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CURRENT PROBLEMS IN RESEARCH

Biophysics of Bird Flight

The very low drag of nature's aircraft, birds, sets a goal for man in his striving for efficient aircraft.

August Raspet

There is no doubt that modern mechanical flight owes its inspiration to observations of birds in flight by early philosophers and scientists as well as by interested laymen. The earliest living "flying machine" is dated about 150 million years ago. This was the pterodactyl of geologic times. In contrast, man-made flying machines are only 57 years old. You can see from this contrast of eras that we may look for new knowledge of flight from a study of this age-old concept of bird flight.

In Greek mythology, the story of Daedalus and Icarus is well known. Daedalus designed and built, supposedly, two flying machines, covered with feathers, using a structure of wax to support them. This was really a mythical imitation of bird flight. There was no application of real knowledge of the mechanism of bird flight, merely an imitation, in form, but not in function. But, of course, not having this knowledge, we, even today, cannot duplicate bird flight in the sense of straight imitation on a scale such that a man can fly as a bird does, by his own muscle power.

The first known flying machine constructed on bird-flight concepts was da Vinci's well-known invention. About 1505, da Vinci test-flew this machine, using a test pilot, as is common practice today. The results are indicated in da Vinci's notebooks by the fact that after this test flight there was no more mention of flying. There is rumor that the test pilot broke his leg. The test pilot, in this case, was one of da Vinci's household servants (Fig. 1).

It was Lilienthal (*1*) who also imitated bird flight, even to the point of using such small stabilizing tail surfaces that his machine was only marginally stable. But we must remember that it was also Lilienthal who, by this bird imitation, proved Newton, Kirchhoff, and Helmholtz to be wrong in their concept that lift is generated by a downward deflection of the air, simply as a reflection phenomena, and in disregarding entirely the suction on the upper surface. For his failure to understand that birds possess automatic stability due to instinctive reflexes, in addition to that inherent in their geometry, Lilienthal paid with his life.

The realm of bird flight can be clearly divided into two aspects: that on motionless wings, which is soaring, and that on flapping wings, which is really the working part of flight. The latter is used in take-off and in climbing to altitude, even by soaring birds. It is used as a principal mode of flight by the nonsoaring birds. The soaring phase of flight, or the flight on motionless wings, was divided by Lord Rayleigh in 1883 (*2*) into three separate categories: (i) Flight in which the path is not horizontal—in other words, gliding; (ii) flight in an air mass which has a vertical component—that is, static soaring; and (iii) flight in an air mass which is not uniform in velocity. The latter is, in the strict sense, dynamic soaring. Evidently, a good understanding of the first phase, the motionless wing phase, would contribute much to an understanding of the biophysics of bird flight. The second kind of flight, much more complicated (flapping flight), has been theoretically studied, but very little experimental work has been done to support the various theories. It is the purpose of this article to take up in detail the aerodynamics of a bird's wing—in particular, that of motionless wing flight.

Wind-Tunnel Experiments

When we consider the various tools available to us for studying flight in general, we are apt to resort to the one which has been so useful in helping man to fly—namely, the wind tunnel. It was a wind tunnel which helped the Wright brothers to arrive at proper airfoil sections, and the wind tunnel is still used today for subsonic, transonic, supersonic, and hypersonic flow studies. It will be interesting, therefore, to look at some results from wind-tunnel work on the measurements of bird aerodynamics and compare these results with some data obtained in flight. From this, we can determine the validity of the wind tunnel in bird-flight work. In Fig. 2 is shown a velocity polar of a laughing gull, computed from data measured in the wind tunnel and data measured in flight. The velocity polar is clearly seen to consist merely of a plot of sinking speed, which is really a measure of the energy loss in flight, versus the forward velocity of flight. Actually, this is not a polar, but the terminology is that which is used in aviation. It should be mentioned that the laughing gull measured in the wind tunnel (*3*) was not actually a feathered bird, but rather a clay model sculptured by an artist. The tunnel, however, possessed a rather low turbulence and provided an environment quite representative of that which one might find in the atmosphere. On comparing the sinking speed obtained from the wind-tunnel measurements, one sees that the sinking speed of the clay model is a little more than double that of the actual bird

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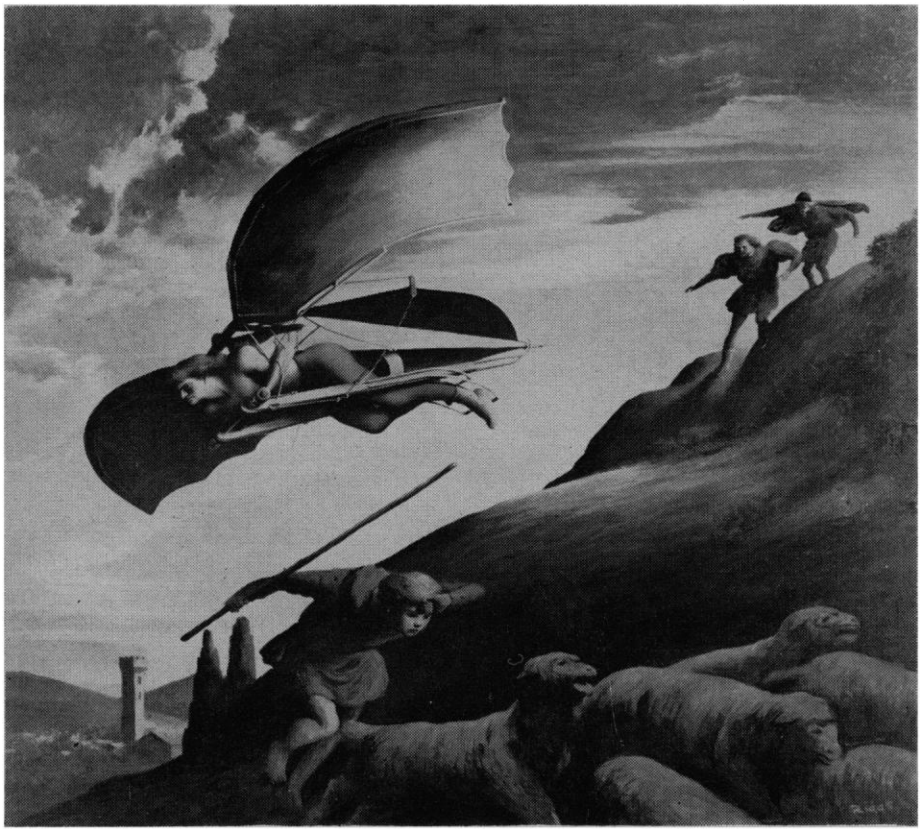


Fig. 1. Artist's conception of Leonardo da Vinci's flying machine in flight. Note that da Vinci, knowing human anatomy as he did, at least tried to harness the powerful thigh muscles, whereas many other experimenters used only the arm muscles. [From a painting by Robert Riggs, courtesy of International Business Machines Corp.]

measured in flight at the speed of 30 miles per hour. The flight measurement consisted of a very simple comparison of the flight of the gull, while soaring on a ridge on Long Island, relative to that of a sailplane. The pilot in the sailplane was able to adjust his speed to follow the bird exactly, and at this particular forward speed, the bird and the sailplane flew back and forth on a ridge for about 2 hours, neither outclimbing the other.

