Origin of Bird Flight: A Physics Viewpoint

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The debate over the origin of bird flight dates back over 100 years. Over the last century two opposing viewpoints have emerged. The first claims that flight originated by running along the ground and then leaping and flapping—this is called the "ground-up" theory.[1] The second claims that flight originated from the trees—from jumping out of trees and gliding—and is called the "tree-down" theory.[2] Recently, Long et al. proposed a new theory—"flutter-gliding"—that combines features from both of these previous theories.[3–5] This paper will discuss all three of these theories of the origin of bird flight in terms of Newton's second law of motion and provides a simplified version of a series of articles published by Long et al.[3–5] We believe this material is a wonderful application of Newton's second law of motion that is appropriate for both high school and college introductory physics courses, and leads naturally into a discussion of the physics of gliding, flying, and sprinting.

Let us consider the forces acting on a bird in flight when the wings execute a down stroke; the forces during an upstroke are significantly smaller and will be neglected in this analysis. The force diagrams of a bird traveling with speed V, but at angles ϕ above and below the horizontal, are shown in Fig. 1. The following forces are acting on the bird. The force of gravity $m\mathbf{g}$, where m is the mass of the bird and $\mathbf{g}$ is the free-fall acceleration, is always straight down. The aerodynamic force $\mathbf{R}$ comes directly from Bernoulli's equation where the aerodynamic shape of the bird's cambered wing causes the air on the top of the wing to travel

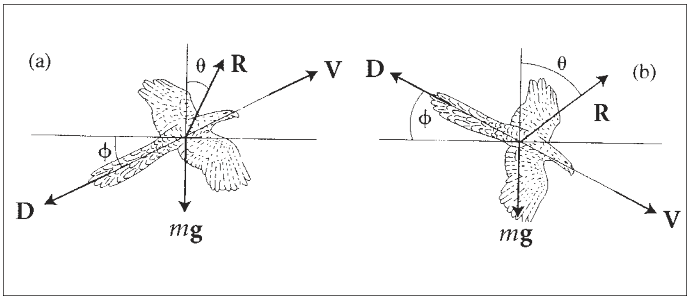

Fig. 1. (a) Force diagram for a proto-bird flying upward with wings on a down stroke after a running jump from the ground. (b) Force diagram for a proto-bird flying downward with wings on a down stroke after leaping from a tree limb. The forces acting on the bird are gravity *m*g, the aerodynamic force R, and drag due to air resistance D.

faster than the air on the bottom of the wing. This force is proportional to the square of the velocity $\mathbf{V}_{rel}$ of the moving wing with respect to the air (which is assumed to be at rest with respect to the Earth). $\mathbf{V}_{rel}$ is the vector sum of the velocity of the bird with respect to the Earth ($\mathbf{V}$) and the velocity of the downward moving wing with respect to the bird's body.[6] The drag force $\mathbf{D}$ is due to the air resistance slowing down the bird. It is always opposite to the direction of $\mathbf{V}$ and is a strong function of both $\mathbf{V}$ and the shape of the bird.

By Newton's second law of motion, the sum of all the y-components of the forces is equal to the mass of the bird times the y-component of the acceleration a_y. Let us first consider Fig. 1(a), where the bird is flying upward after a running jump from the ground. Then

$$R\cos\theta - D\sin\phi - mg = ma_y . \quad (1)$$

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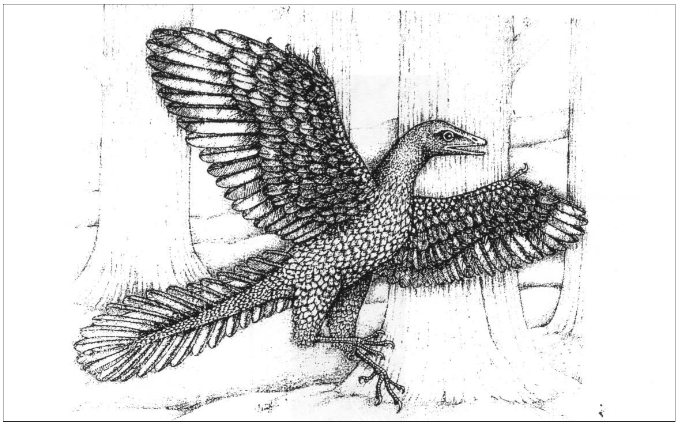

