece, after the manner of the insect wing, the bird takes advantage, to a great extent, of the numerous mechanical adaptations with which nature has endowed it. The flight of the albatros furnishes the best example. The opening up of the feathers during the up stroke facilitates the ascent of the pinion, and permits a more rapid action. The separation of the feathers is, however, not necessary to successful flight, the bat flying remarkably well by the aid of a continuous membrane which, as is well known, is destitute of feathers.

The Wing Vibrates Unequally on either Side of a given Line.—The wing, during its vibration, descends further below the body than it rises above it. This is necessary for *elevating purposes.* In like manner the posterior margin of the wing (whatever the position of the organ) descends further below a given line than it ascends above it. This is requisite for *elevating and propelling purposes,* the under surface of the wing being always presented at a certain upward angle to the horizon, and acting as a true kite. This view is fully explained at p. 345. If the wing oscillated equally above and beneath the body, and if the posterior margin of the wing vibrated equally above and below the line formed by the anterior margin, much of its elevating and propelling power would be sacrificed. The tail of the fish oscillates on either side of a given line, but it is otherwise with the wing of a flying animal. The fish is of nearly the same specific gravity as the water, so that the tail, as a rule, only propels. The flying animal, on the other hand, is very much heavier than the air, so that the wing requires both to propel and *elevate.* The wing to be effective as an *elevating organ* must consequently be vibrated rather below than above the centre of gravity; at all events, the intensity of the vibration should occur rather below that point. In making this statement, it is necessary to bear in mind that the centre of gravity is *ever varying,* the body rising and falling in a series of curves as the wings ascend and descend.

To *elevate* and *propel,* the posterior margin of the wing must rotate round the anterior one, the posterior margin being, as a rule, always on a lower level than the anterior one (*vide* pages 414, 415, and 416). By the oblique and more vigorous play of the wings *under* rather than *above* the body, each wing expends its entire energy in pushing the body *upwards* and *forwards.* Fig. 12, page 342, will illustrate my meaning. Let the oar x, s, represent the wing. If the wing be made to play equally above (*a b*) and below (*c d*) the body, the tendency is to drive the body in an *undulating line,* away from *x,* in the direction *s x.* As, however, the opposite wing tends to push the body in a precisely contrary direction, the forces exercised by the two wings neutralise each other in the mesial line of the bird, the force which ultimately prevails being that of gravity. To destroy the power of gravity, and to elevate and propel the bird, it is necessary that the wings descend further than they ascend, and that the posterior margins of the wings be constantly kept on a lower level than the anterior ones. It is also necessary that the wings be *convex* on their upper surfaces, and *concave* on their under ones, and that the concave or biting surfaces be brought more violently in contact with the air during the down stroke, than the convex ones during the up stroke. The greater range of the wing below than above the body, and of the posterior margin below than above a given line, may be readily made out by watching the flight of the larger birds. It is also well seen in the upward flight of the lark. The range of the wing of the gull in ordinary flight is shown at Plate XIV. fig. 19. When the wing is elevated high above the body, as represented at 3 of figures 5 and 18, Plates XI. and XIV., it is generally in the effort of rising, or in picking up garbage from the surface of the sea, or in suspending or letting the body down gradually prior to alighting. In such cases the wings expend their greatest force when a little above or on a level with the body, as is well exemplified in the hovering of the kestrel.

Compound Rotation of the Wing of the Bird.—To work the tip and posterior margin of the wing independently and yet simultaneously, two axes are necessary, one axis (the short axis) corresponding to the root of the wing; the second (the long axis) to the anterior margin. This renders the wing eccentric in its nature. The primary or rowing feathers are also eccentric, the shaft of each feather being placed nearer the anterior than the posterior margin, an arrangement which enables the feathers to open up and separate during the up stroke, and approximate and close during the down one. The axes of rotation in the wing of the bird are given at figure 19, Plate XIV., *a* representing the short axis around which the tip of the wing rotates with a radius *e b f; c,* the long axis, around which the posterior margin of the wing revolves with a radius *g d h.*

These points are more fully illustrated at figure 45, p. 376, where *a b* represents the short axis (root of wing), with a radius *e f; e d,* the long axis (anterior margin of wing), with a radius *g p.*

The Wing of the Bird cranked slightly Forwards—the Compound Rotation of the Rowing Feathers.—It will be observed from figure 45 (p. 376), that the wing is cranked somewhat forwards (compare position of axis *a b* with that of axis *c d*), a very slight movement of rotation along the anterior margin (*c d*) being accompanied by a considerable rotation of the posterior margin (*h i j k l*). This figure also shows that the individual primary, secondary, and tertiary feathers of the bird's wing have each what is equivalent to a long and a short axis. Thus the primary and secondary feathers marked *h i j, k l* are capable of rotating on their long axes (*r s*) and upon their short axes (*m n*). The feathers rotate upon their long axes in a direction from below upwards during the down stroke, to make the wing impervious to air; and from above downwards during the up stroke, to enable the air to pass through it. The primary, secondary, and tertiary feathers have thus a distinctly valvular action.* They rotate upon their short axes (*m n*) during the descent and ascent of the wing, the tips of the feathers rising slightly during the descent of the pinion and falling during its ascent.

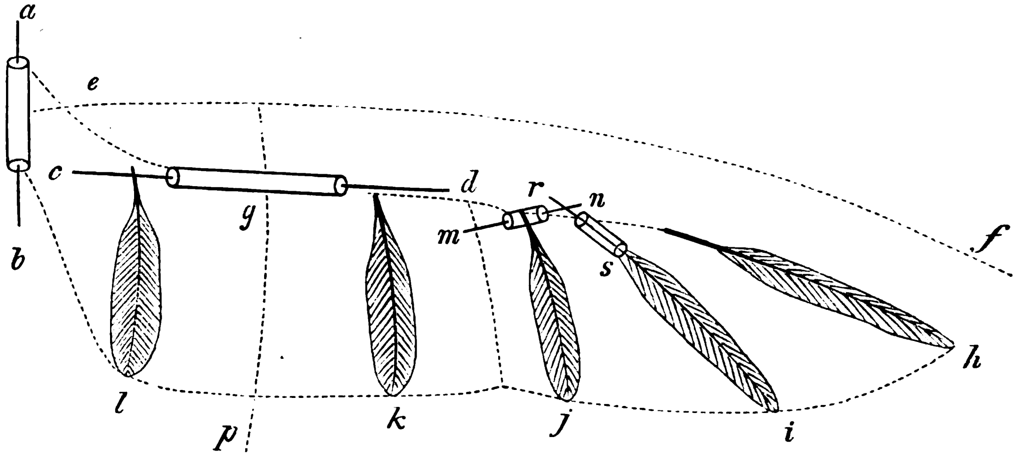

Fig. 45.

The Primary, Secondary, and Tertiary Feathers are Geared to each other, and Act in Concert.—To admit of the primary, secondary, and tertiary feathers rotating upon their long axes (*r s*), a very elaborate combination of fibrous and elastic structures, with a certain admixture of muscular substance, is necessary. The arrangement, as witnessed in the crested crane, is given at Plate XVI. figures 24, 25, 26, 27, and 28.

The roots of the primary, secondary, and tertiary feathers are imbedded behind the muscular mass (*f, f, h*), fig. 24, Plate XVI. The insertions of the roots of the feathers are shown in figure 28, Plate XVI. Each root is enveloped by a continuous elastic ligament (*o p q* of fig. 24), this ligament being provided with fibrous bands, which run in the direction of the length of the wing (*r s, t u, v w* of figs. 25 and 27, Plate XVI.) and obliquely (*g h, g h*). Two oblique bands (*g* and *h*) run between every two feathers (*x*), and are joined to the longitudinal ones (*rs tu vw*), and to the feathers in such a manner that the whole are geared together, an arrangement combining great freedom of movement with great strength. The longitudinal bands run along the roots of all the feathers, and

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* The valve action, as explained, is called more or less into play according to circumstances.

are three in number, the outermost band breaking up at the root of each feather, and giving off two processes (*a d, b e, c f* of figure 25, Plate XVI.), the one of which coils round the root of the feather in a spiral manner from right to left; the other coiling in an opposite direction, or from left to right (*m, n* of figure 26, Plate XVI.) The root of each feather is consequently enveloped by a fibrous investment, capable of rotating it in opposite directions. The fibrous bands referred to are arranged with much precision, and as they are geared to each other at stated intervals, they cause the feathers (right wing) to rotate at nearly the same instant from right to left, and from below upwards, during extension; and from left to right, and from above downwards, during flexion. The arrangement of the fibrous bands is much the same on the dorsal and ventral aspects of the wing (compare figs. 24 and 28). It varies slightly in different species of birds, but the function of the bands is the same in all.

The tips of the primary, secondary, and tertiary feathers are prevented from rising too high during the descent of the wing by the oblique overlapping of the feathers forming the primary, secondary, and tertiary coverts (*m, n, o* of figure 28, Plate XVI.), those feathers acting as buffers and limiting the action.

The Up or Return Stroke of the Wing of the Bird—Diminution of Area of Wing—Valvular Action, &c.—Towards the termination of the down stroke, the wing is suddenly flexed and drawn towards the body, as shown at 4, 5, 6 of figures 6 and 19, Plates XI. and XIV. This is necessary to convert the wing from a long (Plate XI. figure 6, *c d*) into a short lever (Plate XI. figure 6, *a b*), and to destroy the momentum acquired by the wing during its more or less vertical descent. While the wing is being shortened, the angles which the several portions of its under surface make with the horizon are being diminished (*c d e f* of figures 16 and 17, page 349); the angles made by the under surfaces of the rowing feathers from within outwards being increased (1 2 3 4 5 6 7 8 9 of fig. 46, p. 378). These changes prepare the wing of the bird for making an effective up or return stroke, and are necessitated by the more vertical play of the bird's wing, as compared with that of the insect. But for the diminution of the actual area of the wing during the up stroke, the upper or dorsal surface of the pinion would experience much resistance from the air during its ascent. This difficulty is in a great measure obviated by the wing being drawn close to the side of the body, and by its being made to assume a somewhat crippled appearance, the tip of the wing folding upon the root in a direction from below upwards, and in such a manner as to displace comparatively little air (*vide* 4, 5, 6 of figure 6, Plate XI.) The pinion is then, as a rule, elevated as a short lever (*a b* of figure 6, Plate XI.), until it attains the position indicated at 1 of figures 5 and 18, Plates XI. and XIV. In these situations the wing is for the most part deeply arched (*vide* figure 13, Plate XIII.) When the wing has assumed the position indicated by 1 of figures 5 and 18, Plates XI. and XIV., it is suddenly pushed away from the body, extended and elevated, as shown at 2 and 3 of the same figures; the angles made by the several portions of its under surface with the horizon being increased, while those formed by the under surfaces of the rowing feathers are decreased (1 2 3 4 5 6 7 8 9 of fig. 47). The wing thus comes to form a kind of natural parachute, as shown at 2, 2′ and 3, 3′ of figure 18, Plate XIV. This completes the up or return stroke. While the wing is ascending, the primary, secondary, and tertiary feathers rotate upon their long axes, and present their thin margins to the air, into which they cut like so many knives. The feathers are most widely separated at the beginning of the up stroke, and least at the termination of that act, as they then flap together to make the wing impervious, and prepare it for making the down stroke. The individual primary, secondary, and tertiary feathers are so arranged and so rotated that they open up, and close, and present the precise angles required for flight, whatever the shape and whatever the position of the wing.

Fig. 46.

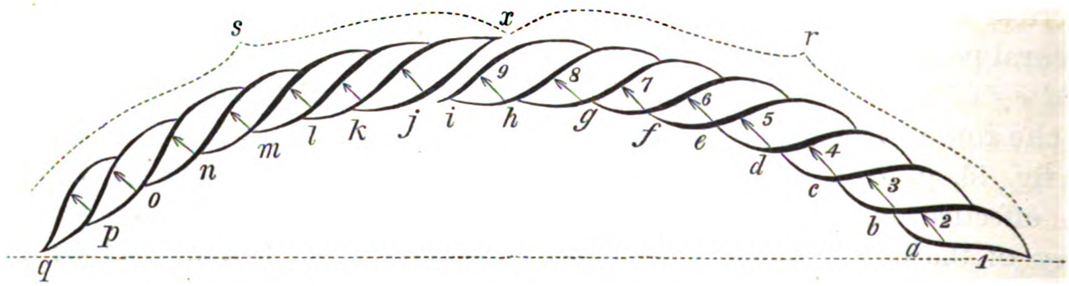

Fig. 47.

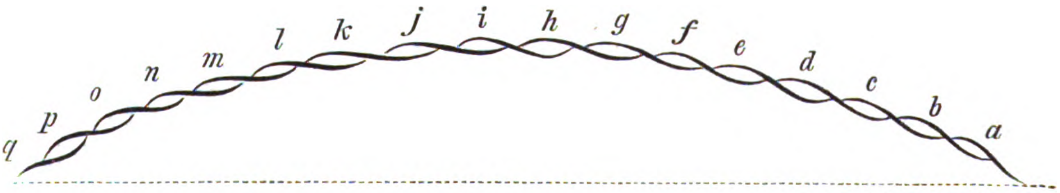

Fig. 48.

Figure 46 shows the tips of the primary (*r*) and secondary (*s*) feathers in the wing of the piet during flexion, and it will be observed that the angles made by the rowing feathers with the horizon (see straight dotted line) in a direction from within outwards is greater than those made by the same feathers (*r*), in extension, as represented at figure 47. In figure 46 the wing is folded upon itself at *x*, and presents two arches, a larger (*r*) and a smaller (*s*), the numbers 1 2 3 4 5 6 7 8 9 giving the position of the primary feathers when counted from without inwards, the arrows indicating the direction in which the primary and secondary feathers open up and cut into the air from below upwards and from within outwards during the up stroke. This figure shows that the primary and secondary feathers (particularly the former), when viewed from the tip, or when cut across, present a spiral contour (*c g* of figure 49). This arises from the primary and secondary feathers being twisted upon themselves, as represented at *a b*, *c d* of figure 50.

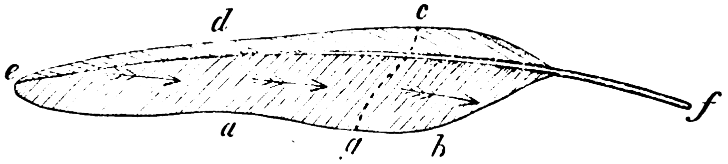

Fig. 49. Primary Feather, showing double curves at anterior margin (*c d*), posterior margin (*a b*), and across (*c g*).

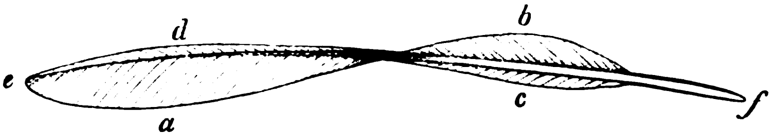

Fig. 50. The same, seen from before edgeways. Here the anterior (*c d*) and posterior (*a b*) margins cross each other.

Figure 47 shows that the primary and secondary feathers of the wing of the piet are thrown into a beautiful groined arch in extension, preparatory to the down stroke, the advantage in favour of a concave surface over a convex one for seizing air or water being something like 2 to 1. It also shows that the primary (*r*) and secondary (*s*) feathers in extension, and during the down stroke, rotate upon their long axes in a direction from below upwards, as indicated by the arrows *a b c d e f g h i j k l m n o p q*, so as to form an arch which cannot be destroyed so long as the individual feathers remain intact. In fact, the integral parts of the arch are so disposed that the greater the pressure the greater the strength. Figure 48 shows a similar groined arch formed by the roots of the primary and secondary feathers, the spirals constituting the arch (*a b c d e f g h i j k l m n o p q*) running in an opposite direction to those seen in figure 47, from the fact of the primary and secondary feathers being twisted upon themselves as already explained (compare *b c* with *a d* of figure 50). Fig. 20, Plate XIV. shows how the air is forced during the down stroke in a spiral direction (*vide* arrows) from without inwards, from before backwards, and from above downwards, the spiral currents from the two wings impinging upon the sides of the bird, which is wedge shaped, in such a manner as to force it upwards and forwards. The currents also cross and neutralise each other below the body of the bird, and thus supply additional buoyancy and propelling power. The arch made by the wing of the gull, when fully extended and ready to give the down stroke, is seen at 3, 3′ of figure 18, Plate XIV.; that made at the middle of the down stroke at figure 15, Plate XIII.; and that made at the end of the down stroke at figure 13, Plate XIII. The arch made by the wing of the gannet in extreme extension is shown at figure 16, Plate XIII.

The Primary, Secondary, and Tertiary Feathers Imbricate or Overlap.—Another point of interest in the bird's wing is the manner in which the various feathers (primary, secondary, and tertiary) overlap (fig. 20, Plate XIV.), and the varying degrees of strength which they exhibit. Proceeding from the tip of the wing towards the root we find as a rule that the first three primary feathers are longer and stronger and overlap more than the second three—the second three being longer, stronger, and overlapping more than the third three. These points are well seen in the acuminate scythe-like wing, of which that of the gull (fig. 15, Plate XIII.) and gannet (fig. 16, Plate XIII.) are good examples.* Similar remarks may be made of the secondary and tertiary feathers, as a reference to *p q* of fig. 16, Plate XIII., will show. Another not less interesting feature is the varying position of the vanes of the primary, secondary, and tertiary feathers. Thus, in the first primary the vane (*e f* of fig. 49, page 379), is placed quite on the anterior margin (*c d*) the posterior margin (*a b*) being three or four times broader than the anterior one to admit of overlapping. The vane of the feather occupies a more and more central position as we proceed from the tip in the direction of the root of the wing, as shown at *h i j k l* of fig. 45, page 376, and also at 1, 2, 3, 4, 5, 6, 7, 8, 9, *j k l m n*, &c., of fig. 20, Plate XIV. The first primary, as will be seen from this account, is eccentric in its nature. It is more eccentric than the second—the second being more eccentric than the third, and so of all the primary and secondary feathers, until the stem of the feather is found to occupy its centre. The posterior margin of the first primary, as a consequence, rotates more than that of the second—the second than the third, and so of the others—the valvular action of the wing being most marked at the tip of the pinion, and gradually diminishing in the direction of the root. The rowing feathers are necessarily eccentric. If the axis of each feather was not placed nearer the anterior than the posterior margin the anterior margin would rise as much as the posterior margin is depressed. This, however, is prevented

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* In some cases, as for instance in the more rounded form of wing shown in fig. 20, Plate XIV., the 4th, 5th, and 6th primaries are longer and stronger, and overlap more than the 1st, 2d, and 3d.

by the axis of the feather occupying an anterior position, the feather when it is made to rotate causing the posterior margin (because of its greater breadth) to move through a greater arc of a circle than the anterior margin. It is owing to the greater travel of the posterior margin as compared with the anterior one, that the feathers of the wing so readily open in flexion and close in extension. The gradation in the length, and strength, and in the degree of overlapping is necessitated by the fact that the feathers at the tip of the wing are exposed to a much greater strain than those nearer the root—the former always travelling through a much greater space in a given time than the latter.

The Wing of the Bird not always Opened Up to the same extent in the Up Stroke.—The elaborate arrangements and adaptations just referred to for increasing the area of the wing, and making it impervious to air during the down stroke, and for decreasing the area and opening up the wing during the up stroke, although necessary to the flight of the heavy-bodied, short-winged birds, as the grouse, partridge, and pheasant, are by no means indispensable to the flight of the long-winged oceanic birds, unless when in the act of rising from a level surface ; neither do the short-winged heavy birds require to fold and open up the wing during the up stroke to the same extent in all cases, less folding and opening up being required when the birds fly against a breeze, and when they have got fairly under weigh. All the oceanic birds, even the albatros, require to fold and flap their wings vigorously when they rise from the surface of the water. When, however, they have acquired a certain degree of momentum, and are travelling at a tolerable horizontal speed, they can in a great measure dispense with the opening up of the wing during the up stroke—nay, more, they can in many instances dispense even with flapping. This is particularly the case with the albatros, which (if a tolerably stiff breeze be blowing) can sail about for an hour at a time without once flapping its wings. In this case the wing is wielded in one piece like the insect wing, the bird simply screwing and unscrewing the pinion on and off the wind, and exercising a restraining influence—the breeze doing the principal part of the work. In the bat the wing is jointed as in the bird, and folded during the up stroke. As, however, the bat's wing, as has been already stated, is covered by a continuous and more or less elastic membrane, it follows that it cannot be opened up to admit of the air passing through it during the up stroke. Flight in the bat is therefore secured by alternately diminishing and increasing the area of the wing during the up and down strokes—the wing rotating upon its root and along its anterior margin during its ascent and descent precisely as in the bird.

Analysis of the Movements of Extension and Flexion in the Wing of the Gannet.—The changes which the wing undergoes in extension and flexion are seen to great advantage in the gannet (figs. 9, 10, and 11, Pate XII.)

The pinion of this bird is remarkable for its great length as compared with its breadth, and for the general elegance of its shape (*vide* figs. 11 and 16, Plates XII. and XIII.) It is especially interesting from the fact that the wing movements can be more readily and satisfactorily analysed by its aid than by the aid of any other British wing with which I am acquainted. The following account, taken from a perfectly fresh specimen, may prove interesting.

The joints of the gannet's wing, particularly the shoulder joint (*x* of figs. 16 and 17, Plate XIII.) admit of very free movements. When the wing is slightly flexed the under surface of the posterior margin of the pinion can be rotated downwards and forwards until it makes a right angle with the horizon—the greatest angle which it makes in extension amounting to something like 45°. In flexion the elbow (*s* of figs. 9, 10, and 11, Plate XII.), wrist (*t*), and metacarpal joints (*v w*) admit of a great variety of movements, the forearm (*c d*) moving on the arm (*e f*), and the hand (*a b*) upon the forearm (*c d*) in an oblique spiral direction from above downwards and from below upwards. The whole pinion, in fact, is flaccid, and the feathers opened up and thrown out of position as shown more especially at figs. 9 and 10, Plate XII. The forearm is folded upon the arm in nearly the same plane (*vide x s t* of fig. 17, Plate XIII.), the secondary and tertiary feathers (*c e g* of fig. 9, Plate XII.) being inclined slightly upwards and forwards, so that they form inclined surfaces with the horizon —the secondaries forming an inclined surface which looks inwards and upwards as indicated by the arrow marked *c d* of fig. 9, Plate XII., the tertiary feathers forming two inclined surfaces, one of which is directed upwards and outwards as indicated by the arrow *e f* of fig. 9, Plate XII., the other inclining upwards and inwards as shown at *g h* of fig. 9, Plate XII. The hand rotates upon the wrist (*t* of fig. 9, Plate XII.,) as upon a hinge, the tip of the wing as it darts out and in describing the segment of a circle (*m n* of fig. 9, Plate XII.) The hand is folded upon the forearm in such a manner that the anterior margin of the tip of the wing (*v w b* of fig. 9, Plate XII.) ascends, while the posterior margin (*a* of fig. 9, Plate XII.) descends. As a consequence the hand and tip of the wing are folded beneath the forearm or body of the wing as indicated by the radius *m n* of fig. 9, Plate XII. The hand and tip of the wing form with the horizon an inclined surface, which is directed *outwards* and *upwards* as indicated by the arrows *a b* of fig. 9, Plate XII. The *upward* and *outward inclination* of the under surface of the outer portion of the wing of the gull is well seen at *a b* of fig. 12, Plate XII. The tip of the wing, it will be observed, acts during flexion as a true kite from *below upwards* and from *within outwards*.* We have in the flexed wing of the gannet four different sets of

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* The same happens in the wings of all birds, and in the wing of the bat and insect. The outward and upward inclination of the tip of the wing is well seen in the beetle. This portion of the wing acts as a true kite, when the wing is being extended or thrust away from the body towards the termination of the up stroke. The under surface of the tip of the wing consequently contributes to flight during the up stroke.

inclined surfaces, two directed upwards and *outwards*, viz., *e f* and *a b* of fig. 9, Plate XII., and two directed upwards and *inwards*, viz., *c d* and *g h* of fig. 9, Plate XII. Those surfaces when the wing is moving are ever varying, and cause the different portions of the pinion to act like so many kites. Thus, during extension, the two portions of the wing marked *a b* and *e f* (fig. 9, Plate XII.,) fly outwards and upwards, the two portions marked *c d* and *g h* (fig. 9, Plate XII.,) flying inwards and upwards during flexion. As the two portions of the wing, marked *a b* and *e f*, draw a current after them during extension, on which the two portions marked *c d* and *g h* operate during flexion, it follows that one part of the wing, whatever its position in space, makes a current on which another portion inevitably acts. This result is facilitated by the manner in which the primary and secondary feathers rotate upon their long axes in flexion and extension, and also by the ascent and descent of the wing, inasmuch as flexion always occurs towards the end of the down stroke, and extension towards the end of the up stroke. The wing, I may add, as a rule produces a current during the up stroke on which it operates during the down stroke and *vice versa.* The inclined surfaces represented at fig. 9, Plate XII., are reproduced in the partly extended wing at fig. 10, Plate XII., and a comparison of the arrows marked by the same letters in the two figures will show that the angles of inclination formed by the surfaces in question are somewhat changed. The wing when fully extended is seen at fig. 11, Plate XII. Complete extension is followed by the obliteration of the inclined surfaces indicated by the arrows *a b*, *e f*, *c d*, *g h* of figs. 9 and 10, Plate XII. The obliteration of the inclined surfaces *a b*, *e f*, *c d*, *g h* of figs. 9 and 10, Plate XII., is followed by the production of other inclined surfaces, these being occasioned by the rotation of the wing upon its anterior margin (long axis) towards the termination of extension. The angles of inclination formed by the under surface of the wing in the extended condition are greatest towards the root and least towards the tip of the wing, as shown at *q p o* of fig. 16, Plate XIII. When the gannet's wing is extended and flexed by the aid of the hand, as represented at figs. 16 and 17, Plate XIII., it shows the screwing and unscrewing action of the pinion to perfection; the dorsal and ventral surfaces of the wing oscillating on either side of a given line—the dorsal surface appearing above the line in flexion (figs. 17, Plate XIII.,) and the ventral surface under the line in extension (fig. 16, Plate XIII.) The upward and downward screwing of the wing in flexion and extension is also shown at fig. 8, Plate XII.—the wing to the right of the observer being flexed, and having its anterior margin (*d e f*) directed slightly downwards (*vide* arrow), the wing to the left being extended, and having its anterior margin (*d′ e′ f′*) directed decidedly upwards (*vide* arrow.)

The Angles of Inclination which the Under Surface of the Gannet's Wing makes with the Horizon in Extension and Flexion vary.—When the wing of the gannet is extended the angle which its under surface makes with the horizon, especially the portion opposite the elbow joint (*q* of fig. 16, Plate XIII.), is much greater than one would anticipate—indeed, it is little short of 45°. The tip of the wing (*o p* of fig. 16, Plate XIII.,) does not, however, make an angle of more than 25° or 30°. This is a most interesting point, as it shows that the different portions of the wing in extension make different angles with the horizon—that made by the tip of the wing being the least, and that made by the root of the wing the greatest. The inclined surfaces are no doubt adapted to suit the travel of the wing, and to produce a uniform result as far as buoyancy is concerned. Thus the wing acts with a gradually decreasing angle from the root towards the tip—the speed of the wing increasing in the direction of its extremity. This is important, as a surface with a small angle travelling at a high speed supplies the same amount of buoying power as a surface with a greater angle moving at a lower speed. Indeed, on making a careful examination of the gannet's wing I have had no difficulty in determining that the different parts of the wing not only make various angles of inclination with the horizon in an antero-posterior direction at every stage of extension flexion in the down and up strokes, but that they also make various angles of inclination with the horizon in a direction from within outwards. In other words, I find that in extension the wing attacks the air from behind forwards and from within outwards at one and the same instant—the different parts of the pinion tacking upon the air kite fashion, precisely as a sailing vessel would. The same thing happens in the wing of the insect. Here, as I have already pointed out, the posterior margin twists upon and partially rotates round the anterior margin, so as to convert the wing into a screw which moves in all its parts. This twisting and untwisting has the effect of alternately producing a surface which attacks the air (at various angles of inclination) from within outwards, and from behind forwards, and from without inwards and from before backwards. Curiously enough, the inclined surfaces formed by the different portions of the insect's wing with the horizon vary to accommodate themselves to the velocity acquired by its different parts—the surfaces being least inclined where the speed is highest, and *vice versa.* This, therefore, is a fundamental point in the construction and application of all wings, and affords the only rational solution of the involved problem of flight. The various angles of inclination made by the wing with the horizon from within outwards and the reverse, and from behind forwards and the reverse, are all necessary to produce a perfect buoyancy.

When the wing of the gannet is fully extended it is also rendered more or less rigid. The joints, however, even the metacarpal ones, are free to move, which shows that the wing, to be effective during the down stroke, must be thoroughly under the control of the muscular and ligamentary system. This is all the more necessary, as the roots of the primary and secondary feathers have an inclination to move in an upward direction, and require to be restrained.