This is proof that their sinking speeds at this forward speed were identical. It is just this concept of comparison flying which I will discuss in connection with some measurements of the black buzzard. The technique was developed to a higher state and used to get the complete measurement of the drag of a bird over the speed range of its flight in the gliding phase.

However, in order to determine the nature of the aerodynamics of birds in terms of the known parameters used in aeronautics, we must refer the drag to a nondimensional drag coefficient C_D:

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S},$$

where D is the drag in force units, ρ is the air density, V is the velocity of flight, and S is the wing area, including that intercepted by the body.

In a similar matter we define the lift coefficient C_L,

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S},$$

where L is the lift in force units. If, now, the velocity polar of Fig. 2 is transformed into a curve of C_L^2 versus C_D, we obtain Fig. 3. The reason for plotting against the square of the lift coefficient is quite evident when one sees that the induced drag coefficient—that is, the drag due to lift—is a function of the square of the lift coefficient:

$$C_{D_i} = \frac{C_L^2}{AR_e},$$

where AR_e is the effective aspect ratio:

$$AR_e = \frac{b^2}{S}e,$$

b being the span and e the span efficiency factor.

What one sees from the linearized drag polar of Fig. 3, is that the flight-measured point lies on an extension of the linear portion of the wind-tunnel measurements. This indicates that the wind-tunnel results must be in error below a lift coefficient equal to 0.8.

Obviously, the clay model was not representative of a feathered bird in flight. In fact, it is doubtful that even a feathered model could accurately duplicate the aerodynamic properties ascribable to the elasticity and mobility of the feathers on a live bird.

However, one can admire the finesse with which nature has designed her flying machines in observing the neat intersection of wing and body in Fig. 4, which shows a drawing of the laughing gull, taken from Feldmann's paper. In this drawing, the very pointed tips of the soaring birds of the sea are conspicuous. In Fig. 5 the distinctly different tips of soaring land birds are shown. The question then arises, "What is the function of this pointed tip as contrasted with the slotted wing tip of soaring land birds?"

It has been suggested that since soaring land birds must land and take off from trees, a large span would be a handicap. Therefore, the slotted wing tip serves to diffuse the vortex flow at the tip, permitting the soaring land bird to attain good performance in spite of limited aspect ratio. The sea bird on the other hand is not limited by its environment with respect to aspect ratio.

However, an analytic investigation by Newman (*4*) disputes the premise that the slotted tip can reduce the induced drag over that of a solid tip. We are then left without a logical explanation for the slotted tip of soaring land birds. Wind-tunnel tests with smoke streams and a live bird trained to fly in a tunnel could add to our knowledge of this important distinction between soaring land birds and soaring sea birds.

In order to duplicate this complicated model, the live bird, one might freeze a bird and then test it in a wind tunnel. This was done at the Washington Naval Shipyard wind tunnel some years ago, but again we have the criticism that a change occurs in the elasticity of the support of the feathers, as well as in the feathers themselves, in the process of freezing the bird. Another criticism of the frozen-bird technique lies in the fact that the bird uses its wing muscles even in gliding flight as a means of control. This is necessary, since the bird possesses little or no inherent aerodynamic stability except possibly along the body axis in roll. In yaw and, to a lesser extent, in pitch, the bird with fixed geometry appears to have neutral or negative stability. In

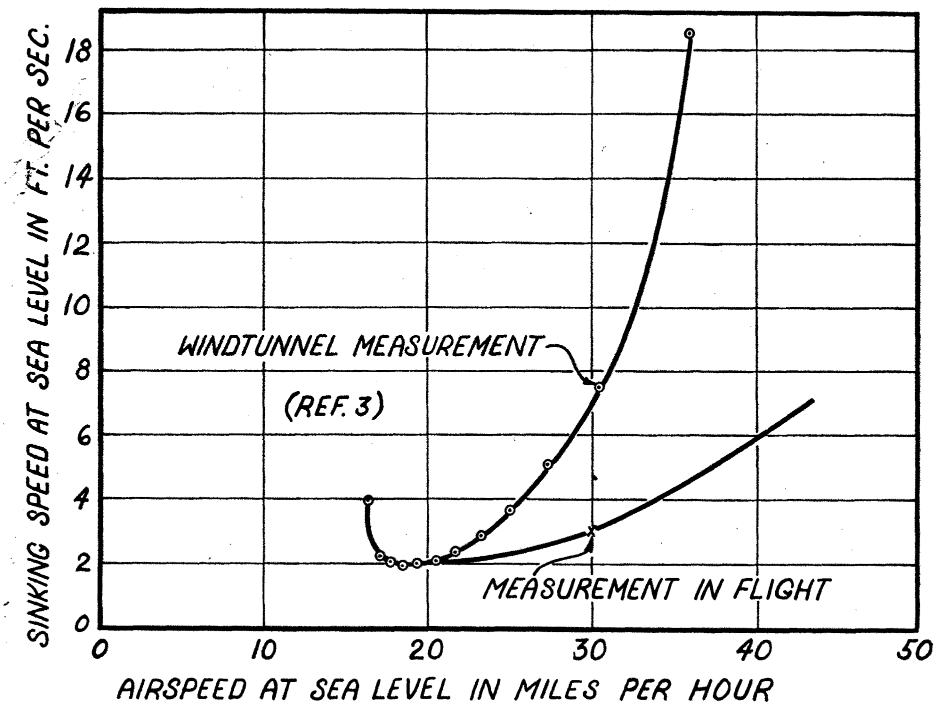


Fig. 2. Velocity polar of a laughing gull.

other words, the flight of a bird is stabilized by minute involuntary control deflections. This is similar to the process of walking in man, in his erect posture.

Another feature of the bird's aerodynamics is the porosity of the feathers. Whether this feature plays an important role in the aerodynamics of the bird or not has not yet been established. Victor Loughheed is reported to have measured the porosity of the bird's feathers, finding the porosity ten times greater in the downward direction than in the direction up through the wing feathers.

In some birds, in addition to the usual features of the feathers—flexibility, mobility, and porosity—there is also a toothed leading edge. This is true particularly in owls, which must fly silently and stealthily upon their prey in the field. Graham (*5*) believes that this toothed leading edge reduces the velocity of the flow over the wing. This may be so, but if there is too much loss of velocity in the flow near the leading edge, a wing with a toothed leading edge will not develop as high a lift as one without this edge. This means that the bird with a toothed leading edge to its wing would have to fly faster than one with a smooth-edged wing. Thus, the noise would not be essentially reduced. Yet the owl does fly silently.

