MET 200 Lecture 17
The Simple Science of Flight

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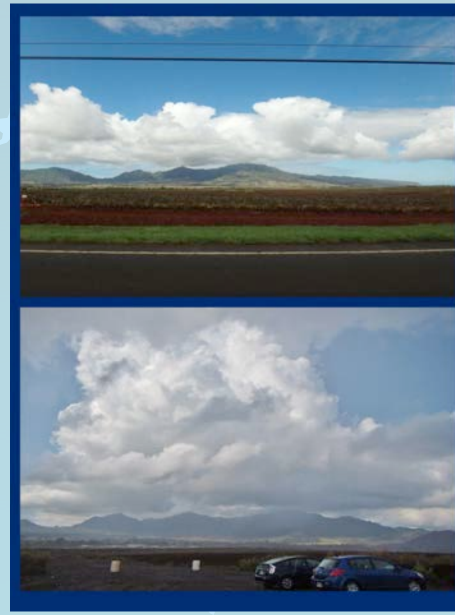
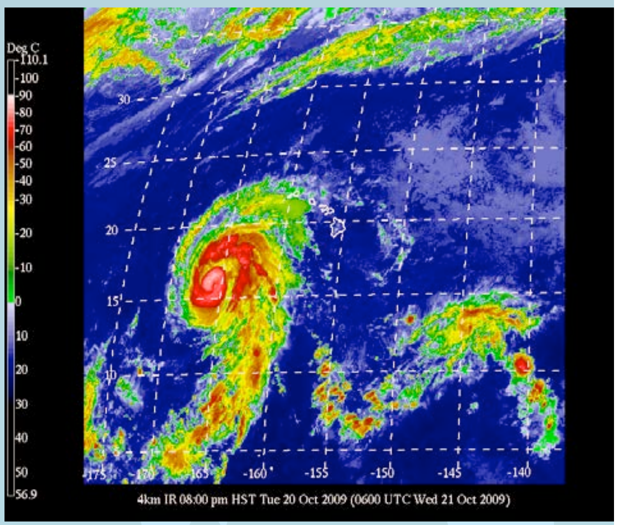


Hurricanes in Hawaii Hazards and Forecasting



Hurricane Neki

- Hurricane's in Hawaii
- Hurricane hazards
- Hurricane forecasting

The Simple Science of Flight

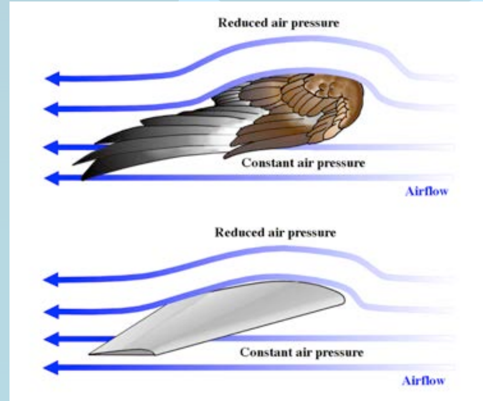
Why do birds fly? I'm not sure, but that's a different lecture.

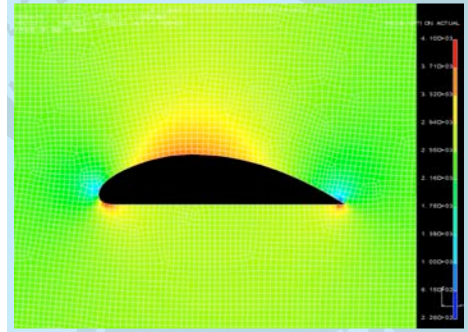
The Simple Science of Flight

Some quick definitions used in this lecture

Velocity – distance per unit time, m/s
Acceleration – change in velocity per change in time, m/s^2
Force – mass times acceleration, Newton, $kg*m/s^2$, 1N = 102 gm
Energy (Work) – force over a distance: Joule, J = Nm = $kg*m^2/s^2$
Power – energy per time, Watt = J/s = Nm/s = force x speed