After carefully analysing the movements of the gannet's wing in the dead bird, I felt deeply impressed with the necessity of studying the same movements in the living one. I therefore made an excursion to the Bass Rock (North Berwick, Scotland) for this purpose, in July 1870. It was breeding season, and the birds were in myriads, and so tame that they wheeled around and above me at distances, in some cases, not exceeding from six to eight yards. The gannets which were hatching permitted me to approach within a yard of them, and required to be driven from their nests by the aid of a stick. I had, therefore, every facility for analysing the flight of this the most cherished and beautiful of the British birds. Before proceeding to describe the results of the expedition in question I may state, briefly, the measurement, weight, &c., of the gannet, the movements of whose wings I have just recorded. For the sake of comparison I will also give the weight and measurements of a heron—this bird differing widely from the gannet in the configuration of its wings.

Measurement, Weight, &c., of Gannet and Heron.—The following details of weight, measurement, &c., of the gannet were supplied by an adult specimen which I dissected during the winter of 1869. Entire weight, 7 lbs. (minus 3 ounces); length of body from tip of bill to tip of tail, 3 feet 4 inches; head and neck, 1 foot 3 inches; tail, 12 inches; trunk, 13 inches; girth of trunk, 18 inches; expanse of wing from tip to tip across body, 6 feet; widest portion of wing across primary feathers, 6 inches; across secondaries, 7 inches; across tertiaries, 8 inches. Each wing, when carefully measured and squared, gave an area of 19½ square inches. The wings of the gannet, therefore, furnish a supporting area of 3 feet 3 inches square. As the bird weighs close upon 7 lbs., this gives something like 13 square inches of wing for every 36⅓ ounces of body, *i.e.*, 1 foot 1 square inch of wing for every 2 lbs. 4⅓ ounces of body.

The heron, a specimen of which I dissected at the same time, gave a very different result, as the subjoined particulars will show. Weight of body, 3 lbs. 3 ounces; length of body from tip of bill to tip of tail, 3 feet 4 inches; head and neck, 2 feet; tail, 7 inches; trunk, 9 inches; girth of body, 12 inches; expanse of wing from tip to tip across the body, 5 feet 9 inches; widest portion of wing across primary and tertiary feathers, 11 inches; across secondary feathers, 12 inches.

Each wing, when carefully measured and squared, gave an area of 26 square inches. The wings of the heron, consequently, furnish a supporting area of 4 feet 4 inches square. As the bird only weighs 3 lbs. 3 ounces, this gives something like 26 square inches of wing for every 25½ ounces of bird, or 1 foot 5¼ inches square of wing for every 1 lb. 1 ounce of body.

In the gannet there is only 1 foot 1 square inch of wing for every 2 lbs. 4⅓ ounces of body. The gannet has, consequently, less than half of the wing area of the heron. The gannet's wing is, however, a long narrow wing (that of the heron is broad), extended transversely across the body in the direction of its length; and this is found to be the most powerful form of wing—the wings of the albatros, which measure 14 feet from tip to tip (and only one foot across), elevating 18 lbs. without difficulty. If the wings of the gannet, which have a superficial area of 3 feet 3 inches square, are capable of elevating 7 lbs., while the wings of the heron, which have a superficial area of 4 feet 4 inches, can only elevate 3 lbs., it is evident (seeing the wings of both are twisted levers, and formed upon a common type) that the gannet's wing must be vibrated with greater energy than the heron's wing; and this is actually the case. The heron's wing, as I have stated (foot note to page 392), makes 60 down and 60 up strokes every minute; whereas the wing of the gannet, when the bird is flying in a straight line to or from its fishing ground, makes close upon 150 up and 150 down strokes during the same period. The wings of the divers and other short-winged, heavy-bodied birds are urged at a much higher speed, so that a comparatively small wing can be made to elevate a comparatively heavy body, if the speed with which the wing is driven only be increased sufficiently.* Flight, therefore, is a question of power, speed, and small surfaces *versus* weight. While there is apparently no fixed relation between the area of the wing and the animal to be raised, there is (unless in the case of sailing birds, which have acquired momentum) an unvarying relation as to the weight to be elevated and the number of oscillations; so that the problem of flight would seem to resolve itself into one of weight, power, velocity, and small surfaces, as against comparative levity, debility, diminished speed, and extensive surfaces.† Elaborate measurements of wing area and minute calculations of speed can, consequently, only determine the minimum of wing for elevating the maximum of weight—flight being attainable within a comparatively wide range. That the superficies of the wings destined to carry a certain weight may, and does vary, is proved by the fact that large portions of the wings of insects and birds, as I have pointed out,‡ may be removed without destroying or even impairing the function of flight. In such cases the speed with which the wings are driven is increased in the direct ratio of the mutilation. It is further proved by the ingenious researches of M. DE LUCY, who has shown, by careful measurements, that the

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* The grebes among birds and the beetles among insects furnish examples where small wings, made to vibrate at high speeds, are capable of elevating great weights.

† "On the Mechanism of Flight," by the Author, Trans. Linn. Soc., vol. xxvi. page 219.

‡ *Vide* page 326 and foot-note to pages 361 and 362 of the present memoir, and pages 219, 220, 221, and 222 of my memoir "On the Mechanical Appliances by which Flight is Attained in the Animal Kingdom," Trans. Linn. Society, vol. xxvi.

area of the wings decreases as the size and weight of the body increase. M. de Lucy has tabulated his results, which I subjoin.*

Insects.				Birds.			
Names.	Referred to the kilogramme. =2 lbs. 8 oz. 3 dwt. 2 gr. Avoird. =2 lbs. 3 oz. 4·428 dr.			Names.	Referred to the kilogramme.		
	sq. yds.	ft.	in.		sq. yds.	ft.	inch.
Gnat,	11	8	92	Swallow,	1	1	104½
Dragon-fly (small),	7	2	56	Sparrow,	0	5	142½
Coccinella (Lady-bird),	5	13	87	Turtle dove,	0	4	100½
Dragon-fly (common),	5	2	89	Pigeon,	0	2	113
Tipula, or Daddy-long-legs,	3	5	11	Stork,	0	2	20
Bee,	1	2	74½	Vulture,	0	1	116
Meat-fly,	1	3	54½	Crane of Australia,	0	0	139
Drone (blue),	1	2	20				
Cockchafer,	1	2	50				
Lucanus cervus Stag-beetle (female),	1	1	39½				
Lucanus cervus Stag-beetle (male),	0	8	33				
Rhinoceros-beetle,	0	6	122½				

"It is easy, by the aid of this table, to follow the order, always decreasing, of the surfaces, in proportion as the winged animal increases in size and weight. Thus, in comparing the insects with one another, we find that the gnat, which weighs 460 times less than the stag-beetle, has 14 times more of surface. The lady-bird weighs 150 times less than the stag-beetle, and possesses 5 times more of surface, &c. It is the same with the birds. The sparrow weighs about 10 times less than the pigeon, and has twice as much surface. The pigeon weighs about 8 times less than the stork, and has twice as much surface. The sparrow weighs 339 times less than the Australian crane, and possesses 7 times more surface, &c. If now we compare the insects and the birds, the gradation will become even much more striking. The gnat, for example, weighs 97,000 times less than the pigeon, and has 40 times more surface; it weighs three millions of times less than the crane of Australia, and possesses 140 times more of surface than this latter, the weight of which is about 9 kilogrammes 500 grammes (25 lbs. 5 oz. 9 dwt. troy, 20 lbs. 15 oz. 2¼ dr. avoirdupois.

"The Australian crane is the heaviest bird that I have weighed. It is that which has the smallest amount of surface, for, referred to the kilogramme, it does not give us a surface of more than 899 square centimetres (139 square inches), that is to say, about an eleventh part of a square metre. But every one

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* "On the Flight of Birds, of Bats, and of Insects, in reference to the subject of Aërial Locomotion," by M. de Lucy, Paris.

knows that these Grallatorial animals are excellent birds of flight. Of all travelling birds they undertake the longest and most remote journeys. They are, in addition, the eagle excepted, the birds which elevate themselves the highest, and the flight of which is the longest maintained."

Flight of Gannet as witnessed at the Bass Rock.—But to return to the gannet, the flight of which, as witnessed from the Bass, I was about to describe.

The wings and body of the bird, as I fully satisfied myself, can be moved in all their parts. The wings and body are, moreover, thoroughly under control. The body can be twisted about in a remarkable manner—sideways and in an upward and downward direction. The individual feathers of the wing are likewise under control. In fact, the muscular movements can be seen extending along the pinion to the roots of the rowing feathers, the muscular influence spreading thence to the tips. This could readily be ascertained, as the birds wheeled round and round right overhead, and within a very few yards of where I was standing.

When the gannet throws itself from a cliff it makes a large curve, the convexity of which is directed downwards. It acquires speed and momentum by a few gentle flappings of the wings, or it holds the wings comparatively motionless, and sails for a great distance without effort—the weight of the trunk doing the principal portion of the work.* In the sailing movement the body is forced into an upward or downward curve, according to circumstances.

When the bird has acquired momentum, either by flapping its wings or by projecting itself from a cliff, it has the air perfectly under control. If it wishes to turn to the right it elevates the left wing and depresses the right one, the head and neck bending in the direction of the curve to be described. If it would turn to the left the movements are reversed.† If it desires to ascend, the head, neck, body, and wings are elevated in an upward direction, so as to increase the angle made by them with the horizon, the angle referred to being decreased or reversed when the bird wishes to descend. If the bird aims at horizontal flight, the head, neck, body, and wings are arranged so as to be nearly parallel with the surface of the sea. The gannet wheels and skims about with all imaginable ease and grace—now oscillating on the long axis of the body as a centre, and now upon the long axes of the wings as a centre. In all these movements the head, neck, tail, and body perform an important part.

When the gannet throws itself from a rock it rises to nearly the same level as that from which it precipitated itself, without any apparent effort, thus showing that the friction experienced in flight must be almost *nil.*

The neck, body, and tail, of the gannet are exceedingly flexible, and admit

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* Compare with mechanical experiment described at pages 355 and 356.

† The swallow and crane, which dart along at a very high speed, tilt their bodies in turning; but, in addition, flap their wings and fly round the curve they wish to describe.

of being curved in every direction. The feet are extended straight out behind the bird, and appear on the under surface of the tail. The body forms an elongated and very graceful ellipse, admirably adapted for cleaving the air and eluding resistance.

When the gannet propels itself by the more or less vertical flappings of its wings, the angles which the under surfaces of the wings and body make with the horizon are very considerable—something like 25° or 30°. Of this I convinced myself in a variety of ways.* When the bird has acquired speed and momentum, and begins to sail, the angle made by the under surfaces of the body and wings is reduced according to circumstances, and in some instances nearly obliterated, the bird gliding along for long distances with its body and wings apparently parallel to the surface of the ocean.

The wings of the gannet, when fully extended, are curved alternately forwards and backwards. Thus, the arm and hand are inclined backwards, and the forearm forwards. When the wings are flexed in ordinary flight the movement occurs principally at the wrist joint, the arm and forearm bending comparatively little, and affording a wide basis of support both during the down and up strokes. In forced flight in flexion the wing bends perceptibly at the elbow as well as the wrist, the wing during the up stroke forming a short lever, and being thrown into a fine arch, the convexity of which is directed upwards. The tip of the wing works out and in during the down and up strokes; and a close examination satisfied me that the bird has the power of forcing the posterior margin of its wings *into wave curves* while the wings are rising and falling, the air taking no part in the production of the waved movements.

The down stroke is delivered with perceptibly greater rapidity and energy than the up stroke. Of this there can be no doubt whatever. This allows the air, set in motion by the wing during its descent, time to re-act on the under surface of the pinion so as to contribute to its elevation. This result is facilitated by the wing striking very decidedly *downwards and forwards*.

When the gannet alights at its nest it delivers a few very energetic strokes at right angles to the direction of its flight, and thus slows itself.

When the gannet plunges into the sea from a height it tilts its body until it assumes a more or less perpendicular position, and descends with such impetuosity as to displace the water in an upward direction, until it attains an altitude of from 10 to 15 feet. It flies beneath the water with remarkable rapidity, and emerges without difficulty, the momentum acquired during the descent assisting it through and out of the water. In fact the gannet, when it stoops to pick up a fish, simply describes a continuous downward curve, part of the curve being

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* In the dragon-fly the anterior pair of wings make a smaller angle with the horizon than the posterior pair. The first pair of wings are, consequently, more actively engaged as propellors—the second pair as elevators.

formed in the air and part in the water. Those movements, so numerous, varied, and beautiful, are all the result of volition. It is impossible to resist this conclusion after deliberate and careful watching.

A Regulating Power necessary in Flight.—That the wing is propelled for the most part by voluntary movements, may be ascertained in the following manner.

If the sentient nerve of a pigeon's wing be divided (the motor nerve being left intact) the bird flutters most energetically, but altogether fails to fly.* In this experiment neither the flexibility, elasticity, nor the power which the wing possesses of moving in all its parts, are tampered with. The guiding or controlling power alone is impaired.

That the wing is vibrated intelligently admits of direct proof. Thus if we hold a captured bird in the hand, we feel that it directs and controls the action of its wings in such a manner that a tractile force is produced, now in one direction now in another, in its efforts to escape; nay more, that the force after a brief fluttering is concentrated at that point where it is most loosely held, and which offers the greatest chance of escape.

Second, The wings of birds, as any one may readily ascertain by watching the flight of rooks, are visibly under control both during the down and up strokes. They are, moreover, deliberate leisurely movements. By leisurely movements, I mean such as are the result of design, and not such as would be produced by the sudden recoil of a merely elastic apparatus. Those who have watched, as I have frequently done, the rapid vibrations of natural and artificial wings, will readily understand the difference here indicated. In the living wing we have a smooth soft fanning continuous movement, quite devoid of dead points; whereas in artificial elastic wings, especially if worked vertically and without elastic bands at their roots, we have a wavering, jerking, irregular motion, particularly at the beginning of the up stroke.

Third, The blow-fly, as stated (p. 326), can fly with only one-third of its original wing area, the two-thirds which represent the more highly elastic portions of the wing being removed. In this case the wing is wielded intelligently figure of 8 fashion, the mutilation not interfering either with the freedom of motion enjoyed by the pinion at its root, or the power the insect possesses of directing and controlling the wing throughout its entire vibration.

There are therefore at least five separate items to be considered in flight, viz., intelligence and voluntary movements; secondly, mobility or the power which the wing possesses of moving its several parts; thirdly, the flexibility and elasticity of the wing; fourthly, the resistance and resiliency of the air upon which the wing operates; fifthly, the weight of the body of the flying animal, which may be regarded as an independent moving power.

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* "Experiments practically demonstrating the laws by which birds fly," by Dr W. Smyth. Second Annual Report of the Aëronautical Society of Great Britain for 1867.

The wings of bats and birds are mobile because of their numerous joints (shoulder, elbow, wrist, meta carpal, &c.), and because of the muscles and fibro-elastic ligaments which operate upon these joints. They are also flexible and elastic, the one (the bat) because of its long, thin tapering fingers and enveloping membrane; the other (the bird) because of its tapering, primary, secondary, and tertiary feathers.

The insect wing is also mobile, the insect having the power not only of moving the pinion in various directions at its root, but of causing the movements generated at the roots to extend intelligently along the margins. The insect wing is flexible and elastic in the same sense that the wing of the bat and bird are flexible and elastic. The mobility, flexibility, and elasticity peculiar to the living wing is more intimately blended in the wing of the insect than in that of either the bat or bird. This arises from the fact that the wing of the insect is usually in one piece, and jointed only at its root.

The Wing at all times thoroughly under Control.—The advantage which the wing derives from being movable in all its parts, consists in this, that it can be wielded intelligently even to its extremity. This enables the insect, bat, and bird, to tread and rise upon the air as a master—to subjugate it in fact. The wing, no doubt, abstracts an upward and onward recoil from the air, but in doing this it exercises a selective and controlling power; it seizes one current, evades another, and creates a third; it feels and paws the air as a quadruped would feel and paw a treacherous yielding surface. It is not difficult to comprehend why this should be so. If the flying creature is living, endowed with volition, and capable of directing its own course, it is surely more reasonable to suppose that it transmits to its travelling surfaces the peculiar movements necessary to progression, than that those movements should be the result of impact from fortuitous currents which it has no means of regulating. That the bird requires to control the wing, and that the wing requires to be in a condition to obey the behests of the will of the bird, is pretty evident from the fact that most of our domestic fowls can fly for considerable distances when they are young and when their wings are flexible; whereas when they are old and the wings stiff, they either do not fly at all or only for short distances, and with great difficulty. This is particularly the case with tame swans. This remark also holds true of the steamer or race-horse duck (*Anas brachyptera*), the younger specimens of which only are volant. In the older birds the wings become too rigid and the bodies too heavy for flight. Who that has watched a sea-mew struggling bravely with the storm, could doubt for an instant that not only the wings but every individual feather of the wing was perfectly under control? The whole bird is an embodiment of animation and power. The intelligent active eye, the easy graceful oscillation of the head and neck, the folding or partial folding of one or both wings, nay more, the slight tremor or quiver of the individual feathers of parts of the wings so rapid, that only an experienced eye can detect it, all confirm the belief that the living wing has not only the power of directing, controlling, and utilising natural currents, but of creating and utilising artificial ones, which is not less important. But for this power, what would enable the bat and bird to rise and fly in a calm, or steer their course in a gale? It is erroneous to suppose that anything is left to chance where living organisms are concerned, or that animals endowed with volition and travelling surfaces, should be denied the privilege of controlling the movements of those surfaces quite independently of the medium on or in which they are destined to operate. What would we say of that quadruped or that fish which depended for the major portion of its movements on the ground it trod or the water it navigated? I will never forget the gratification afforded me on one occasion at Carlow (Ireland) by the flight of a pair of magnificent swans. The birds flew towards and past me, and I had my attention directed to their presence by a peculiarly loud whistling noise made by their wings. They flew about fifteen yards from the ground, and as their pinions were urged not much faster than those of the heron,* I had abundant leisure for studying their movements. The sight was very imposing, and as novel as it was grand. I had never seen anything before, and certainly have seen nothing since that could in any way convey a more adequate idea of the prowess and guiding power which a bird may exert. What particularly struck me was the perfect mastery which they seemed to possess over everything. They had their wings and bodies visibly under control, and the air was attacked in a manner and with an energy which left little doubt in my mind that it played quite a subordinate part in the great problem before me. The necks of the birds were stretched out, and their bodies to a great extent rigid. They advanced with a steady stately motion, and swept past with a vigour and force which greatly impressed, and to a certain extent overawed, me at the time.† Their flight was what one could imagine that of a flying machine constructed in accordance with natural laws would be.

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* I have frequently timed the beats of the wings of the common heron (*Ardea cinerea*) at Warren Point (Ireland). In March 1869 I was placed under unusually favourable circumstances for obtaining reliable results. I timed one bird high up over a lake for fifty seconds, and found that in that period it made fifty down and fifty up strokes; *i.e.*, one down and one up stroke per second. I timed another one in a heronry belonging to Major Hall. It was snowing at the time (March 1869), but the birds, notwithstanding the inclemency of the weather and the early time of the year, were actively engaged in hatching, and required to be driven from their nests on the top of the larch trees by knocking against the trunks thereof with large sticks. One unusually anxious mother refused to leave the immediate neighbourhood of the tree containing her tender charge, and circled round and round it right overhead. I timed this bird for ten seconds, and found that she made ten down and ten up strokes; *i.e.*, one down and one up stroke per second precisely as before. I have therefore no hesitation in affirming that the heron, in ordinary flight, makes exactly sixty down and sixty up strokes per minute. The heron, however, like all other birds when pursued or agitated, has the power of greatly augmenting the number of its beats.

† The above observation was made at Carlow on the Barrow in October 1867, and the account of it is abstracted from my note-book.

How the Wing is Attached to the Body—Movements of the Shoulder, Elbow, Wrist, and other Joints.—Having endeavoured to prove, in a variety of ways, that insects, bats, and birds have their wings thoroughly under control both during the down and up strokes, I now proceed to show that the configuration of the wing, its structure, its attachments to the body, its joints, its muscles (voluntary in their nature), and its elastic ligaments, many of which have muscular fibres running into them, all tend to confirm this belief.

While, however, saying so much, I take this opportunity of stating that the structure of the living wing and its relations and attachments to the body are such that if it moves at all it must move in such a manner as shall contribute to flight. In other words, the wing is mechanically perfect; and if it be made to vibrate, even by artificial means, all its movements will tend in the direction of flight. This, however, is a very different thing from asserting that the movements of the living wing are purely mechanical in their nature. By mechanical I mean such movements as would be produced by the elasticity of the wing and the reaction of the air, minus volition, minus the voluntary muscles—musculo-elastic ligaments and nerves of the wing. Flight is vito-mechanical in its nature and intelligence, or that form of action which results from *the habitual use* of intelligence, is necessary to its production.

All wings are constructed upon a common type. They are in every instance carefully graduated, the wing tapering from the root towards the tip, and from the anterior margin in the direction of the posterior margin. They are of a generally triangular form, and twisted upon themselves in the direction of their length, to form a helix or screw. They are convex above and concave below, and more or less flexible and elastic throughout, the elasticity being greatest at the tip and along the posterior margin. They are also movable in all their parts. In all the wings which I have examined, whether in the insect, bat, or bird, the wing is recovered, flexed, or drawn towards the body by the action of elastic ligaments, these structures, by their mere contraction, causing the wing, when fully extended and presenting its maximum of surface, to resume its position of rest and plane of least resistance. The principal effort required in flight is, therefore, made during extension and at the beginning of the down stroke. The elastic ligaments are variously formed, and the amount of contraction which they undergo is in all cases accurately adapted to the size and form of the wing and the rapidity with which it is worked, the contraction being greatest in the short-winged and heavy-bodied insects and birds, and least in the light-bodied and ample-winged ones, particularly in such as skim or glide. The mechanical action of the elastic ligaments, I need scarcely remark, ensures an additional period of repose to the wing at each stroke; and this is a point of some importance, as showing that the lengthened and laborious flights of insects and birds are not without their stated intervals of rest.

The twisting of the wing upon itself during its action, to which I have frequently directed attention, is occasioned in the bat and bird by the insertions and direction of the muscles—by the spiral configuration of the articular surfaces of the bones of the wing, and by the rotation of the bones of the arm, forearm, and hand upon their long axes. In the insect it is due to the insertions and direction of the muscles, and the conformation of the shoulder-joint, this being furnished with a system of check-ligaments, and with horny prominences or stops, set, as nearly as may be, at right angles to each other, and fashioned so as to necessitate the wing acting in the manner specified.

To confer on the pinion the multiplicity of movement which it requires, it is supplied with *a double hinge or compound joint*, which enables it to move not only in an upward, downward, forward and backward direction, but also at various intermediate degrees of obliquity. An insect furnished with wings thus hinged may, as far as steadiness of body is concerned, be not inaptly compared to a compass set upon gimbals, the universality of the wing-movements rendering any elaborate attempt at balancing quite unnecessary.

In the bird the head of the humerus is convex and somewhat oval (not round), the long axis of the oval being directed from above downwards, *i.e.*, from the dorsal towards the ventral aspect of the bird. The humerus can, therefore, *glide up and down* in the *facettes* occurring on the articular ends of the coracoid and scapular bones with great facility, much in the same way that the head of the radius glides upon the distal end of the humerus. But the humerus has another motion; it moves *like a hinge from before backwards, and vice versa.* The axis of the latter movement is almost at right angles to that of the former. As, however, the shoulder-joint is connected by long ligaments to the body, and can be drawn away from it to the extent of one-eighth of an inch or more, it follows that *a third and twisting movement can be performed*, the twisting admitting of rotation to the extent of something like a quarter of a turn. In raising and extending the wing preparatory to the downward stroke two opposite movements are required, viz., one from before backwards, and another from below upwards. As, however, the axes of these movements are at nearly right angles to each other, a spiral or twisting movement is necessary to run the one into the other—to turn the corner, in fact.

From what has been stated it will be evident that the movements of the wing, particularly at the root, are remarkably free, and very varied. A directing and restraining, as well as a propelling force, is therefore necessary.

Such complex force is to be found in the voluntary muscles which connect the wing with the body in the insect, and which in the bat and bird, in addition to connecting the wing with the body, extend along the pinion even to its tip. It is also to be found in the musculo-elastic and other ligaments. I do not propose entering upon a consideration of the muscular system of the wing of the bat and bird, as this has been satisfactorily done already. I will, therefore, confine the present remarks to the elastic ligaments, and more especially to those of the bird, as being the most illustrative, alike from their size and situation.

The Wing Flexed and partly Elevated by the Action of Elastic Ligaments—the Nature and Position of such Ligaments in the Pheasant, Snipe, Crested Crane, Swan, &c.—When the wing is drawn away from the body of the bird by the hand the posterior margin of the pinion formed by the primary, secondary, and tertiary feathers rolls down to make a variety of inclined surfaces with the horizon. When, however, the hand is withdrawn, even in the dead bird, the wing instantly folds up; and in doing so, reduces the amount of inclination in the several surfaces referred to. This it does in virtue of certain elastic ligaments, which are put upon the stretch in extension, and which recover their original form and position in flexion. This simple experiment shows that the various inclined surfaces requisite for flight are produced by the mere act of extension and flexion in the dead bird. It is not, however, to be inferred from this circumstance that flight in the animal kingdom is a purely mechanical act any more than ordinary walking is. The muscles, bones, ligaments, feathers, &c. are so adjusted with reference to each other that if the wing is moved at all, it must be moved in the proper direction—an arrangement which enables the bird to fly without thinking just as we can walk without thinking. There cannot, however, be a shadow of a doubt that the bird has the power of controlling its wings both during the down and up strokes; for how otherwise could it steer and direct its course with such precision in obtaining its food? how fix its wings on a level with or above its body for skimming purposes? how form a curve? how fly with, against, or across a breeze? how project itself from a rock directly into space, or how elevate itself from a level surface by the laboured action of its wings?

The wing of the bird is elevated to a certain extent in flight by the reaction of the air upon its under surface; but it is also elevated by muscular action—by the contraction of the elastic ligaments, and by the body falling downwards and forwards in a curve.

That muscular action is necessary is proved by the fact that the pinion is supplied with distinct elevator muscles*—nay, more, that the bird can, and always does, elevate its wing prior to flight, quite independently of the air. When the bird is fairly launched into space the elevator muscles are assisted

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* C. J. L. KRARUP, a Danish author, gives it as his opinion that the wing is elevated by a vital force, viz., by the contraction of the *pectoralis minor;* this muscle, according to him, acting with $\frac{1}{7}$th the intensity of the *pectoralis major* (the depressor of the wing). He bases his statement upon the fact that in the pigeon the pectoralis minor or elevator of the wing weighs $\frac{1}{8}$th of an ounce, whereas the pectoralis major or depressor of the wing weighs $\frac{7}{8}$ths of an ounce. It ought, however, to be borne in mind that the volume of a muscle does not necessarily determine the precise influence exerted by its action; for the tendon of one muscle may be made to act upon a long lever, and, under favourable conditions, for developing its powers, while that of another muscle may be made to act upon a short lever, and, consequently, under unfavourable conditions.—*On the Flight of Birds*, p. 30. Copenhagen, 1869.

by the falling forward of the body, by the reaction of the air, and by the contraction of the elastic ligaments. The air and the elastic ligaments contribute to the elevation of the wing, but both are obviously under control—they, in fact, form links in a chain of motion which at once begins and terminates in the muscular system.

That the elastic ligaments are subsidiary and to a certain extent under the control of the muscular system in the same sense that the air is, is evident from the fact that voluntary muscular fibres run into the ligaments in question at various points. Thus, in the pheasant, as shown at *a b* of figure 23, Plate XV., red muscular fibres are seen terminating in the fibrous and elastic tissues *c* and *k*. These structures act in conjunction, and fold or flex the forearm on the arm. At *f h* voluntary muscle is seen acting in concert with the elastic ligament *g i* to flex the hand upon the forearm. The arm is drawn towards the body by the elastic ligament *d* and by the muscles *v w*.

The elastic ligaments, while occupying a similar position in the wings of all birds, are variously constructed in the several species. In the common snipe, for example, as represented at figure 21, Plate XV., the voluntary muscular slip *a* terminates in the fibro-elastic band *k;* this again being geared to voluntary muscle *x*, and to certain musculo-fibrous bands *j*. Their conjoined action is to flex the forearm upon the arm, the arm being drawn towards the body by a musculo-fibrous ligament *d, e*. The elastic ligament *g i* flexes the hand upon the forearm, and the ligament *r* the fingers upon the hand. A somewhat similar arrangement is formed in the wing of the crested crane, as shown at figure 24, Plate XVI. Thus, at *a*, *b*, voluntary muscular slips are seen terminating in the elastic band *k*, this splitting up into two portions at *k*, *m*. A somewhat similar band is seen at *j*, and all three are united to, and act in conjunction with, the great fibro-elastic web *c* to flex the elbow. The musculo-fibro-elastic ligament *f g*, *h i*, as already explained, envelopes the root of each primary, secondary, and tertiary feather. It also forms a symmetrical network, so that it at once supports the feathers and limits their peculiar actions. In the swan the muscular slip which corresponds to *a* of figure 24, Plate XVI. (crested crane), terminates in a fibrous band, which corresponds to *k;* but the muscular slip corresponding to *b* terminates in a well-defined tendon, not in the fibrous band *m*, but in a distinct muscle, 5 inches in length and ¼ of an inch in breadth. This muscle is situated in the anterior margin of the wing, midway between the shoulder and wrist joints, and exercises a most potent influence in folding the elbow. The band marked *j* in the crane's wing is at least four times broader in the swan's wing.

