The Simple Science of Flight

From Insects to Jumbo Jets

revised and expanded edition

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1 Wings According to Size

Imagine that you are sitting in a jumbo jet, en route to some exotic destination. Half dozing, you happen to glance at the great wings that are carrying you through the stratosphere at a speed close to that of sound. The sight leads your mind to take wing, and you start sorting through the many forms of flight you have encountered: coots and swans on their long takeoff runs, seagulls floating alongside a ferry, kestrels hovering along a highway, gnats dancing in a forest at sunset. You find yourself wondering how much power a mallard needs for vertical takeoff, and how much fuel a hummingbird consumes. You remember the kites of your youth, and the paper airplane someone fashioned to disrupt a boring class. You recall seeing hang gliders and parawings over bare ski slopes, and ultralights on rural airstrips.

What about the wings on a Boeing 747? They have a surface area of 5,500 square feet, and they can lift 800,000 pounds into the air—a ''carrying capacity'' of 145 pounds per square foot. Is that a lot? A 5 × 7-foot waterbed weighs 2,000 pounds, and the 35 square feet of floor below it must carry 57 pounds per square foot—almost half the loading on the jet's wings. When you stand waiting for a bus, your 150 pounds are supported by shoes that press about 30 square inches (0.2 square foot) against the sidewalk. That amounts to 750 pounds per square foot—5 times the loading on the jet's wings. A woman in high heels achieves 140 pounds per square inch, which is 20,000 pounds per square foot.

From a magazine article you read on a past flight, you recall that a Boeing 747 burns 12,000 liters of kerosene per hour. A hummingbird consumes roughly its own weight in honey each day—about 4 percent of its body weight per hour. How does that compare to the

747? Midway on a long intercontinental flight, the 747 weighs approximately 300 tons (300,000 kilograms, 660,000 pounds). The 12,000 liters of kerosene it burns each hour weigh about 10,000 kilograms (22,000 pounds), because the specific gravity of kerosene is about 0.8 kilogram per liter. This means that a 747 consumes roughly 3 percent of its weight each hour.

A hummingbird, however, is not designed to transport people. Perhaps a better comparison, then, is between the 747 and an automobile. At a speed of 560 miles per hour, the 747 uses 12,000 liters (3,200 U.S. gallons) of fuel per hour—5.7 gallons per mile, or 0.18 mile per gallon. Your car may seem to do a lot better (perhaps 30 miles per gallon, or 0.033 gallon per mile), but the comparison is not fair. The 747 can seat up to 400 people, whereas your car has room for only four. What you should be comparing is fuel consumption per *passenger*-mile. A 747 with 350 people on board consumes 0.016 gallon per passenger-mile, no more than a car with two people in it. With all 400 seats occupied, a 747 consumes 0.014 gallon per passenger-mile. A fully loaded subcompact car consuming 0.025 gallon per mile (40 miles per gallon) manages 0.006 gallon per passenger-mile.

Nine times as fast as an automobile, at comparable fuel costs: no other vehicle can top that kind of performance. But birds perform comparable feats. The British house martin migrates to South Africa each autumn, the American chimney swift winters in Peru, and the Arctic tern flies from pole to pole twice a year. Birds can afford to cover these enormous distances because flying is a relatively economical way to travel far.

Lift, Weight, and Speed

A good way to start when attempting to understand the basics of flight performance is to think of the weight a pair of wings can support. This ‘‘carrying capacity’’ depends on wing size, airspeed, air density, and the angle of the wings with respect to the direction of flight.

Unfortunately, most of us learned in high school that one needs the Bernoulli principle to explain the generation of lift. Your science teacher told you that the upper face of a wing has to have a convex curvature, so that the air over the top has to make a longer journey than that along the bottom of the wing. The airspeed over the top of the wing has to be faster than that below, because the air over the top ‘‘has to rejoin’’ the air along the bottom. An appeal to Bernoulli then ‘‘proves’’ that the air pressure on top is lower than that below. The biologist Steven Vogel, who has written several delightful books on biomechanics, says: ‘‘A century after we figured out how wings work, these polite fictions and misapprehensions still persist.’’ Polite fiction, indeed. It does not explain how stunt planes can fly upside down, it does not explain how the sheet-metal blades of a home ventilator or an agricultural windmill work, it does not explain the lift on the fabric wings of the Wright Flyer, it fails to explain the aerodynamics of paper airplanes and butterfly wings, and so on. If your high school teacher had taken the trouble to do the math, he would have found that the mistaken appeal to Bernoulli does not produce nearly enough lift to keep a bird or an airplane aloft. The principal misapprehension in the conventional explanation is that the air flowing over the top of a wing has to rejoin the air flowing along the bottom when it reaches the trailing edge. In fact, all along the wing the airspeed over the top is higher than that over the bottom. Rejoining is not necessary and does not occur.

We will have to do better. I will use a version of Newton’s Second Law of Motion, not familiar to most high school physics teachers, that is a cornerstone of aerodynamics and hydrodynamics. I also will appeal to Newton’s Third Law, which says that action and reaction are equal and opposite. Applied to wings, these two laws imply that a wing produces an amount of lift that is equal to the downward impulse given to the surrounding air. According to the version of the Second Law that I will use, force equals rate of change of momentum and can be computed as mass flow times speed change.

How much air flows around a wing? The mass flow is proportional to the air density ρ, the wing area S, and the airspeed V. Let's check the dimensions of the product of the three factors ρ, V, and S. The density ρ is measured in kilograms per cubic meter, the wing area S (taken as the planform surface seen from above) in square meters, and the speed V in meters per second. This means that the units for ρVS are kilograms per second, which indeed is a mass flow. For a Boeing 747-400 cruising at 39,000 feet, the mass flow around the wings computes as 42 tons of air per second, or 2,500 tons per minute. By the way, the mass flow into each of a 747-400's jet engines is about 500 pounds per second.

How much downward motion is imparted to the air flowing around a wing? The downward component of the airspeed leaving the wing is proportional to the flight speed (V) and the angle of attack of the wing (α). It is easy to get a feeling for the effect of the angle of attack: just stick your hand out of the window of a car moving at speed. When you keep your hand level you feel only air resistance, but when you turn your wrist your hand wants to move up or down. You are now generating aerodynamic lift. Note also that you start generating more resistance while losing much of the lift when you increase the angle of your hand in the airstream. Airplanes and birds have similar problems: when the angle of attack of their wings reaches about $15°$, the air flow over the top surface is disrupted. Pilots call this ''stall.'' When the airflow is stalled, the lift decreases; it is no longer proportional to the angle of attack. On top of that, the drag increases a lot, causing a plane to drop like a brick.

With the mass flow pinned down as ρVS and with the deflection speed proportional to the product of α and V, the lift on a wing is proportional to $\alpha\rho V^2 S$. Note that the *square* of the airspeed V is involved. When you fly twice as fast with the same wings at the same angle in the air flow, you obtain 4 times as much lift. You'll have to reduce the angle of attack if you merely need to support your weight, or you may decide to make a tight turn. At an altitude of 12 kilometers, where the air density is only one-fourth its sea-level value, you will have to fly twice as fast to sustain your weight.