Perhaps we might speculate on the function of the toothed leading edge by drawing on an analogy. If a piece of wire of cylindrical form about 3 millimeters in diameter and 1 meter long is swung through the air in a rotating motion similar to that of a propeller, a distinct tone similar to that of a singing telephone wire is emitted. Now, if instead of a single cylindrical wire, two wires of 1.5-millimeter diameter are twisted together in a tight spiral and then spun, the noise level is much lower in intensity and in frequency. In fact, only the free end emits a noise.

From this experiment we might say that the toothed leading edge behaves in the same way that the twisted wire does—that is, in a manner to reduce the vortex noise emitted by the flow leaving the wing. However, remember that this is merely a hypothesis and not absolute proof of the function of the toothed leading edge of the wings of owls.

Since the bird possesses little or no inherent stability in pitch, the question of the function of the tail arises. In general, the tail is used as a landing aid similar to the flap on an airplane. Photographs show clearly that the tail of most birds fans out to increase the lifting area just before touchdown and is folded during gliding flight.

At the same time, during the landing, it will be seen that the alula or false feather, representing the thumb of our hand, opens in order to increase the lifting power of the wing. This same alula is used as a lateral control for initiating rapid turns.

The reader may wish to try a simple experiment which illustrates the function of the alula. If, while driving at about 50 miles per hour, one puts his hand out of a car window with the hand cupped slightly and at a positive angle to the wind, he can, by simply moving his thumb up or down, cause a large change in the lifting force his arm experiences. This is how the bird applies control in roll about his longitudinal body axis.

Having seen, in Fig. 2, that windtunnel tests of bird flight are fraught with possible large errors, we are forced to look for new means of determining

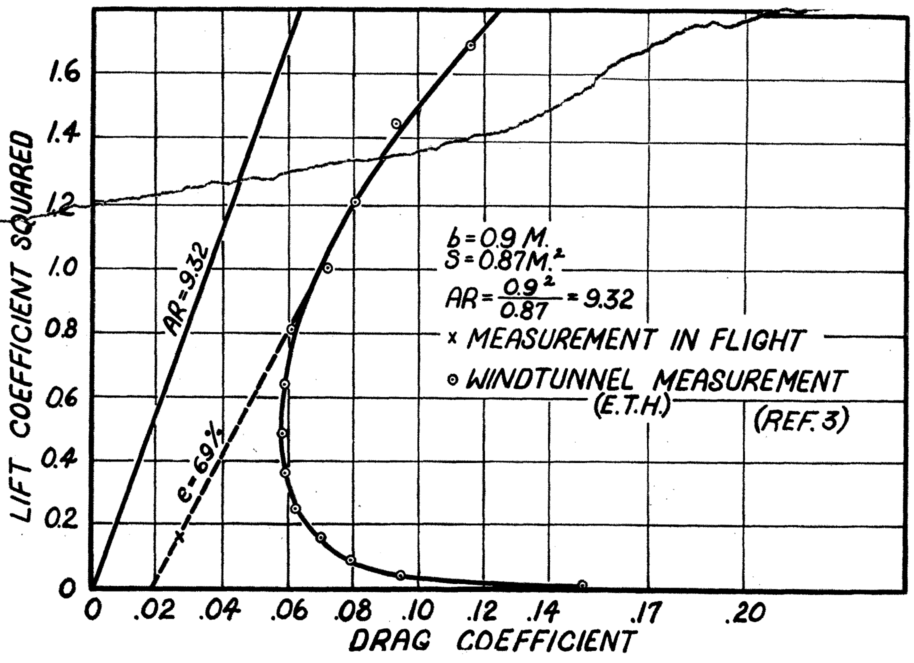
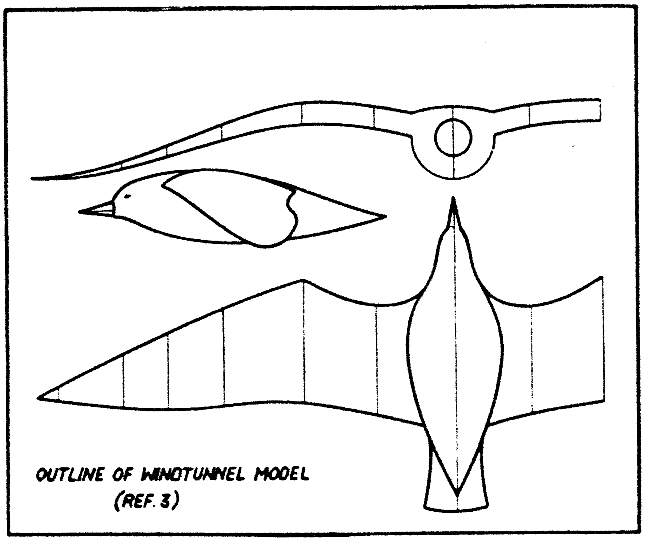


Fig. 3. Linearized drag polar of a laughing gull.



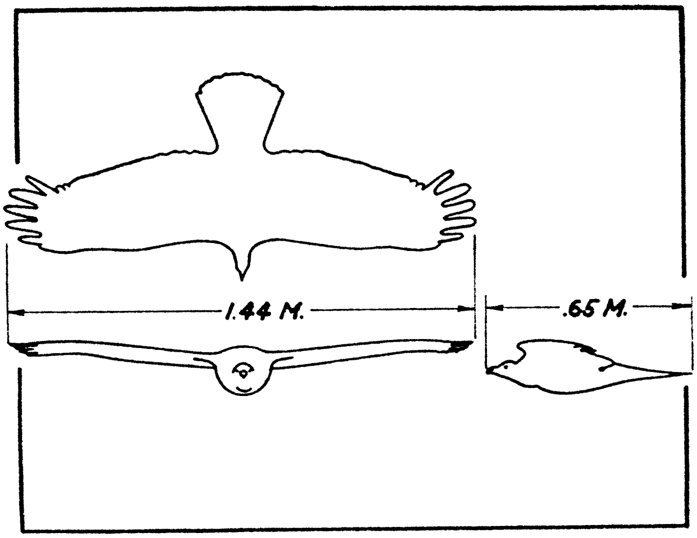


Fig. 4 (left). Three views of a laughing gull. Fig. 5 (right). Three views of the black buzzard.

the aerodynamic properties of bird flight.

From about 1890 to 1900, S. P. Langley, then director of the Smithsonian Institution, attempted to determine the flight characteristics of buzzards in the neighborhood of Washington, D.C., by photographing the birds with two telephoto cameras, arranged stereoscopically. Such a technique would certainly have determined the geometry of the bird while the bird was airborne, but it would not have determined the energy losses, unless a time-lapse method had been used, together with triangulation by double theodolite methods.

In view of the difficulty of studying the flight of wild birds from the ground, George Carter and I, in 1945, started an experiment in which a young wild buzzard was to be trained to carry a small recording barograph and anemograph attached to its belly. The bird was trained successfully to do its job and to carry a mock-up of the recording instrument, which was to weigh 30 grams and have dimensions of 2 by 3 by 5 centimeters. However, before the actual measurements could be made, the bird died of an intestinal stoppage. Our success in training this bird was due to the skill and understanding of George Carter.