The Elastic Ligaments more Highly Differentiated in Wings which Vibrate Rapidly.—From what has been stated, it will be evident that the elastic ligaments of the swan are more complicated and more liberally supplied with voluntary muscle than those of the crane, and this is no doubt owing to the fact that the wings of the swan are driven at a much higher speed than those of the crane. In the snipe the wings are vibrated very much more rapidly than in the swan, and as a consequence we find that the fibro-elastic bands are not only greatly increased, but they are also geared to a much greater number of voluntary muscles, all which seems to prove that the elastic apparatus employed by nature for recovering or flexing the wing towards the end of the down stroke become more and more highly differentiated in proportion to the rapidity with which the wing is moved.* The reason for this is obvious. If the wing is to be worked at a higher speed, it must, as a consequence, be more rapidly flexed and extended. The rapidity with which the wing of the bird is extended and flexed is in some instances exceedingly great; so great, in fact, that it escapes the eye of the ordinary observer. The rapidity with which the wing darts in and out in flexion and extension would be quite inexplicable, but for a knowledge of the circumstance that the different portions of the pinion are disposed at various angles of inclination (*vide x, s, t, w* of figures 9 and 10, Plate XII.), these angles being instantly increased or diminished by the slightest quiver of the muscular and fibro-elastic systems. If we take into account the fact that the wing of the bird is recovered or flexed by the combined action of voluntary muscles and elastic ligaments; that it is elevated to a considerable extent by voluntary muscular effort; and that it is extended and depressed entirely by muscular exertion, we shall have difficulty in avoiding the conclusion that the wing is thoroughly under the control of the muscular system, not only in flexion and extension, but also throughout the entire down and up strokes.

An arrangement in every respect analogous to that just described is found in the wing of the bat, the covering or web of the wing in this instance forming the principal elastic ligament. In fact, the bones and muscles of the bat's wing, and the inclined surfaces made by its different portions with each other and with the horizon during flexion and extension, and during the down and up strokes, so closely resemble those of the bird that a separate description is unnecessary. From the foregoing description it will be obvious that the wing of the bird and bat is a highly differentiated organ, endowed with independent movements, which enable it to direct and control the air for a purpose.

How Balancing is Effected in Flight.—The manner in which insects, bats, and birds balance themselves in the air has hitherto, and with reason, been regarded a mystery, for it is difficult to understand how they maintain their equilibrium when the wings are beneath their bodies. Figures 3 and 4, page 338, throw considerable light on the subject in the case of the insect. In those figures the space (*a*, *g*) mapped out by the wing during its vibrations is entirely

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[*] A careful account of the musculo-elastic structures occurring in the wing of the pigeon is given by Mr MACGILLIVRAY in his admirable "History of British Birds," pages 37 and 38. Lond. 1837.

occupied by it; *i.e.*, the wing (such is its speed) is in every portion of the space at nearly the same instant, the space representing what is practically a solid basis of support. As, moreover, the wing is jointed to the upper part of the body (thorax) by a universal joint, which admits of every variety of motion, the insect is always suspended (very much as a compass set upon gimbals is suspended), the wings, when on a level with the body, vibrating in such a manner as to occupy a circular area, in the centre of which the body is placed (*vide r d b f* of fig. 51, page 399). The wings, when vibrating above and beneath the body occupy a conical area, the apex of the cone being directed upwards when the wings are below the body, and downwards when beneath it. Those points are well seen in the bird at figures 18 and 19, Plate XIV. In figure 18 the inverted cone formed by the wings when above the body is represented, and in figure 19 that formed by the wings when below the body is given. In these figures it will be observed that the body, from the insertion of the roots of the wings into its upper portion, is always suspended, and this, of course, is equivalent to suspending the centre of gravity. In the bird and bat, where the stroke is delivered more vertically than in the insect, the *basis of support* is increased by the tip of the wing folding inwards and backwards in a more or less horizontal direction at the end of the down stroke; and outwards and forwards at the end of the up stroke. This is accompanied by the rotation of the outer portion of the wing upon the wrist as a centre (*vide t* of figures 9 and 10, Plate XII.), the tip of the wing, because of the ever varying position of the wrist, describing an ellipse. In insects whose wings are broad and large (butterfly), and which are driven at a comparatively low speed, the balancing power is diminished. In insects whose wings, on the contrary, are long and narrow (blow-fly), and which are driven at a high speed, the balancing power is increased. It is the same with short and long winged birds, so that the function of balancing is in some measure due to the form of the wing, and the speed with which it is driven, the long wing and the wing vibrated with great energy increasing the capacity for balancing. When the body is light and the wings very ample (butterfly and heron), the descent of the wing and the reaction of the air during the up stroke displaces the body to a marked extent. When, on the other hand, the wings are small and the body large, the reaction produced on the trunk by the vibration of the wing is scarcely perceptible. Apart, however, from the shape and dimensions of the wing, and the rapidity with which it is urged, it must never be overlooked that all wings (as has been pointed out) are attached to the bodies of the animals bearing them by some form of universal joint, and in such a manner that the bodies, whatever the position of the wings, are accurately balanced, and swim about precisely after the fashion of a compass set upon gimbals. To such an extent is this true, that the position of the wing is a matter of indifference. Thus the pinion may be above, beneath, or on a level with the body; or it may be directed forwards, backwards, or at right angles to the body. In either case the body is balanced mechanically and without effort. To prove this point, I made an artificial wing and body, and united the one to the other by a universal joint. I found, as I had anticipated, that place the wing in whatever position I chose, whether above, beneath, or on a level with the body, or at either side of it, the body almost instantly attained a position of rest. The body was, in fact, equally suspended and balanced from all points.

Rapidity of Wing Movements partly Accounted for.—Much surprise has been expressed at the enormous rapidity with which some wings are made to vibrate. The wing of the insect is, as a rule, very long and narrow. As a consequence, a comparatively slow and very limited movement at the root confers great range and immense speed at the tip, the speed of each portion of the wing increasing as the root of the wing is receded from. This is explained on a principle well understood in mechanics, viz., that when a rod hinged at one end is made to move in a circle, the tip or free end of the rod describes a much wider circle *in a given time* than a portion of the rod nearer the

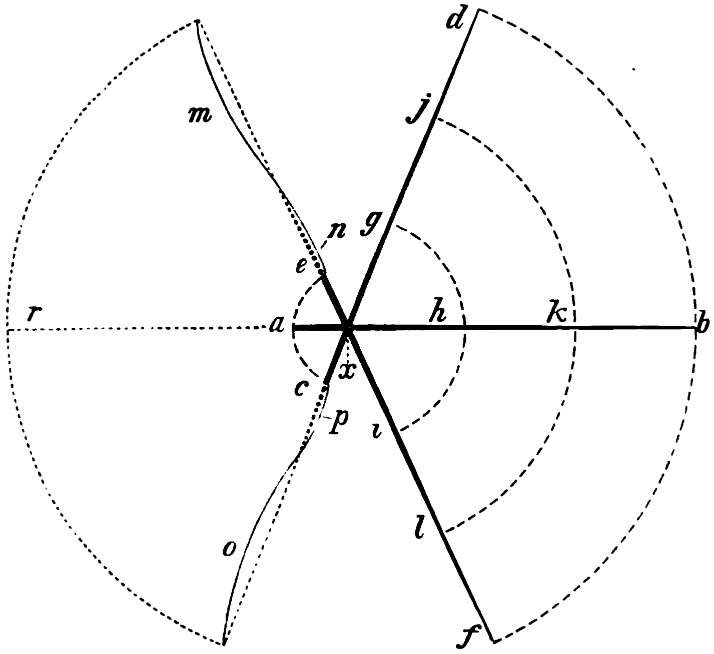

Fig. 51.[*]

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[*] In this diagram I have represented the wing by a straight *rigid* rod. The natural wing, however, is curved, *flexible*, and *elastic*. It likewise *moves in curves*, the curves being most marked towards the end of the down and up strokes, as shown at *m*, *n*, *o*, *p*. The curves, which are double figure of 8 curves, are obliterated towards the middle of the strokes (*r*, *a*). This remark holds true of all natural wings, and of all artificial wings properly constructed. The curves and the reversal thereof are necessary to give continuity of motion to the wing during its vibrations, and what is not less important, to enable the wing alternately to seize and dismiss the air.

hinge. Thus if *a b* of figure 51 (p. 399) be made to represent the rod hinged at *x*, it travels through the space *d b f* in the same time that it travels through *j k l*; and through the space *j k l* in the same time that it travels through the space *g h i*; and through the space *g h i* in the same time it travels through *e a c*, which is the area occupied by the thorax of the insect. If, however, the rod *a b* travels through the space *d b f* in the same time that it travels through the space *e a c*, it follows of necessity that the portion of the rod marked *a* moves very much slower than that marked *b*. The muscles of the insect are applied at the point *a*, as short levers (the point referred to corresponding to the thorax of the insect), so that a comparatively slow and limited movement at the root of the wing produces the marvellous speed observed at the tip, the tip and body of the wing being those portions which occasion the blur or impression produced on the eye by the rapidly oscillating pinion. But for this mode of augmenting the speed originally inaugurated by the muscular system, it is difficult to comprehend how the wings could be driven at the velocity attributed to them. The wing of the blow-fly is said to make 300 strokes per second, *i.e.*, 18,000 strokes per minute. Now it appears to me that muscles to contract at the rate of 18,000 times in the minute would be exhausted in a very few seconds, a state of matters which would render the continuous flight of insects impossible. (The heart contracts only between 60 and 70 times in a minute.) I am therefore disposed to believe that the number of contractions made by the thoracic muscles of insects has been greatly overstated, the high speed at which the wing is made to vibrate being due less to the separate and sudden contractions of the muscles at its roots than to the fact that the speed of the different parts of the wing is increased in a direct ratio as the portions in question are removed from the driving point, as already explained. Speed is certainly a matter of great importance in wing movements, as the elevating and propelling power of the pinion depends to a great extent upon this condition. Speed, however, may be produced in two ways —either by a series of separate and opposite movements, such as is witnessed in the action of a piston, or by a series of separate and opposite movements, acting upon an instrument so designed that a movement applied at one part increases in rapidity as the point of contact is receded from, as happens in the wing. In the piston movement the motion is uniform, or nearly so, all parts of the piston travelling at very much the same speed. In the wing movements, on the contrary, the motion is gradually accelerated towards the tip of the pinion, where the pinion is most effective as an elevator, and decreased towards the root, where it is least effective; an arrangement calculated to reduce the number of muscular contractions, while it contributes to the actual power of the wing. This hypothesis, it will be observed, guarantees to the wing a very high speed, with comparatively few reversals and comparatively few muscular contractions.

In the bat and bird the wings do not vibrate with the same rapidity as in the insect, and this is accounted for by the circumstance, that in them the muscles do not act exclusively at the root of the wing. In the bird and bat the muscles run along the wing towards the tip for the purpose of flexing or folding the wing prior to the up stroke, and for opening out or expanding it prior to the down stroke.

As the wing must be folded or flexed and opened out or expanded every time the wing rises and falls, and as the muscles producing flexion and extension are long muscles with long tendons, which act at long distances as long levers, and comparatively slowly, it follows that the great short muscles (pectorals, &c.) situated at the root of the wing must act slowly likewise, as the muscles of the thorax and wing of necessity act together to produce one pulsation or vibration of the wing. What the wing of the bat and bird loses in speed it gains in power, the muscles of the bird and bat's wing acting directly upon the points to be moved, and under the most favourable conditions. In the insect, on the contrary, the muscles act indirectly, and consequently at a disadvantage. If the pectorals only acted, they would act as short levers, and confer on the wing of the bat and bird the rapidity peculiar to the wing of the insect. The tones produced by the bird's wing would in this case be heightened. The swan in flying produces a loud whistling sound, and the pheasant, partridge, and grouse a sharp whirring noise like the stone of a knife-grinder.

It is a mistake to suppose, as many do, that the tone or note produced by the wing during its vibrations is a true indication of the number of beats made by it in any given time. This will be at once understood, when I state that a long wing will produce a higher note than a shorter one driven at the same speed and having the same superficial area, from the fact that the tip and body of the long wing will move through a greater space in a given time than the tip and body of the shorter wing. This is occasioned by all wings being jointed at their roots, the sweep made by the different parts of the wing in a given time being longer or shorter in proportion to the length of the pinion. It ought, moreover, not to be overlooked that in insects the notes produced are not always referrible to the action of the wings, these, in many cases, being traceable to movements induced in the legs and other parts of the body.

It is a curious circumstance that if portions be removed from the posterior margins of the wings of a buzzing insect, such as the wasp, bee, blue-bottle fly, &c., the note produced by the vibration of the pinions is raised in pitch. This is explained by the fact that an insect, whose wings are curtailed, requires to drive them at a much higher speed in order to sustain itself in the air. That the velocity at which the wing is urged is instrumental in causing the sound, is proved by the fact that in slow flying insects and birds no note is produced; whereas in those which urge the wing at a high speed, a note is elicited which corresponds within certain limits to the number of vibrations and the form of the wing. It is the posterior or thin flexible margin of the wing which is more especially engaged in producing the sound, and if this be removed, or if this portion of the wing, as is the case in the bat and owl, be constructed of very soft materials, the character of the note is altered. An artificial wing, if properly constructed and impelled at a sufficiently high speed, emits a drumming noise, which closely resembles the note produced by the vibration of short-winged, heavy-bodied birds, all which goes to prove that sound is a concomitant of rapidly vibrating wings.

ARTIFICIAL FLIGHT.

The subject of artificial flight, notwithstanding the large share of attention bestowed upon it, has been particularly barren of results. This is the more to be regretted, as the interest which has been taken in it from early Greek and Roman times has been universal. The unsatisfactory state of the question is to be traced to a variety of causes, the most prominent of which are—

1*st,* The extreme difficulty of the problem.

2*d,* The incapacity or theoretical tendencies of those who have devoted themselves to its elucidation.

3*d,* The great rapidity with which wings, especially insect wings, vibrate, and the difficulty experienced in analysing their movements.

4*th,* The great weight of all flying things when compared with a corresponding volume of air.

5*th,* The discovery of the balloon, which has retarded the science of aërostation, by misleading men's minds and causing them to look for a solution of the problem by the aid of a machine lighter than the air, and which has no analogue in nature. Flight has been unusually unfortunate in its votaries. It has been cultivated by profound thinkers, especially mathematicians, who have worked out innumerable theorems, but who, it would appear, never bethought them of verifying their results by experiment; and by uneducated charlatans who, despising the abstractions of science, have made the most ridiculous attempts at a practical solution of the problem. Thus bandied about, artificial flight has become the idol of a few and the jest of the many. The term has been employed, on the one hand, to represent the highest soarings of the human mind, and on the other, to typify the extinction or aberration of intellect, the word flighty signifying whatever is utopian or foolish.

Flight, as the question stands at present, may be divided into two principal varieties which represent two great sects or schools—

1*st,* The Balloonists, or those who advocate the employment of a machine specifically lighter than the air.

2*d,* Those who believe that weight is necessary to flight.

The second school may be subdivided into (*a*) those who advocate the employment of rigid inclined planes driven forward in a straight line, or revolving planes (aërial screws); and (*b*) such as trust for elevation and propulsion to the vertical flapping of wings.

Balloon.—The balloon, as all are aware, is constructed on the obvious principle that a machine lighter than the air must necessarily rise through it. The MONTGOLFIER brothers invented such a machine in 1782. Their balloon consisted of a paper globe or cylinder, the motor power being super-heated air supplied by the burning of vine twigs under it. The Montgolfier or fire balloons, as they were called, were superseded by the hydrogen gas balloon of MM. CHARLES and ROBERT, this being in turn supplanted by the ordinary gas balloon of Mr GREEN. Since the introduction of coal gas in the place of hydrogen gas, no radical improvement has been effected, all attempts at guiding balloons having signally failed. This arises from the vast extent of surface which they necessarily present, rendering them a fair conquest to every breeze that blows, and because the power which animates them is a mere lifting power which, in the absence of wind, must act in a vertical line, all other motion being extraneous and foreign to it. It consequently rises through the air in opposition to the law of gravity, very much as a dead bird falls in a downward direction in accordance with it. Having no hold upon the air, this cannot be employed as a fulcrum for regulating its movements, and hence the cardinal difficulty of ballooning as an art.

Finding that no marked improvement has been made in the balloon since its introduction in 1782, the more advanced thinkers have within the last quarter of a century turned their attention in an opposite direction, and have come to regard flying creatures, all of which are much heavier than the air, as the true models for flying machines. An old doctrine is more readily assailed than uprooted, and accordingly we find the followers of the new faith met by the assertion that insects and birds have large air cavities in their interior, that those cavities contain heated air, and this heated air in some mysterious manner contributes to, if it does not actually produce, flight. No argument could be more fallacious. To render a flying creature buoyant by means of air-cells, it would require to have its superficial area increased a thousand fold (would, in fact, require to be converted into a balloon); and, besides, many admirable fliers, such as the bats, have no air-cells, while many birds, the apteryx for example, and many animals never intended to fly, such as the orang-outang and a large number of fishes, are provided with them. It may therefore be reasonably concluded that flight is in no way connected with air-cells, and the best proof that can be adduced is to be found in the fact that it can be performed to perfection in their absence.

The Inclined Plane.—The modern school of flying is in some respects quite as irrational as the ballooning school.

The favourite idea with most is the wedging forward of *an inclined plane* upon the air by means of a "*vis a tergo.*"

The inclined plane may be made to advance in *a horizontal line* or made *to rotate* in the form of a screw. Both plans have their adherents. The one recommends a large supporting area extending on either side of the weight to be elevated, the surface of the supporting area making an all but inappreciable angle with the horizon, the whole being wedged forward by the action of vertical screw propellers. This was the plan suggested by HENSON and STRINGFELLOW, and partly carried out by the latter.

WENHAM* has advocated the employment of *superimposed planes,* with a view to augmenting the support furnished while it diminishes the horizontal space occupied by the planes. These planes WENHAM designates *Acroplanes.* They are inclined at a very slight angle to the horizon, and are wedged forward either by the weight to be elevated or by the employment of vertical screws. WENHAM'S plan was adopted by STRINGFELLOW† in a model which he exhibited at the Aëronautical Society's Exhibition, held at the Crystal Palace in the summer of 1868.

The subjoined woodcut (fig. 52), taken from a photograph, gives a very good idea of the model in question, *a b c* representing the superimposed planes, *d* the tail, and *e f* the vertical screw propellers.

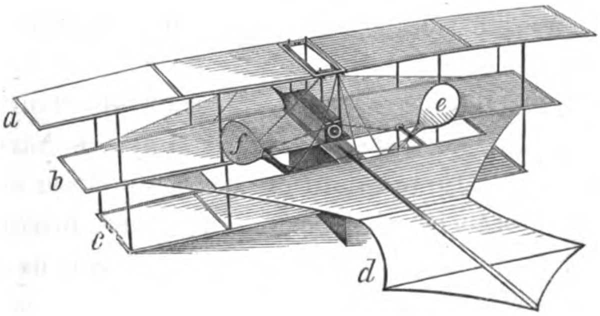

Fig. 52.

The superimposed planes (*a b c*) in this machine contained a sustaining area of 28 square feet in addition to the tail (*d*).

Its engine represented a third of a horse power, and the weight of the whole (engine, boiler, water, fuel, superimposed planes, and propellers) was under 12 lbs. Its sustaining area, if that of the tail (*d*) be included, was something like 36 square feet, *i.e.*, 3 square feet for every pound—the sustaining area of the gannet (p. 385), it will be remembered, being less than one foot of wing for every two pounds of body.

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* On Aërial Locomotion, by F. H. WENHAM, Esq., World of Science for June, 1867.

† Flying Machines, by F. W. BREARY, Esq., Popular Science Review for January, 1869.

The model was forced by its propellers along a wire at a great speed, but, so far as I could determine, failed to lift itself notwithstanding its extreme lightness and the comparatively very great power employed.*

Mr HENSON'S† aërial machine was very similar in principle to Mr STRINGFELLOW'S. "The chief feature of the invention was the very great expanse of its sustaining planes, which were larger in proportion to the weight it had to carry than those of many birds. The machine advanced with its front edge a little raised, the effect of which was to present its under surface to the air over which it passed, the resistance of which, acting upon it like a strong wind on the sails of a windmill, prevented the descent of the machine and its burden. The sustaining of the whole, therefore, depended upon the speed at which it travelled through the air, and the angle at which its under surface impinged on the air in its front. . . . The machine, fully prepared for flight, was started from the top of an inclined plane, in descending which it attained a velocity necessary to sustain it in its further progress. That velocity would be gradually destroyed by the resistance of the air to the forward flight; it was, therefore, the office of the steam engine and the vanes it actuated simply to repair the loss of velocity; it was made therefore only of the power and weight necessary for that small effect. . . ." The editor of "Newton's Journal of Arts and Science" speaks of it thus—"The apparatus consists of a car containing the goods, passengers, engines, fuel, &c., to which a rectangular frame, made of wood or bamboo cane, and covered with canvas or oiled silk, is attached. This frame extends on either side of the car in a similar manner to the outstretched wings of a bird; but with this difference, that the frame is immovable. Behind the wings are two vertical fan wheels, furnished with oblique vanes, which are intended to propel the apparatus through the air. The rainbow-like circular wheels are the propellers, answering to the wheels of a steam-boat, and acting upon the air after the manner of a windmill. These wheels receive motion from bands and pulleys from a steam or other engine contained in the car. To an axis at the stern of the car a triangular frame is attached, resembling the tail of a bird, which is also covered with canvas or oiled silk. This may be expanded or contracted at pleasure, and is moved up and down for the purpose of causing the machine to ascend or descend. Beneath the tail is a rudder for directing the course of the machine to the right or to the left; and to facilitate the steering a sail is stretched between two masts which rise from the car. The amount of canvass or oiled silk necessary for buoying up the machine is stated to be equal to one square foot for each half pound of weight.‡

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* Mr STRINGFELLOW stated that his machine occasionally left the wire, and was sustained by its superimposed planes alone.

† Mr HENSON designed his aërostat in 1843.

‡ Astra Castra, by HATTON TURNER, Esq. London, 1865, pages 311 and 312.

The idea embodied by HENSON, STRINGFELLOW, and WENHAM is plainly that of a boy's kite sailing upon the wind. The kite, however, is a more perfect flying apparatus than that furnished by HENSON, STRINGFELLOW, and WENHAM, inasmuch as the inclined plane formed by its body strikes the air at various angles—the angles varying according to the length of string, strength of breeze, length and weight of tail, &c. HENSON'S, STRINGFELLOW'S, and WENHAM'S methods, although carefully tried, have hitherto failed. The objections are numerous. In the first place, the supporting planes (aëroplanes or otherwise) are *rigid.* This is a point to which I wish particularly to direct attention. Second, They stroke the air *at a given angle.* Here again, there is a departure from nature. Third, A machine so constructed must be precipitated from a height or driven along the surface of the land or water at a high speed to supply it with initial velocity. Fourth, It is unfitted for flying with the wind unless its speed greatly exceeds that of the wind. Fifth, It would have considerable difficulty in flying across the wind, and considerable risk would be incurred in landing because of the velocity attained. Sixth, The sustaining surfaces are comparatively very large. They are, moreover, passive or dead surfaces, *i.e.,* they have no power of moving or accommodating themselves to altered circumstances. In this respect they somewhat resemble the surfaces presented by a balloon—their great extent rendering them liable to be seized and tossed by the wind.

The Aërial Screw.—Our countryman, Sir GEORGE CAYLEY, gave the first practical illustration of the efficacy of the screw as applied to the air in 1796. In that year he constructed a small machine consisting of two screws made of quill feathers. The screws were each composed of four feathers stuck in a piece of cork, the corks being drilled in the centre to receive a driving shaft or axis. To the shaft a whalebone spring, with a string which coiled round the shaft (and by which the spring was wound up), was affixed. By turning the upper screw (the lower one being secured) a sufficient number of times, the proper degree of tension was conferred on the spring; and the instant the apparatus was liberated it flew into the air. CAYLEY'S screws were peculiar, inasmuch as they were superimposed and rotated in opposite directions. He estimated that if the area of the screws was increased to 200 square feet, and moved by a man, they would elevate him. CAYLEY'S interesting experiment is described at length, and the apparatus figured in "Nicholson's Journal" for 1809, p. 175. In 1842 Mr PHILLIPS also succeeded in elevating a model by means of revolving fans. Mr PHILLIPS'S model was made entirely of metal, and when complete and charged weighed 2 lbs. It consisted of a boiler or steam generator and four fans supported between eight arms. The fans were inclined to the horizon at an angle of 20°, and through the arms the steam rushed on the principle discovered by HERO of Alexandria. By the escape of steam from the arms, the fans were made to revolve with immense energy, so much so that the model rose to a great altitude, and flew across two fields before it alighted. The motive power employed in the present instance was obtained from the combustion of charcoal, nitre, and gypsum, as used in the original fire annihilator, the products of combustion mixing with water in the boiler, and forming gas charged steam, which was delivered at a high pressure from the extremities of the eight arms. This model is remarkable as being probably the first which actuated by steam has flown to any considerable distance.[*] The French have espoused the aërial screw with great enthusiasm, and within the last few years (1863) M. M. NADAR,[†] DE PONTIN D'AMÉCOURT, and DE LA LANDELLE have constructed clockwork models (*orthopteres*), which not only raise themselves into the air, but carry a certain amount of freight. These models are exceedingly fragile, and because of the prodigious force required to propel them usually break after a few trials. The above woodcut (figure 53) embodies M. DE LA LANDELLE's ideas.

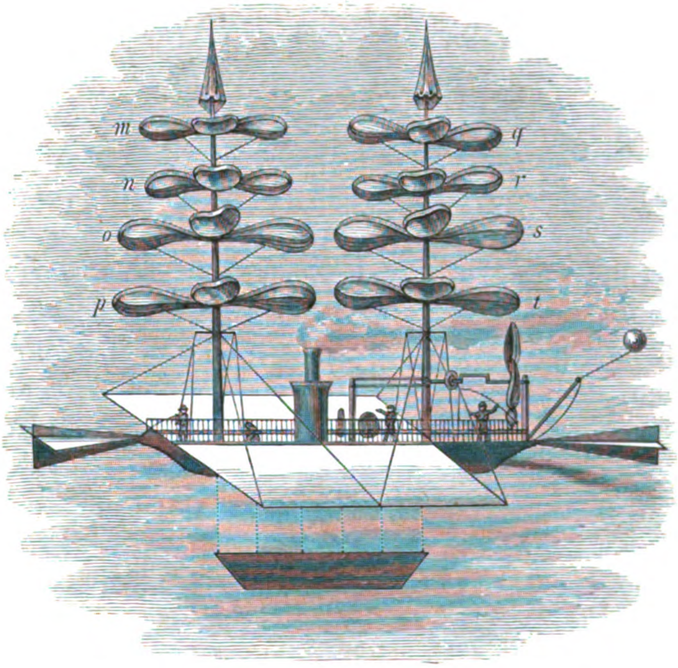

Fig. 53. Flying Machine designed by M. DE LA LANDELLE.

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[*] Report on the First Exhibition of the Aëronautical Society of Great Britain, held at the Crystal Palace, London, in June 1868, page 10.

[†] Mons. NADAR, in a paper written in 1863, enters very fully into the subject of artificial flight, as performed by the aid of the screw. Liberal extracts are given from NADAR's paper in "Astra Castra," by Captain HATTON TURNER. London, 1865, page 340. To TURNER's handsome volume the reader is referred for much curious and interesting information on the subject of Aërostation.

In the helecopteric models made by M. M. NADAR, PONTIN D'AMÉCOURT, and DE LA LANDELLE, the screws (*m n o p q r s t*, figure 53, p. 407) are arranged in tiers, *i.e.*, the one screw is placed above the other. In this respect they resemble the aëro-planes recommended by Mr WENHAM, and tested by Mr STRINGFELLOW, (compare *m n o p q r s t* of fig. 53. p. 407, with *a b c* of fig. 52, p. 404). The superimposed screws, as already explained, were first figured and described by Sir GEORGE CAYLEY. The French screws, and that employed by Mr PHILLIPS, are *rigid or unyielding,* and strike the air *at a given angle,* and herein, I believe, consist their principal defect. This arrangement results in a ruinous expenditure of power, and is accompanied by a great amount of slip. The aërial screw, and the machine to be elevated by it, can be set in motion without a preliminary run, and in this respect it has the advantage over the machine supported by sustaining planes. It has, in fact, a certain amount of inherent motion, its sustaining surfaces being active or moving surfaces. It is accordingly more independent than the machine designed by HENSON, STRINGFELLOW, and WENHAM.

I may observe with regard to the system of rigid inclined planes wedged forward at a given angle in a line or in a circle, that it does not embody the principle carried out in nature.