What about Bernoulli? The conventional explanation is that the air over the top surface has to flow faster than the air below, so that the pressure on the top surface will be lower than that along the bottom surface. That ‘‘logic’’ is inverted. A wing gives the surrounding air a downward deflection. It does so by creating a region of reduced pressure on the top surface (a kind of ‘‘suction’’), which pulls the passing air downward. The partial vacuum over the top surface manifests itself as lift. Yes, the suction over the top accelerates the local airflow, and yes, the pressure difference can be computed with the Bernoulli formula, but the ‘‘polite fictions’’ involved in what you learned in high school lead you astray.

Birds and airplanes can change the angle of attack of their wings to fit the circumstances. They fly nose up, with a high angle of attack, when they have to fly slowly or have to make a sharp turn; they fly nose down when speeding or diving. But everything that flies uses about the same angle of attack in long-distance cruising; 6° is a reasonable average. At higher angles of attack the aerodynamic drag on wings increases rapidly; at smaller angles wings are underutilized.

Since wings have to support the weight of an airplane or a bird against the force of gravity, the lift L must equal the weight W. The lift is proportional to the wing area S and to ρV^2, and so is the weight:

$$W = 0.3\rho V^2 S. \tag{1}$$

(The 0.3 is related to the angle of attack in long-distance flight, for which the average value of 6° has been adopted.)

We must make sure we aren’t violating the rules of physics when we use equation 1. We must give clear and mutually consistent definitions for the units in which ρ, V, and S are expressed. (Clearly the numbers would look different if velocities were given in miles rather than in millimeters per minute.) The best way to ensure consistency is to use the metric system, expressing S in square

Great tit (*Parus major*): $W = 0.2$ N, $S = 0.01$ m^2, $b = 0.23$ m.

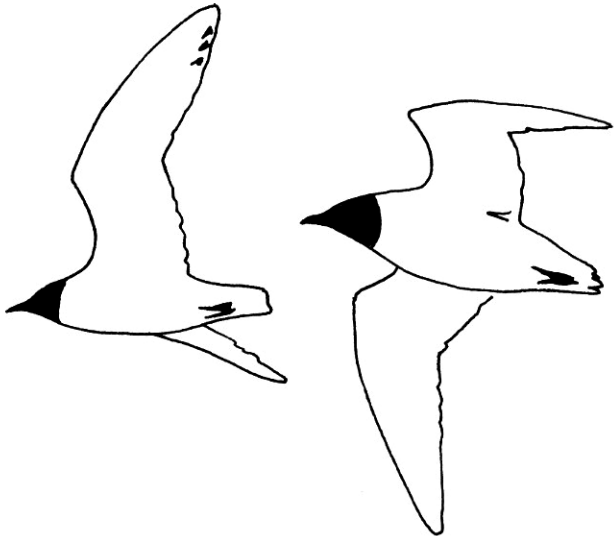
meters, V in meters per second, and ρ in kilograms per cubic meter. The rules of physics then require that the weight W in equation 1 be given in kilogram-meters per second squared. This frequently used unit is known as the *newton*, after Sir Isaac Newton (1642–1727), the founder of classical mechanics. A newton is slightly more than 100 grams (3.6 ounces). A North American robin weighs about 1 newton, a common tern a little bit more, a starling a little bit less. Since there are roughly 10 newtons to a kilogram, a 70-kilogram (154-pound) person weighs about 700 newtons.

The distinction between mass and weight still causes confusion in the public mind. Mass is the amount of matter; weight is the downward force that all matter experiences in Earth's gravity field. One reason for the confusion is that the force of gravity is proportional to the mass of an object and is independent of everything else. None of the other forces in nature have this outrageously simple property. I have chosen to work with the weight of flying objects, not their mass, because all flying has to be done on Earth and is therefore subject to terrestrial gravity. If gravity were absent, wings would not be needed. Classical Italian painters understood this well: their Cupids, being little angels, feature miniature wings, mere adornments. Angels need not worry about gravity.

Sparrow hawk (*Accipiter nisus*): $W = 2.5$ N, $S = 0.08$ m^2, $b = 0.75$ m.

If we respect the rules, we can play with equation 1 in whatever way we want. For example, a Boeing 747-200 has a wing area of 5,500 square feet (511 square meters) and flies at a speed of 560 miles per hour (900 kilometers per hour; 250 meters per second) at an altitude of 12 kilometers (40,000 feet), where the air density is only one-fourth its sea-level value of 1.25 kilogram per cubic meter. Using $\rho = 0.3125$ kilogram per cubic meter, $V = 250$ meters per second, and $S = 511$ square meters, we calculate from equation 1 that W must equal 2,990,000 newtons. Because a newton is about 100 grams, this corresponds to approximately 300,000 kilograms, or 300 tons. That is indeed the weight of a 747 at the midpoint of an intercontinental flight. At takeoff it is considerably heavier (the maximum takeoff weight of a 747-200 is 352 tons), but it burns 10 tons of kerosene per hour.

Equation 1 can be used in several ways. Consider a house sparrow. It weighs about an ounce (0.3 newton), flies close to the ground (so that we can use the sea-level value of ρ, 1.25 kilogram per cubic meter), and has a cruising speed of 10 meters per second (22 miles per hour). We can use equation 1 to find that the sparrow needs a wing area of 0.01 square meter, or 100 square centimeters. That's 20 centimeters from wingtip to wingtip, with an average

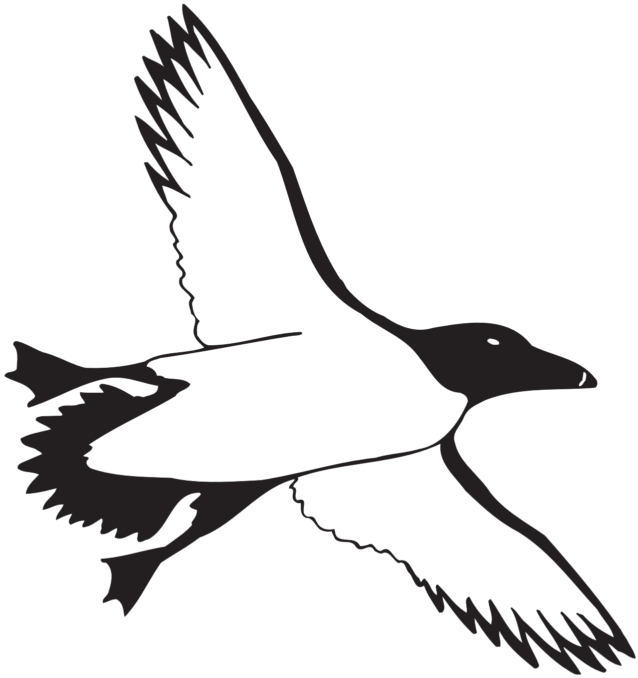


Little gull (*Larus minutus*).

width of 5 centimeters. Or we can use the same equation in designing a hang glider. Taken together, the pilot and the wing weigh about 1,000 newtons (100 kilograms, 220 pounds). So if you want to fly as fast as a sparrow (20 miles per hour), you need wings with a surface area of 33 square meters. On the other hand, if you want to fly at half the speed of a sparrow, your wing area must be more than 100 square meters (more than 1,000 square feet).