Bernoulli's Principle and Lift

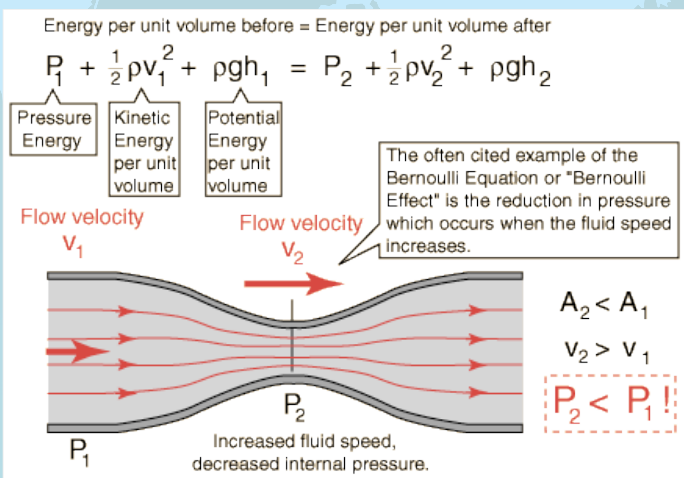




To understand flight, a good place to start is the weight a pair of wings can support. Bernoulli's principle applied to airfoils: the airspeed over the top of the wing has to be faster than that below, because the air over the top "has to rejoin" the air along the bottom, faster air means lower pressure and hence the generation of lift on the wing.

Bernoulli's Principle and Lift

Bernoulli's principle states that, "In a flow where no energy is being added or taken away, the sum of its various energies is a constant: consequently where the velocity increases the pressure decreases and vice versa."



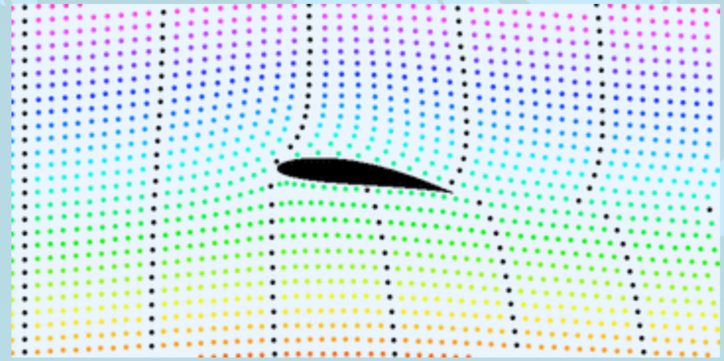
Where are the Airfoils?

Wright Flyer: Kitty Hawk, North Carolina; December 17, 1903

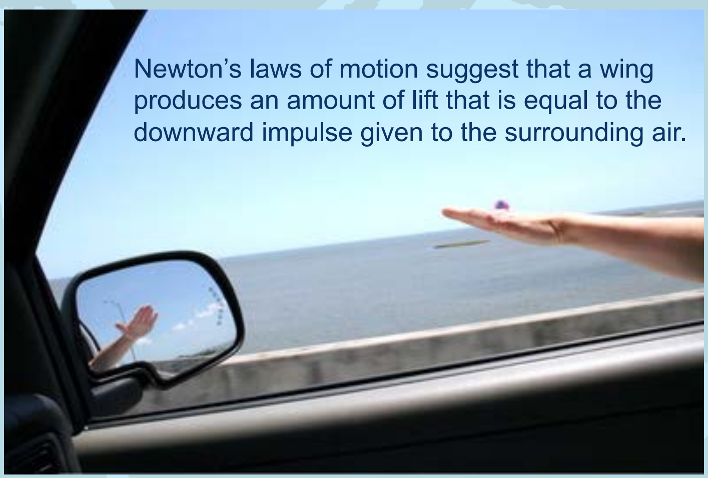
Wait a Minute, What about Bernoulli!

Bernoulli's Principle

Bernoulli's principle evoked to explain flight is a "polite fiction." It does not provide nearly enough lift to keep a bird or an airplane aloft. In fact the air flowing over and under the wing does not rejoin as your high school teacher told you.



Lift



Newton's laws of motion suggest that a wing produces an amount of lift that is equal to the downward impulse given to the surrounding air.

When the angle of attack reaches ~15˚, the airflow over to top surface is disrupted causing the drag to increase a lot and the plane to drop like a brick. Pilots call this "stall."

Taking a Lift

Force (or lift) equals the rate of change of momentum or mass flow past a wing times the change in speed.

Mass flow = ρVA *kg/s*

where ρ = air density, V = air velocity, and A = Area of the wing.