The wing of a flying creature, as I have taken pains to show, is *not rigid;* neither does it always attack the air *at one angle.* On the contrary, it is capable of moving in all its parts, and attacks the air at *an infinite variety of angles.* Above all, the surface exposed by a natural wing, when compared with the great weight it is capable of elevating, is remarkably small. This is accounted for by the length and the great range of motion of natural wings, the latter enabling the wings to convert large tracts of air into supporting areas. It is also accounted for by the multiplicity of the movements of natural wings, these enabling the pinions to create and rise upon currents of their own forming, and to select and utilise existing currents.

If any one watches an insect, a bat, or a bird when dressing its wings, he will observe that it can incline the under surface of the wing at a great variety of angles to the horizon. This it does by causing the wing to rotate along its anterior or thick margin, or by twisting the posterior or thin yielding margin around the anterior or thick margin. As a result of this movement, the two margins are forced into double and opposite curves, and the wing converted into *a plastic helix or screw.* He will further observe that the bat and bird, and some insects, have, in addition, the power of folding and drawing the wing towards the body during the up stroke, and of pushing it away from the body and extending it during the down stroke, so as alternately to diminish and increase its area, arrangements necessary to decrease the amount of resistance experienced by the wing during its ascent, and increase it during its descent. It is scarcely necessary to add, that in the aëro-planes and aërial screws, as at present constructed, no provision whatever is made for suddenly increasing or diminishing the sustaining area, of conferring elasticity upon it, or of giving to the supporting surfaces that infinite variety of angles which would enable them to seize and disentangle themselves from the air with rapidity. Many investigators are of opinion that flight is a question of mere levity and power, and that if a machine could only be made light enough and powerful enough, it must of necessity fly, whatever the nature of its flying surfaces. A grave fallacy lurks here. Birds are not more powerful than quadrupeds of equal size, and STRINGFELLOW's machine, which, as we have seen, only weighed 12 *lbs.*, exerted *one-third of a horse power*. The probabilities therefore, are, that flight is dependent to a great extent on the nature of the flying surfaces, and the mode of applying those surfaces to the air.

Artificial Wings (BORELLI's *Views*).—With regard to the production of *flight by the flapping of wings*, much may and has been said. Of all the methods yet proposed, it is unquestionably by far the most ancient. Discrediting as apocryphal the famous story of DÆDALUS and his waxen wings, we certainly have a very graphic account of artificial wings in the "De Motu Animalium" of BORELLI, published as far back as 1680, *i.e.*, nearly two centuries ago.*

Indeed it will not be too much to affirm, that to this distinguished physiologist and mathematician belongs almost all the knowledge we at present possess of artificial wings and their actions. He was well acquainted with the properties of the wedge, as applied to flight, and he was likewise cognisant of the flexible and elastic properties of the wing. To him is to be traced the purely mechanical theory of the wing's action. He figured a bird with artificial wings, each wing consisting of *a rigid rod in front* and *flexible feathers* behind. I have thought fit to reproduce BORELLI's figure, both because of its great antiquity, and because it is eminently illustrative of his text.†

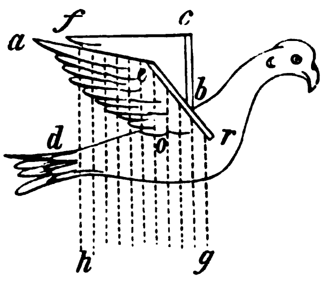

Fig. 54.

The wings, as a reference to fig. 54 will show, are represented as striking vertically downwards (*g h*). They remarkably accord with those described by STRAUS-DURCKHEIM, GIRARD, and quite recently by Professor MAREY.‡

BORELLI was of opinion that flight resulted from the application of an inclined plane, which beats the air, and which has a wedge action. He, in fact, endeavours to prove that a bird wedges itself forward upon the air by the perpendicular

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* BORELLI. De Motu Animalium. Sm. 4to. 2 vols. Romæ 1680.

† "De Motu Animalium," Lugduni Batavorum apud Petrum Vander. Anno MDCLXXXV. Tab. XIII. figure 2. (New edition.)

‡ Revue des Cours Scientifiques de la France et de l'Etranger. Mars 1869.

vibration of its wings, the wings during their action forming a wedge, the base of which (*c b e*) is directed towards the head of the bird, the apex (*a f*) being directed towards the tail (*d*). This idea is worked out in propositions 195 and 196 of the first part of BORELLI's book. In proposition 195 he explains how, if a wedge be driven into a body, the wedge will tend to separate that body into two portions; but that if the two portions of the body be permitted to react upon the wedge, they will communicate *oblique impulses* to the sides of the wedge, and expel it, base first, in a straight line.

Following up the analogy, BORELLI endeavours to show in his 196th proposition, "that if the air acts obliquely upon the wings, or the wings obliquely upon the air (which is, of course, a wedge action), the result will be *a horizontal transference of the body of the bird.*" In the proposition referred to (196) BORELLI states—"If the expanded wings of a bird suspended in the air shall strike the undisturbed air beneath it with a motion *perpendicular to the horizon,* the bird will fly *with a transverse motion* in a plane parallel with the horizon." In other words, if the wings *strike vertically downwards,* the bird will fly *horizontally forwards.* He bases his argument upon the belief that the anterior margins of the wings are *rigid and unyielding,* whereas the posterior and after parts of the wings are *more or less flexible,* and readily give way under pressure. If, he adds, the wings of the bird be expanded, and the under surfaces of the wings be struck by the air *ascending perpendicularly to the horizon,* with such a force as shall prevent the bird gliding downwards (*i.e.*, with a tendency to glide downwards) from falling, it will be urged *in a horizontal direction.* This follows because, in BORELLI's opinion, the two osseous rods (*virgæ*) forming the anterior margins of the wings resist the upward pressure of the air, and so retain their original form (literally extent or expansion), whereas the flexible after parts of the wings (posterior margins) are pushed up and approximated to form a cone, the apex of which (*vide a f* of figure 54, p. 409) is directed towards the tail of the bird. In virtue of the air playing upon and compressing the sides of the wedge formed by the wings, the wedge is driven forwards in the direction of its base (*c, b, e*), which is equivalent to saying that the wings carry the body of the bird to which they are attached *in a horizontal direction.*" BORELLI restates the same argument in different words, as follows:—

"If," he says, "the air under the wings be struck by the flexible portions of the wings (*flabella,* literally fly flaps or small fans) with a motion perpendicular to the horizon, the sails (*vela*) and flexible portions of the wings (*flabella*) will yield in an upward direction, and form a wedge, the point of which is directed towards the tail. Whether, therefore, the air strikes the wings from below, or the wings strike the air from above, the result is the same—the posterior or flexible margins of the wings *yield in an upward direction,* and in so doing urge the bird in a *horizontal direction.*"

In his 197th proposition, BORELLI follows up and amplifies the arguments contained in propositions 195 and 196. Thus, he observes, "It is evident that the object of flight is to impel birds upwards, and keep them suspended in the air, and also to enable them to wheel round in a plane parallel to the horizon. The first (or upward flight) could not be accomplished unless the bird were impelled upwards by frequent leaps or vibrations of the wings, and its descent prevented. And because the downward tendency of heavy bodies is perpendicular to the horizon, the vibration of the plain surfaces of the wings must be made by striking the air beneath them in a direction perpendicular to the horizon, and in this manner nature produces the suspension of birds in the air.

With regard to the second or transverse motion of birds (*i.e.*, horizontal flight) some authors have strangely blundered; for they hold that it is like that of boats, which, being impelled by oars, moved horizontally in the direction of the stern, and pressing on the resisting water behind, leaps with a contrary motion, and so are carried forward. In the same manner, say they, the wings vibrate towards the tail with a horizontal motion, and likewise strike against the undisturbed air, by the resistance of which they are moved forward by a reflex motion. But this is contrary to the evidence of our sight as well as to reason; for we see that the larger kinds of birds, such as swans, geese, &c., never vibrate their wings, when flying, towards the tail with a horizontal motion like that of oars, but always bend them downwards, and so describe circles raised perpendicularly to the horizon.*

Besides, in boats the horizontal motion of the oars is easily made, and a perpendicular stroke on the water would be perfectly useless, inasmuch as their descent would be impeded by the density of the water. But in birds such a horizontal motion (which indeed would rather hinder flight) would be absurd, since it would cause the ponderous bird to fall headlong to the earth; whereas it can only be suspended in the air by constant vibration of the wings perpendicular to the horizon. Nature was thus forced to show her marvellous skill in producing a motion which, by one and the same action, should suspend the bird in the air, and carry it forward in a horizontal direction. This is effected by striking the air below perpendicularly to the horizon, but with oblique strokes—an action which is rendered possible only by the flexibility of the feathers, for the fans of the wings in the act of striking acquire the form of a wedge, by the forcing out of which, the bird is necessarily moved forwards in a horizontal direction."

The points which BORELLI endeavours to establish are these:—

First, That the action of the wing is a wedge action.

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* It is clear from the above that BORELLI did not know that the wings of birds strike *forwards* as well as downwards during the down stroke. He seems to have been equally ignorant of the fact that the wings of insects vibrate in a more or less horizontal direction.

Second, That the wing consists of two portions—*a rigid* anterior portion, and a *non-rigid* flexible portion. The rigid portion he represents in his artificial bird (figure 54, page 409) as consisting of *a rod* (*e, r*), the yielding portion of *feathers* (*a, o*).

Third, That if the air strikes the under surface of the wing perpendicularly in a direction from below upwards, the flexible portion of the wing will yield in an upward direction, and form a wedge with its neighbour.

Fourth, Similarly and conversely, if the wing strikes the air perpendicularly from above, the posterior and flexible portion of the wing will yield and be forced in an upward dirction.

Fifth, That this *upward yielding* of the posterior or flexible margin of the wing results in and necessitates *a horizontal transference* of the body of the bird.

Sixth, That to sustain a bird in the air the wings must strike *vertically downwards,* as this is the direction in which a heavy body, if left to itself, would fall.

Seventh, That to propel the bird in a horizontal direction, the wings must descend in a perpendicular direction, and the posterior or flexible portions of the wings *yield in an upward direction,* and in such a manner as virtually to communicate *an oblique action* to them.

Eighth, That the feathers of the wing are *bent in an upward direction* when the wing *descends,* the upward bending of the elastic feathers contributing to the horizontal travel of the body of the bird.

I have been careful to expound BORELLI's views for several reasons :—

1*st,* Because the purely mechanical theory of the wing's action is to be traced to him.

2*d,* Because his doctrines have remained unquestioned for nearly two centuries, and have been adopted by all the writers since his time, without, I regret to say in the great majority of cases, any acknowledgment whatever.

3*d,* Because his views have been revived by the modern French school, and

4*th,* Because in commenting upon and differing from BORELLI I will necessarily comment upon and differ from all his successors.

The Duke of ARGYLL agrees with BORELLI in believing that the wing invariably strikes *perpendicularly downwards.* His words are—" Except for the purpose of arresting their flight birds can never strike except *directly downwards;* that is, against the opposing force of gravity." Professor OWEN in his " Comparative Anatomy," Mr M'GILLIVRAY in his " British Birds," Mr BISHOP in his article Motion in the " Cyclopedia of Anatomy and Physiology," and M. LIAIS " on the flight of birds and insects" in the " Annals of Natural History," all assert that the stroke is delivered *downwards* and more or less *backwards.* To obtain an *upward* recoil, one would naturally think all that is required is a *downward* stroke, and to obtain an *upward and forward* recoil, one would naturally conclude a *downward and backward* stroke alone is requisite. This reasoning is true of water and wings, but it is not true of air and wings.

In the first place, a natural wing, or a properly constructed artificial one, cannot be depressed either *vertically downwards, or downwards and backwards.* It will of necessity descend *downwards and forwards in a curve.* This arises from its being flexible and elastic throughout, and in especial from its being carefully graduated as regards thickness, the tip being thinner and more elastic than the root, and the posterior margin than the anterior margin.

In the second place, there is only one direction in which the wing could strike so as at once *to support and carry the bird forward.* The bird, when flying, is a body in motion. It has therefore acquired momentum. If a grouse is shot on the wing *it does not fall vertically downwards,* as BORELLI and his successors assume, but *downwards and forwards.* The flat surfaces of the wings are consequently made to strike downwards and forwards, as they in this manner act as kites to the falling body, which they bear, or tend to bear, *upwards and forwards.* So much for the direction of the stroke during the descent of the wing. Let us now consider to what extent the posterior margin of the wing yields in *an upward direction* when the wing descends. BORELLI does not state the exact amount. The Duke of ARGYLL, who agrees with BORELLI that the posterior margin of the wing is elevated during the down stroke, avers that, whereas the air compressed in the hollow of the wing cannot pass through the wing owing to the closing upwards of the feathers against each other, or escape forwards because of the rigidity of the bones and of the quills in this direction, it passes backwards, and in so doing *lifts by its force the elastic ends of the feathers.* In passing backwards it communicates to the whole line of both wings a corresponding push forwards to the body of the bird. The same volume of air is thus made, in accordance with the law of action and reaction, *to sustain the bird and carry it forward.** Mr M'GILLIVRAY observes that "to progress *in a horizontal direction* it is necessary that the downward stroke should be modified *by the elevation in a certain degree of the free extremities of the quills.*†

MAREY'S *Views.*—Professor MAREY states that during *the down stroke* the posterior or flexible margin of the wing yields in *an upward direction,* to such an extent as to cause the under surface of the wing *to look backwards,* and make a backward angle with the horizon of 45° plus or minus according to circumstances.‡ That the posterior margin of the wing yields in a slightly upward direction during the down stroke to prevent shock, I admit. The amount of

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* Reign of Law. "Good Words," February 1865, p. 128.

† History of British Birds. Lond. 1837, p. 43.

‡ Méchanisme du vol chez les insectes. Comment se fait la propulsion, by Professor E. J. MAREY. Revue des Cours Scientifiques de la France et de l'Etranger for 20th March 1869, p. 254.

yielding is, however, in all cases very slight, and the little upward movement there is, is in part the result of the posterior margin of the wing rotating around the anterior margin as an axis. That the posterior margin of the wing never yields in *an upward direction* until the under surface of the pinion makes a backward angle of 45° with the horizon, as MAREY remarks, is a matter of absolute certainty. This statement admits of direct proof. If any one watches the horizontal or upward flight of a large bird, he will observe that the posterior or flexible margin of the wing never rises during the down stroke to a perceptible extent, so that *the under surface of the wing* never looks backwards. On the contrary, he will find that *the under surface of the wing* (during the down stroke) invariably *looks forwards*—the posterior margin of the wing being inclined *downwards and backwards*, the anterior one *upwards and forwards*, as shown at *c d e f*, *j k l m* of fig. 15, page 345; *h j* of fig. 38, page 361; 1, 2, 3; 4, 5, 6 of figs. 18 and 19, Plate XIV.; and *q p o* of figs. 14 and 15, Plate XIII.

The under surface of the wing, as will be seen from this account, not only *looks forwards*, but it forms a true kite with the horizon, the angles made by the kite varying at every part of the down stroke, as shown more particularly at *c*, *d*, *e*, *f*; *j*, *k*, *l*, *m* of fig. 15, page 345.

Professor MAREY goes on to state that not only does the posterior margin of the wing yield *in an upward direction* during the *down stroke* until the under surface of the pinion makes a backward angle of 45° with the horizon (page 415, fig. 55, *x c*; *a b*), but that during the *up stroke* it yields to the same extent *in an opposite direction* (*x d*; *a b*). The posterior flexible margin of the wing, according to MAREY, thus passes through a space of 90° every time the wing reverses its course, this space being dedicated to the mere adjusting of the planes of the wing for the purposes of flight. The planes, moreover, he asserts, are adjusted not by vital and vito-mechanical acts but by *the action of the air alone*; this operating on the under surface of the wing and forcing its posterior margin *upwards* during *the down stroke*; the air during the *up stroke* acting upon the posterior margin of the upper surface of the wing, which it forces *downwards*. MAREY thus delegates to the air, the difficult and delicate task of arranging the details of flight. The time, power, and space occupied in reversing the wing alone, according to this view, are such as to render flight impossible. That the wing does not act as stated by MAREY, may be readily proved by experiment. It may also be proved diagrammatically, as a reference to fig. 55, page 415, will show.

Let *a*, *b* of fig 55 represent the horizon; *m*, *n* the line of vibration; *x*, *c* the wing inclined at an upward backward angle of 45° in the act of making the down stroke, and *x*, *d* the wing inclined at a downward backward angle of 45° and in the act of making the up stroke. When the wing *x c* descends it will tend to dive downwards in the direction *f* (giving very little of any horizontal support); when the wing $x\ d$ ascends it will endeavour to rise in the direction g, as it darts up like a kite (the body bearing it being in motion). If we take the resultant of these two forces, we have at most propulsion in the direction $a\ b$. This, moreover, would only hold true if the bird was as light as air. As, however, gravity tends to pull the bird downwards as it advances, the real flight of the bird, according to this explanation, would fall in a line between b and f, probably in $x\ h$. It could not possibly be otherwise; the wing described and figured by Marey is in one piece, and vibrated vertically on either side of a given line. If, however, a wing in one piece is elevated and depressed in a strictly perpendicular direction, it is evident that the wing will experience a greater resistance during *the up stroke,* when it is acting *against gravity,* than during *the down stroke,* when it is acting *with gravity.* As a consequence, the bird will be more vigorously depressed during the ascent of the wing than it will be elevated during its descent. That the mechanical wing referred to by Marey is *not a flying wing,* but a mere propelling apparatus, seems evident to himself, for he states that "the winged machine designed by him has unquestionably *not motor power enough* to *support its own weight.*"[*]

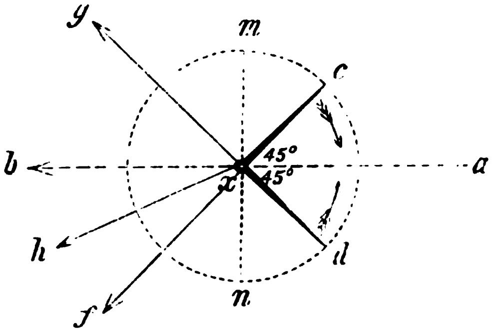

Fig. 55.

The manner in which the natural wing (and the artificial wing properly constructed and propelled) evades the resistance of the air during the up stroke, and gives continuous support and propulsion, is very remarkable. Fig. 56, page 416, will illustrate the principle. Let $a\ b$ represent the horizon; $m\ n$ the direction of vibration; $x\ s$ the wing ready to make the down stroke, and $x\ t$ the wing ready to make the up stroke. When the wing $x\ s$ descends, the posterior margin (s) is screwed *downwards* and *forwards* in the direction s, t, the forward angle which it makes with the horizon increasing as the wing is lowered. The air is thus seized by a great variety of inclined surfaces, and as the under surface of the wing, which is a true kite, looks *upwards* and *forwards,* it tends to carry the body of the bird *upwards* and *forwards* in the direction $x\ w$. When the wing x, t makes the *up stroke,* it rotates from below upwards to prepare for the second down stroke. The wing does not, however, ascend in the direction t, s. On the contrary, it darts up like a true kite, which it is, in the direction x, v, in virtue of the reaction of the air, and because the body of the bird, to which it is attached, had a forward motion communicated to it by the wing during the down stroke. The resultant of the forces acting in the lines $x\ v$ and $x\ b$, is one acting in the

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[*] Revue des Cours Scientifiques de la France et de l'Etranger. 8vo. March 20, 1869.

direction *x w*, and if allowance be made for the operation of gravity, the flight of the bird will fall somewhere between *w* and *b*, probably in the line *x, r*. This arises from the wing acting as an eccentric—from the upper concave surface of the pinion being always directed upwards, the under concave surface downwards—from the under surface, which is a true kite, darting forwards in wave curves both during the down and up strokes, and never making a backward angle with the horizon; and lastly, from the wing employing the air under it as a fulcrum during the down stroke, the air, on its part, reacting on the under surface of the pinion, and when the proper time arrives, contributing to the elevation of the wing.

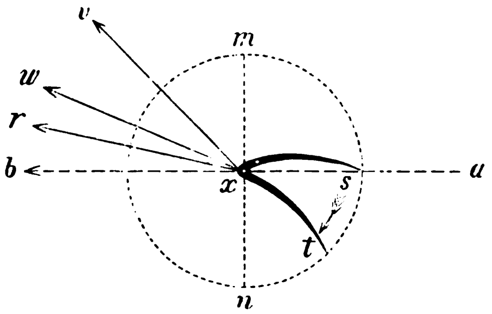

Fig. 56.

If, as Borelli and his successors believe, the posterior margin of the wing yielded to any marked extent in *an upward direction* during the *down stroke*, and more especially if it yielded to such an extent as to cause the under surface of the wing to make *a backward angle with the horizon of* 45°, one of two things would inevitably follow—either the air on which the wing depended for support and propulsion would be permitted to escape before it was utilised, or the wing would dart rapidly downward, and carry the body of the bird with it. If the posterior margin of the wing yielded in an upward direction to any marked extent during the down stroke it would be tantamount to removing the fulcrum (the air) on which the lever formed by the wing operates. The wing of the bird, as I have fully explained (see pages from 366 to 384 inclusive), acts as a kite both during *the down* and *up* strokes, the ventral aspect of the kite being always directed *forwards* (*vide* from *c* to *m* of fig. 15, page 345).

If a bird flies in a horizontal direction the angles made by the under surface of the wing with the horizon *are very slight*, but they *always look forwards*. If a bird flies upwards the angles in question are increased. In no instance, however, unless when the bird is everted and flying downwards, is the *posterior margin* of the wing *on a higher level* than the anterior one. This holds true of natural flight, and, consequently, ought to hold true of artificial flight.

With regard to the cone formed, according to Borelli, by the vertical descent of the two wings, or what, in his opinion, is the same thing, the perpendicular ascent of the air, and which is represented at *f e c* of figure 54, page 409; I think it would be more accurate to state that, instead of the two wings taken together forming *one cone*, that each wing by itself forms *two cones*.

The base of Borelli's cone (*e b c*, figure 54, p. 409), it will be remembered, is inclined forwards in the direction of the head of the bird—the bases of the cones formed by each natural wing being, on the contrary, directed *outwards* (*vide x b d* of figure 12, page 342) and *backwards* (see *q p n* of same figure). This arises from the fact that the wing rotates upon two axes (*a b* and *c d* of figure 45, page 376); because it rotates on its root (*a* of figure 19, Plate XIV.) to form one cone (*a f e* of same figure), and because, while it is rotating on its root, it is also rotating along its anterior margin (*a b*) to form a second cone, *c h g*. The wing, in forming the cone *a f e* elevates, and in forming the cone *c h g* propels. The base of the wedge which furnishes the horizontal transference is, therefore, turned in the direction of the tail of the bird, which is just the opposite of what BORELLI maintains, the base of his wedge being turned in the direction of the head.

BORELLI, and all who have written since his time, are unanimous in affirming that the horizontal transference of the body of the bird is due to the perpendicular vibration of the wings, and to the yielding of the posterior or flexible margins of the wings in an upward direction as the wings descend. I am, however, disposed to attribute it to the fact (1st), that the wings, both when elevated and depressed, *leap forwards in curves*, those curves uniting to form a continuous waved track; (2d), to the tendency which the body of the bird has to swing forwards, in a more or less horizontal direction, when once set in motion; (3d), to the construction of the wings (they are elastic helices or screws, which twist and untwist while they vibrate, and tend to bear upwards and onwards any weight suspended from them); (4th), to the reaction of the air on the under surfaces of the wings; (5th), to the ever-varying power with which the wings are urged, this being greatest at the beginning of the down stroke, and least at the end of the up one; (6th), to the contraction of the voluntary muscles and elastic ligaments, and to the effect produced by the various inclined surfaces formed by the wings during their oscillations; (7th), to the weight of the bird—weight itself, when acting upon wings, becoming a propelling power, and so contributing to horizontal motion. This is proved by the fact that if a sea bird launches itself from a cliff with expanded motionless wings, it sails along for an incredible distance before it reaches the water.

The authors who have adopted BORELLI'S plan of artificial wing, and who have indorsed his mechanical views of the wing's action most fully, are CHABRIER, STRAUS-DURCKHEIM, GIRARD, and MAREY. BORELLI'S artificial wing, as a reference to fig 54, page 409, will show, consists of *a rigid rod* in front, and *a flexible sail*, composed of feathers, behind. It acts upon the air, and the air acts upon it, as occasion demands.

CHABRIER'S *Views*.—CHABRIER states that the wing has only one period of activity—that, in fact, if the wing be suddenly lowered by the depressor muscles, it is elevated solely by the reaction of the air. There is one unanswerable objection to this theory—the bats and birds, and some, if not all, the insects have distinct elevator muscles. The presence of well-developed elevator muscles implies an elevating function; and, besides, we know that the insect, bat, and bird can elevate their wings when they are not flying, and when, consequently, no reaction of the air is induced (pages 364, 365, 395, 396, and 397).

STRAUS-DURCKHEIM'S *Views.*—DURCKHEIM believes that the insect abstracts from the air by means of *the inclined plane* a component force (composant) which it employs *to support* and *direct* itself. In his Theology of Nature he describes a schematic wing as follows:—It consists of *a rigid ribbing* in front, and *a flexible sail* behind. A membrane so constructed will, according to him, be fit for flight. It will suffice if such a sail *elevates* and *lowers* itself successively. It will, of its own accord, dispose itself as an inclined plane, *and receiving obliquely the reaction of the air,* it transfers *into tractile force* a part of the *vertical impulsion it has received.* These two parts of the wing are moreover equally indispensable to each other. If we compare the schematic wing of DURCKHEIM with that of BORELLI they will be found to be identical, both as regards their construction and the manner of their application.

MAREY'S *Views continued.*—Professor MAREY, so late as 1869, repeats BORELLI'S arguments and views with very trifling alterations. MAREY describes two artificial wings, the one composed of a *rigid rod* and *sail*—the rod representing *the stiff anterior margin* of the wing; the sail, which is made of paper bordered with card board, *the flexible posterior portion.* The other wing consists of a *rigid nervure* in front and behind of thin parchment which supports *fine rods of steel.* He states, that if the wing only elevates and depresses itself, "*the resistance of the air* is sufficient to produce all the other movements. In effect the wing of an insect has not the power of equal resistance in every part. On the anterior margin the extended nervures make it *rigid,* while behind it is fine and *flexible.* During the vigorous depression of the wing the nervure has the power of *remaining rigid,* whereas the *flexible portion,* being pushed in *an upward direction* on account of the resistance it experiences from the air, *assumes an oblique position* which causes the upper surface of the wing *to look forwards.*" The reverse of this takes place during the elevation of the wing—the resistance of the air from above causing the upper surface of the wing *to look backwards.* . . . "At first the plane of the wing is parallel with the body of the animal. It lowers itself—the *front part* of the wing *strongly resists,* the sail which follows it *being flexible yields.* Carried by the ribbing (the anterior margin of the wing) which lowers itself, the sail or posterior margin of the wing being raised meanwhile by the air, which sets it straight again, the sail will take an intermediate position, and *incline itself about* 45° plus or minus according to circumstances."

"The wing continues its movements of depression inclined to the horizon, but the impulse of the air which continues its effect, and naturally acts upon the surface which it strikes, has the power of resolving itself into two forces, *a vertical* and *a horizontal force,* the first suffices *to raise* the animal, the second to *move it along.*"[*]

I have already adverted at considerable length (pages 413, 414, and 415) to the movements and peculiarities of Professor Marey's artificial wing, and need not again return to it. I will only observe, in passing, that it is not a little curious that Borelli's artificial wing should have been reproduced at a distance of nearly two centuries.

The Author's Views:—his Method of Constructing and Applying Artificial Wings as Contradistinguished from that of Borelli, Chabrier, Durckheim, Marey, *&c.*—The artificial wings which I have been in the habit of making for several years differ from those recommended by Borelli, Durckheim, and Marey in four essential points:—

1st, The mode of construction.

2d, The manner in which they are applied to the air.

3d, The nature of the power employed.

4th, The necessity of adopting certain elastic substances at the root of the wing if in one piece, and at the root and in the body of the wing if in several pieces.

And, first, as to the manner of construction.

Borelli, Durckheim, and Marey maintain that *the anterior margin of the wing* should be *rigid;* I, on the other hand, believe that no part of the wing whatever should be rigid, *not even the anterior margin,* and that the pinion should be flexible and elastic throughout.