Wing Loading

To make equation 1 easier to work with, let us replace the variable ρ (air density) with its sea-level value: 1.25 kilogram per cubic meter. This should not make any difference to most birds, which fly fairly close to the ground. For airplanes and birds flying at higher altitudes, we will have to correct for the density difference or return to equation 1; we can worry about that detail when it becomes necessary. Another improvement in equation 1 is to divide both sides by the wing area S. The net result of these two changes is



Razorbill (*Alca torda*): $W = 8$ N, $S = 0.038$ m^2, $b = 0.68$ m.

$$W/S = 0.38V^2. \quad (2)$$

This formula tells us that the greater a bird's ''wing loading'' W/S, the faster the bird must fly. Within the approximations we are using here, sea-level cruising speed depends on wing loading only. No other quantity is involved. This is the principal advantage of equation 2. But it is a simplification.

The predecessor of the Fokker 50 was the Fokker Friendship, with a weight of 19 tons (190,000 newtons) and a wing area of 70 square meters. Its wing loading was 2,700 newtons per square meter, good for a sea-level cruising speed of 85 meters per second (190 miles per hour). The wing loading of a Boeing 747 is about 7,000 newtons per square meter, and it must fly a lot faster to remain airborne. The wing loading of a sparrow is only 38 newtons per square meter, corresponding to a cruising speed of 10 meters per second (22 miles per hour). From these numbers one gets the impression that wing loading might be related to size. If larger birds have higher wing loadings, it is no coincidence that a Boeing 747 flies much faster than a sparrow.

Our understanding of the laws of nature is due in part to people who have been driven by the urge to investigate such questions. One person in particular deserves to be mentioned: Crawford H. Greenewalt, a chemical engineer who was chairman of the board of DuPont and a longtime associate of the Smithsonian Institution. For many years Greenewalt's chief hobby was collecting data on the weights and wing areas of birds and flying insects. Hummingbirds were his favorites, and he carried out many strobe-light experiments to measure their wing-beat frequencies.

Some of the data collected by Greenewalt and later investigators are listed in table 1. For the sake of clarity, the selection is restricted to seabirds: terns, gulls, skuas, and albatrosses. Looking at table 1, we find that wing loading and cruising speed generally increase as birds become heavier. But the rate at which this happens is not spectacular. A wandering albatross is 74 times as heavy as a common tern, but its wing loading is only 6 times that of its small cousin, and it flies only 2.5 times as fast (equation 2). In terms of weight, the wing loading isn't terribly progressive.

To improve our perception of what is happening, let us plot the weights and wing loadings of table 1 in a proportional or ‘‘double-logarithmic'' diagram, which preserves the relative proportions between numbers. In a proportional diagram a particular ratio (a twofold increase, say) is always represented as the same distance, no matter where the data points are located. Four is 2×2, and 100 is 2×50; in a proportional diagram the distance between 2 and 4 is equal to the distance between 50 and 100. (See figure 1.)

The steeply ascending line in figure 1 suggests that there must be a simple relation between size and wing loading. There are deviations from this line, of course; for example, the fulmar has a rather high wing loading for its weight. But before you look at the exceptions, let me explain the rule.

Table 1 Weight, wing area, wing loading, and airspeeds for various seabirds, with W given in newtons (10 newtons = 1 kilogram, roughly), S in square meters, and V in meters per second and miles per hour. The values of W and S are based on measurements; those for V were calculated from equation 2. In general, larger birds have to fly faster.

				V	
	W	S	W/S	m/sec	mph
Common tern	1.15	0.050	23	7.8	18
Dove prion	1.70	0.046	37	9.9	22
Black-headed gull	2.30	0.075	31	9.0	20
Black skimmer	3.00	0.089	34	9.4	21
Common gull	3.67	0.115	32	9.2	21
Kittiwake	3.90	0.101	39	10.1	23
Royal tern	4.70	0.108	44	10.7	24
Fulmar	8.20	0.124	66	13.2	30
Herring gull	9.40	0.181	52	11.7	26
Great skua	13.5	0.214	63	12.9	29
Great black-billed gull	19.2	0.272	71	13.6	31
Sooty albatross	28.0	0.340	82	14.7	33
Black-browed albatross	38.0	0.360	106	16.7	38
Wandering albatross	87.0	0.620	140	19.2	43

All gulls and their relatives look more or less alike, with long, slender wings, pointed wingtips, and a beautifully streamlined body with a short neck and tail; however, they vary considerably in size. Now compare two types of gull, one having twice the wingspan of the other. If the larger of the two is a scaled-up version of its smaller cousin, its wings are not only twice as long but also twice as wide, making its wing area 4 times as large. The same holds for weight. Because weight goes as length times width times

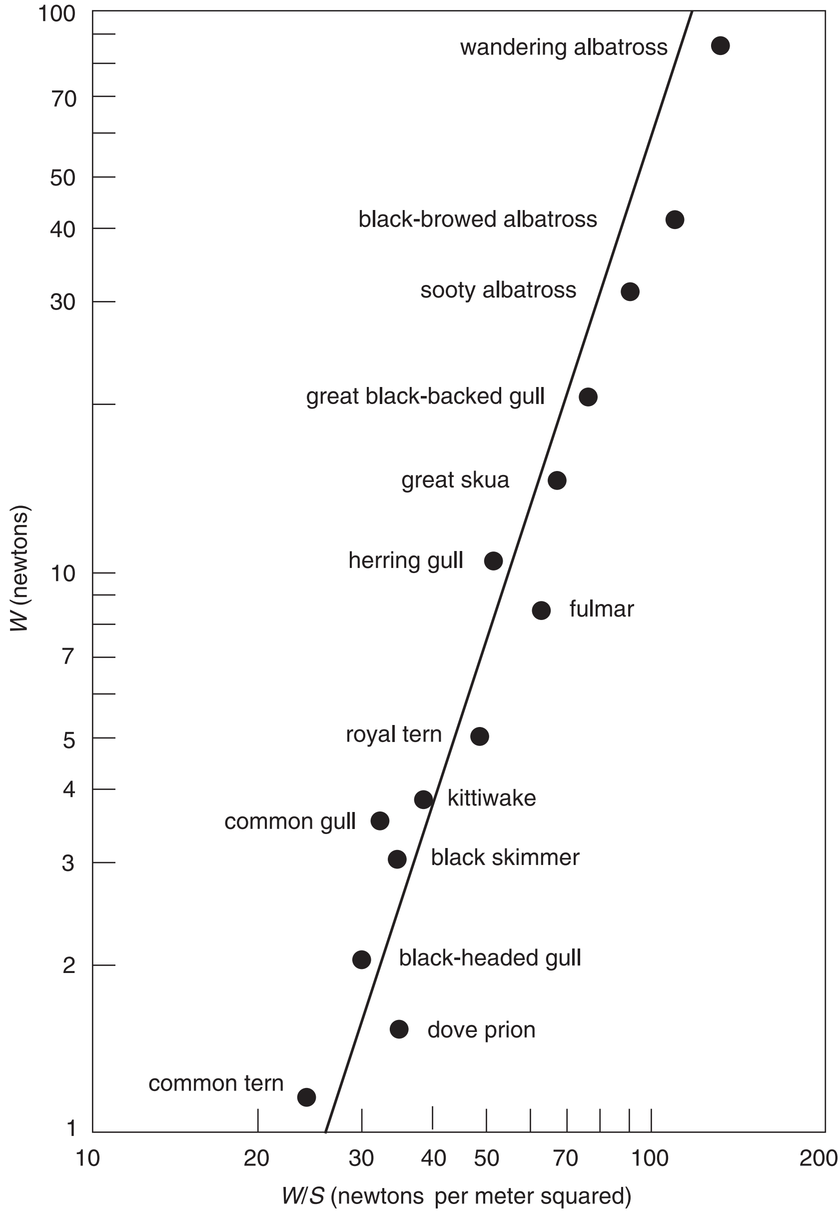
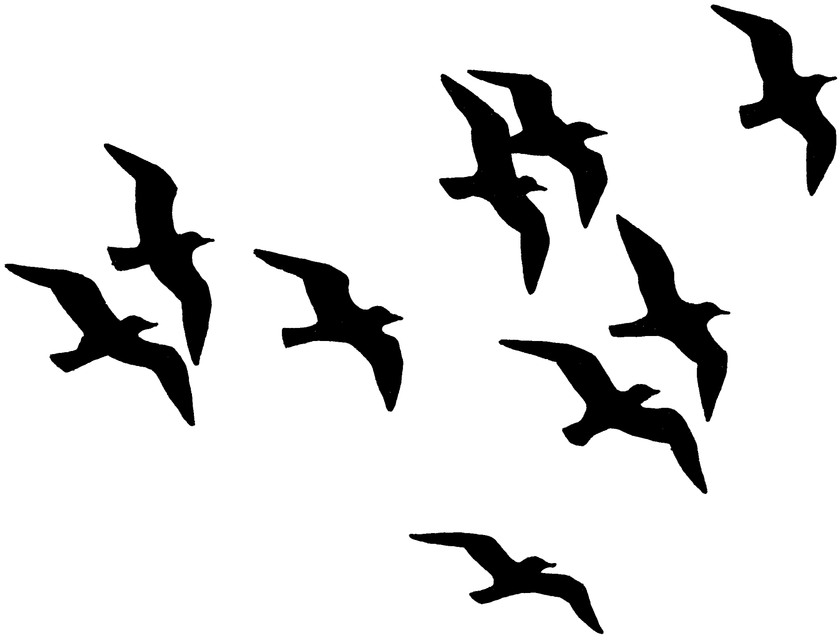