Had this experiment been successful, it would have yielded the sinking speed as a function of air speed—that is, the speed polar, similar to that in Fig. 2. But for a soaring land bird we would need to observe the mode in which the bird is flying in order to delineate the function of the variable geometry of the slotted wing tip.

Furthermore, the success achieved in training this one bird by Carter clearly supports his contention that it would be possible to train live birds to fly in a wind tunnel whose axis could be inclined to the horizon. Thus, one could force the bird to fly at different gliding angles and at different air speeds, simply by inclining the tunnel and varying the air speed so that the bird would remain motionless in the throat of the tunnel. With this method, one could delineate the function of the slotted wing tip as well as derive drag polars for various changes in geometry which the bird would be compelled to make in order to stay in the tunnel.

Comparison-Flight Studies

Since the technique of using trained birds was so dependent on the training of the birds and so time-consuming, the comparison method of flying with birds in a sailplane was developed in 1949 (6) as a refinement of the simple one-point comparison test made on the laughing gull, as represented in Fig. 2.

In the comparison method for determining the speed polar and consequently the drag polar of a bird in free and natural flight, a sailplane of low sinking speed and low forward speed capability is needed. In addition, the sailplane must be highly maneuverable, since the pilot must follow birds that can turn with extreme rapidity.

Figure 6 shows a sailplane rigged for bird-flight research. A small radio transmitter and receiver are carried, for transmitting data to a data recorder on the ground. The telephoto camera on the nose of the sailplane is used to record the geometry of the bird. However, the results obtained with this camera were not helpful, because it was not possible to determine the orientation of the tip feathers from the nonstereoscopic photographs.

In making these measurements, the sailplane was launched either by a ground tow behind an automobile on a long runway or by an airplane tow. When the sailplane reached an altitude where upcurrents were strong enough to support it, the pilot would release and soar in a good upcurrent. Ground observers would scan the skies for buzzards, and when one was found, would direct the pilot to the buzzard by radio. When the pilot located the bird he would descend to the altitude of the bird and then follow it, staying no more than 5 to 10 meters behind it. At 30-second intervals, the pilot would report the air speed at which he and the bird were flying and the altitude of the bird above the horizon, measured in wing spans.

Subsequently plots of the altitude of the bird against time yielded, from the slope of this plot, the difference in sinking speed between the bird and the sailplane. Then, by measuring carefully the sinking speed of the sailplane in the still air of the morning at various air speeds, one can obtain the speed polar of the sailplane. Adding to this polar the differences in sinking speed between the bird and the sailplane, we arrive at the speed polar of the bird (Fig. 7).

In this illustration, the two modes of gliding flight yield two different speed polars for the bird. In the soaring mode the bird flies with open tip slots, while in the gliding mode it flies usually on a long descent at relatively high speeds, with tip slots closed. Also, in the latter mode the bird introduces an M-shaped sweepback, whereas in the soaring mode there is a pronounced forward sweep of the wing. Figure 5 shows the black buzzard (*Coragyps atratus*) in its soaring mode.

Returning to Fig. 7, we see that at a speed of 17 meters per second the speed polars cross. Above this speed the bird chooses the gliding phase, for when the bird is gliding its sinking speed is considerably lower than it is with the tip feathers opened. Below 17 meters per second the bird finds that it can reduce its sinking speed by opening the tip slots, and can thereby increase its glide ratio (*L/D*). The glide-ratio curves represent the distance the bird can fly for each unit loss of altitude. In other words, the black buzzard is capable of gliding 23 miles in still air from an altitude of 1 mile at its best glide ratio. This remarkable feat is possible at a relatively slow forward speed of 15 meters per second with tip slots open.

An interesting biophysical constant can be derived from the velocity polar of Fig. 7. If we wish to determine the minimum power required for the bird to maintain level flight, we take the product of the minimum sinking speed of 0.62 meters per second and the weight of the bird. This yields the rate of loss of potential energy which must be compensated by muscle power for the black buzzard in level flapping flight. The minimum power required to maintain level flight is 0.019 horsepower. For this bird, which weighs 2.3 kilograms, this results in a power loading of 122 kilograms per horsepower. A rough value for the capability of muscles to put out continuous power is 1 horsepower for 50 kilograms of muscle.

The value of 122 kilograms per horsepower then implies that flight muscles must constitute 42 percent of the bird's weight. If, then, flapping muscles do not constitute at least 42 percent of the black buzzard's weight, we can conclude that this buzzard could not maintain continuous level flight without help either from upcurrents or from dynamic soaring, in which energy is extracted from the fluctuations in the wind.

In order to compare the afore-mentioned free-flight method for determining the aerodynamics of a bird in gliding flight with wind-tunnel measurements, the data of Fig. 7 have been transformed into a linearized drag polar (Fig. 8). In this illustration are shown the drag polars of the black buzzard in the two modes of gliding flight and wind-tunnel data for the laughing gull, the cheel (pariah kite), and the Alsatian swift. The same conclusion that was drawn from the single laughing gull measurement is borne out by the complete polars of the black buzzard—namely, wind-tunnel measurements of models of birds cannot yield valid information concerning the aerodynamic properties of birds in natural flight. For this reason, progress in understanding the more difficult phases of flapping flight will only be possible when theory can be supported by flight measurements made under natural conditions. In general, the measurements made in wind tunnels tend to ascribe to the bird much higher energy losses than it actually experiences. For this reason, any biophysical conclusions would lead to absurdities if they are based on wind-tunnel measurements made on model or stuffed birds.

However, the comparison-flight method is subject to some criticism at the present state of the art. Since the measurements with wild birds had to be made in the middle of the day when birds were soaring—that is, in a turbulent environment—one cannot absolutely say that the black buzzard possessed the very low drag coefficient which was measured. We say that either it possesses this low drag coefficient or else it must be utilizing a source of energy which the sailplane was not. The only possible means of extracting such energy from the environment lies in dynamic soaring. However, we do have rather positive evidence that the lowest measured drag values are valid for the high speed points on the speed polars of Fig. 7, since they were obtained near sunset when the air was quite smooth, during a glide to roost of a black buzzard.

Nevertheless, there cannot but be some doubt about the validity of data taken in turbulent air. For this reason, making a measurement during the early hours of the morning when the air is very still suggests itself. For this test, several wild captured buzzards would be carried aloft in a two-seater sailplane. On tow, behind the same towplane, would be the measuring sail-

Fig. 6. Sailplane for research on bird flight.

plane, of light, maneuverable design, fitted with radio communication equipment. After the two sailplanes reach an altitude of 1500 meters, they will be released from the towplane, which will descend to the airport. The bird-carrying two-seater will move ahead of the measuring sail plane, headed toward the airport where the birds have been cooped. On a signal from the measuring sailplane, the bird handler will release a bird from the two-seater by dropping it out in an open-ended bag, to which is attached a line. At the end of the line, the bird will fall out of the bag, head first, and will start gliding toward its coop. Whether every bird will cooperate in this manner is yet to be determined. However, if the birds merely glide in any direction, useful data can be obtained, for the measuring sailplane is capable of landing in any small field and can be disassembled for return to its base by trailer (*6a*).