That the anterior margin of the wing should not be composed of a rigid rod

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[*] Compare Marey's description with that of Borelli, a translation of which I subjoin. "Let a bird be suspended in the air with its wings expanded, and first let the under surfaces (of the wings) be struck by the air ascending perpendicularly to the horizon with such a force that the bird gliding down is prevented from falling: I say that it (the bird) will be impelled with a horizontal forward motion, because the two osseous rods of the wings are able, owing to the strength of the muscles, and because of their hardness, *to resist the force of the air,* and therefore to retain the same form (literally extent, expansion), but the total breadth of the fan of each wing *yields to the impulse of the air* when the flexible feathers are permitted to rotate around the "*manubria*" or osseous axis, and hence it is necessary that the extremities of the wings approximate each other: wherefore the wings acquire the form of a wedge whose point is directed towards the tail of the bird, but whose surfaces are compressed on either side by the ascending air in such a manner that it is driven out in the direction of its base. Since, however, the wedge formed by the wings cannot move forward unless it carry the body of the bird along with it, it is evident that it (the wedge) gives place to the air impelling it, and therefore the bird flies forward in a horizontal direction. But now let the substratum of still air be struck by the fans (feathers) of the wings with a motion perpendicular to the horizon. Since the fans and sails of the wings acquire the form of a wedge, the point of which is turned towards the tail (of the bird), and since they suffer the same force and compression from the air, whether the vibrating wings strike the undisturbed air beneath, or whether, on the other hand, the expanded wings (the osseous axis remaining rigid) receive the percussion of the ascending air; in either case the *flexible feathers yield to the impulse,* and hence approximate each other, and thus the bird moves in *a forward direction.*"—*De Motu Animalium,* pars prima, prop. 196, 1685.

may, I think, be demonstrated in a variety of ways. If a rigid rod be made to vibrate by the hand the vibration is not smooth and continuous; on the contrary, it is irregular and jerky, and characterised by two halts or pauses (dead points), the one occurring at the end of the *up stroke*, the other at the end of the *down stroke*. This mechanical impediment is followed by serious consequences as far as power and speed are concerned—the slowing of the wing at the end of the down and up strokes involving a great expenditure of power and a disastrous waste of time. The wing, to be effective as an elevating and propelling organ, should have no dead points, and should be characterised by a rapid winnowing or fanning motion. It should reverse and reciprocate with the utmost steadiness and smoothness—in fact, the motions should appear as continuous as those of a fly-wheel in rapid motion: they are so in the insect.

To obviate the difficulty in question, it is necessary, in my opinion, to employ *a tapering elastic rod* or *series of rods* bound together for the anterior margin of the wing.

If a longitudinal section of bamboo cane, 10 feet in length, and 1 inch in breadth (*vide* fig. 57, p. 421), be taken by the extremity and made to vibrate, it will be found that a wavy serpentine motion is produced, the waves being greatest when the vibration is slowest (fig. 58, p. 421), and least when it is most rapid (fig. 59, p. 421). It will further be found that at the extremity of the section where the impulse is communicated there is *a steady reciprocating movement devoid of dead points*. The continuous movement in question is no doubt due to the fact that the different portions of the reed reverse at different periods—the undulations induced being to an interrupted or vibratory movement very much what the continuous play of a fly-wheel is to a rotatory motion.

The Wave Wing of the Author.—If a similar reed has added to it, tapering rods of whalebone, which radiate in an outward direction to the extent of a foot or so, and the whalebones be covered by a thin sheet of india-rubber, an artificial wing, resembling the natural one in all its essential points, is at once produced (*vide* fig. 60, p. 421). I propose to designate this wing, from the peculiarities of its movements, *the wave wing* (fig. 61, p. 421). If the wing referred to (fig. 61) be made to vibrate at its root, a series of longitudinal (*c d e*) and transverse (*f g h*) waves are at once produced, the one series running in the direction of *the length of the wing*, the other in the direction of *its breadth* (*vide* p. 330). This wing further *twists* and *untwists*, figure of 8 fashion, during the down and up strokes, as shown at figure 62, page 423 (compare with figure 2, p. 336). There is, moreover, a continuous play of the wing, the down stroke gliding into the up one, and *vice versa*, which clearly shows that the down and up strokes are parts of one whole, and that neither is perfect without the other.

This wing is endowed with the very remarkable property that it will fly in any direction, demonstrating more or less clearly that flight is essentially a progressive movement, *i.e.*, a horizontal rather than a vertical movement. Thus, if the anterior or thick margin of the wing be directed upwards, and the angle which the under surface of the wing makes with the horizon be something like 45°, the wing will, when made to vibrate by the hand, fly with an undulating motion *in an upward direction,* like a pigeon to its dovecot. If the under surface of the wing makes no angle, or a very small angle, with the horizon, it will

Fig. 57.*

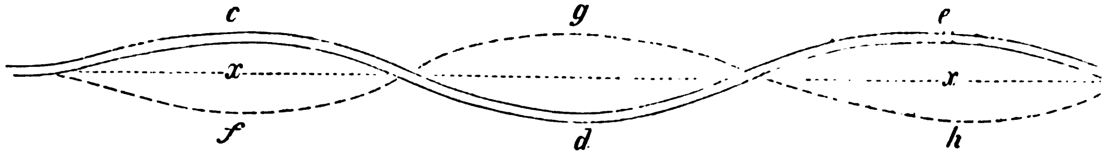

Fig. 58.†

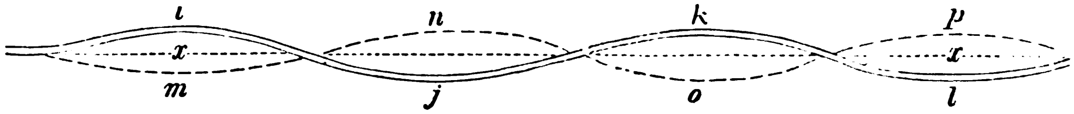

Fig. 59.‡

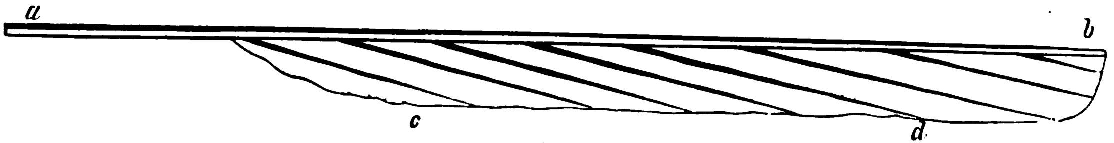

Fig. 60.§

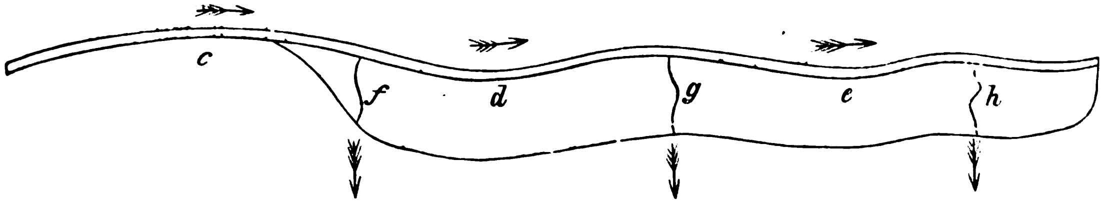

Fig. 61.||

* Fig. 57 represents a longitudinal section of bamboo reed 10 feet long, and 1 inch wide.

† Fig. 58. The appearance presented by the same reed when made to vibrate by the hand. The reed vibrates on either side of a given line (*x x*), and appears as if in two places at the same time, viz., *c* and *f*, *g* and *d*, *e* and *h*. It is thus during its vibration thrown into figures of 8 or opposite curves.

‡ Fig. 59. The appearance presented by the same reed when made to vibrate more rapidly. In this case the waves made by the reed are less in size, but more numerous than in fig. 58. The reed vibrates alternately on either side of the line *x x*, being now at *i* now at *m*, now at *n* now at *j*, now at *k* now at *o*, now at *p* now at *l*. This reed, when made to vibrate by the hand, has no dead points, a circumstance due to the fact that no two parts of it reverse or change their curves at precisely the same instant. It is because of this curious reciprocating motion that the wing can seize and disengage itself from the air with such rapidity.

§ Fig. 60. The same reed with a flexible elastic curtain or fringe added to it. The curtain consists of tapering whalebone rods covered with a thin layer of india-rubber. *a b* anterior margin of wing. *c d* posterior ditto.

|| Fig. 61 gives the appearance presented by the artificial wing (fig. 60) when made to vibrate by the hand. It is thrown into longitudinal and transverse waves. The longitudinal waves are represented by the arrows *c d e*, and the transverse by the arrows *f g h*. A wing constructed on this principle gives a continuous elevating and propelling power. It developes figure of 8 curves during its action in longitudinal, transverse, and oblique directions. It literally floats upon the air. It has no dead points—is vibrated with amazingly little power, and has apparently no slip. It can fly in an upward, downward, or horizontal direction by merely altering its angle of inclination to the horizon. It must be applied to the air by an irregular motion—the movement being most sudden and vigorous always at the beginning of the down stroke.

dart forward in a series of curves in a *horizontal direction,* like a crow in rapid horizontal flight. If the angle made by the under surface of the wing be reversed, so that the thick margin of the wing be directed downwards, the wing will describe a waved track, and *fly downwards,* as a sparrow from a house-top or from a tree. In all those movements progression is a necessity. The movements are continuous gliding *forward movements.* There is no halt or pause between the strokes, and if the angle which the under surface of the wing makes with the horizon be properly regulated, the amount of steady tractile and buoying power developed is truly astonishing. This form of wing, which may be regarded as the realisation of the figure of 8 theory of flight, elevates and propels both during the down and up strokes, and its working is accompanied with almost no slip. It seems literally to float upon the air. No wing that is rigid in the anterior margin can twist and untwist during its action, and produce the figure of 8 curves generated by the living wing. To produce the curves in question, the wing must be flexible, elastic, and capable of change of form in all its parts. The curves made by the artificial wing, as has been stated (p. 420), are largest when the vibration is slow, and least when it is quick. In like manner, the air is thrown into large waves by the slow movement of a large wing, and into small waves by the rapid movement of a smaller wing. The size of the *wing curves* and *air waves* bear a fixed relation to each other, and both are dependent on the rapidity with which the wing is made to vibrate. This is proved by the fact that insects, in order to fly, require, as a rule, to drive their small wings with immense velocity. It is further proved by the fact that the small humming bird, in order to keep itself stationary before a flower, requires to oscillate its tiny wings with great rapidity, whereas the large humming bird (*Patagona gigas*), as was pointed out by DARWIN, can attain the same object by flapping its large wings with a very slow and powerful movement. In the larger birds the movements are slowed in proportion to the size, and more especially in proportion to the length of the wing, the cranes and vultures moving the wings very leisurely, and the large oceanic birds dispensing in a great measure with the flapping of the wings, and trusting for progression and support to the wings in the expanded position.

This leads me to conclude that very large wings may be driven with a comparatively slow motion, a matter of some inportance in artificial flight secured by the flapping of wings.

How to Construct an Artificial Wave Wing on the Insect Type.—The following appear to me to be essential features in the construction of an artificial wing :—

The wing should be of a generally triangular shape.

It should taper from the root towards the tip, and from the anterior margin in the direction of the posterior margin.

It should be convex above and concave below, and slightly twisted upon itself.

It should be flexible and elastic throughout, and should twist and untwist during its vibration, to produce figure of 8 curves along its margins and throughout its substance.

Such a wing is represented at figure 62.

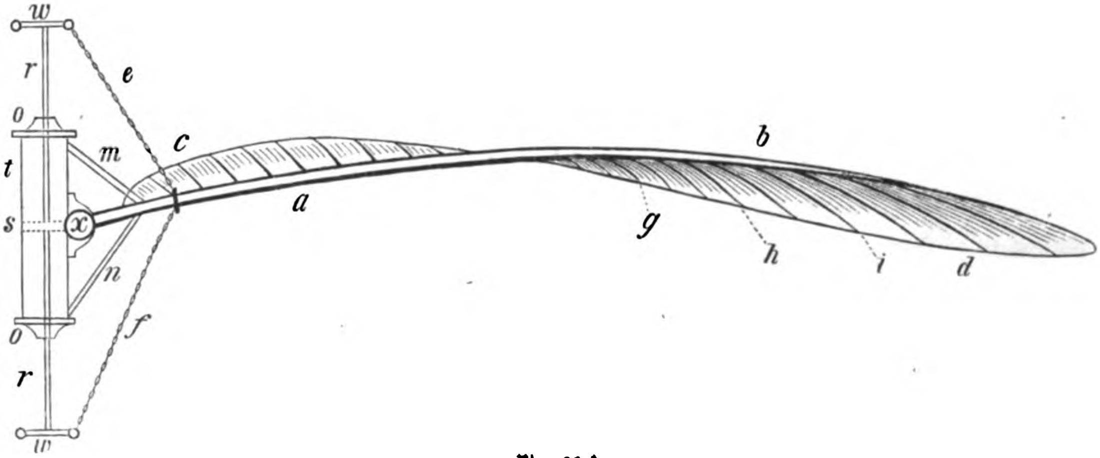

Fig. 62.[*]

If the wing is in more than one piece, joints and springs require to be added to the body of the pinion.

In making a wing in one piece on the model of the insect wing, such as that shown at figure 62, I employ one or more tapering elastic reeds, which arch from above downwards (*a b*) for the anterior margin. To this I add tapering elastic reeds, which radiate towards the tip of the wing, and which also arch from above downwards (*g*, *h*, *i*). These latter are so arranged that they confer *a certain amount of spirality* upon the wing, the anterior (*a b*) and posterior (*c d*) margins being arranged in different planes, so that they appear to cross each other. I then add the covering of the wing, which may consist of india-rubber, silk, tracing cloth, linen, or any similar substance.

If the wing is large, I employ steel tubes, bent to the proper shape. In some cases I secure additional strength by adding to the oblique ribs or stays (*g h i* of figure 62) a series of very oblique stays, and another series of cross stays, as shown at *m* and *a*, *n*, *o*, *p*, *q* of fig. 63, page 424.

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[*] Fig. 62. Elastic spiral wing, which twists and untwists during its action, to form *a mobile helix or screw*. This wing is made to vibrate by a direct piston action, and by a slight adjustment can be propelled vertically, horizontally, or at any degree of obliquity.

a, *b*, Anterior margin of wing, to which the neuræ or ribs are affixed. *c*, *d*, Posterior margin of wing crossing anterior one. *x*, Ball and socket joint at root of wing, the wing being attached to the side of the cylinder by the socket. *t*, Cylinder. *r*, *r*, Piston, with cross heads (*w*, *w*) and piston head (*s*). *o*, *o*, Stuffing boxes. *e*, *f*, Driving chains. *m*, Superior elastic band, which assists in elevating the wing. *n*, Inferior elastic band, which antagonises *m*. The alternate stretching of the superior and inferior elastic bands contributes to the continuous play of the wing, by preventing dead points at the end of the down and up strokes.

This form of wing is made to oscillate upon two centres (x and l of fig. 63), to bring out the peculiar eccentric action of the pinion.

If I wish to produce a very delicate light wing, I do so by selecting a fine tapering elastic reed, as represented at a b of figure 64, p. 425.

To this I add successive layers ($i, h, g, f, e,$) of some flexible material, such as parchment, buckram, tracing cloth, or even paper. As the layers overlap each other, it follows that there are five layers at the anterior margin (a b), and only one at the posterior (c d). This form of wing is not twisted upon itself structurally, but it twists and untwists, and becomes a true screw during its action.

How to Construct a Wave Wing which shall evade the superimposed Air during the Up Stroke.—To construct a wing which shall elude the air during the up stroke, it is necessary to make it valvular, as shown at fig. 65, p. 425.

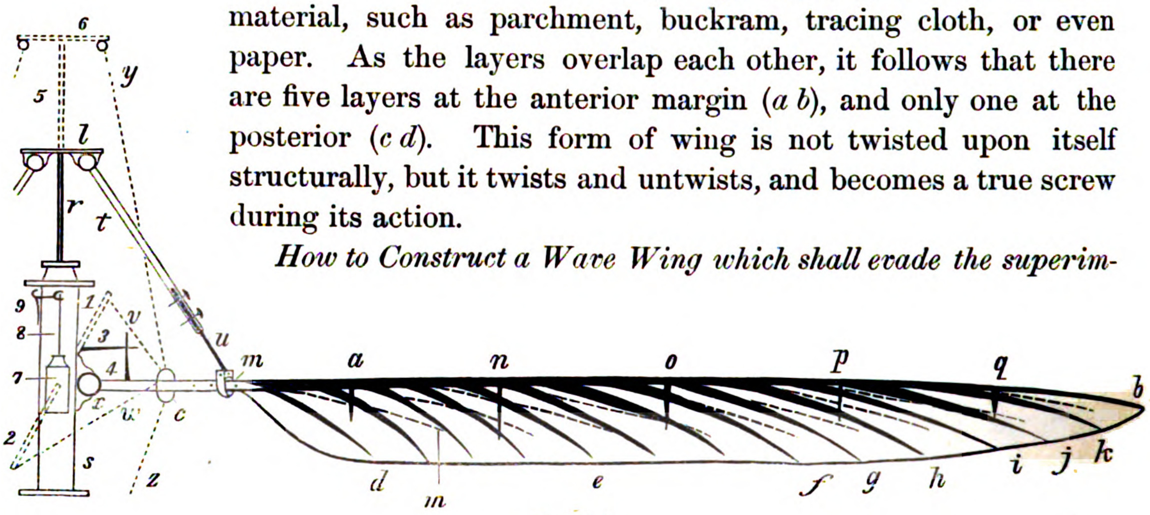

Fig. 63.[*]

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[*] Fig. 63. *Artificial Wing with Driving Apparatus.*

a b, Strong elastic rod, which tapers towards the tip of the wing.

d, e, f, g, h, i, j, k, Tapering curved reeds, which run obliquely from the anterior to the posterior margin of the wing, and which radiate towards the tip.

m, Similar curved reeds, which run still more obliquely.

a, n, o, p, q, Tapering curved reeds, which run from the anterior margin of the wing, and at right angles to it. These support the two sets of oblique reeds, and give additional strength to the anterior margin.

x, Ball and socket joint, by which the root of the wing is attached to the cylinder.

s, Steam cylinder.

r, Piston, with cross bar, with which driving gear (t) is connected by ball and socket joint (l), and by a hinge joint (m). The hinge joint is mounted on a tube, through which the root of the wing passes, and within which it can rotate in the direction of its length (long axis). The hinge joint and the tube on which it is mounted can be moved *out and in* upon the root of the wing, and fixed by the aid of pins. By this means the range of the wing, *i.e.*, the length of the stroke, can be increased or diminished. The driving gear is arranged on a similar principle. Thus, by causing the portion marked u to move within the tube (t) in an upward direction, the wing vibrates on a higher level than natural. If, on the other hand, the portion marked u be moved in a downward direction, the wing vibrates on a lower level. The range of the wing and its arc of vibration are thus easily regulated.

1, 2, Cross bar attached to steam chest (7) and to cylinder (s). To this anterior (v) and posterior (w) elastic bands are affixed. Those elastic bands (anterior and posterior) are bound to the anterior and posterior portions of the ring c; y, superior elastic band; z, inferior ditto.

3, 4, Steel springs running at right angles to each other, and attached respectively to the cross bar and the root of the wing anteriorly. They come in contact when the wing descends, and prevent the anterior margin of the wing from dipping, *i.e.*, from diving downwards during the down stroke. This result is also secured by inserting the superior elastic band (y) into the upper and anterior portion of the ring c. Indeed, by employing a cross bar or lever, similar to that marked 4, in place of the ring c, the amount of rotation of the posterior margin round the anterior one can be regulated both during the down and up strokes. If the superior elastic band (y) be moved towards the tip of the lever, the degree of rotation is increased; if it be moved towards the root of the lever, it is diminished.

5. Rod fixed to posterior of cylinder, and bearing cross bar (6), to which the superior elastic band (y) is attached.

NOTE.—In the present arrangement the steam chest (7) and valve occupy the centre of the cylinder *posteriorly*, the valve being opened and closed by the aid of an idle rod (furnished with two kickers), which passes through a loop projecting from the piston *anteriorly*. The idle rod and kickers move a small lever (9), which in turn moves the spindle (8), to which the steam valve is attached. The cylinder is fixed to the top of the boiler, and the ports for the admission of steam to the cylinder are unequal in size, the *upper port* being larger than the *under one*. Unequal quantities of steam are thus admitted to the top and bottom of the cylinder respectively, the greater quantity admitted to the top causing the wing to descend much more quickly than it ascends. From the above figure it will be seen that the movements of the wing are communicated directly from the *piston*, a great saving in weight and power being thus effected.

This wing, as the figure indicates, is composed of *numerous narrow segments* (*fff, ggg*), so arranged that the air, when the wing is made to vibrate, opens or separates them at the beginning of the up stroke, and closes or brings them together at the beginning of the down stroke.*

Fig. 64.*

The time and power required for opening and closing the segments is comparatively trifling, owing to their extreme narrowness and extreme lightness. The space, moreover, through which they pass in performing their valvular action is exceedingly small. The wing under observation is flexible and elastic throughout, and resembles in its general features the other wings described.

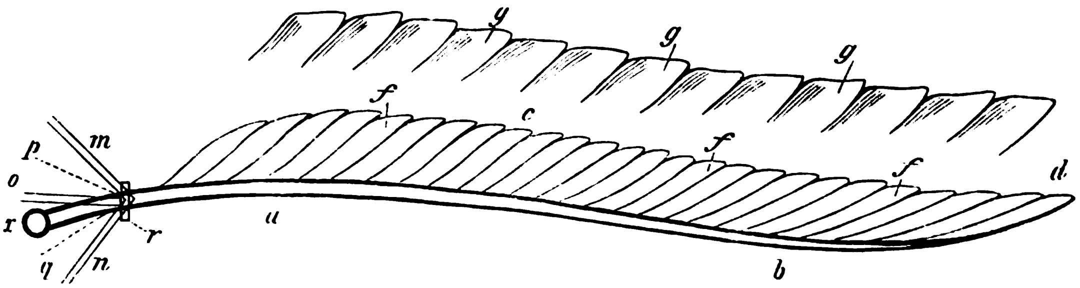

Fig. 65.†

I have also constructed a wing which is self-acting in another sense. This consisted of two parts—the one part being made of an elastic reed, which tapered towards its extremity, the other of a flexible sail. To the reed, which corresponded to the anterior margin of the wing, delicate tapering reeds were fixed at right angles, the principal and subordinate reeds being arranged on the same plane. The flexible sail was attached to the under surface of the principal reed, and was stiffer at its insertion than towards its free margin. When the wing was made to ascend, the sail, because of the pressure exercised upon its upper surface by the air, assumed a very oblique position, so that the resistance experienced by it during the *up stroke* was very slight. When, however, the wing descended, the sail instantly flapped in an upward direction, the

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* Fig. 64. *x*, Ball and socket joint at root of wing. *a*, *b*, Anterior margin of wing. *c*, *d*, Posterior margin of wing. *i*, Portion of wing composed of one layer of flexible material. *h*, Portion of wing composed of two layers. *g*, Portion of wing composed of three layers. *f*, Portion of wing composed of four layers. *e*, Portion of wing composed of five layers.

† Fig. 65. Flexible *valvular wing* with India-rubber springs attached to its root.
a, *b*, Anterior margin of wing, tapering and elastic. *c*, *d*, Posterior margin of wing, elastic. *f*, *f*, *f*, Segments which open during the up stroke and close during the down, after the manner of valves. These are very narrow, and open and close instantly. *g*, *g*, *g*, The same segments magnified. *x*, Universal joint. *m*, Superior elastic band. *n*, Ditto inferior. *o*, Ditto anterior. *p*, *q*, Ditto oblique. *r*, Ring into which the elastic bands are fixed.

subordinate reeds never permitting its posterior or free margin to rise above its anterior or fixed margin. The under surface of the wing consequently descended so as to present a flat surface to the earth. It experienced much resistance from the air during the *down stroke*, the amount of buoyancy thus furnished being very considerable. The above form of wing is more effective during the down stroke than during the up. It, however, elevates and propels during both, the forward travel being greatest during the down stroke.

Compound Wave Wing.—In order to render the movements of the wing as simple as possible, I was induced to devise a form of pinion, which for the sake of distinction I shall designate the *Compound Wave Wing*. This wing consists of two wave wings united at their roots, as represented at *b, c,* (A, A′) of fig. 66. It is attached by its centre to the head of the piston by a compound joint

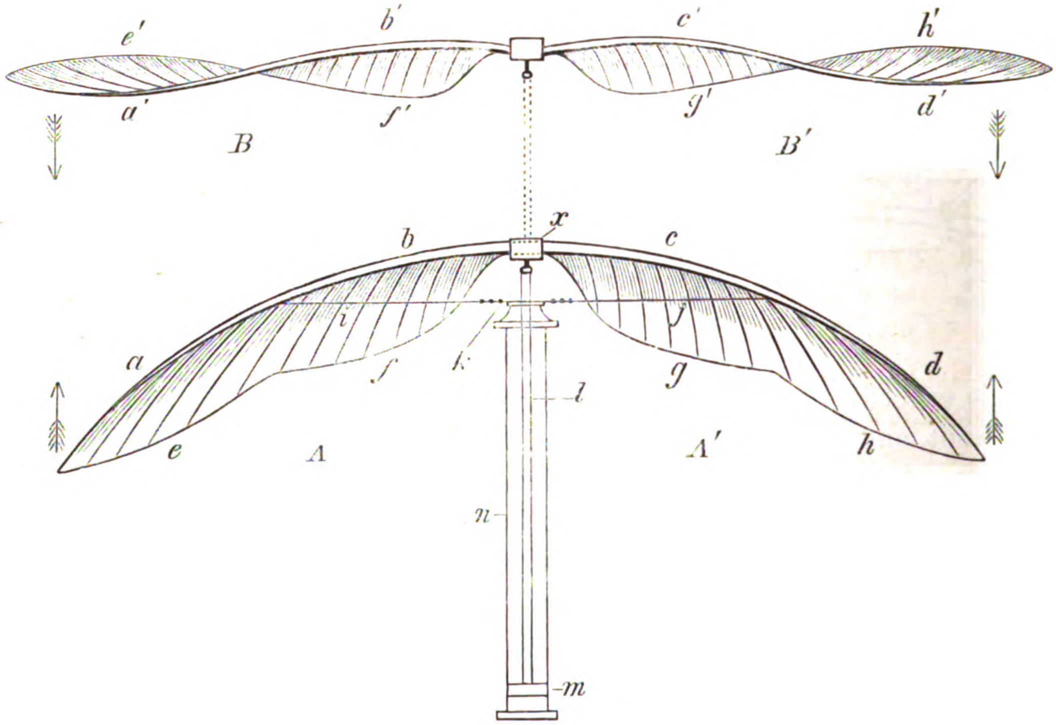

Fig. 66.

(*x*), which enables it to move in a circle, and to rotate along its anterior margin (*a, b, c, d,* A, A′) in the direction of its length. The circular motion is for steering purposes only. The wing rises and falls with every stroke of the piston, and the movements of the piston are quickened during the down stroke, and slowed during the up one (*vide* note to fig. 63, p. 424, also pp. 432 and 433).

During the up stroke of the piston the wing is very decidedly convex on its upper surface (*a, b, c, d,* A, A′), its under surface being deeply concave and inclined obliquely upwards and forwards. It thus evades the air during the up stroke.

During the down stroke of the piston the wing is flattened out in every direction, and its extremities twisted in such a manner as to form two screws, as shown at *a′ b′ c′ d′* ; *e′ f′ g′ h′* ; B, B′ of figure. The active area of the wing is by this means augmented, so that it seizes the air with great avidity during the down stroke. The area of the wing may be still further increased and diminished during the down and up strokes by adding joints to the body of the wing on the principle recommended at pages 428, 429, 430, and 431, figs. 67, 68, and 69. The degree of convexity given to the upper surface of the wing can be increased or diminished at pleasure by causing a cord (*i j*; A, A′) and elastic band (*k*) to extend between two points, which may vary according to circumstances. The wing is supplied with vertical springs, which assist in slowing and reversing it towards the end of the down and up strokes, and these, in conjunction with the elastic properties of the wing itself, contribute powerfully to its continued play. The compound wave wing produces the currents on which it rises. Thus during the up stroke it draws after it a current, which being met by the wing during its descent, confers additional elevating and propelling power. During the down stroke the wing in like manner draws after it a current which forms an eddy, and on this eddy the wing rises, as explained at page 438, fig. 72. The ascent of the wing is favoured by the superimposed air playing on the upper surface of the posterior margin of the organ, in such a manner as to cause the wing to assume a more and more oblique position with reference to the horizon. This change in the plane of the wing enables its upper surface to avoid the superincumbent air during the up stroke, while it confers upon its under surface a combined kite and parachute action. The compound wave wing leaps forward in a curve both during the down and up strokes, so that the wing during its vibration describes a waved track, as shown at *a, c, e, g, i* of fig. 14, page 344. The compound wave wing possesses most of the peculiarities of single wings when made to vibrate simultaneously. It forms a most admirable elevator and propeller, and has this advantage over ordinary wings, that it can be worked without injury to itself, when the machine which it is intended to elevate is resting on the ground. Two or more compound wave wings may be arranged on the same plane, or superimposed, and made to act in concert. They may also by a slight modification be made to act horizontally instead of vertically. The length of the stroke of the compound wave wing is determined in part, though not entirely, by the stroke of the piston—the extremities of the wing, because of their elasticity, moving through a greater space than the centre of the wing. By fixing the wing to the head of the piston all gearing apparatus is avoided, and the number of joints and working points reduced—a matter of no small importance when it is desirable to conserve the motor power and keep down the weight.