Figure 1 The relation between weight and wing loading represented in a proportional diagram. When the weight increases by a factor of 100, the value of *W/S* increases by a factor of 5 and the airspeed by a factor of more than 2.



Herring gull (*Larus argentatus*): $W = 11.4$ N, $S = 0.2$ m^2, $b = 1.34$ m.

height, the weight of the larger gull is 8 times that of its smaller cousin. Eight times as heavy, with a wing area 4 times as large, a bird with a wingspan twice that of its smaller cousin has twice the wing loading. And according to equation 2 it has to fly 40 percent faster (the square root of 2 is about 1.4). It is useful to write this down in an equation. If the wingspan (the distance from wingtip to wingtip with wings fully outstretched) is called b, the wing area is proportional to b^2 and the weight is proportional to b^3. The wing loading, W/S, then is proportional to b. But b itself is proportional to the cube root of W. In this way we obtain the scale relationship

$$W/S = c \times W^{1/3}. \qquad (3)$$

Strictly speaking, this formula holds only for birds that are "scale models" of one another. The steeply ascending line in figure 1 corresponds to equation 3, the coefficient having been determined empirically. For the seabirds in figure 1, $c = 25$: at a weight of 1 newton, the wing loading is 25 newtons per square meter.

The scale relation (equation 3) is universally applicable whenever weights and supporting surfaces or cross-sectional areas are involved. Galileo Galilei (1564–1642) wrote the first scientific treatise on this subject, asking himself why elephants have such thick legs and similar questions. The answer is that the larger an animal gets, the more crucial the strength of the legs becomes. The stress on leg bones increases as the cube root of weight; for this reason, a land animal much larger than an elephant is not a feasible proposition. This is the same problem that engineers face when they design bridges, skyscrapers, or even stage curtains, which would give way under their own weight were they not reinforced by steel cables. Another good example is that of walking barefoot on a stony beach. Walking on gravel is an uncomfortable experience for adults, but not for little children. A father who is twice as tall and 8 times as heavy as his 8-year-old daughter must support himself on feet whose surface area is only 4 times that of her feet. Thus, his ‘‘foot loading’’ is twice hers. No wonder he seems to be walking on hot coals.

The scale relation given in equation 3 is not a hard-and-fast rule. Most birds are not exact ‘‘scale models’’ of others, and we must also allow some latitude for deviations to fit designers’ visions and nature’s idiosyncrasies. On the other hand, designers are confronted by tough technical problems whenever they deviate too far. The margins permitted by the laws of scaling are finite.

The Great Flight Diagram

Thanks to the dedicated work of Crawford Greenewalt and other enthusiasts, and assisted by the airplane encyclopedia *Jane’s All the World’s Aircraft*, we can now collect everything that flies in a single proportional diagram: figure 2. The results are impressive: 12 times a tenfold increase in weight, 4 times a tenfold increase in wing loading, and 2 times a tenfold increase in cruising speed!