During the glide of the bird, the measuring sailplane will record data in the manner ascribed for the comparison-flight method.

The precision of this method should be much greater, for, in this case, both the bird and the sailplane will be flying in smooth air, that in which the sailplane has been calibrated.

The results of these measurements in still air should either confirm the measurements given in Fig. 7 or perhaps, under certain flight conditions, especially at the lower speeds with the bird's slotted wing-tips open, reveal a disparity. If the difference is significant and if the sinking speed measurements made in turbulent air are lower than those made in still air, then we must look to the mechanism of dynamic soaring for an explanation. As a matter of fact, the investigation of the nature of this energy extraction will yield valuable information on the little-known science of dynamic soaring, of which some aspects are discussed below.

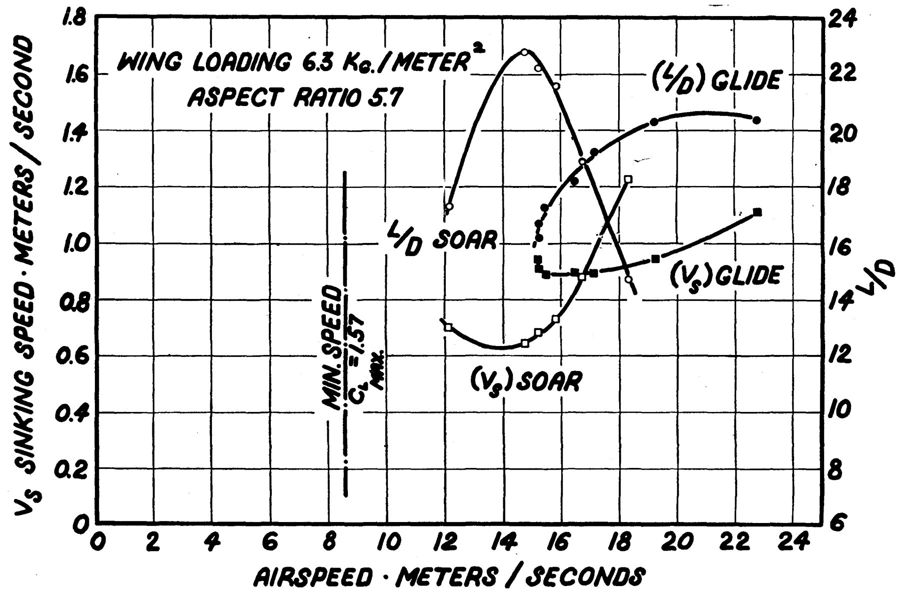


Fig. 7. Velocity polar and glide ratio of a black buzzard.

Bird and Airplane

Up to now, all of our comparisons of bird aerodynamics have been "within the family." The question naturally arises, "How good is the bird compared with modern aircraft?" Obviously, trying to compare a bird cruising at 30 to 60 miles per hour with a supersonic airplane would be absurd. Even if we compare the bird with some of our subsonic airplanes, we still have the problem of scale and speed differences. Fortunately, we can rely on the well-known Reynolds number as a means for eliminating the objection that we are comparing vehicles in different domains of the viscous-flow regime.

In Fig. 9, the drag polar of the black buzzard in its two modes, gliding and soaring, has been transformed into a plot of average skin-friction drag coefficient versus Reynolds number. On the same plot are shown the Blasius curve for pure laminar flow over a flat plate and the von Karman curve for turbulent flow over a flat plate. These two curves provide us a standard over the rather large scale and speed domain covered, from birds to large airplanes.

It should be mentioned that the data for the airplane shown were also obtained in gliding flight, with propellers feathered after the plane had climbed to altitude on its engines. When we ~~look~~ at Fig. 9 we find that the black buzzard's skin friction coefficient is only 30 percent higher than that of the laminar plate, whereas our best man-made flying machine, a sailplane, possesses a skin friction coefficient 330 percent higher than the laminar flat plate flow. And our best-measured air-

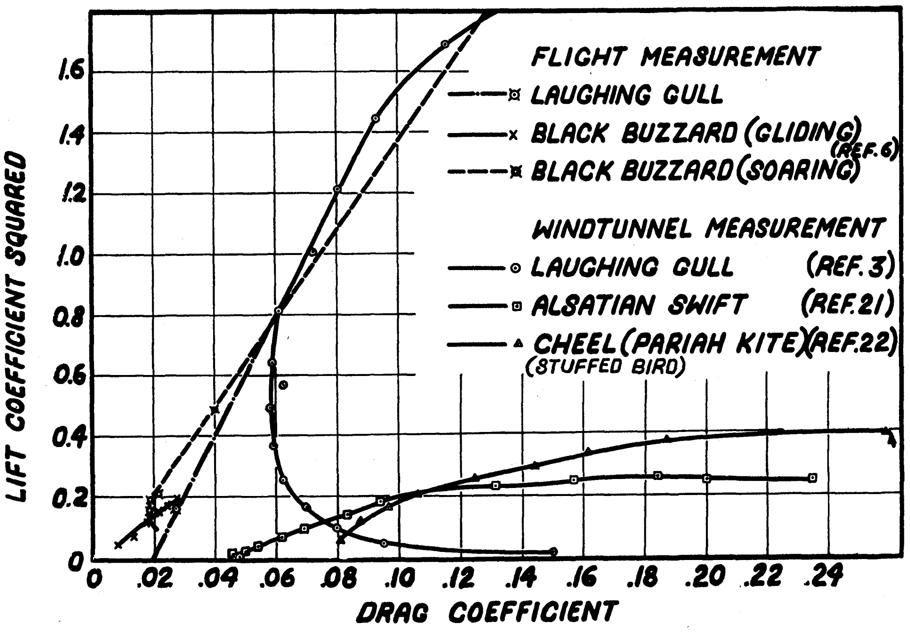


Fig. 8. Linearized drag polar of the black buzzard, laughing gull, Alsatian swift, and cheel.