How to Construct a Wave Wing on the Bat and Bird type.—In order to imitate the bat and bird's wing successfully it is necessary to introduce joints: the artificial wing, in fact, requires to be composed of several pieces, so that it will flex or fold towards the end of the down stroke, and open out or expand towards the end of the up stroke. This is requisite for several reasons. In the first place, the wing of the bat and bird is made to vibrate in a much more vertical direction (figs. 5 and 6, Plate XI., figs. 18 and 19, Plate XIV.,) than that of the insect (fig. 4, Plate XI.) They have therefore to contend directly with the resistance furnished by the superimposed air. As a consequence, the wing in such of the bats and birds as do not sail or skim must be folded more or less completely during the up stroke to diminish the wing area, so as to elude the resistance offered by the air when the wing is being elevated. It is for this reason too, that in the bird the rowing feathers open up or separate during the up stroke. As the wings of the bat and bird afford comparatively little support during the up stroke, it follows that the wing area must be increased to its utmost during the down stroke. But for the folding or closing of the wing towards the termination of the down stroke, the downward passage of the pinion, as I have repeatedly satisfied myself by experiment, could not be suddenly arrested and a new upward passage commenced. In other words, the wing could not be reversed. At the beginning of the down stroke the wing is a long lever, and acts as such, (*vide c d* of fig. 6, Plate XI.) It is depressed with extreme energy and acquires during its descent a degree of momentum which could not possibly be checked if the wing was not suddenly flexed and instantly converted from a *long* into a *short* lever, (*vide a b* of fig. 6, Plate XI.) The wing is therefore by this very simple contrivance, not only robbed of its momentum, but what is quite as important, it is prepared for making the up or return stroke. If the wing of a gull just dead be taken, and the air winnowed by it in a more or less vertical direction, it will be found to fly open and to extend itself during the down stroke, and to fold up or close during the up stroke. The quicker the wing is made to vibrate, the more admirable is the result. Indeed, the gull's wing, when made to oscillate as recommended, reverses perfectly and has no dead points. It moreover furnishes a steady persistent buoying power which is quite remarkable when the limited dimensions of the pinion are taken into account.

To construct a bat or bird's wing, I take a tapering flexible reed, and cut it into three pieces, each piece varying in length. These I bend to the shape required as shown at *a*, *d*, and *g* of figs. 67 and 68, page 429.

The shortest and thickest piece (*a*) I furnish with a ball and socket joint at one end (*x*), and a hinge joint (*b*) at the other. The second shortest and strongest piece (*d*) I supply with a hinge joint at either end (*b* and *e*); and the third piece, which is the longest and weakest, I provide with a hinge joint at its thicker or proximal end (*e*). When the three pieces are joined together as shown in the figures, I apply to each of the pieces at intervals tapering elastic curved reeds (*o, p, q,* fig. 68), the reeds radiating in the direction of the tip of the wing, and in such a manner as to confer a certain degree of spirality upon it. I then cause elastic substances (*h i, j k,* of figs. 67 and 68,) to extend between the pieces (*a, d, g*). The covering is then added in one piece if a bat's wing is desired, and in several (see valvular wing, fig. 65, page 425,) if the more highly differentiated wing of the bird is aimed at.

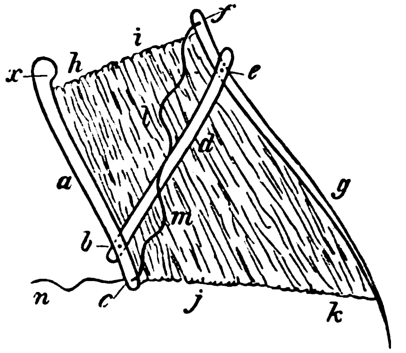

Fig. 67.*

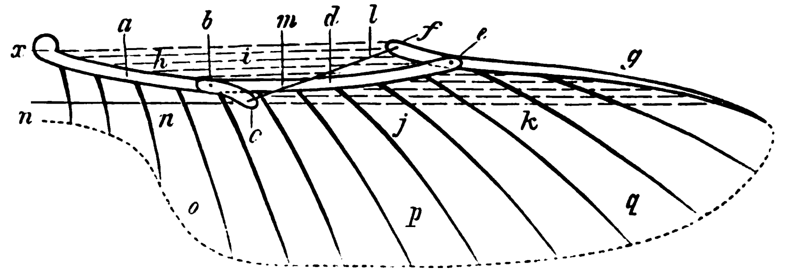

Fig. 68.

The covering may consist of a thin layer of india-rubber, silk, linen, or any other flexible material.

To the inner extremity of the distal reed (*f*) I attach a cord or wire, and this cord or wire (*l, m, n,*) I pass through an aperture in the outer extremity (*c*) of the proximal reed. I then fix the free end of the cord to a loop in the cylinder (*vide q* of fig. 69, p. 430), from which the wing receives its movements by a direct piston action.

The arrangement is represented at fig. 69, page 430.

When the wing is elevated from B to A (fig. 69) by the direct action of the

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[*] Figures 67 and 68. Wing made to close or fold during the up stroke, and to open out or expand during the down stroke.

At fig. 67, the wing is represented as folded upon itself. *x* Universal joint at root of wing. *a* Proximal portion of wing. *d* Central portion of wing. *g* Distal portion of wing. *b* Joint uniting proximal and central portions of wing. *e* Joint uniting central and distal portions. *h i, j k* Sheet of elastic substance which when contracted as represented, tends to approximate the proximal (*a*), central (*d*), and distal (*g*), portions of wing. *l, m, n* A cord or wire fixed at *f* and running through an aperture at *c*. If this cord be rendered taught (provided the root of the wing (*x*) is fixed in its socket), it causes the proximal (*a*), central (*d*), and distal (*g*) portions of the wing suddenly to dart out and arrange themselves in a nearly straight line as shown at *a, d, g* of fig. 68.

At fig. 68 the wing is represented as fully extended or spread out. The lettering is the same as in fig. 67. *o, p, q* Ribs or stays of the wing which support the covering or curtain.

piston (r r), and the gearing apparatus (y z), it is likewise extended or spread out, the mere elevation of the piston rendering the cord or wire (l, n,) taught—

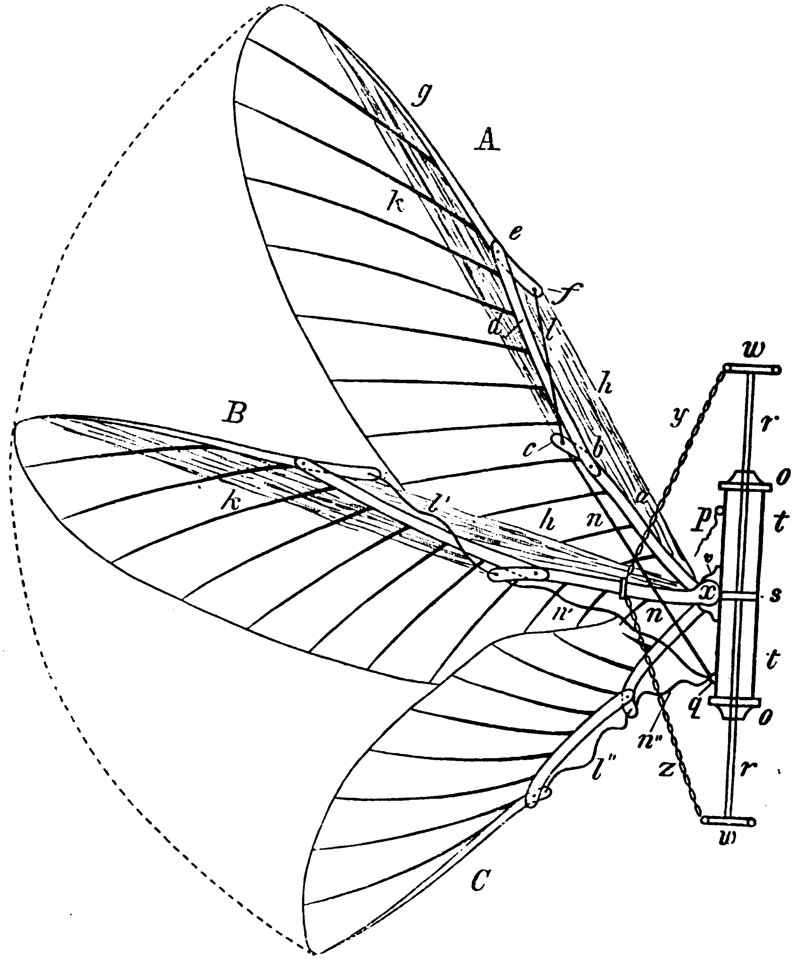

Fig. 69.*

the taughtness of the cord causing the different parts of the wing to fly outwards, while it at the same time puts the elastic substances (h k) on the stretch.

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* Fig. 69. Wing which folds upon itself during the up stroke, and expands during the down one, made to vibrate by a direct piston action. At A the wing is fully expanded and in the act of commencing the down stroke. At B the wing is at mid stroke and very slightly folded. At C the wing is fully folded, and ready to begin the up stroke. It is thus that the wing acts as a *long lever* at the beginning of the down stroke, and a *short one* at the beginning of the up one. Compare with figs. 18 and 19, Plate XIV., and also with figs. 9, 10, and 11, Plate XII. The lettering of the wing in the present fig. is the same as in fig. 68, p. 429.

x Universal joint at root of wing received into cup-shaped cavity (v) of cylinder (t).

a Proximal, d central, and g distal portions of wing.

b, e, Joints which unite the three portions of the wing to each other.

f, q, Points to which the cord or wire of wing is fixed.

c, Aperture through which cord or wire of wing glides as the wing ascends and descends. When the piston ascends it elevates the wing by its gearing y z. It also renders the cord l n taught, the cord in its turn extending the wing (A) and the elastic substance h k. When the piston descends to mid stroke the wing is very slightly folded (B) and the cord l' n' somewhat relaxed. When the piston has quite descended the cord l'' n'' is very much relaxed, and as a consequence the elastic substance extending between the different portions of the wing has contracted, the wing being thereby folded upon itself (C). The elastic substance may be dispensed with, if a strong elastic cord be employed instead of the non-elastic one l, n. If two cords be fixed to two points on the cylinder as at p and q, and the one cord be passed on the upper surface of the wing, and the remaining one on the under surface, the wing will be under control during the whole of the down and up strokes, the one cord extending the wing, the other flexing it.

t, t, Cylinder. o, o, Stuffing boxes. r r, Piston. w, w, Cross heads for driving gear. y z Driving gear. s Piston head. v, Cup-shaped cavity for receiving root of wing.

The instant the wing begins to descend, the cord is more or less relaxed, and a struggle ensues between the air, which endeavours to keep the wing open, and the elastic substances (*h k*) which endeavour to close it. If the wing is very forcibly depressed, it is kept open till quite near the end of the down stroke, when the elastic bands close it (C), destroy its momentum, and prepare it for the up stroke. This form of wing acts as a short lever (C) during the up stroke, and a long one (A) during the down stroke. It therefore eludes the superimposed air to a great extent when it is being elevated. If it is thought desirable to differentiate the wing still further in imitation of the bird's wing, it is only necessary to add a series of segments similar to those represented at fig. 65, page 425, these segments representing the individual rowing feathers. What especially struck me on analysing the movements of the artificial bat and bird's wing, was the fact, that during their vibrations figure of 8 curves were developed along their anterior and posterior margins similar to those found in the living wings; that the under surfaces of the pinions made various angles of inclination with the horizon analogous to those made by the natural wings; these changes being induced in a great measure independently of the air, in virtue apparently of inherent structural peculiarities. This I regard as a very remarkable circumstance, and one well worthy the attention of the physiologist and mechanician.

How to apply Artificial Wings to the Air.—BORELLI, DURCKHEIM, MAREY, and all the writers with which I am acquainted, assert that the wing should be made to vibrate *vertically*. I believe that if the wing be in one piece it should be made to vibrate *obliquely and more or less horizontally*. If, however, the wing be made to vibrate *vertically*, it is necessary to supply it with a ball and socket joint, and with springs at its root (*m n* of fig. 62, page 423), to enable it *to leap forward in a curve* when it descends, and in another and *opposite curve* when it ascends (*vide a, c, e, g, i* of fig. 14, page 344). This arrangement practically converts the vertical vibration into *an oblique one*. If this plan be not adopted the wing is apt to foul at its tip. In applying the wing to the air it ought to have a figure of 8 movement communicated to it either directly or indirectly. It is a peculiarity of the artificial wing properly constructed, (as it is of the natural wing), to *twist and untwist and make figure of* 8 *curves during its action* (see *a b, c d* of fig. 62, page 423), this enabling it to seize and let go the air with wonderful rapidity, and in such a manner as to avoid dead points. If the wing be in several pieces it may be made to vibrate more vertically than a wing in one piece, from the fact that the outer half of the pinion moves forwards and backwards when the wing ascends and descends so as alternately to become a short and long lever. (Compare C with A of fig. 69, page 430), this arrangement permitting the wing to avoid the resistance experienced from the air during the up stroke, while it vigorously seizes the air during the down stroke.

If the body of a flying animal be in a horizontal position, a wing attached to it in such a manner that its under surface shall look forwards, and make an upward angle of 45° with the horizon, is in a position to be applied either vertically (figs. 5 and 6, Plate XI.), or horizontally (figs. 3, 4, 5, and 6, page 338). Such, moreover, is the conformation of the shoulder joint in insects, bats, and birds, that the wing can be applied vertically, horizontally, or at any degree of obliquity without inconvenience.* It is in this way that an insect which may begin its flight by causing its wings to make figure of eight horizontal loops (*vide* fig. 8, page 340), may gradually change the direction of the loops, and make them more and more oblique until they are nearly vertical (see fig. 13, page 342). In the beginning of such flight the insect is screwed *nearly vertically upwards;* in the middle of it, it is screwed *upwards and forwards;* whereas, towards the end of it, the insect advances in *a waved line* almost horizontally (see *q*, *r*, *s*, *t*, of fig. 11, page 341). The muscles of the wing are so arranged that they can propel it in a horizontal, vertical, or oblique direction. It is a matter of the utmost importance that the direction of the stroke and the angles made by the surfaces of the wing during its vibration with the horizon should be distinctly understood, as it is on these that all flying creatures depend when they seek to elude the upward resistance of the air, and secure a maximum of elevating and propelling power with a minimum of slip.

Nature of the Forces required for Propelling artificial wings.—BORELLI, DURCKHEIM, and MAREY affirm that it suffices if the wing merely elevates and depresses itself by a rythmical movement in a perpendicular direction, while CHABRIER is of opinion that a movement of depression only is required. All those observers agree in believing that the details of flight are due to the reaction of the air on the surface of the wing. Repeated experiment has, however, convinced me that the artificial wing must be thoroughly under control, both during the down and up strokes—the details of flight being in great measure due to the movements communicated to the wing by an intelligent agent. In order to reproduce flight by the aid of artificial wings I find it necessary to employ a power which varies in intensity at every stage of the down and up strokes. The power which I find suits best is one which is made to act very suddenly and forcibly at the beginning of the down stroke, which gradually abates in intensity until the end of the down stroke where it ceases to act in a downward direction. The power is then made to act in an upward direction, and gradually to decrease until the end of the up stroke. The force is thus applied more or less continuously, its energy being increased and diminished according to the position

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* The human wrist is so formed that if a wing be held in the hand at an upward angle of 45°, the hand can apply it to the air in a vertical or horizontal direction without difficulty. This arises from the power which the hand has of moving in an upward and downward direction, and from side to side with equal facility. The hand can also rotate on its long axis, so that it virtually represents all the movements of the wing at its root.

of the wing, and the amount of resistance which it experiences from the air. The flexible and elastic nature of my peculiar form of wing (wave-wing), assisted by certain springs to be presently explained, ensure a continuous vibration where neither halts nor dead points are observable. I obtain the varying power required by a direct piston action, and by working the steam expansively (*vide* figs. 62, 63, and 69, pages 423, 424, and 430). The power employed is materially assisted, particularly during the up stroke, by the reaction of the air and the elastic structures about to be described. An artificial wing, propelled and regulated by the forces recommended, is in some respects as completely under control as the wing of the insect, bat or bird.

Necessity for supplying the root of artificial wings with elastic structures in imitation of the muscles and elastic ligaments of flying animals.—BORELLI, DURCKHEIM, and MAREY, who advocate the perpendicular vibration of the wing, make no allowance, so far as I am aware, for the wing *leaping forward in curves* during *the down and up strokes.* As a consequence, the wing is jointed in their models to the frame by a simple joint which moves only in one direction, viz., from above downwards, and *vice versa.* Observation and experiment have, however, convinced me that an artificial wing, to be effective as an elevator and propeller, ought to be able to move not only in an upward and downward direction, but also in a *forward, backward,* and *oblique direction,* nay, more, that it should be free to rotate along its anterior margin *in the direction of its length:* in fact, that its movements should be universal. Thus it must be able to rise or fall, to advance or retire, to move at any degree of obliquity, and to rotate along its anterior margin. To secure the several movements in question I furnish the root of the wing with a ball and socket-joint, *i.e.,* a universal joint (see *x* of fig. 62, page 423; and *x* of fig. 63, page 424). To regulate the several movements when the wing is vibrating, and to confer on the wing the various inclined surfaces requisite for flight, as well as to delegate as little as possible to the air, I employ a cross system of elastic bands. These bands vary in length, strength, and direction, and are attached to the anterior margin of the wing (near its root), and to the cylinder (or a rod extending from the cylinder) of the model respectively (*vide m, n* of fig. 62, page 423). The principal bands are four in number: a superior (fig. 63, page 424, *y*), inferior (*z*), anterior (*v*), and posterior (*w*). The superior band extends between a rod proceeding from the upper part of the cylinder (5) of the model, and the upper surface of the anterior margin (*a, b,*) of the wing; the inferior band (*z*), extending between the under part of the cylinder or boiler and the inferior surface of the anterior margin (*d, e, f,*) of the pinion. The anterior (*v*), and posterior (*w*), bands are attached to the anterior and posterior portions of the wing and to rods extending from the centre of the anterior and posterior portions of the cylinder. Oblique bands are added (*vide p, q* of fig. 65, page 425), and these are so arranged that they give to the wing during its descent and ascent the precise angles made by the wing with the horizon in natural flight. The superior bands are stronger than the inferior ones, and are put upon the stretch during the down stroke. They thus help the wing over the dead point at the end of the down stroke, and assist, in conjunction with the reaction obtained from the air, in elevating it. The posterior bands are stronger than the anterior ones to restrain within certain limits the strong tendency which the wing has to leap forward in curves towards the end of the down and up strokes. The oblique bands, aided by the air, give the necessary degree of rotation to the wing in the direction of its length. This effect can, however, also be produced independently by the four principal bands. From what has been stated it will be evident that the elastic bands exercise a restraining influence, and that they act in unison with the driving power and with the reaction supplied by the air. They powerfully contribute to the continuous vibration of the wing, the vibration being peculiar in this that it varies in rapidity at every successive stage. I derive the motor power, as has been stated, from a direct piston action, the piston being urged either by steam worked expansively or by the hand, if it is merely a question of illustration. In the hand models the "*muscular sense*" at once informs the operator as to what is being done. Thus if one of the wave wings supplied with a ball and socket joint, and a cross system of elastic bands as explained, has a sudden vertical impulse communicated to it at the beginning of the down stroke, the wing darts *downwards and forwards in a curve* (*vide a, c,* of fig. 14, page 344), and in doing so *it elevates* and carries the piston and cylinder *forwards.* The force employed in depressing the wing is partly expended in stretching the superior elastic band (*y* of fig. 63, page 424), the wing being slowed towards the end of the down stroke. The instant the depressing force ceases to act the superior elastic band (*y*) contracts, and the air reacts; the two together, coupled with the tendency which the model has to fall downwards and forwards during the up stroke, elevating the wing. The wing when it ascends describes an *upward and forward curve,* as shown at *c e* of fig. 14, page 344. The ascent of the wing stretches the inferior elastic band (*z* of fig. 63, page 424) in the same way that the descent of the wing stretched the superior band. The superior and inferior elastic bands antagonise each other and reciprocate with vivacity. While those changes are occurring the wing is *twisting* and *untwisting* in the direction of its length and developing figure of eight curves along its margins (page 423, fig. 62, *a b, c d*), and throughout its substance similar to what are observed under like circumstances in the natural wing (*vide* figs. 39, 40, 41, 42, and 43, page 362). The angles, moreover, made by the under surface of the wing with the horizon during the down and up strokes are continually varying—the wing all the while acting as a kite, which flies steadily *upwards and forwards* (fig. 15, page 345). As the elastic bands, as has been partly explained, are antagonistic in their action the wing is constantly oscillating in some direction, there being no dead point either at the end of the down or up strokes. As a consequence, the curves made by the wing during the down and up strokes respectively, run into each other to form a continuous waved track, as represented at figs. 13, 14, and 15, pages 342, 344, and 345. A continuous movement begets a continuous buoyancy, and it is quite remarkable to what an extent, wings constructed and applied to the air on the principles explained, elevate and propel—how little power is required, and how little of that power is wasted in slip.

If the piston, which in the experiment described has been working *vertically*, be made to work *horizontally*, a series of essentially similar results are obtained. When the piston is worked horizontally, the anterior and posterior elastic bands require to be of nearly the same strength, whereas the inferior elastic band requires to be much stronger than the superior one, to counteract the very decided tendency the wing has to fly upwards. The power also requires to be somewhat differently applied. Thus the wing must have a violent impulse communicated to it when it begins the stroke from right to left, and also when it begins the stroke from left to right (the *heavy parts* of the spiral line represented at fig. 8, page 340, indicate the points where the impulse is communicated). The wing is then left to itself, the elastic bands and the reaction of the air doing the remainder of the work. When the wing is forced by the piston from right to left, it darts forwards in a double curve, as shown at fig. 70, the various inclined surfaces made by the wing with the horizon changing at every stage of the stroke.

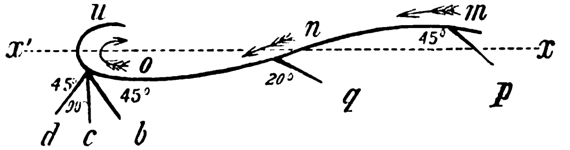

Fig. 70.[*]

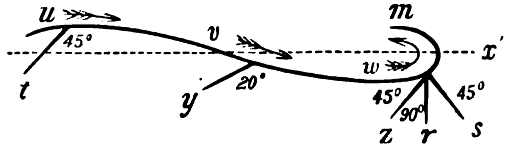

Fig. 71.[†]

At the beginning of the stroke from right to left, the angle made by the under surface of the wing with the horizon (*x x'*) is something like 45°, whereas at the middle of the stroke it is reduced to 20° or 25°. At the end of the stroke the angle gradually increases to 45°, then to 90°, after which the wing suddenly turns a somersault, and reverses precisely as the natural wing does at *e, f, g* of figs. 3 and 5, page 338. The artificial wing reverses with amazing facility, and in the most natural manner possible. The angles made by its under surface

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[*] Fig. 70. Stroke of artificial wave wing from right to left. *x, x'*, Horizon. *m, n, o*, Wave track described by wing from right to left. *p*, Angle made by wing at beginning of stroke. *q*, Ditto, made at middle of stroke. *b*, Ditto, towards end of stroke. *c*, Wing in the act of reversing; at this stage the wing makes an angle of 90° with the horizon, and its speed is less than at any other part of its course. *d*, Wing reversed, and in the act of darting up to *u*, to begin the stroke from left to right (*vide u* of fig. 71).

[†] Fig. 71. Stroke of artificial wave wing from left to right. *x, x'*, Horizon. *u, v, w*, Wave track described by wing from left to right. *t*, Angle made by the wing with the horizon at beginning of stroke. *y*, Ditto, at middle of stroke. *z*, Ditto, towards end of stroke. *r*, Wing in the act of reversing; at this stage the wing makes an angle of 90° with the horizon, and its speed is less than at any other part of its course. *s*, Wing reversed, and in the act of darting up to *m*, to begin the stroke from right to left (*vide m* of fig. 70).

with the horizon, depend chiefly upon the speed with which the wing is urged at different stages of the stroke, the angle always decreasing as the speed increases, and *vice versa*. As a consequence, the angle is greatest when the speed is least.

The course described, and the angles made by the artificial wave wing with the horizon during the stroke from right to left, are represented at fig. 70, page 435.

When the wing reaches the point *b*, its speed is much less than it was at *q*. The wing is, in fact, preparing to reverse. At *c* the wing is in the act of reversing (compare with *c* of figs. 16 and 17, page 349), and, as a consequence, its speed is at its minimum, and the angle which it makes with the horizon at its maximum. At *d* the wing is reversed, its speed being increased, and the angle which it makes with the horizon diminished. Between the letters *d* and *u* the wing darts suddenly up like a kite, and at *u* it is in a position to commence the stroke from left to right, as indicated at *u* of fig. 71 p. 435. The course described, and the angles made by the wing with the horizon during the stroke from left to right, are represented at fig. 71 (compare with figs. 4 and 6, page 338). The stroke from left to right is in every respect the converse of the stroke from right to left, so that a separate description is unnecessary.

The Artificial Wave Wing can be driven at any speed—it can make its own currents, or utilise existing ones.—The remarkable feature in the artificial wave wing is its adaptability. It can be driven slowly, or with astonishing rapidity. It has no dead points. It reverses instantly, and in such a manner as to dissipate neither time nor power. It alternately seizes and evades the air so as to extract a maximum amount of support with a minimum of slip, and with a minimum expenditure of power. It supplies a degree of buoying and propelling power which is truly remarkable. Its buoying area is nearly equal to half a circle. It can act upon still air, and it can create and utilise its own currents. I proved this in the following manner. I caused the wing to make a horizontal sweep from right to left over a candle; the wing rose steadily as a kite would, and after a brief interval, the flame of the candle was persistently blown from right to left. I then waited until the flame of the candle assumed its normal perpendicular position, after which I caused the wing to make another and opposite sweep from left to right. The wing again rose kite fashion, and the flame was a second time affected, being blown in this case from left to right. I now caused the wing to vibrate steadily and rapidly above the candle, with this curious result, that the flame did not incline alternately from right to left and from left to right. On the contrary, it was blown steadily away from me, *i.e.*, in the direction of the tip of the wing, thus showing that the artificial currents produced, met and neutralised each other always at mid stroke. I also found that under these circumstances the buoying power of the wing was remarkably increased.

Compound rotation of the Artificial Wave Wing: the different parts of the Wing travel at different speeds.—The artificial wave wing, like the natural wing, revolves upon two centres (*a b*, *c d* of fig. 45, page 376, and *x*, *l* of fig. 63, page 424), and owes much of its elevating and propelling, seizing and disentangling power to its different portions travelling at different rates of speed (see fig. 51, page 399), and to its storing up and giving off energy as it hastens to and fro. Thus the tip of the wing moves through a very much greater space in a given time than the root, and so also of the posterior margin as compared with the anterior. This is readily understood, by bearing in mind that the root of the wing forms the centre or axis of rotation for the tip; while the anterior margin is the centre or axis of rotation for the posterior margin. The momentum, moreover, acquired by the wing during the stroke from right to left *is expended in reversing the wing*, and in preparing it for the stroke from left to right, and *vice versa*; a continuous to and fro movement devoid of dead points being thus established. If the artificial wave wing be taken in the hand and suddenly depressed *in a more or less vertical direction*, it immediately springs up again, and carries the hand with it. It, in fact, describes a curve whose convexity is directed downwards, and in doing so, carries the hand upwards and forwards. If a second down stroke be added, a second curve is formed; the curves running into each other, and producing a progressive waved track similar to what is represented at *a*, *c*, *e*, *j*, *i* of fig. 14, page 344. This result is favoured if the operator runs forward so as not to impede or limit the action of the wing.

How the Wave Wing creates currents, and rises upon them, and how the air assists in elevating the Wing.—In order to ascertain in what way the air contributes to the elevation of the wing, I made a series of experiments with natural and artificial wings. On concluding these experiments, I felt convinced that when the wing descends it compresses and pushes before it, in a downward and forward direction, a column of air represented by *a*, *b*, *c* of fig. 72, p. 438.* The air rushes in from all sides to replace the displaced air, as shown at *d*, *e*, *f*, *g*, *h*, *i*, and so produces a circle of motion indicated by the dotted line *s*, *t*, *v*, *w*. The wing rises upon the outside of the circle referred to, as more particularly seen at *d*, *e*, *r*, *w*. The arrows, it will be observed, are all pointing upwards, and as these arrows indicate the direction of the reflex or back current, it is not difficult to comprehend how the air comes indirectly to assist in elevating the wing. A similar current is produced to the right of the figure, as indicated by *l*, *m*, *o*, *p*, *q*, *r*, but seeing the wing is always advancing, this need not be taken into account.

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* The artificial currents produced by the wing during its descent may be readily seen by partially filling a chamber with steam, smoke, or some impalpable white powder, and causing the wing to descend in its midst. By a little practice, the eye will not fail to detect the currents represented at *d*, *e*, *f*, *g*, *h*, *i*, *l*, *m*, *n*, *o*, *p*, *q*, *r* of fig. 72, p. 438.