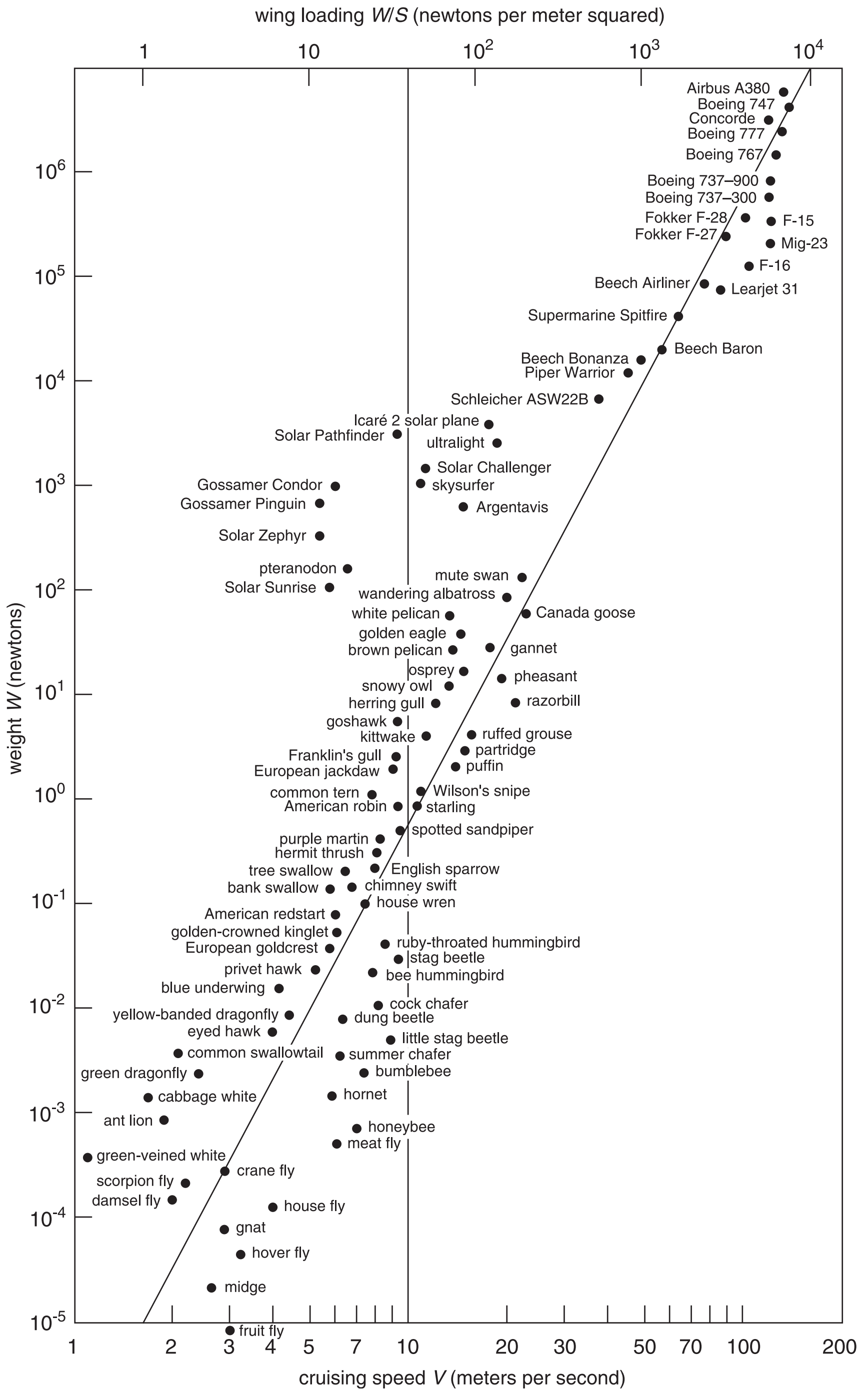


Figure 2 The Great Flight Diagram. The scale for cruising speed (horizontal axis) is based on equation 2. The vertical line represents 10 meters per second (22 miles per hour).

Very few phenomena in nature cover so wide a range; the Hertzsprung-Russell diagram in astronomy is the only other one I am aware of. At the very bottom of the graph we find the common fruit fly, *Drosophila melanogaster*, weighing no more than 7×10^{-6} newton (less than a grain of sugar) and having a wing area of just over 2 square millimeters. At the top is the Boeing 747, weighing 3.5×10^{6} newtons, 500 billion times as much as a fruit fly. The 747's wings, with an area of 511 square meters, are 250 million times as large. Despite these enormous differences, a 747 flies only 200 times as fast as a fruit fly.

Allow yourself time to study figure 2 carefully. It is loaded with information. The ascending diagonal running from bottom left to top right is the scale relation of equation 3. The constant c has been set equal to 47, almost twice as large as the value in figure 1. The vertical line marks a cruising speed of 10 meters per second, corresponding to 22 miles per hour and to force 5 on the Beaufort scale used by sailors and marine meteorologists. Birds that fly slower than this (those to the left of the vertical line) may not be able to return to their nest in a strong wind. (To return home in a headwind, a bird must be able to fly faster than the rate at which the wind sets it back.)

Deviations from the rule can be seen both to the left and to the right of the diagonal representing the scale relation of equation 3. The diagonal acts as a reference, a ''trend line,'' a standard against which individual designs can be evaluated. Let's start with the birds and airplanes that follow the trend—the commonplace types found on or near the diagonal. The starling is a good example. A thrush-size European blackbird, 100 of which were released in 1890 in New York's Central Park, it has become a most successful immigrant (and somewhat of a nuisance, too). With a weight of 0.8 newton (80 grams, a little over 3 ounces) and a wing loading of 40 newtons per square meter, the starling is clearly an ordinary bird and does not have to meet any special performance criteria. But the Boeing 747 also follows the trend. In its weight class the 747 is a perfectly ordinary ''bird,'' with ordinary wings and a middle-of-the-road wing loading. The weight of the 747 is no longer very special, either: today several other planes of similar weight are in service.

Deviations from the trend line may be necessary when special requirements are included in the design specifications. The 747's little brother, the 737, weighs only 50 tons (5×10^5 newtons), one-eight the weight of a 747-400. If the 737 had been designed as a scale model of the 747, its wing loading would have been half that of the larger plane (the cube root of 8 is 2). And according to equation 2 its cruising speed would have been only 71 percent of its big brother's: not 560 miles per hour but only 400. This would have been a real problem in the dense air traffic above Europe and North America, where backups are much easier to avoid if all planes fly at approximately the same speed. To make it almost as fast as the 747, the 737 was given undersize wings. Its wing loading is higher than those of ordinary planes of the same weight class, and it is therefore located to the right of the trend line in figure 2. (With a cruising speed 60 miles per hour less than that of the 747, the 737 would still be a bit of a nuisance in dense traffic were it not consigned to lower flight levels.)

Far left of the diagonal, in the center of figure 2, is *Pteranodon*, the largest of the flying reptiles that lived in the Cretaceous era. Weighing 170 newtons (37 pounds), it was almost twice as heavy as a mute swan or a California condor. It had a wingspan of 23 feet (7 meters) and a wing area of 108 square feet (10 square meters)—comparable to a sailplane. Its wing loading was 17 newtons per square meter, about one-tenth that of a swan but comparable to that of a swallow. *Pteranodon* spent its life soaring above the cliffs along the shoreline, since its flight muscles were not nearly strong enough for continuous flapping flight. Its airspeed was about 7 meters per second (16 miles per hour)—not fast for an airborne animal that must return to its roost in a maritime climate. However, there were no polar ice caps during the Cretaceous era, and there was less of a temperature difference between the equator and the poles than there is today; as a result there was much less wind.

The largest flying animal that ever lived, however, was not a reptile, but a giant bird that roamed the windy slopes of the Andes and the pampas of Argentina 6 million years ago. Looking much like an oversized California condor, *Argentavis magnificens* weighed 700 newtons (150 pounds). With a wing area of 8 square meters and a wingspan of 7 meters, its speed in soaring flight was about 15 meters per second, much the same as that of a golden eagle. It defies the conventional wisdom that birds much heavier than 25 pounds cannot fly. Exceptions to the rule add spice to the work of a scientist.

After centuries of experimentation, humans finally managed to fly under their own power. That required feather-light machines with extremely large wings. The only way to reduce the power requirement to a level that humans could attain was to reduce the airspeed to an absolute minimum. Humans pedaling through the air on gossamer wings are the real mavericks in the Great Flight Diagram (figure 2). They are represented there by Paul McCready's *Gossamer Condor*, the first successful example of the breed. Also shown are a number of solar-powered planes. A severe lack of engine power forces them also to the far left of the trend line. As a mode of transportation they are just as fragile as human-powered planes or extinct flying reptiles. We'll have to wait for much more efficient solar cells before solar-powered flight will succeed in the struggle for survival in this technological niche.