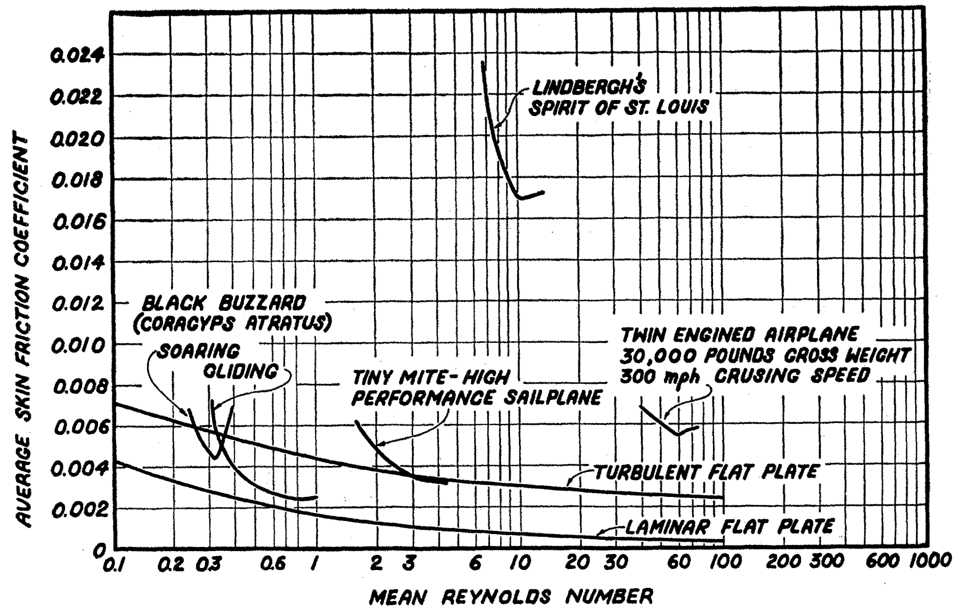


Fig. 9. Skin friction curves plotted against mean Reynolds number for the black buzzard, a high-performance sailplane, and a high-performance twin-engined airplane.

plane has the poorest showing, having 29 times greater skin friction than the laminar flat plate.

From this curve we can conclude that the many generations of selective breeding have resulted in a flying machine, the bird, which still gives man a goal toward which to strive.

Furthermore, the fact that the high-speed end of the curve of skin friction for the bird came from data points taken in calm air gives some validity to a speculation that the bird must, through the porosity of its feathers, exercise some type of boundary layer control—that is, that there must be some automatic fluid mechanical process in the bird's make-up by which a good portion of the flow over the bird's surface is kept laminar. The difference in porosity measured by Victor Lougheed may be the key to this process.

In fact, on the basis of this speculation, I was inspired to attempt to duplicate the boundary layer control which I suspected the birds were achieving. By making many small holes in a section of a sailplane wing and sucking the boundary layer air into the wing with a fan, I was able to measure drag reductions of the order of 50 percent when even the power required for the suction fan was considered to be a loss (*7*). Later on, it was also discovered on this sailplane that this same suction could increase the lifting power of the wing. We may thus further speculate that the bird may be utilizing boundary layer control, both for high lift and for low drag.

Recently, a very fascinating discovery was reported by Kramer (*8*)—that there exists an automatic boundary layer control in the skin of the porpoise. Examination of the skin of the porpoise disclosed that the porpoise is completely covered with a hydraulic skin 1/16 inch thick that is elastic and ducted. Kramer was able to duplicate this natural boundary layer control device by selecting a rubber skin of suitable stiffness and by introducing a damping fluid behind the skin. The stiffness was controlled by small rubber stubs. Between the stubs was the damping fluid.

But it is conceivable that nature has solved this problem for birds in a manner that is not analogous to the solution for the porpoise.

The problem of trimming an aircraft for various speeds is particularly vexing on flying-wing aircraft. Since all birds are essentially flying-wing aircraft, it is possible that we can learn a trick or two from the way birds apply trimming moments for various flight conditions. We know that the bird's wing is in general fairly highly cambered. Therefore, we can expect large pitching moments. In order to achieve stable flight, these pitching moments must be balanced by aerodynamic moments developed by the tail of a conventional airplane or by twisting and deflected elevators at the wing tips on a swept flying wing.

Let us look at a comparison of a flying-wing sailplane and the black buzzard (Fig. 10). Instead of plotting C_L^2 versus C_D, as we did before for the linearized polar, we have plotted C_L^2/AR versus C_D, which is in actuality a plot of the theoretical induced-drag coefficient versus total-drag coefficient C_D. The purpose in doing this was to be able to derive some information on the induced drag from aircraft of widely different aspect ratios—namely, 5.7 for the bird and 21.8 for the sailplane.

It is immediately apparent that the slope of the curve for the buzzard is much steeper than that for the sailplane. This means that if the two had the same aspect ratio, the bird would outperform the sailplane, especially at

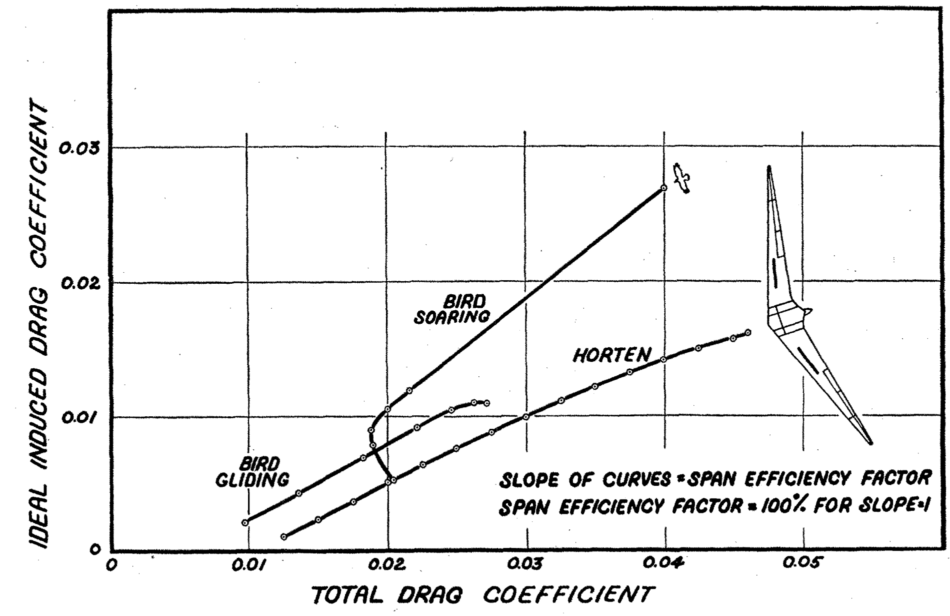


Fig. 10. Comparison of span efficiency factors of the black buzzard and the Horten IV tailless sailplane.

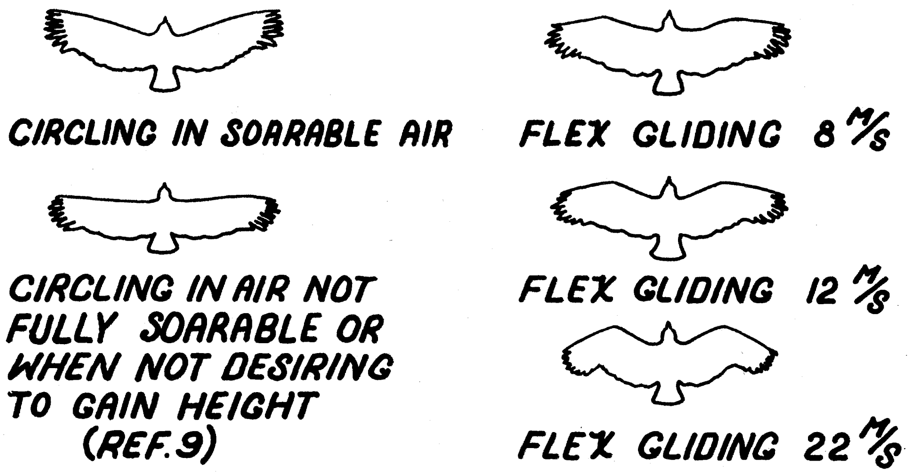


Fig. 11. Wing configurations at various flying speeds for *Otogyps calvus*.

the high lift coefficients used in soaring. In studying the reason for the high induced drag of the Horten IV flying-wing sailplane, we found that the elevators at the trailing edge of the wing caused a severe induced drag, due to the change in the spanwise lift distribution necessary for trimming the sailplane at high angles of attack.