If fig. 72 be made to assume a horizontal position, instead of the oblique position which it at present occupies, the manner in which *an artificial current* is produced by one sweep of the wing from right to left, and utilised by it in a subsequent sweep from left to right, will be readily understood. The artificial wave wing makes a horizontal sweep from right to left, *i.e.*, it passes from the point *a* to the point *c* of fig. 72. During its passage it has displaced a column of air. To fill the void so created, the air rushes in from all sides, viz., from *d, e, f, g, h, i; l, m, o, p, q, r*. The currents marked *g, h, i; p, q, r*, represent the reflex or *artificial currents*. These are the currents which, after a brief interval, force the flame of the candle from right to left. It is those same currents which encounter the wing, and contribute so powerfully to its elevation, when it sweeps from left to right. The wing, when it rushes from left to right, produces a new series of artificial currents, which are equally powerful in elevating the wing when it passes a second time from right to left, and thus the process of making and utilising currents goes on so long as the wing is made to oscillate. In waving the artificial wing to and fro, I found the best results were obtained when the range of the wing and the speed with which it was urged were so regulated as to produce a perfect reciprocation. Thus, if the range of the wing be great, the speed should also be high, otherwise the air set in motion by the right stroke will not be utilised by the left stroke, and *vice versa*. If, on the other hand, the range of the wing be small, the speed should also be low, as the short stroke will enable the wing to reciprocate as perfectly as when the stroke is longer and the

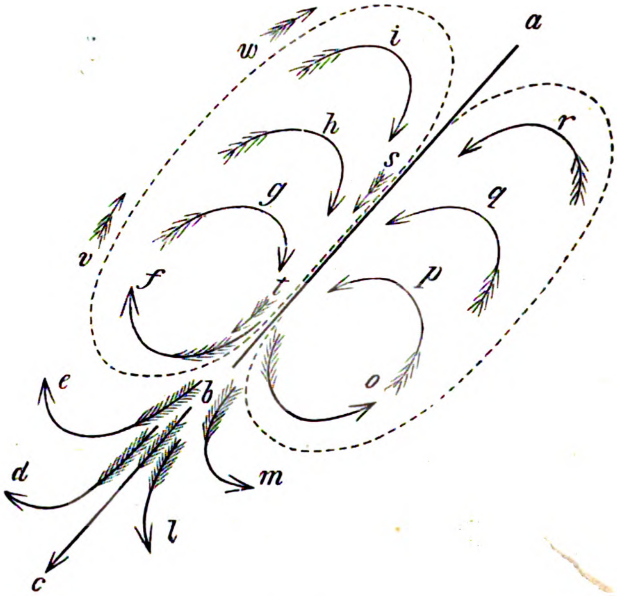

Fig. 72.

speed quicker. When the speed attained is high, the angles made by the under surface of the wing with the horizon are diminished; when it is low, the angles are increased. From these remarks it will be evident that the artificial wave wing reciprocates in the same way that the natural wing reciprocates, the reciprocation being most perfect when the wing is vibrating in a given spot, and least perfect when it is travelling at a high horizontal speed.

The Artificial Wing propelled at various degrees of speed during the down and up strokes.—The tendency which the artificial wave wing has to rise again when suddenly and vigorously depressed, explains why the *elevator* muscles of the wing should be so small when compared with the *depressor* muscles—the latter being something like seven times larger than the former. That the contraction of the elevator muscles is necessary to the elevation of the wing, is abundantly proved by their presence, and that there should be so great a difference between the volume of the elevator and depressor muscles is not to be wondered at, when we remember that the whole weight of the body is to be elevated by the rapid descent of the wings—the descent in question being entirely due to the vigorous contraction of the pectoralis major. If, however, the wing was elevated with as great a force as it is depressed, it is plain that the good effected during the descent would be utterly undone, as the wing, during its ascent, would experience a much greater resistance from the air than it did during its descent. The wing is consequently elevated more slowly than it is depressed, the elevator muscles exercising a controlling and restraining influence. By slowing the wing during the up stroke, the air has an opportunity of reacting on its under surface, as explained at page 351.

The Artificial Wave Wing as a Propeller.—The wave wing makes an admirable propeller if its tip be directed *vertically downwards*, and the wing lashed from side to side with a sculling figure of 8 motion, similar to that executed by the tail of the fish. Three wave wings may be made to act in concert and with a very good result; two of them being made to vibrate figure of 8 fashion in a more or less horizontal direction with a view to elevating, the third being turned in a downward direction, and made to act vertically for the purpose of propelling.

A New Form of Aerial Screw.—If two of the wave wings represented at fig. 62, page 423, be placed end to end, and united to a vertical portion of tube to form a two-bladed screw, similar to that employed in navigation, a most powerful elastic aerial screw is at once produced, as seen at fig. 73, page 440.

This screw, which for the sake of uniformity I denominate *the aerial wave screw*, possesses advantages for aerial purposes to which no form of *rigid* screw yet devised can lay claim. The way in which it clings to the air during its revolution, and the degree of buoying power it possesses are quite astonishing. It is a self-adjusting, self-regulating screw, and as its component parts are flexible and elastic, it accommodates itself to the speed at which it is driven, and gives a uniform buoyancy. The slip I may add is nominal in amount. This screw is exceedingly light, and owes its efficacy to its shape and the graduated nature of its blades, the anterior margin of each blade being comparatively rigid, the posterior margin being comparatively flexible and more or less elastic. The blades are kites in the same sense that natural wings are kites, and are flown as such when the screw revolves. I find the aerial wave screw flies best and elevates most when its blades are inclined at a certain upward angle as indicated in the figure (73). The aerial wave screw may have the numbers of its blades increased by placing the one above the other, and two or more screws may be combined and made to revolve in opposite directions so as to make them reciprocate, the one screw producing the current on which the other rises, as happens in natural wings.

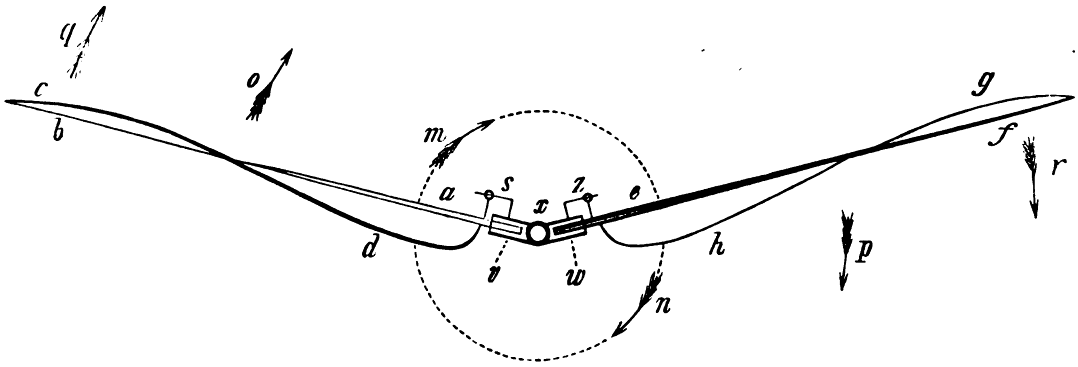

Fig. 73.[*]

The Aerial Wave Screw operates also upon Water.—The form of screw just described is adapted in a marked manner for water, if the blades be made of carefully tempered finely graduated steel plates and reduced in size. It bears the same relation to, and produces the same results upon, water as the tail and fin of the fish. It throws its blades during its action into double figure of 8 curves, similar in all respects to those produced on the anterior and posterior margins of the natural and artificial flying wing. As the speed attained by the several portions of each blade varies, so the angle at which each part of the

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[*] Fig. 72. Aerial wave screw whose blades are slightly twisted upon themselves (*a b*, *c d*; *e f*, *g h*), so that those portions nearest the root (*d h*) make a greater angle with the horizon than those parts nearer the tip (*b f*). The angle is thus adjusted to the speed attained by the different portions of the screw. The angle admits of further adjustment by means of the steel springs *z*, *s*, these exercising a restraining, and to a certain extent a regulating influence which effectually prevents shock.

It will be at once perceived from this figure that the portions of the screw marked *m* and *n* travel at a much lower speed than those portions marked *o* and *p*, and these again more slowly than those marked *q* and *r*. As however the angle which a wing or a portion of a wing, as I have pointed out, varies to accommodate itself to the speed attained by the wing, or a portion thereof, it follows, that to make the wave screw mechanically perfect, the angles made by its several portions must be accurately adapted to the travel of its several parts as indicated above.

x, Vertical tube for receiving driving shaft. *v*, *w*, Sockets in which the roots of the blades of the screw rotate, the degree of rotation being limited by steel springs *z*, *s*. *a b*, *e f*, Tapering elastic reeds forming anterior or thick margins of blades of screw. *d c*, *h g*, Posterior or thin elastic margins of blades of screw. *m n*, *o p*, *q r*, Radii formed by the different portions of the blades of the screw when in operation. The arrows indicate the direction of travel.

blade strikes varies, the angles being always greatest towards the root of the blade and least towards the tip. The angles made by the different portions of the blade are diminished in proportion as the speed with which the screw is driven is increased. The screw in this manner is self-adjusting, and extracts a large percentage of propelling power with very little force and surprisingly little slip.

A similar result is obtained, if two finely graduated angular-shaped steel plates be placed end to end and applied to the water (vertically or horizontally matters little), with a slight sculling figure of 8 motion, analogous to that performed by the tail of the fish, porpoise, or whale. If the thick margin of the plates be directed forwards, and the thin ones backwards, an unusually effective propellor is produced. This form of propellor is likewise very effective in air.

EXPLANATION OF THE PLATES.

Plate XI.

Figures 1, 2, and 3 show how the wing of the gull is elevated and extended towards the termination of the up stroke to prepare it for making the down stroke. At figure 3 the wing is represented as folded upon itself, and in the act of being elevated. It is, therefore, elevated as a *short lever*, the resistance experienced from the superimposed air being thus greatly diminished. The wing acts as a short lever from the time it leaves the position indicated by 6 of figure 6 until it assumes the position indicated by *o* of figure 3. At figure 2 the wing is raised higher than in figure 3, and partly extended—the elevation and extension of the wing occurring simultaneously. At figure 1 the wing is fully elevated and fully extended, and, consequently, ready to make the down stroke. It descends as a *long lever*, with great energy, until it assumes the position indicated by 4 of figure 6. The resistance which the wing experiences from the air beneath, is consequently, very great, the buoying power of the wing bearing a fixed relation to the resistance in question. The under surface of the wing, when in the position represented at figure 3, makes a very slight angle with the horizon *b d*. This arises from the fact that the different portions of the wing, when the wing is folded upon itself, are on nearly the same plane. The angle or angles —for they are numerous—made by the under surface of the wing with the horizon become larger when the wing is partly extended, as shown at figure 2 : *b d*, representing the horizon, and *c b d* the angle which the root of the wing makes with it. The angles become still larger when the wing is fully extended, as a comparison of *c b d* of figure 1 with *c b d* of figure 2 will show. The under surface of the wing, it will be observed, makes a variety of inclined surfaces with the horizon while the pinion is being extended. The angles of inclination made by the inclined surfaces in question are increased and diminished by the ascent or descent of the posterior margin of the wing, *o p q* (the anterior margin acts as an axis to the posterior one), the angles being always greatest when the wing is extended, and least when it is flexed. The angles, moreover, made by the root of the wing are always greater than those made by the tip. The various inclined surfaces made by the under surface of the wing are intimately associated with the power the wing possesses of alternately seizing and evading the air. The angles are greater at the root of the wing than at the tip, because the portions of the pinion nearer the root travel at a lower speed than portions nearer the tip. The various inclined surfaces made by the wing in flexion and extension are well seen at figures 16 and 17, Plate XIII. At figure 17 the anterior margin of the wing (*x s t r w*) is nearly on a level with the posterior margin (*o, p, q*). At figure 16, on the other hand, the anterior margin (*x, s, t, r, w*) is elevated and the posterior margin (*o p q*) depressed. A careful examination of those figures (particularly figure 16) will also show that the angles of inclination made by the several portions of the under surface of the wing vary—the angle made by the part *q* of figure 16 with the horizon being greater than that made by the part *p*—this, again, being greater than that made by the tip of the wing *o*. Those points are also illustrated at figure 8, Plate XII. The letters in figures 1, 2, and 3 (Plate XI.) represent the same parts of the wing—*x*, shoulder joint; *s*, elbow joint; *t*, wrist joint; *v*, *w*, hand and finger joints; *x s t v w*, anterior margin of wing; *o p q*, posterior margin.

Figure 4 represents the very oblique and almost horizontal direction of the stroke of the wing in the flight of the insect (wasp)—how the wing is twisted upon itself at the end of the up (*a*) and down (*b*) strokes, and how the tip of the wing, during its vibration, describes a figure of 8 track in space (*a, c, b*).

Figures 5 and 6 show the more or less perpendicular direction of the stroke of the wing in the flight of the bird (gull)—how the wing is gradually extended as it is elevated (1, 2, 3 of figure 5)—how it descends as a long lever until it assumes the position indicated by 4 of figure 6—how it is flexed towards the termination of the down stroke, as shown at 4, 5, 6 of figure 6, to convert it into a short lever (*a b*), and prepare it for making the up stroke. The difference in the length of the wing during flexion and extension is indicated by the short and long levers *a b* and *c d* of figure 6. The sudden conversion of the wing from a long into a short lever at the end of the down stroke is of great importance, as it robs the wing of its momentum, and prepares it for reversing its movements. Those same points are illustrated at figures 18 and 19, Plate XIV. At 4 of figure 19 the wing is represented as fully extended, and in the middle of the down stroke. At 5 of the same figure the wing is being flexed and slowed, and at 6 it is fully flexed, and its momentum destroyed. The wing is then elevated as a short lever until it assumes the position indicated at 1′ of figure 18. It is subsequently elevated and extended, as shown at 2′ and 3′ (fig. 18). At 3′ it is transformed into a long lever, and in a condition to make a second down stroke. Figure 19 also shows the compound rotation of the wing—the tip of the wing rotating upon the axis *c d*, and describing an arc of a circle, *e f*—the posterior margin of the wing rotating upon the axis (*a b*), and describing the arc *g h*. The compound rotation of the wing occurs simultaneously with the down and up strokes, and it is to it that the great variety of inclined surfaces made by the under surface of the wing is principally due.

Plate XII.

Figure 7 is designed to show that the angle made by the under surface of the wing (more particularly at its root) with the horizon, is much greater than is generally supposed. This arises from the fact that the body of the bird is inclined in an upward direction in flight, and because the anterior margin of the wing (*a*) curves in a downward direction in such a manner as to conceal the actual angle made. Thus, if *e f* be taken to represent the horizon, the angle apparently made by the under surface of the wing with it is *a b d*. The real angle, however, is *c b d*.

Figure 8. The lapwing, or green plover (*Vanellus cristatus*, Meyer), with one wing fully extended (*c b*, *d′ e′ f′*), the other being in a semiflexed condition (*d e f*, *c b*). In the extended wing the anterior or thick margin (*d′ e′ f′*) of the pinion is directed *upwards and forwards* (*vide* arrow), the posterior or thin margin (*c b*) downwards and backwards. The reverse of this happens during flexion, the anterior or thick margin (*d e f*) of the pinion being directed slightly *downwards and forwards* (*vide* arrow), the posterior or thin margin bearing the rowing feathers slightly *upwards and backwards*. The wings, therefore, twist in opposite directions during extension and flexion. In the flexed condition of the wing the anterior (*d e f*) and posterior (*b c*) margins are nearly on the same level, and the wing acts as a short lever. In this condition of the pinion the primary or rowing feathers (*b*) are separated from each other, and inclined obliquely upwards and outwards. (These feathers are also shown at 1, 2, 3, 4, 5, 6, 7, 8, 0, 9 of figure 46, page 378.) When, therefore, the wing ascends, the feathers in question (as well as the secondary feathers) cut into the air like so many knives. They thus diminish the resistance experienced from the superimposed air during the up stroke, a result to which the flexing or folding of the wing and its conversion into a short lever contributes. From this account it will be seen that when the wing is flexed the angles made by its under surface with the horizon are diminished, whereas those made by the individual primary and secondary feathers are increased. When the wing is extended it rotates in the direction of its length, the anterior margin (*d e f*) being gradually inclined upwards and backwards, the posterior

one downwards and forwards. The rotation of the wing on its long axis during extension increases the angles made by the under surface of the wing with the horizon, but decreases the angles made by the individual primary and secondary feathers, these being made to flap together, and to assume a more or less horizontal position, as is well shown at *a b c d e f g h i j k l m n o p q* of figure 48, page 378. This flapping together of the primary and secondary feathers during extension effectually prevents the air from passing between them. The power of the wing is greatly augmented during the down stroke—1st, by its being converted into a long lever; 2d, by the flapping of the feathers together; 3d, by its under surface being rendered deeply concave (page 378, figure 48); and 4th, by the various angles of inclination made by the several portions of the under surface of the wing with the horizon being increased. These points are further illustrated at figures 16 and 17, Plate XIII. At figure 17 the margins of the primary (*o p*) and secondary (*q*) feathers, as seen in flexion, are given; whereas in figure 16 the flat of the feathers (*o p q*), as seen in extension, are shown. These figures also show that, as the angles made by the under surface of the wing with the horizon increase, the angles made by the individual primary and secondary feathers (*o p q*) decrease, and *vice versa.* The angles made by the primary and secondary feathers are increased during the up stroke, when the speed of the wing is slowed, and decreased during the down stroke, when the speed is increased, an inclined surface, which forms a large angle with the horizon, giving, when forced against the air at a low speed, the same amount of buoying power as an inclined surface, which forms a smaller angle when urged at a lower speed.

Figures 9, 10, and 11 (Plate XII.) show the wing of the gannet in the flexed, semiflexed, and extended condition. Those figures are also intended to illustrate how the various inclined surfaces made by different portions of the under surface of the wing in extension and flexion are directed forwards, backwards, outwards, and inwards. Thus in flexion and semiflexion (figures 9 and 10), the portions of the wing marked *g h* and *c d*, are inclined upwards and inwards (*vide* arrows), whereas the portions marked *e f* and *a b* are inclined upwards and outwards. When the wing is being extended, as in figure 10, the portions marked *e f* and *a b* produce or draw after them a current, on which the portions marked *c d* and *g h* operate when the wing is being flexed, and *vice versa.* When the wing is fully extended, as at figure 11, the inclined surfaces indicated by *g h*, *c d*, *e f*, and *a b* of figures 9 and 10 disappear, the under surface of the wing making a variety of inclined surfaces, which are directed principally upwards and forwards, as shown at figure 16, Plate XIII. It is in this way that the wing is capable of change of form in all its parts, and it will be observed that those changes are induced irrespectively of any resistance experienced from the air. When the wing ascends, it draws after it a current on which it operates when it descends; and when the wing descends, it produces a current which assists in the elevation of the wing. By the acts of flexion and extension, and by the down and up strokes, the wing of the bird and bat produces the whirlwind on which it depends for support and progress. The tip of the wing rotates upon *t* of figures 9 and 10 (Plate XII.) as a centre, and by its alternately darting in and out in flexion and extension, it describes the segment of a circle (*m n*), and contributes to the stability of the bird by increasing the area of support.

The letter *x* in figures 9, 10, and 11 indicates the shoulder joint; *s*, the elbow joint; *t*, the wrist joint; *v* and *w*, the hand and finger joints; *o p* (fig. 11), the primary feathers; *p q*, the secondary feathers; *r* the tertiary feathers; *x s t v w*, the anterior margin of the wing; and *o p q r* the posterior margin.

Figure 12 shows how the wing is twisted upon itself structurally, and how the tip of the wing forms an inclined surface, which is directed upwards and outwards (see arrows marked *a* and *b*). *x*, *m*, *n*, anterior margin of wing; *o p q*, posterior margin.

PLATE XIII.

Figures 13, 14, and 15 represent the flight of the gull with the wings in the flexed, semi-flexed, and extended conditions. The letters indicate the same parts of the wing in all the figures, *x* representing the shoulder joint, *s* the elbow joint, *t* the wrist joint, and *v* and *w* the hand and finger joints; *o p* the primary feathers, and *q* the secondary ones. At figure 15 the wings are fairly twisted upon themselves, and form true screws. In this figure the pinions are extended to their utmost, and affording their maximnm of support. They are represented as they are seen at the middle of the down stroke. At figure 14 the wings are slightly flexed and deeply concave on their under surfaces, the greater concavity of the wings compensating in part for the diminution in their length. They are also further depressed than in figure 15. At figure 13 the wings are represented as seen at the end of the down stroke, the concavity of their under surfaces being still more increased, and their length still more diminished. The wings are now short levers, and prepared to make the up stroke, the great convexity of their upper surfaces diminishing the resistance which they experience from the superimposed air during their ascent. Figures 13, 14, and 15 illustrate very clearly how the downward and forward fall of the body during the up stroke contributes to the elevation of the wings. Thus in figure 13 the body is up and the wings down. At figure 14 the body has fallen a little, and the wings are elevated and spread out more than in fig. 13. At figure 15 the body has fallen further, and the wings are spread out to their utmost, and on a level with the body. If we now turn to figure 18 of Plate XIV. we will see that the body continues to fall and the wings to rise, as shown at 1, 2, 3; 1′ 2′ 3′. At 3, 3′ of this figure the wings are elevated to their utmost, and the body depressed to its utmost. The wings are consequently in a position to make a new down stroke. From these figures it will be evident that the wings and body rise and fall alternately, the fall of the body contributing to the elevation of the wings, and the descent of the wings necessitating the ascent of the body. It is in this way that the weight of the body comes to play an important part in flight. The alternate waved tracks described by the wings and body in flight are given at figure 14, page 344; *a*, *c*, *e*, *g*, *i* giving the undulations made by the wings; 1, 2, 3, 4, 5, those made by the body.

Figures 16 and 17 (Plate XIII.) show the wing in the extended and flexed condition in the gannet. In these figures the body of the bird is exactly in the same position. When the wing is flexed, as in figure 17, it is crushed together, the tip of the wing (*s*, *p*, *v*, *w*) folding beneath the central portion (*p*, *q*, *t*), the central portion and root (*x s r*) flapping together on nearly the same plane. It is by this means that the wing is converted from a long into a short lever. The flexing of the wing reduces the angles of inclination formed by the several portions of the under surface of the wing with the horizon, and causes the anterior (*x*, *s*, *t*, *v*, *w*) and posterior (*o p q*) margins of the pinion to occupy nearly the same level. It, however, increases the angles of inclination made by the primary and secondary feathers, these changes being necessary to reduce the resistance experienced from the air during the up stroke. When the wing is flexed, all its parts are in a lax condition, the wing being principally under the control of the elastic ligaments, the muscles acting more especially during extension. When the wing is pushed away from the side of the body, and extended as represented at figure 16, the angles of inclination made by the several portions of the under surface of the pinion with the horizon are increased, while those made by the primary (*o p*) and secondary (*p q*) feathers are diminished. The pinion, moreover, is rendered more or less rigid. When the wing is fully extended, it acts as a long lever (compare length of wing in figures 16 and 17). By increasing its length, the wing also increases its power and speed towards the tip. It therefore attacks the air with great violence during the down stroke, and insures a corresponding upward recoil of the body. The angles of inclination made by the several portions of the under surface of the wing with the horizon vary. Thus the angle made by the portion *q s* is greater than that made by the portion *p v*, and that made by *p v* greater than that made by *o w*. The diminution and increase of the angles bears a fixed relation to the speed at which the different portions of the wing travel, the angle always being greatest when the speed is lowest, and *vice versa*. The change in the angles is principally due to the rotation of the wing in the direction of its length, the posterior margin of the pinion rotating round the anterior one in a *downward direction* during extension (figure 16, *vide* arrows), and in an *upward direction* during flexion (figure 17, *vide* arrows). It is this rotation of the wing upon its long axis which presents the upper or dorsal surface of the pinion to the spectator in flexion (figure 17), and the under or ventral surface in extension (figure 16.) These points are further illustrated at figure 8, Plate XII. (see description of figure 8.) In figures 16 and 17 the same letters are affixed to the same portions of the wing in both; *x* representing the shoulder joints; *s*, the elbow joint; *t* the wrist joint; *v*, *w*, the hand and finger joints; *o p*, the primary feathers; *p*, *q*, the secondary feathers; *r*, the tertiary feathers; *x*, *s*, *t*, *v*, *w*, the anterior margin of the pinion; *o p q*, the posterior margin.

PLATE XIV.

Figures 18 and 19 represent the several positions assumed by the wing of the gull during extension and flexion, and during the down and up strokes. Figure 19 also shows how the wing during its ascent and descent rotates upon two axes. At 4 of figure 19 the wings are represented as they appear at the middle of the down stroke. They are fully extended, and affording their maximum of support. At 5 of this figure the wings are slightly flexed, and more deeply arched than at 4. They are also on a lower level. At 6 the wings are represented as they appear at the end of the down stroke. They are now fully flexed and form short levers. They are also more deeply arched than at 5, a circumstance which prepares them for making the up stroke, as the arching renders the upper or dorsal surfaces of the wings very markedly convex. The wings, when in the positions indicated by 6 of figure 19, are elevated as short levers, until they assume the positions indicated by 1, 1′ of figure 18. The wings are then pushed away from the body, and extended and elevated, as shown at 2, 2′ and 3, 3′ (fig 18). At 3 3′ the wings are fully extended and fully elevated, and ready to make the down stroke. They descend as long levers, until they assume the positions indicated by 4 of figure 19, the changes in position just described being repeated in rapid succession as the wings vibrate. The wings are flexed towards the termination of the down stroke (5 and 6 of figure 19) to convert them into short levers, to destroy the momentum acquired by them during their descent, and to prepare them for making the up stroke. They are extended towards the termination of the up stroke (2, 2′; 3, 3′ of figure 18) to convert them into long levers, and to prepare them for making the down stroke. Figure 18 represents the bird when it is flying vigorously, or when it is rising or picking up garbage from the surface of the sea. In leisurely flight the wings do not rise much above the level of the body, as shown at figure 19. In this case the wings are made to play rather under than above the body (*vide* p. 374). The compound rotation of the wing is shown at figure 19, the wing rotating at its root (*a*) and along its anterior margin (*c b*), the tip of the wing describing the arc of one circle (*e b f*), and the posterior margin of the wing the arc of another circle (*g d h*). The compound rotation of the wing is further illustrated at figure 45, page 376.

Figure 20. Wing of the piet in the extended position.—In this figure the under lapping of the primary (1 2 3 4 5 6 7 8 9) and secondary (*j k l m n o p q r s*) feathers are shown, and how the axis of each primary feather occupies a more and more central position in proportion as it is placed nearer the secondary feathers. This want of symmetry in the primary feathers is necessary to their valvular action during flexion and extension. The wing during its vibration forces a certain portion of the air in waves along its under surface in the direction of its root, as indicated by the arrows and dotted lines; the greater portion of the air, however, is urged from the tip and posterior margin of the wing in a backward and downward direction, the reaction propelling the body upwards and forwards. The commotion produced in the air by the tip and posterior margin of the wing is on all occasions very great, as the exposure of a flame behind or to the outside of the wing will readily satisfy.

PLATE XV.

Figures 21 and 22 represent the muscles and elastic ligaments of the wings of the snipe, as seen on the ventral and dorsal aspects. In figure 21 (ventral aspect) the wing to the right of the observer is fully extended, and the elastic ligaments put upon the stretch. The wing to the left of the observer is represented as flexed, the elastic ligaments being in a state of contraction. The same points are illustrated at figure 22, which represents the dorsal aspect of the bird. The wing is flexed principally by the action of the elastic ligaments. It is extended chiefly by voluntary muscular efforts. Those figures show the difference in the length of the wing in the extended and flexed condition, the pinion being a long lever in extension, and a short one in flexion. That the elastic ligaments are subsidiary, and to a certain extent under the control of the muscular system, is evident from the fact that voluntary muscular fibres run into the ligaments in question. Thus the voluntary muscular slip marked *a* in figure 21 terminates in the fibro-elastic band *k*; this, again, being geared to voluntary muscle *x*, and to certain musculo-fibrous bands *j*. Their conjoined action is to flex the forearm upon the arm, the arm being drawn towards the body by a musculo-fibrous ligament *d*, *e*. The elastic ligament *g*, *i* flexes the hand upon the forearm, and the ligament *r* the fingers upon the hand.

Figure 23 shows the muscles and elastic ligaments in the wings of the pheasant, as seen on the dorsal aspect, the wing to the right of the observer being fully extended, that to his left being fully flexed. In the former the elastic ligaments are put upon the stretch; in the latter, they are in a state of contraction.

a, *b*, Voluntary muscular fibres, terminating in fibrous and elastic tissues *c* and *k*. These structures act in conjunction, and fold or flex the forearm on the arm.

f h, Voluntary muscular fibres, sending processes into elastic ligament *g i*, to flex the hand upon the forearm. The arm is drawn towards the body by the elastic ligament *d*, and by the muscles *v*, *w*.

Plate XVI.