Fig. 2. Artist's sketch of Archaeopteryx. (*courtesy of Patricia J. Wynne*)[9]

The y-component of the acceleration must be greater than zero for the bird to leave the ground, which means that the vertical component of **R** has to be able to overcome both gravity and a component of the drag force. Given that the bird's initial velocity is limited by its terminal running speed (see below) and given that R is proportional to V_{rel}^2, as well as the fact that the underdeveloped wings of a proto-bird are not designed for lift, it's unlikely that a_y will be positive.

By contrast, let us consider Fig. 1(b), where the bird is moving downward after leaping from a tree limb. In the y-direction:

$$R \cos \theta + D \sin \phi - mg = ma_y . \qquad (2)$$

For the tree-down gliding theory, first notice that the drag force is helping the bird to counteract gravity. Second, because the bird is falling it has no trouble gaining velocity, and thus R can make a significant positive contribution. In this scenario, it is very plausible that a_y is close to zero.

There is a potential problem with this gliding theory. By jumping from greater heights, the proto-bird can generate greater velocities, greater R, and thus travel significantly greater distances, but it also increases its chances of fatally crashing into the ground. This danger of crashing is an important negative factor not only for survival of the animal but over long periods of geological time to the evolution of flight.

We now consider the third theory, flutter-gliding, where the proto-bird jumps out of a tree and flaps its poorly developed wings as it glides. Now the vertical component of **R** is increased due to the increase in the air velocity with respect to the moving wing, and the magnitude of **D** is increased due to the disturbance of the air and its flow by the flapping wings.[6] Both of these contribute toward a zero or positive a_y and to minimizing the odds of fatally crashing into the ground. The flapping of the wings during flutter-gliding can then easily evolve into muscle-powered flight.

Let us return to the ground-up theory. A similar force analysis as in Fig. 1 can be applied to a bird or human being running on a horizontal surface. A force in the horizontal direction, due to the ground pushing back on the running legs of the animal, and a normal force in the vertical direction, due to the ground, must now be added to **R**, $m\mathbf{g}$, and **D**. The leg force precipitously decreases to almost zero with increasing running speed. In the case of world-class 100-m sprinters, the leg force at the very beginning of the race is about 854 N and after three seconds 27 N.[7] After 3 s, the runner reaches terminal velocity where the 27 N are just sufficient to balance the drag force. The dramatic reduction in leg thrust is due to the fact that almost all the power the leg muscles can generate is used just to rapidly move the runner's legs. The best strategy for the proto-bird is to start flapping its poorly developed wings after it runs and reaches its terminal velocity. At that moment of take-off, the question is whether enough R has been generated so that the bird can overcome gravity in the vertical direction and frictional drag in the horizontal direction. One biological calculation of the bird's maximum leg thrust and striding rate strongly suggests a terminal velocity of about 7 m/s and insufficient R for flight.[3] A different calculation where the proto-bird flaps its wings from the beginning of its run generates a velocity of 8 m/s and sufficient R for flight.[8] For most modern birds, their wings generate sufficient R needed to fly without any running or falling starts.

Finally, it is informative to end this paper with a brief mention of the fossil record. The most relevant fossil to this discussion is Archaeopteryx, which is believed to be the earliest bird fossil found (from the Jurassic period about 150 million years ago).[9] An artist's sketch of Archaeopteryx is shown in Fig. 2. The reader may also want to learn about the recent fossil find (from the Cretaceous Age, 125 million years ago) of a four-winged gliding dinosaur, Microraptor gui. It is believed that this fossil is not a direct descendent of birds but from a nearby extinct branch.[10] Archaeopteryx is about the size of a pigeon and has well-developed feathered wings consistent with flapping. It has clawed fingers, suggesting tree clambering. It has a long tail useful for gliding but a hindrance for running. On the other hand, it has a bipedal stance in support of the ground-up theory and small pectoral muscles in support of the tree-down gliding theory. When combining the physics and biological information, we believe the flutter-glide theory makes the strongest case, but this is still not a settled question in the scientific community.

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