The question is, then, "How does the bird accomplish this trimming without suffering the resultant induced drag rise?" Figure 11, taken from Hankin (*9*), shows the plan form of a buzzard (*Otogyps calvus*) in various flight modes. At low speeds, the wings are swept forward. In other words, the center of pressure of the wing is moved forward of the center of gravity of the bird. As a result, an upward pitching moment is developed which counterbalances the nose down-pitching moment of the highly cambered wing.

Whether the trimming by means of forward and backward sweep results in a stable configuration in pitch cannot be determined without a knowledge of the camber and the angle of attack distribution of the bird's wing. However, the bird is capable of correcting for instability by means of intuitive sensing and associated reflexes.

The process of trimming to different speeds is clearly seen from Fig. 11. At very high speeds, the tips are swept back by bending the elbow of the wing. This tends to move the center of pressure of the wing farther back, a nose down-pitching moment and trimming for higher speeds thus being achieved.

The foregoing explanation of the control of a bird in pitch is admittedly sketchy. It would, however, be entirely possible to carry out experiments on the control and stability of a bird which had been trained to fly in a tunnel that could be inclined with the horizon so as to force the bird to fly at different glide ratios and speeds. By adding weight to the bird ahead of, or behind, its center of gravity, it would be possible to introduce pitching moments for which the bird would have to compensate with sweep of the wings.

Soaring

So far we have discussed only the aerodynamics of the bird in gliding flight and the bird's stability. Now we will consider the process of gaining energy from the atmosphere—namely, soaring. Static soaring is accomplished by flying in an upward-moving air mass having a higher vertical velocity than the bird's minimum sinking speed. By staying within the confines of such upcurrents, the bird will gain altitude.

One common cause of upcurrents is orographic lifting as the wind passes over a ridge. Birds are capable of soaring on declivities of very small dimensions. However, they also soar on mountain sides, the best example being the soaring of hawks on Hawk Mountain in Pennsylvania.

With a sailplane fitted with a sensitive instrument measuring the rate of climb, a pilot is able to duplicate the bird's feat of soaring on a ridge. In fact, often a sailplane pilot merely needs to follow the bird in order to find the best lift.

Just how the bird measures the vertical velocity and just how it determines which way to turn in order to stay in the upcurrent are questions which we cannot presently answer.

Another source of energy for soaring is that provided by thermal upcurrents. These exist both in hilly and in flat country. A very thorough exposition of the nature of birds soaring on thermal upcurrents is given by Huffaker (*10*). Not only did Huffaker in 1897 clearly describe the bird's thermal soaring but he also indicated that there is good reason to believe that birds have some means for detecting thermal upcurrents at a distance, for they often head directly for a given area and be-

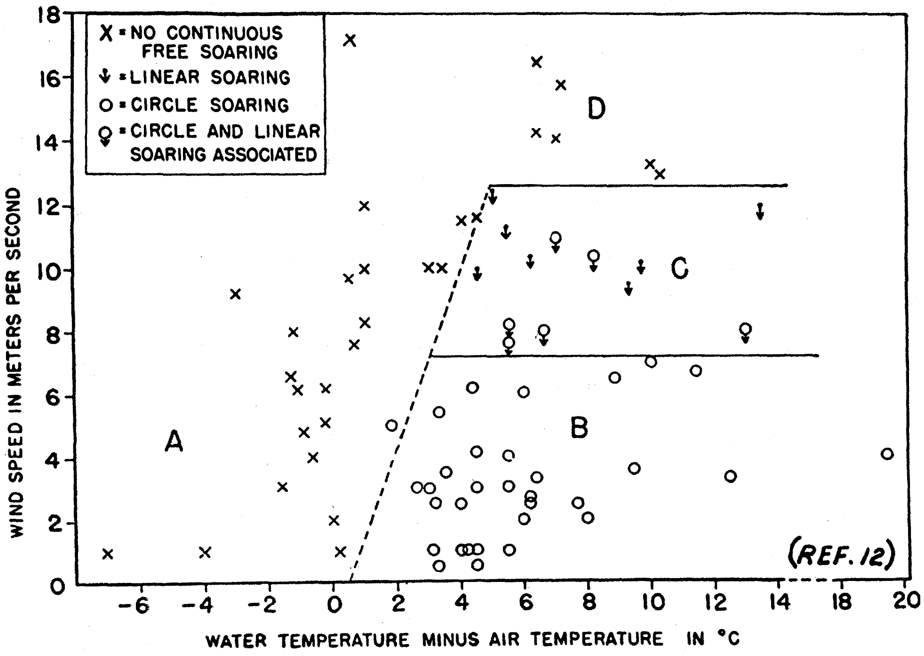


Fig. 12. Modes of soaring of herring gulls, based on temperature increment and wing speed.

gin circling. They inevitably gain altitude.

Some years ago I speculated that the bird must measure in some way the temperature gradient in the horizontal plane and that from this gradient it is able to determine the direction toward the warm upcurrent core. An attempt to do this in a sailplane merely proved that we know too little about the nature of thermal upcurrents to be able to devise instruments for prospecting for the thermal upcurrents (*11*).

Another form of upcurrent, still a thermal upcurrent but over water instead of land, was beautifully studied by Woodcock (*12*), using herring gulls as his indicators of the nature of the upcurrent. In Fig. 12 is shown a plot taken from Woodcock's paper, which delineates the type of thermal upcurrent, a columnar or cylindrical vortex with axis horizontal. This research is a clear example of the careful observation and analysis which should be applied to more of the problems of bird flight.

The third source of energy for soaring is that which Lord Rayleigh described as flight through air which possesses velocity fluctuations. On the basis of this thesis, S. P. Langley (*13*) made a study of the energy available in the wind. However, the actual mechanism of dynamic soaring was not clearly disclosed until Klemperer (*14*) published his paper. Reduced to its simplest form, dynamic soaring is merely correcting for the turbulence in the air mass in such a way that potential energy is gained. Klemperer's contribution points a clear path toward the duplication of this process by man. So far, only certain birds are known to utilize dynamic soaring—in particular, the albatross.

The strict condition to be fulfilled, as Klemperer points out, is that the sailplane or bird must be immobile against pitching under the influence of gusts. Under this condition, an upwardly direct gust results in increasing the angle of attack, thereby lifting the bird or sailplane. A gust having a horizontal component of velocity will result in an increase in effective air speed, thereby increasing the lift. In practice, this process might be accomplished on a sailplane by using modern gyroscopes and servo controls.