What about the Concorde? Wasn't it supposed to fly at about 1,300 miles per hour? How come it didn't have higher wing loading and therefore smaller wings? The answer is that the Concorde suffered from conflicting design specifications. Small wings suffice at high speeds, but large wings are needed for taking off and landing at speeds comparable to those of other airliners. If it could not match the landing speed of other airliners, the Concorde would have needed special, longer runways. The plane's predicament was that it has to drag oversize wings along when cruising in the stratosphere at twice the speed of sound. It could compensate somewhat for that handicap by flying extremely high, at 58,000 feet. Still, its fuel consumption was outrageous.

Convergence and Divergence

The Great Flight diagram (figure 2) exhibits many curious features. Let me name a few. Sports planes tend to be underpowered, but crawl toward the trend line as the engine power increases. Small birds fly much faster than computed when they are migrating. Insects are either too fast for their size or too slow. Large soaring birds deviate more from the trend line than their smaller cousins. Large airliners tend to have the same wing loading, irrespective of size. Biologists believe that creatures that exhibit better all-around performance have a better chance to survive. They tend to evolve in similar ways, much as insects, birds, and airplanes cluster around the trend line in figure 2. The label given to this idea is *convergence*. In short, evolutionary success is determined by functional superiority. Good designs perform better than alternative ones, so alternative solutions are weeded out. Creatures that venture far from the trend line, human-powered airplanes for example, have little chance of survival in the long run. In fact, human-powered airplanes have become extinct.

In the very beginning of powered flight, airplanes tended to be underpowered. Early aircraft engines weighed many pounds per horsepower. In order to keep the total weight within limits, relatively small engines had to be used. One hundred years ago, the cruising speed of most airplanes was 40 miles per hour at best. The advantage is obvious: those early planes could take off and land on grass strips. Also, crashes were relatively easy to repair. The major disadvantage was that these planes had to be kept on the ground in high winds. The best fighters in World War I were a lot faster: with engines delivering up to 200 horsepower, speeds of 100 miles per hour or more could be obtained. In World War II, Mustangs and Spitfires reached speeds up to 450 miles per hour.

When you decide to install a more powerful engine in your next plane, the total weight will increase because the engine is heavier and the fuel tank bigger. This requires a larger wing. But a larger engine allows you to fly faster, and that permits you to choose a smaller wing. The net result is that the wing area stays about the same as engine power increases. Typical private planes have a wing area of about 20 square meters. When *S* is fixed, the wing loading *W*/*S* does not increase as the third root of *W*; it increases in linear proportion to *W* itself. This is exactly what happens as you move from the Wright Flyer or the Skysurfer to the Beechcraft Baron and the Beechcraft Bonanza in figure 2. A clear case of evolutionary convergence: as aircraft engines improve in terms of horsepower per pound of engine weight, it pays to install a larger engine, which allows a higher cruising speed. The trend line is rejoined at speeds around 60 meters per second (130 miles per hour), a typical plane then weighing about 4,000 pounds. This is just one example of the rapid pace of convergence in technological evolution.

Curiously, the Supermarine Spitfire, the famous British World War II fighter, is right on the trend line in figure 2. Thus, you might think it is rather ordinary. But sometimes appearances are deceiving. With a wing area of 22.5 square meters and a takeoff weight of 40 kilonewtons, a Spitfire's cruising speed computes as 69 meters per second (250 kilometers per hour, 155 miles per hour). What about the reported top speed of 700 kilometers per hour, then? And why was a 1,600-horsepower Rolls-Royce Merlin engine installed? Spitfires were interceptors: they had to climb to 25,000 feet just in time to attack approaching German bombers. That is what the famous 48-valve Merlin engine was for. You can't fly fast and climb fast at the same time. It pays to have a rather low cruising speed, because most of the power then can be used to climb fast. If you plan on modifying a Spitfire for racing, you should give it much smaller wings and forget about a high rate of climb. Taking off from grass strips then also is out of the question.

Why doesn't the Great Flight Diagram (figure 2) include any bats? The diagram is terribly crowded as is. Also, no new information would have been presented. Bats' wing loading is similar to that of birds of the same size. By omission, the case for convergence is made stronger yet: having to live in the same environments, birds and bats have evolved toward comparable aerodynamic design parameters. There are subtle differences, though. The largest swan weighs about 25 pounds, but the largest bat only 5 pounds. This is probably not a matter of muscle power but a consequence of lung design. The lungs of birds have air sacs behind them, so they are ventilated twice during each respiration cycle and can pick up much more oxygen than the lungs of mammals, which don't have those lung extensions. I wonder why evolution hasn't solved this discrepancy. Is the cause of the handicap that mammals appeared on the scene so much later than birds?

Sometimes a limited amount of divergence from the trend line is unavoidable. Vultures and eagles prefer to soar in ''thermals'' (ascending pockets of hot air) and need a rate of descent less than 1 meter per second in still air. Since these large birds can glide 15 meters for every meter of altitude lost, they should not fly faster than 15 meters per second (33 miles per hour). The wing loading of large soaring birds therefore is fixed at about 80 newtons per square meter. The extinct giant Andes condor *Argentavis magnificens* is no exception. As they grow bigger, the large soaring birds diverge further from the trend line in figure 2. Their lifestyle requires much less muscle power than those of geese and swans, so their flight muscles are relatively small. Continuous flapping is out of the question; they have wait until sufficiently strong thermals develop in the course of the day. It shouldn't surprise you that smaller species start their soaring days earlier than larger ones. Neither should it surprise you that a flock of soaring birds sends scouts aloft in the morning in order to find out whether the updrafts have become strong enough.

Large birds that cannot soar but have to flap their wings have problems of their own. As far as wing loading and flight speed are concerned, swans, geese, and ducks follow the trend line faithfully. But they don't grow much heavier than about 25 pounds. So where's the rub? The muscle power available to flapping birds is about 20 watts per kilogram of body weight. Muscle power is proportional to weight, but the power required to maintain horizontal flight is proportional to the product of weight and flight speed. Bigger birds have to fly faster, so their power reserve decreases as their weight grows larger. The largest species of swans have very little power to spare. According to Swedish researchers, they can gain altitude no faster than 50 feet per minute. I can confirm this number from personal experience. One autumn many years ago, a flock of mute swans landed in a meadow behind my house. After resting for a day and filling their stomachs, they took off. The meadow, however, was surrounded by brushwood and trees on all sides. The leader of the flock realized that he couldn't clear those obstacles head-on and decided instead to fly a large circle, exploiting the width of the meadow. Slowly the flock gained height. After a circle and a half, they cleared the brush on the southwest corner of the field.

From swans and eagles to insects: a large step down in weight, but similar characteristics of convergence and divergence. Big birds either soar slowly with oversized wings or follow the trend line by working hard and flying fast. Among insects, the slow ones, butterflies and the like, follow the trend line rather faithfully, but shifted a bit to the left. Many butterflies are capable of gliding and soaring, and use these styles of flight to conserve energy. If they can take advantage of strong tailwinds, migrating monarch butterflies cross the Gulf of Mexico directly, instead of following the coast. They have been observed by radar to flock in the updrafts between the ''roll vortices'' in the lower atmosphere that stretch at a slight angle to the wind direction. They float without flapping—a perfect way to cross 500 miles of open sea. I don't know how they find out where the updrafts are, but I do know how human observers do : under appropriate circumstances, ''cloud streets'' form in the air between each pair of roll vortices.