The downward motion imparted to the air flowing around a wing is proportional to the flight speed (V) and the angle of attack of the wing (α). Thus the lift (L) on the wing is given by:

$L = \alpha\rho V^2 A$ *kg m/s² or newtons*

First-Class Lift

$L = \alpha \rho V^2 A$ kg m/s^2 *or newtons*

At 12 km the air density is 1/4 that at sea level, you will have to fly twice as fast to obtain the same lift.

To support horizontal flight, lift = weight (*W*). So we can write:

$$L = W = 0.3\rho V^2 A \text{ newtons,} \qquad (1)$$

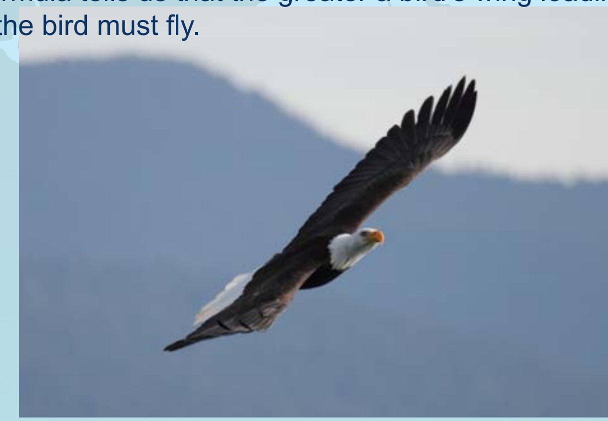
where the constant 0.3 is valid for long distance flight with an average angle of attack of 6˚.

Lift, Weight, and Speed

If we divide both sides of Eq 1 by the wing area *A* and replace the variable density *ρ* by its value at sea level where birds fly, we get:

$$W/A = 0.38V^2$$

This formula tells us that the greater a bird's wing loading, the faster the bird must fly.

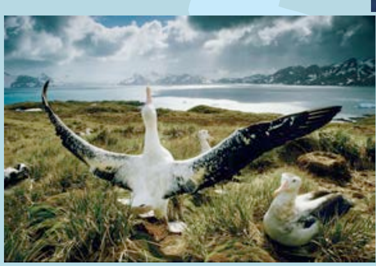


Lift, Weight, and Cruising Speed

Common tern
V = 18 mph

Common gull
V = 21 mph

Herring gull
V = 26 mph



Wandering Albatross V = 43 mph

Laysan Albatross V = 36 mph

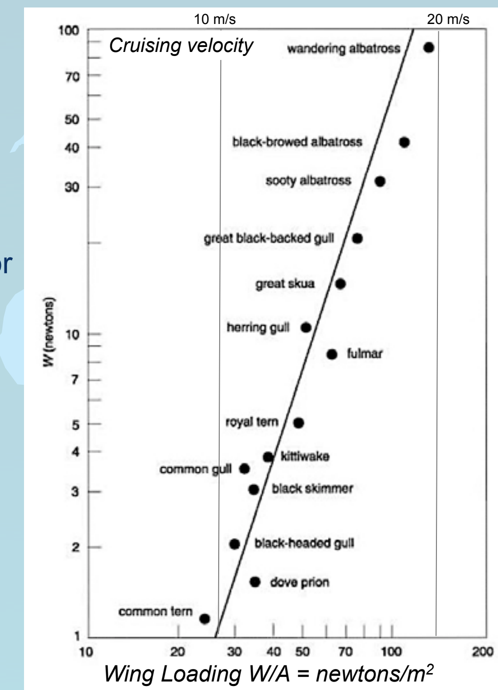
Lift, Weight, and Speed

When the weight increases by a factor of 100, the wing loading increases by a factor of 5, and the airspeed by a factor of more than 2.

The slope in the graph is given by:

$$W/A = c \times W^{1/3} \qquad (2)$$

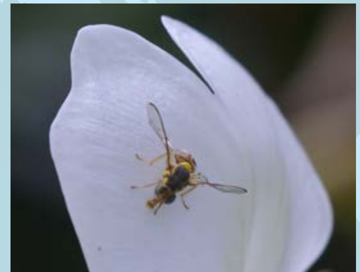
which is a universally applicable scale relation whenever weights and supporting surfaces are involved.