A simple model of an analogy for dynamic soaring is shown in Fig. 13. By oscillating the model along its axis with a higher acceleration in the forward direction than in the reverse, the marble is made to climb to the last stage of the model. Interestingly, Bazin (*15*) and Lanchester (*16*) invented this analogy independently.

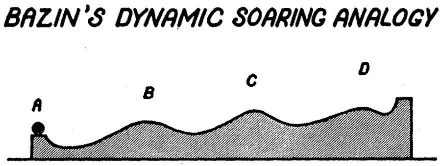


Fig. 13. Bazin's dynamic soaring analogy.

Idrac (*17*) in his carefully documented study of the soaring flight of birds, described a second type of dynamic soaring practiced by the albatross. This bird flies an elliptic path, one vortex of which is in an area of high-velocity flow and the other near the water's surface, in wind of relatively low velocity. In other words, this bird utilizes the energy in the boundary layer of the earth.

The last phase of soaring has yet to be accomplished by man, although many have tried it. The Russians have recently (1956) flown a sailplane with elastically supported flapping wings capable of being "tuned" to the turbulence. No significant gains were reported, nor was any demonstration made to indicate such gains. Perhaps we need to study the dynamic soaring of birds in more detail before we can hope to succeed.

The last and least understood phase of bird flight is that of flapping. Aerodynamic theories for unsteady lifting of wings have been developed, but still there is much to be learned from the complex flapping motion of flexible wings, having slots which can open or close in various phases of the flapping motion.

In so far as the actual motions of flapping flight are concerned, by far the best description is contained in the documentary work of Marey (*18*), who used a time-lapse photographic technique to define the flapping motion of the wings of birds. His three-dimensional models showing the flapping sequence are works of art. However, his studies, while of historic interest, contribute little to an exact understanding of the physical mechanism of bird propulsion by flapping.

Of the more recent works in the field of flapping flight, there is the work of Küchemann and Weber (*19*). In a chapter of their book entitled "Aerodynamic propulsion in nature," the authors make a clear comparison of the oscillating wing and the propeller.

At the very low speeds of landing and take-off of birds, the propulsive efficiency of a propeller would be rather low. However, if the entire wing span is used to accelerate a large mass of air above it, thereby achieving a change in momentum with a relatively small velocity increment applied to the large mass, the efficiency remains quite high. In fact, if the flapping wing as a propulsor could be designed for airplanes which are to take off and land in short distances, it would provide a very important contribution in its high propulsive efficiency at low speeds.

The actual power required for flapping flight and the propulsive efficiency of the bird have not yet been measured. This is a challenging problem, but one fraught with experimental difficulties. However, with modern miniaturized instruments and telemetering, it should be possible to gain some insight into this problem.

From the zoological side, there has been a very thorough study made of the musculature of buzzards by Fisher (*20*). However, the question of determining which muscle plays a part in delivering power to the wing has not been satisfactorily answered. If it were, we would be able to determine the power output which these muscles can provide for flapping flight.

From the standpoint of the biophysics of bird flight, we probably can sum up the state of our present knowledge by saying that we know very little. A few measurements have been made which were quite revealing when the bird was compared to man's creation, the airplane. However, there are still many facets which challenge both the experimentalist and the theorist in this field of natural flight. It is my hope that some of these challenges will be accepted by biologists, physicists, engineers, and mathematicians.

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How Did Life Begin?

Recent experiments suggest an integrated origin of anabolism, protein, and cell boundaries.

Sidney W. Fox

The scientific question of the mechanism of life's beginning is a more sophisticated version of the personal question, "Where did I come from?" This question, appropriately phrased, is one which man generally has long asked himself and which man individually asks from his early childhood. If we accept the proposition that the impetus of the scientist is truly curiosity, virtually all thinking men are to a point scientists because of their special curiosity about this problem.

One consequence of such widespread concern is the large amount of writing on the origin of life. The total number who have done little or no experimentation but have conjectured in print about this problem is remarkably large. The number who are currently active in putting ideas to experimental test is, however, remarkably small. Despite this emphasis, there are many whose thoughtful analyses should be credited with providing stimulating ideas and an increasingly favorable intellectual climate. Especially pertinent are printed speculations of Oparin (*1*), Bernal (*2*), Urey (*3*), Rubey (*4*), and Wald (*5*). Inasmuch as the experiments in our laboratory are treated here in some detail, I am pleased to acknowledge also careful and devoted collaboration, especially that of Kaoru Harada.

The first international symposium on the origin of life was held in Moscow in 1957 under the auspices of the International Union of Biochemistry (*6*). The subject matter was at that time divided into five consecutive stages. A similar division involves (i) synthesis of organic compounds and (ii) synthesis of simple biochemical substances. The majority of the experiments which have been performed fall into these first two stages, which at times are telescoped into one stage. These experiments report production of, principally, amino acids under presumed prebiological conditions. The fact that the production of these biochemically significant organic compounds falls into one or both of the first two stages underlines the outlook that amino acids are rather far from being synonymous with life, a relationship which has not always been recognized.

Stage (iii), having to do with production of large molecules, such as proteins, has received experimental attention for almost as long as have the amino acids, with far fewer results.

It is to be expected that life will ultimately be found to have arisen in stage (iv), which has to do with organized cellular structure, or in stage (v), which concerns evolution of macromolecules and metabolism, or during both. There are in fact reasons to believe that, although it is analytically useful to think of these stages one at a time, the first life involved a simultaneous orchestration of all five.

Production of Amino Acids

Insofar as I am aware, the first bold experiments expressly constructed to provide information on stage (i) in prebiological chemistry were those of Calvin and his associates (*7*). Treatment of carbon dioxide and water in a cyclotron gave significant yields of formaldehyde and formic acid. The production of formaldehyde permitted visualization of the formation of carbon-carbon bonds and, therefrom, of a sufficient variety of organic compounds. Calvin's experiments have been criticized on the basis that the prebiological atmosphere contained only a small proportion of carbon dioxide. One answer to this objection is that no more than a small proportion of any material was needed for the germ of life. I see no adequate basis for assuming, as has often been done, that the origin of life is necessarily a general geochemical problem.

An experimental demonstration that especially focused attention upon this field of inquiry was the production of amino acids by electrical discharge in a mixture of methane, hydrogen, ammonia, and water, as reported more than six years ago (*8*). Miller obtained a few natural amino acids, some that are not found or are very rarely found in proteins, many ninhydrin spots not so far reported as identified, and other acids (*9*). Amino acids are of course more significant in our context than are formaldehyde and formic acid, and the experiments leading to production of those organic compounds are especially well known, undoubtedly for this reason.

Looking backward from 1960 we can see that, in fact, a majority of published experiments in this field have dealt with production of amino acids. These results are comprised in more than ten papers describing scores of experimental modes for production of amino acids under conditions that can be designated prebiological (*10*). One of the discernible reasons for the emphasis on amino acids is the fact that these substances are the components of pro-

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