Mosquitoes, bees, and flies fly in an entirely different way. Their buzzing wings act like the rotor blades of helicopters. Their wing size is not determined by their flight speeds but by their flapping frequency. The speeds suggested in figure 2 are therefore not reliable. Bees can go faster when they have to; 10 meters per second is not uncommon. Some biologists argue that bees diverge farther from the trend line the smaller they become. On the other hand,

Storm petrel (*Hydrobates pelagicus*): $W = 0.17$ N, $S = 0.01$ m^2, $b = 0.33$ m.

the very smallest flies, such as *Drosophila melanogaster*, go only 1 meter per second, one-third as fast as figure 2 suggests. Going into the details of the performance of buzzing insects would lead me astray. For very small creatures, air does not obey the aerodynamic principles that are valid for birds and planes. To a fruit fly, for example, flying must feel very much like swimming in syrup. (For those who want to know more, I recommend reading one of the books on insect flight listed in the bibliography. For most readers, David Alexander's *Nature's Flyers*, though not limited to insects, is by far the best source. And those who insist learning about all the intricate details will have to study Robert Dudley's book *Biomechanics of Insect Flight*.)

In the top right corner of figure 2, another constraint occurs. It is the speed of sound. For good reasons, explained in chapter 6, airliners travel above 30,000 feet, where the speed of sound is 295 meters per second (1,062 kilometers per hour, 664 miles per hour). They have to fly somewhat slower than that, typically 560 miles per hour, in order to avoid making little shock waves that increase airframe drag rapidly as the speed of sound is approached. Curi-

Barn swallow (*Hirunda rustica*): $W = 0.2$ N, $S = 0.013$ m^2, $b = 0.33$ m.

ously, all modern long-distance planes cluster around the original design parameters of the Boeing 747. Convergence in this case is not just toward the trend line but to a quite specific weight class: a small cloud of data points in the top right corner of figure 2. The Airbus A380 is no exception. (Chapter 6 deals with the engineering logic that has led to this curious development. I did explain the logic in the first edition, but I did not see the consequences for the size of future airliners at the time.)

Incidentally, the Boeing 747 is represented in figure 2 as having a wing loading of 7,000 newtons per square meter and a cruising speed of 136 meters per second. But 136 meters per second is 300 miles per hour, roughly half the 747's actual cruising speed. What has gone wrong here? In figure 2 the lower air density at cruising altitudes has been ignored. Since the air density at 39,000 feet is only one-fourth the density at sea level, the high-altitude cruising speed is twice the cruising speed near Earth's surface. Figure 2

Bee hummingbird (*Mellisuga helenae*): $W = 0.02$ N, $S = 0.0007$ m^2, $b = 0.07$ m.

gives the speed at sea level; table 6 (in chapter 6) gives the necessary conversion factors.

Traveling Birds

Several groups of ornithologists have been making radar measurements of actual flight speeds of migrating birds. The Schweizerische Vogelwarte (Swiss Ornithological Institute) published a massive list of radar speed data in 2002, and biologists at the Flight Ecology Department of the University of Lund in Sweden added their own list in 2007. (A selection of these data is presented in the appendix.) Theoreticians have begun to dissect the assumptions underlying the ‘‘aerodynamic theory of bird flight,’’ the theory from which I distilled my way of handling the matter.

Since 1970 or thereabouts, everyone involved with bird flight assumed that the speed at which birds glide best is not too different from the most economical speed in flapping flight. We now know this was an unwarranted simplification. If flapping birds want to conserve energy, they have to fly much faster than when gliding. When birds are in no hurry, like a circling flock of homing pigeons or a great dancing swarm of starlings at sunset, they fly at a speed that requires the least muscle exertion. It turns out that this speed is not too different from the optimum gliding speed. But bird migration is another business altogether. Birds on migration often are in a hurry. Most of them fly faster than the speed that minimizes their ‘‘fuel consumption’’ per hour, near the top speed their muscles allow. The migration speed of small birds may be as much as twice the speed that requires least muscle power. In fact, I have found no numbers below 10 meters per second (22 miles per hour) for any songbird on migration. If you want to amend figure 2, here is your chance. All the data you need are given in the appendix. A typical 10-gram songbird migrates at 10 meters per second, 80-gram starlings and half-pound jackdaws manage 14 meters per second (30 miles per hour), and many wading birds fly 20 meters per second (45 miles per hour) when they are making their seasonal long-distance journeys. If you want to make a sophisticated correction to figure 2, you should choose a curve that makes the flight speed much less dependent on weight instead of the trend suggested in figure 2. That would account for the fact that small birds have lots of power to spare for speeding, while large birds are straining themselves even when flying most economically.

Flapping, Gliding, Soaring, and Landing

What about the various swifts, swallows, and martins in figure 2? They are all found on the left of the trend line. For their weight, they all have rather large wings and fly relatively slowly. There must be something wrong here. Swifts did not get their name for nothing.

In fact, swifts and swallows are fast only when gliding, diving, or fooling around. In level flapping flight, they are not fast at all. Radar data on migrating swifts give speeds around 10 meters per second (22 miles per hour). In wind tunnels, swallows fly no faster than 12 meters per second (27 miles per hour). Their comfortable cruising speeds are lower yet, consistent with the data in figure 2.

Swifts and their relatives can fly very slowly, when they have to, by spreading their wings wide. When they want to fly faster, they

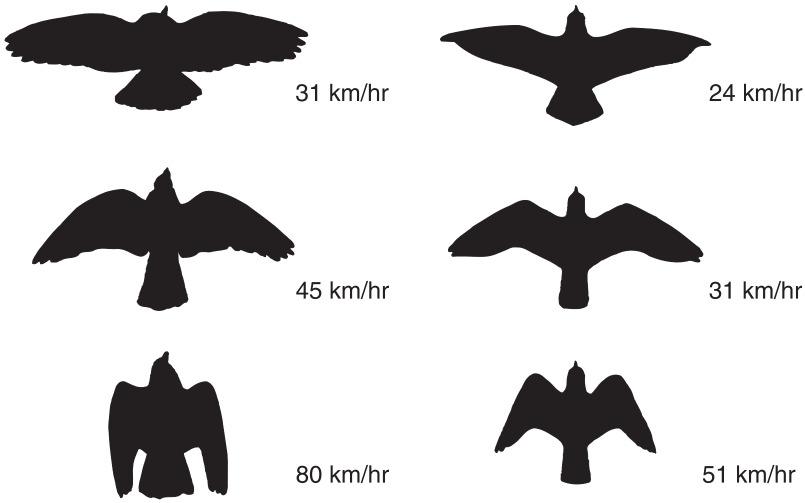


Figure 3 Birds progressively fold their wings as their speed increases. On the left is a pigeon, on the right a falcon. At high speeds, fully spread wings generate unnecessary drag. This can be avoided by reducing the wing area.

can fold their wings. The elegance of their streamlining does not suffer when they reduce their wing area, but the wing loading increases, and with it the cruising speed. Are they poking fun at the laws of nature? According to equation 2, a bird cannot alter its speed at will if it wants to fly economically, once blessed with a particular set of wings. The cruising speed is controlled by the wing loading: $W/S = 0.38V^2$. But if S can be changed to fit the circumstances, this problem vanishes: the cruising speed then changes too. All birds do this to some extent, though not always with the grace and sophistication of swifts and swallows. But gliding, soaring, and maneuvering are altogether different from flapping. In the downstroke of flapping flight, all birds spread their wings fully; however, when gliding, birds can fold their wings at will. Figure 3 shows how gliding falcons and pigeons progressively fold their wings as their speed increases.