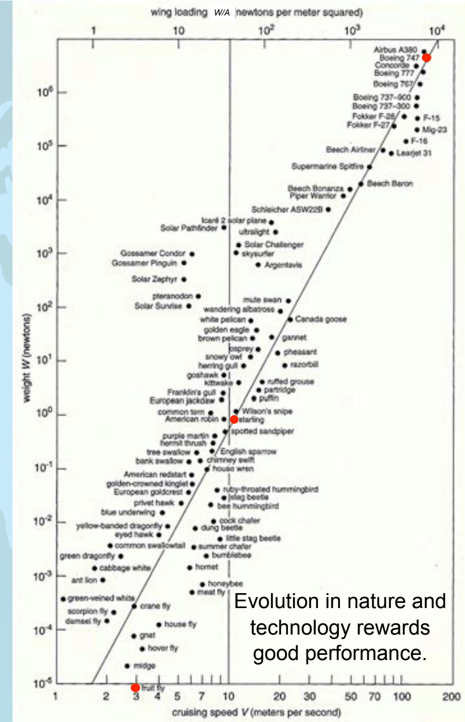


Natural Convergence

Evolution in nature and technology rewards good performance.

The Great Flight Diagram

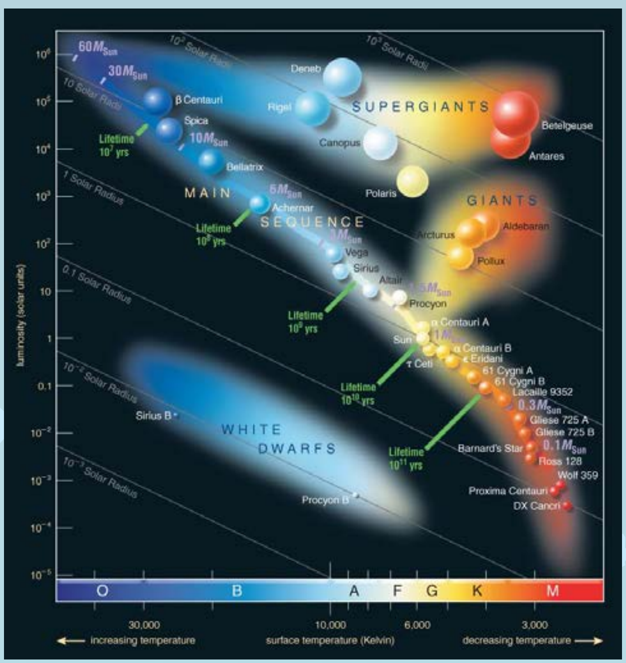


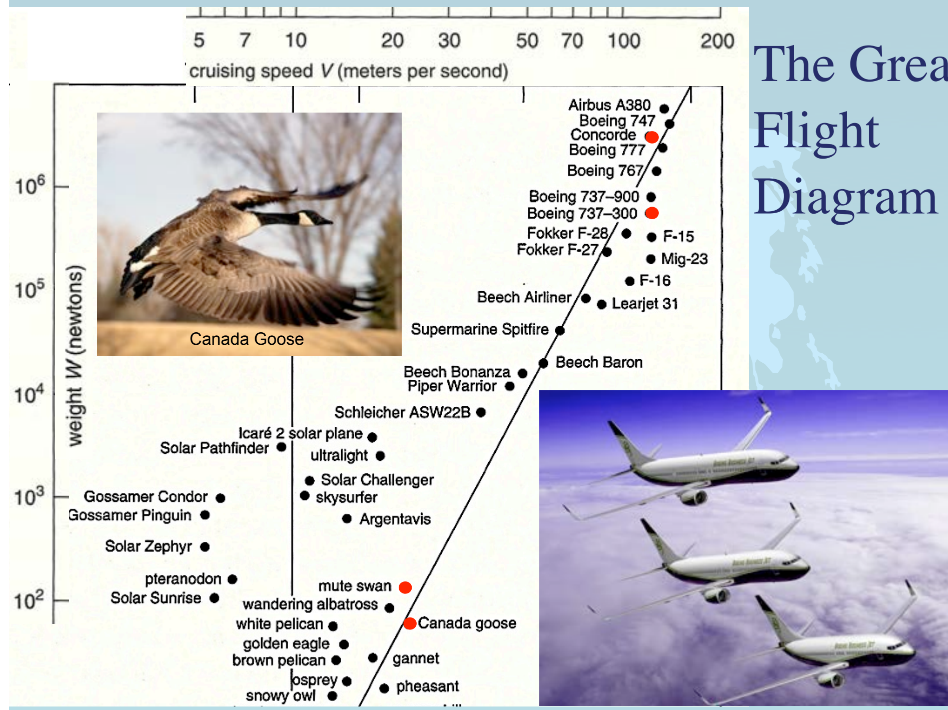


Evolution in nature and technology rewards good performance.