Figures 24 and 28 show the muscles and elastic ligaments, and the arrangement of the primary and secondary feathers on the ventral and dorsal aspects of the wing of the crested crane. The wing is in the extended condition in both cases.

a b, Voluntary muscular fibres terminating in elastic band *k*. This band splits up into two portions (*k*, *m*, figure 24). A somewhat similar band is seen at *j* (figure 24). These three bands are united to, and act in conjunction with, the great fibro elastic web *c*, to flex the forearm on the arm.

f g, *h*, *i*, Musculo-fibro-elastic ligament, which envelopes the roots of the primary and secondary feathers. The musculo-fibro-elastic ligament forms a symmetrical network of great strength and beauty, its component parts being arranged in such a manner as to envelope the root of each individual feather. The network in question supports the feathers, and limits their peculiar valvular action. It is enlarged at figures 25 and 27, and consists of three longitudinal bands, *r s*, *t u*, *v w*. Between these bands two oblique bands, *g* and *h*, run; the oblique bands occurring between every two feathers. The marginal longitudinal band (*v*, *w*) splits up into two processes, one of which curves round the root of each feather (*x*) in a direction from right to left (*a*, *b*, *c*), the other in a direction from left to right (*d*, *e*, *f*). These processes are also seen at *m*, *n* of figure 26. They have the root of each feather completely under control, and their function, in conjunction with the oblique bands, is to rotate the feathers from right to left during flexion, and from left to right during extension. The longitudinal and oblique bands are so geared together that they work in harmony, all the feathers enveloped by them being made to rotate in the same direction at exactly the same instant of time. It is in virtue of the rotation of the individual primary and secondary feathers at their roots that the feathers are separated from each other during flexion, and brought into close contact during extension; and thus it is that the air is avoided during the up stroke, and seized during the down one. The primary and secondary feathers are supported on their dorsal aspects by a series of subsidiary feathers (*m n o p* of figure 28), which are placed obliquely across their roots, and act as buffers. The subsidiary feathers prevent the primary and secondary feathers from rising too far during the down stroke.

Figures 25, 26, and 27. See under figures 24 and 28.

FIG. 1.

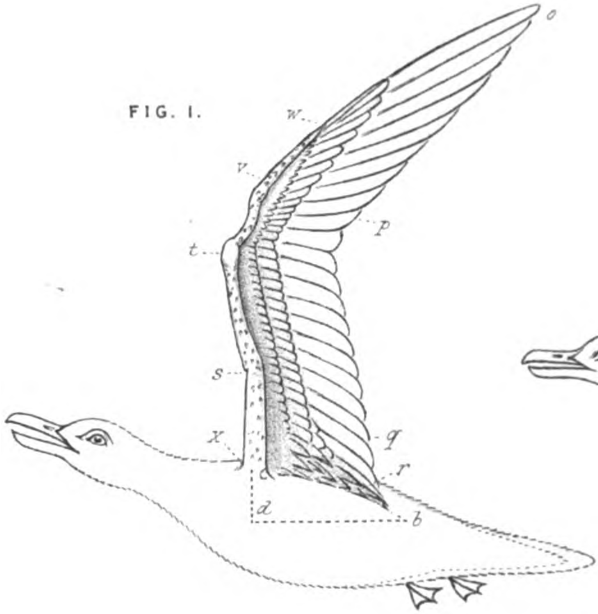


FIG. 2.

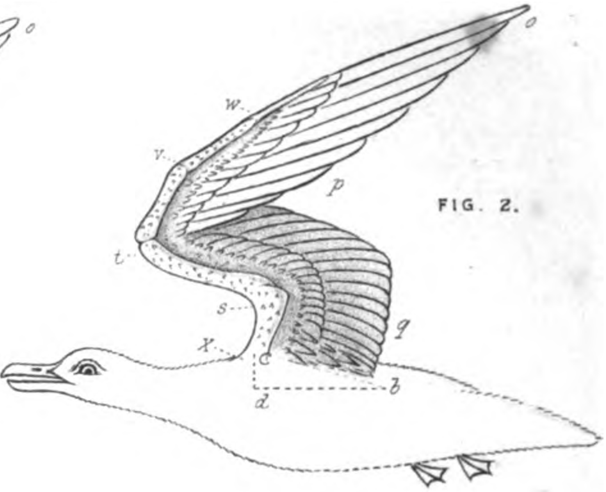


FIG. 4.

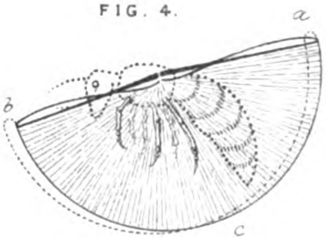


FIG. 3.

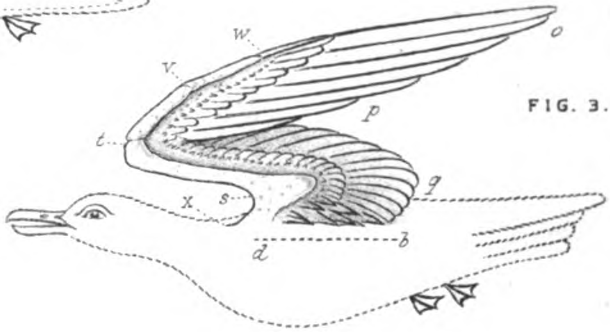


FIG. 5.

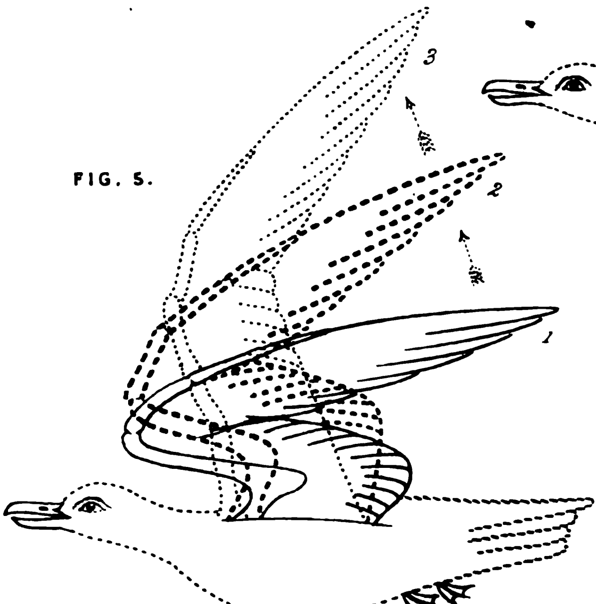
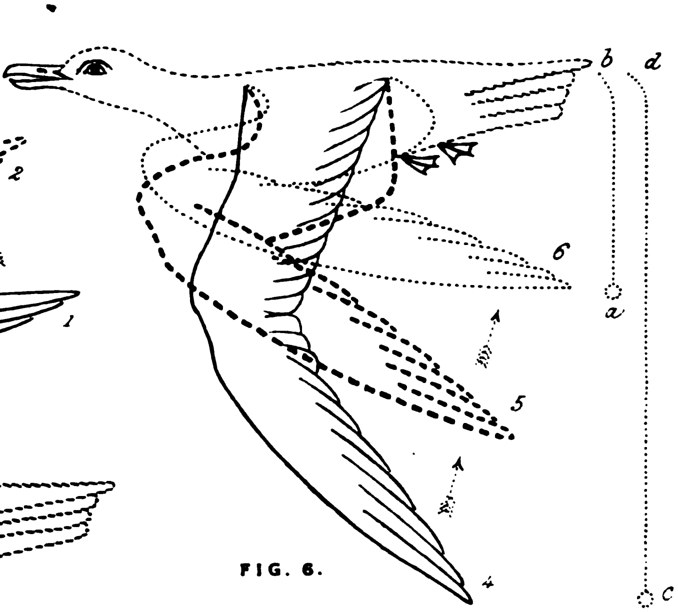


FIG. 6.



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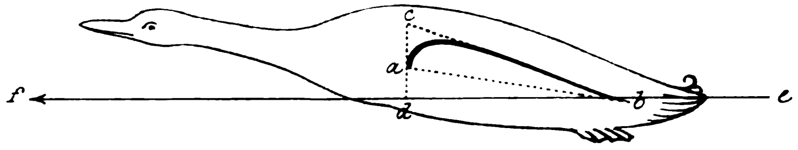

FIG. 7.

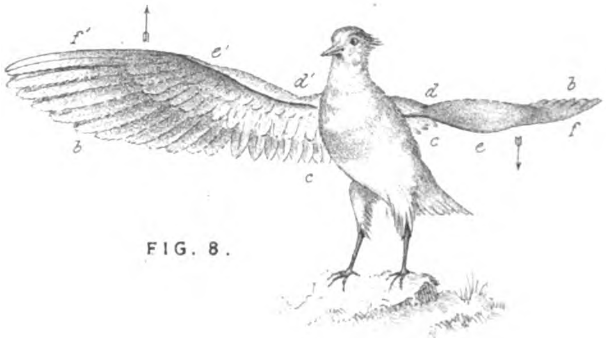

FIG. 8.

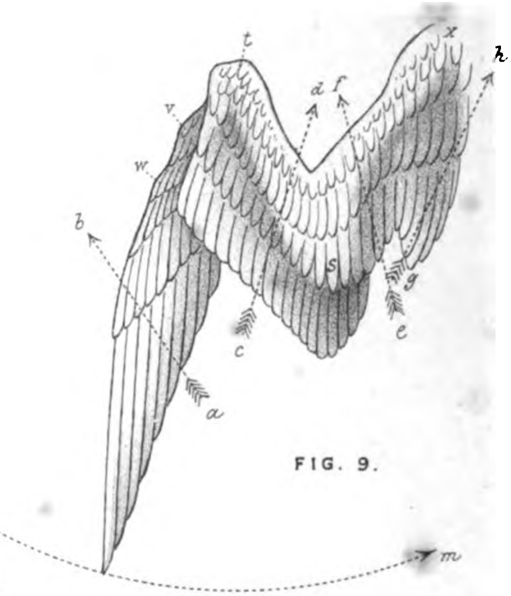

FIG. 9.

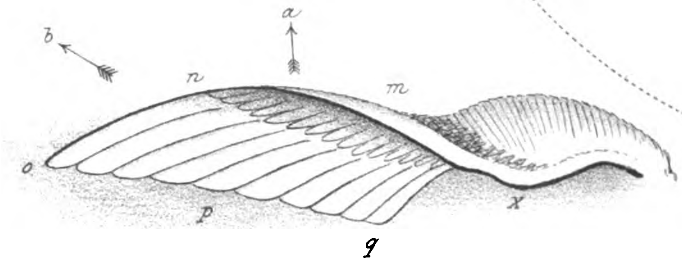

FIG. 12.

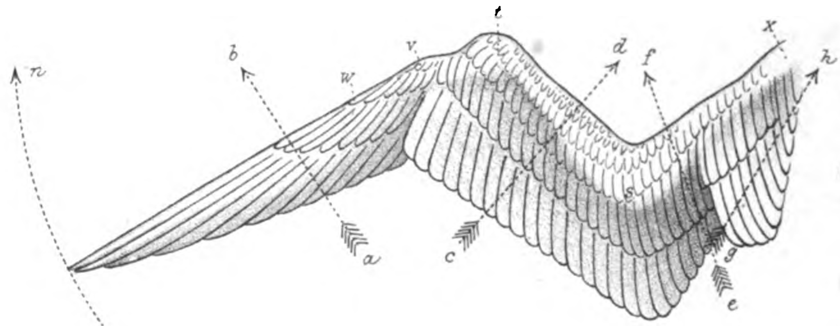

FIG. 10.

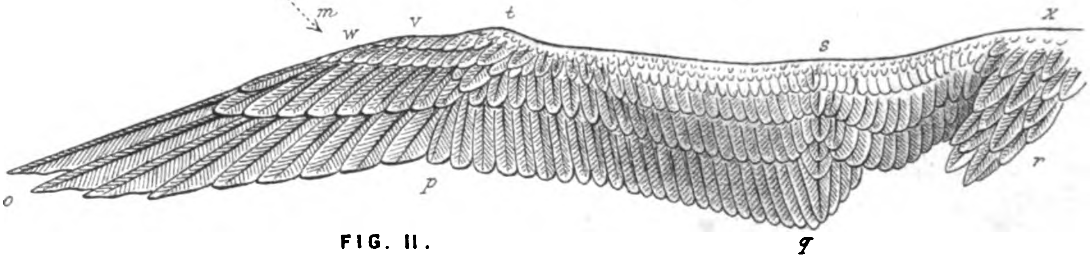

FIG. 11.

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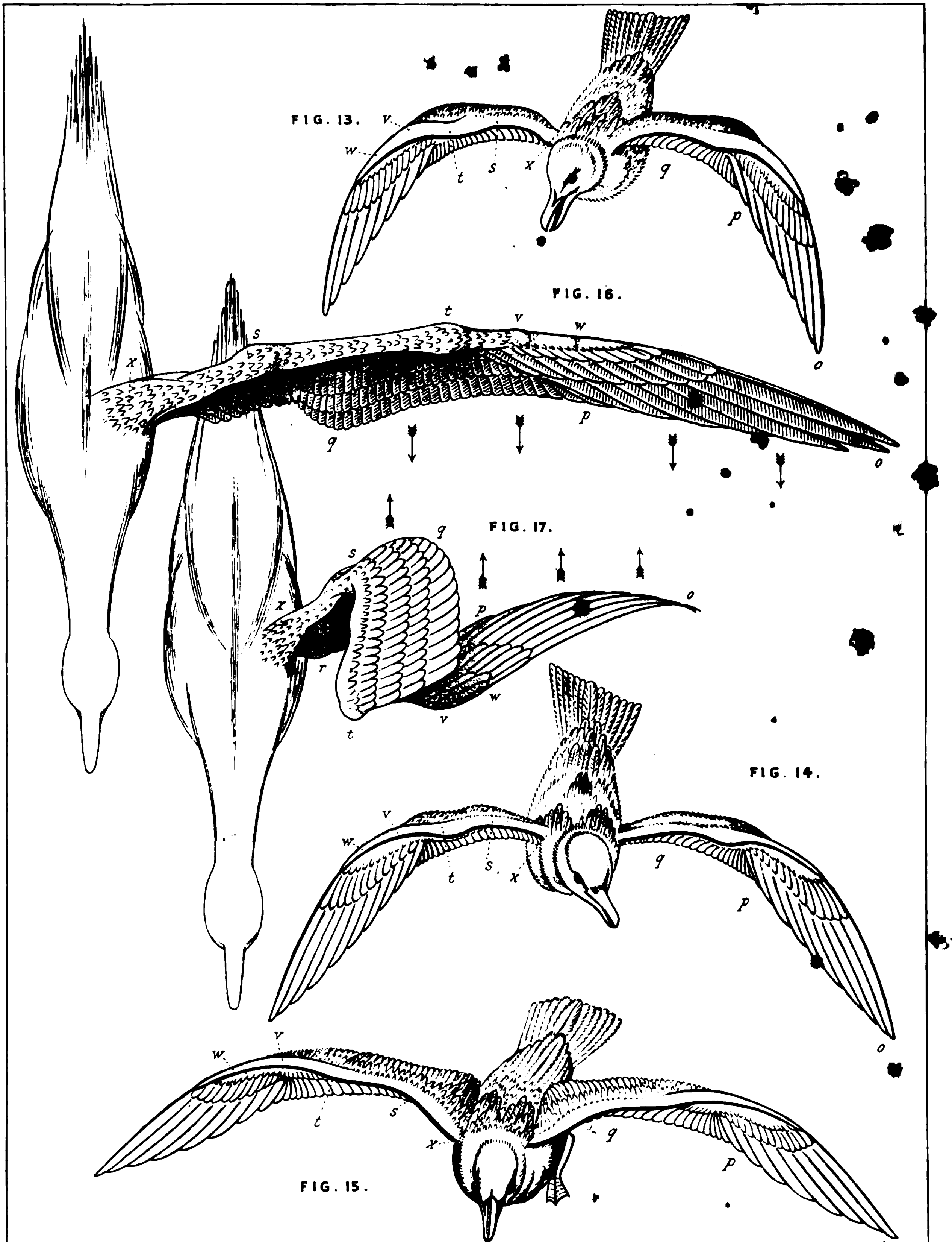

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FIG. 18.

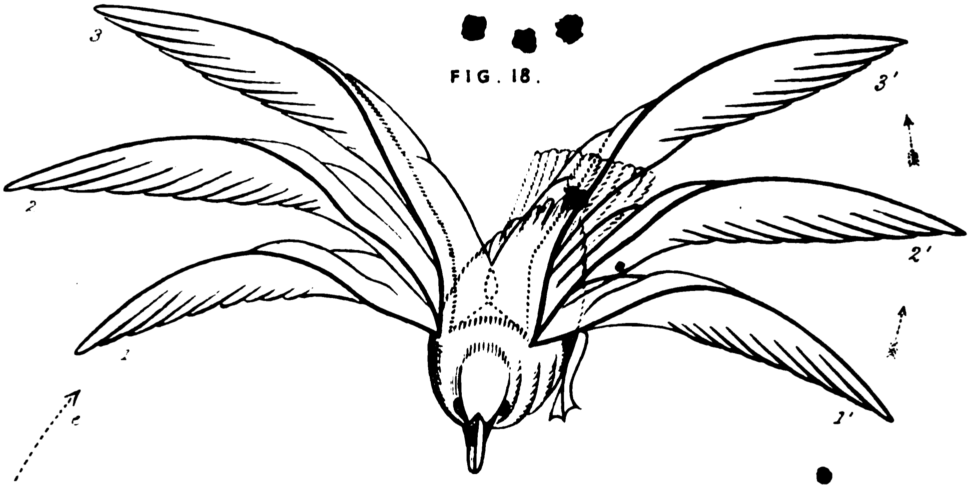


FIG. 19.

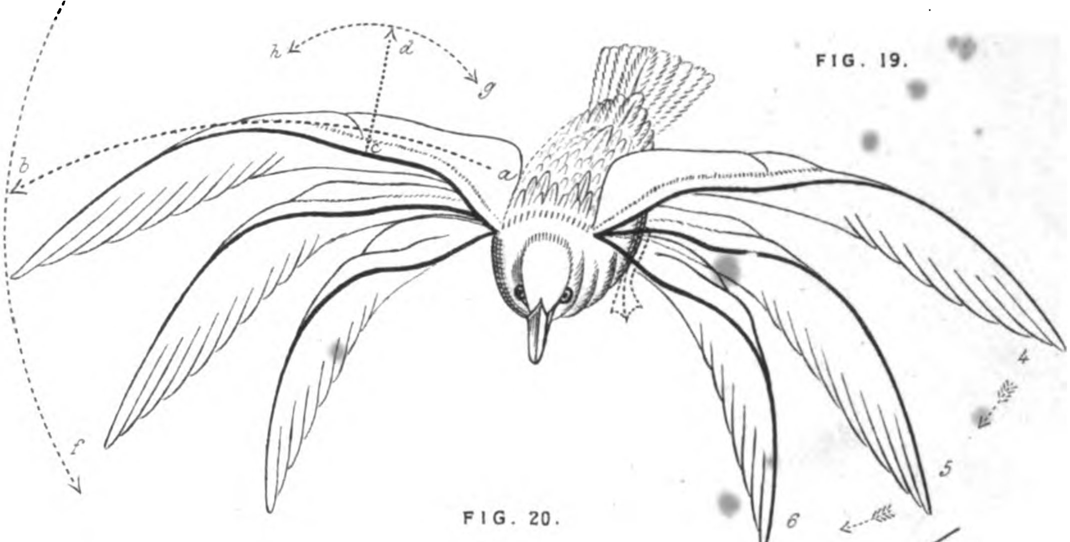
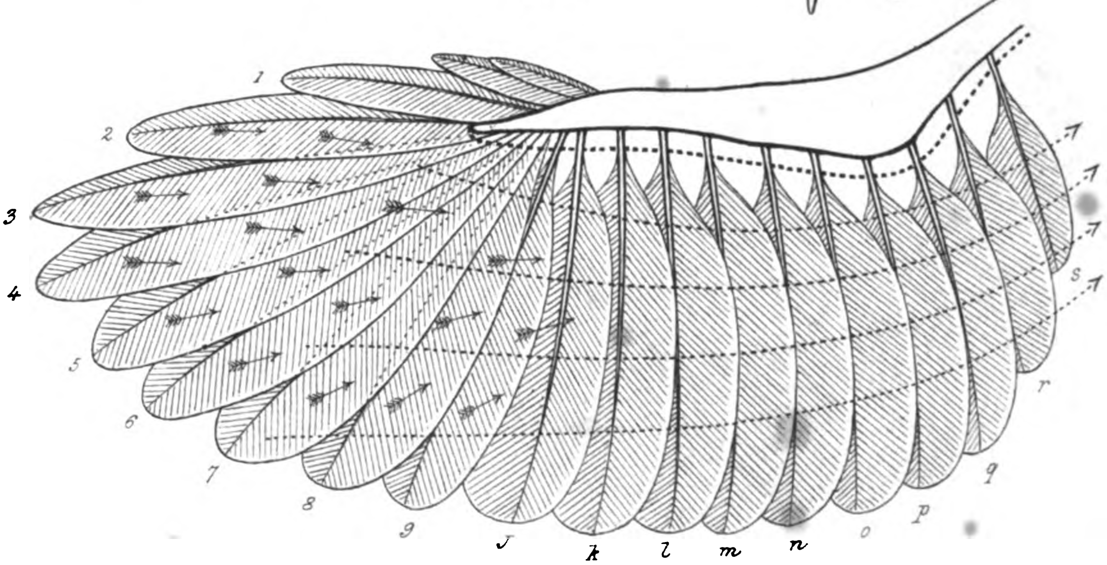


FIG. 20.



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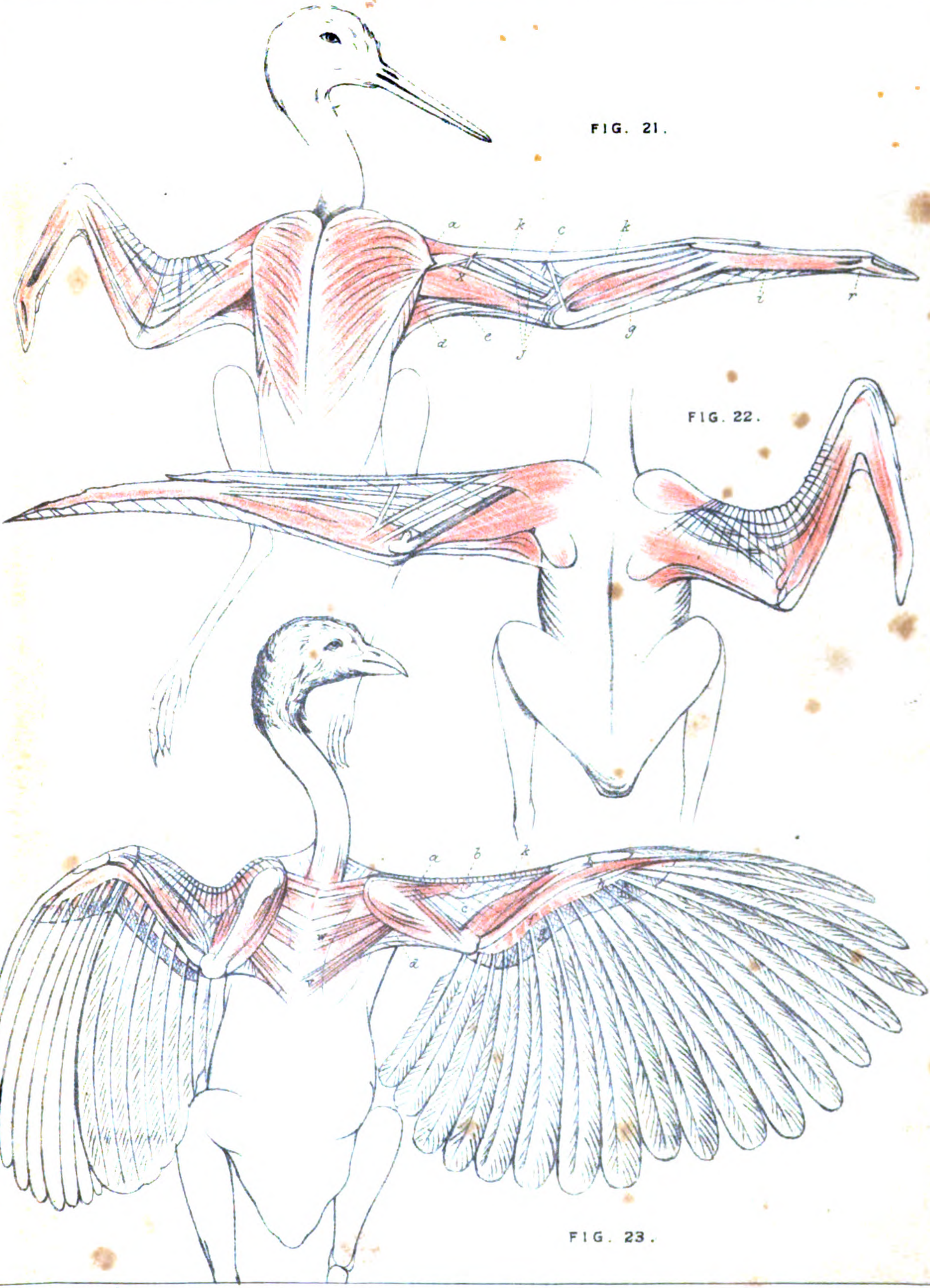

FIG. 21.

FIG. 22.

FIG. 23.

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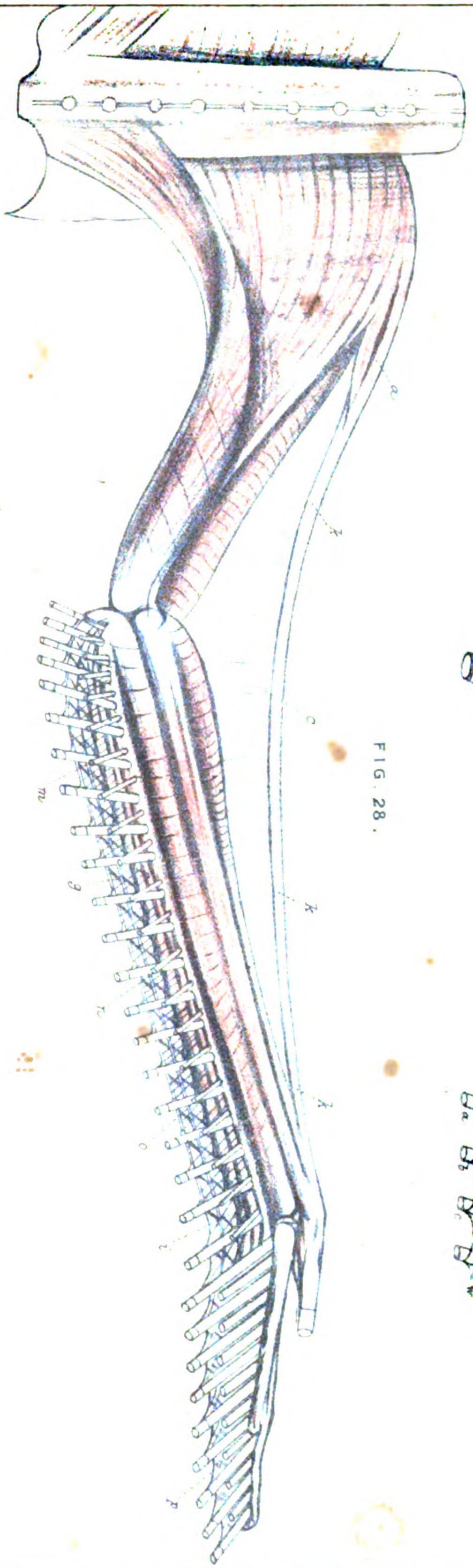

FIG. 28.

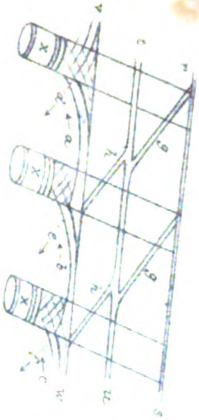

FIG. 25.

FIG. 26.

FIG. 27.

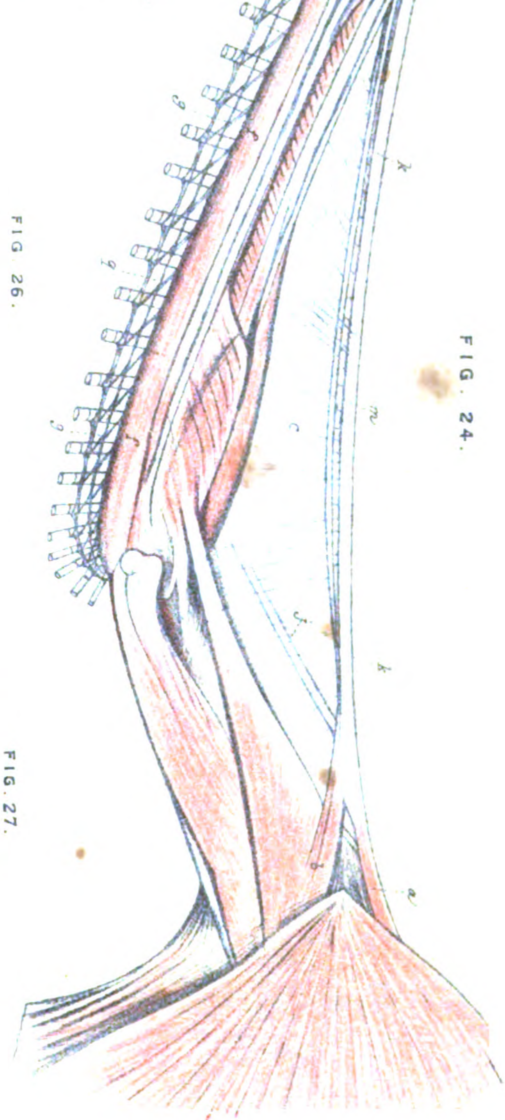

FIG. 24.