When low speeds are needed, all birds make their wing area as large as is possible. The sparrow hawk on final approach (figure 4)

Figure 4 Sparrow hawk (*Accipiter nisus*): $W = 2.5$ N, $S = 0.08$ m^2, $b = 0.75$ m.

is a good example. Since it wants to fly slowly, it spreads its primary quills and tail feathers wide. In fact, many birds deliberately stall their fully stretched wings on final approach, maximizing drag to obtain quick deceleration and not caring about lift during the last seconds of flight. Just for fun, watch pigeons landing on a tree branch or a rooftop, and see how they do it. Airplanes fully extend various slats and flaps in preparation for landing. Airplanes and birds alike minimize their landing speed to reduce the length of runway required or the risk of stumbling.

Swifts' amazing aerial maneuvers are made possible by the superb aerodynamic performance of their sweptback wings. I have seen them dallying in the updrafts in front of the cliffs in southern Portugal, first diving toward the shore and then suddenly shooting up like rockets and disappearing out of sight. In these stunts, flapping would be of no use. With their wings folded far back, swifts have another surprise in store. If they have to make a quick maneuver, they can generate a ''leading-edge vortex'' over their swept-back wings by suddenly increasing their angle of attack. Almost but not quite stalling their wings, they achieve a large momentary increase in lift that way, which allows for very sharp turns. This is how they catch insects in their flight path, and this is how they show off during the sophisticated aerobatics of courtship.

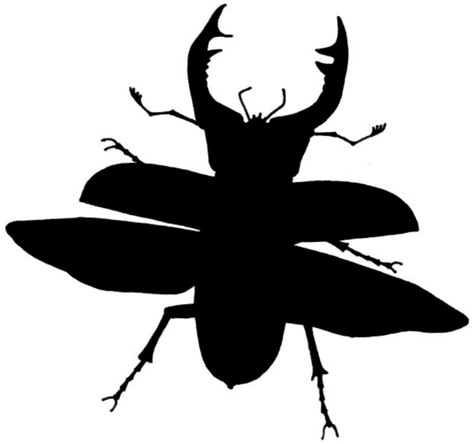
Continuous flapping flight does not support such extreme behavior. Level flapping flight is boxed in by a large number of constraints—kinematic, dynamic, energetic, physiological, and so on. When flapping, wings have to act not only as lift-generating surfaces but also as propellers, a combination never successfully imitated by human technology. Wings act as propellers only in the downstroke. The upstroke is of little use. Many birds fold their wings before they start the upstroke; others drastically reduce the angle of attack before their wings move upward. To keep things simple, I will assume that only the downstroke counts. This means that flapping wings are useless during one half of each wingbeat cycle, and have to produce twice the lift during half the time in order to make sure a bird stays airborne. The immediate consequence is that birds have to endure a roller-coaster ride when flapping at speed. This is obvious when you watch traveling geese fly by overhead. Their heads are kept steady, presumably to make sure that their delicate navigation equipment is not affected, but their bodies are shaking up and down with each wingbeat. Another consequence of the two-stroke cycle of flapping wings is that the angle of attack during the downstroke has to be much larger than when gliding at the same speed. This is fine as far as the flight muscles are concerned, because the airspeed for most economical gliding does not differ much from the speed that requires the least muscle effort when flapping. (Just watch any bird switching from gliding to flapping or vice versa, without change in speed.) But it does pay to choose a higher airspeed in flapping flight, because a bird can also

Cockchafer (*Melolontha vulgaris*): $W = 0.01$ N, $S = 0.0004$ m^2, $b = 0.06$ m.

get twice the lift by flying 40 percent faster (the lift goes as the square of the speed, and the square root of 2 is about 1.4). This option keeps the angle of attack at a value that doesn't compromise the aerodynamic performance of the wings. I know I am not doing justice to the great variety of flapping styles that birds employ, but a useful rule of thumb is that the most economical speed for flapping is 40 percent higher than that for gliding, provided a bird has no shortage of muscle power. Swans and other big birds do not have that option; their speed is limited by their muscle power. This implies that their wings are working at a high angle of attack during the downstroke, an angle that compromises flight efficiency somewhat. The whistling noise made by the flight feathers of mute swans proves that in the downstroke their wings are almost stalling.

Birds and Insects

A curious feature of figure 2 is the continuity between the largest insects and the smallest birds. The largest of the European beetles, the stag beetle *Lucanus cervullus*, weighs 3 grams, about the same as a sugar cube or a fat hazelnut. The smallest bird on Earth, the Cuban bee hummingbird *Mellisuga helenae*, weighs 2 grams. The smallest European bird, the goldcrest, weighs 4 grams. Small bats also weigh about 5 grams, notwithstanding their different flight apparatus. The wing loadings of large insects do not differ much from



Stag beetle (*Lucanus cervus*).

those of small birds, either. This is no minor observation. In theory, conditions may be imagined in which the largest beetle exceeds the smallest bird in size, or a wide gap exists between the largest flying insects and the smallest birds. Such a gap does exist between the largest birds and the smallest airplanes, after all. And there are substantial construction differences, too. The exoskeletons of insects are made up of load-bearing skin panels, while birds (like humans) have endoskeletons, with the load-bearing bones inside the body. Notwithstanding the different construction techniques, the transition from insects to birds is barely perceptible. Apparently, the choice between an exoskeleton and an endoskeleton is a tossup for weights around 3 grams. Just a little heavier and the exoskeleton loses out to the little birds; just a little lighter and the endoskeleton has to make way for the big beetles. What factor determines this switchover? Is it the wing structure, the weight of the skeleton, the geometry of the muscle attachment points, the respiration constraints, or the blood circulation? This would be a wonderful research project for a young aeronautical engineer. Some experience with aircraft construction would give the engineer a head start. Like insects, most airplanes have exoskeletons:

their skins carry most of the structural load. For very small or very large flying objects, an endoskeleton is apparently not a wise choice.

The time has come to look deeper into the energy required for powered flight. Hummingbirds and jetliners consume a few percent of their body weight in fuel per hour. That is a sure sign that energy consumption is a major consideration in flight performance. Most of the time, flying is hard work. When you hear a wren sing its staccato ‘‘tea-kettle, tea-kettle, tea’’ in your backyard, it is not enjoying an idle moment; it is trying to keep competitors off its territory without having to patrol the perimeter. Flying back and forth would use up too much energy. Birds that have to spend much of the day looking for food find it easier to whistle a tune than to chase intruders. Similarly, birds feeding their nestlings must select their food carefully, choosing between the fattened caterpillars in the woods a quarter-mile away and the starving maggots in the meadow below. If a bird doesn’t take care, it will spend more energy on getting food than it and its young get out of it.