Hertzsprung-Russell Diagram

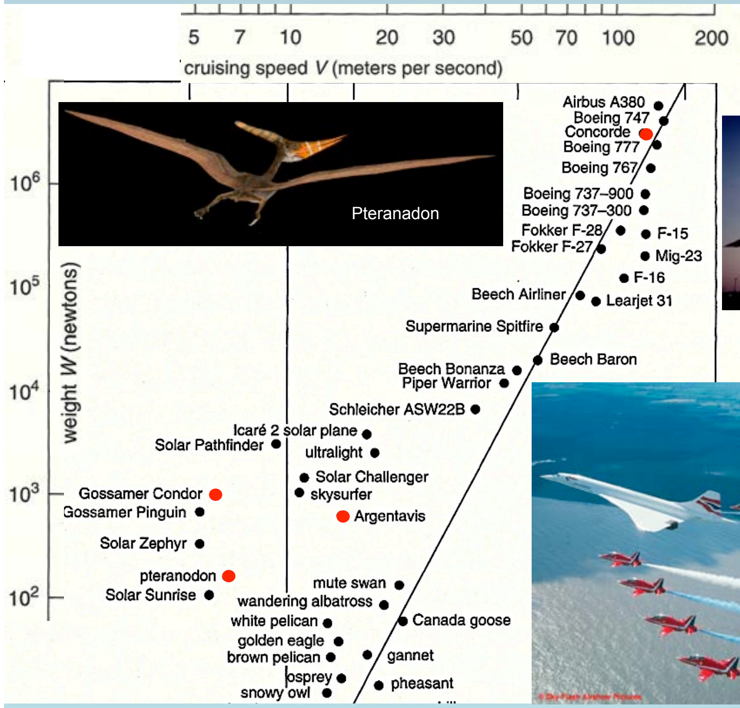
— is a scatter graph of stars showing the relationship between the stars' absolute magnitudes or luminosities versus their spectral types or classifications and effective temperatures.





The Great Flight Diagram

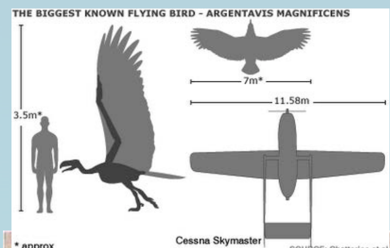
Miss Fits

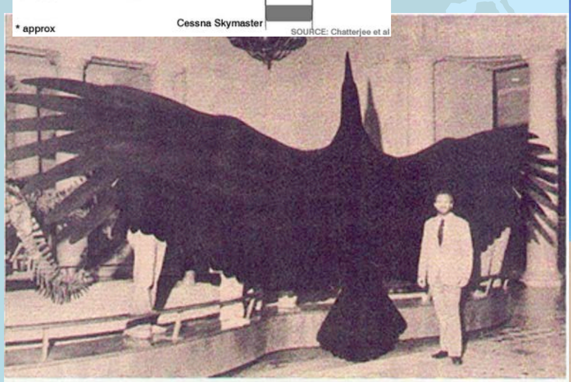


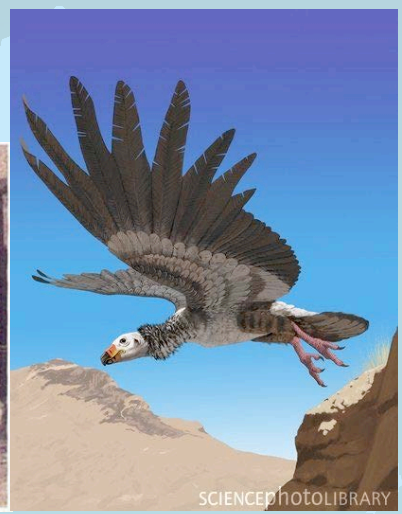
Breaking the Sound Barrier

Breaking the sound barrier is very costly, because of the large increase in aerodynamic drag: 3x the drag of that below the sound barrier. Concord's fuel consumption was outrageous.

Argentavis Magnificens

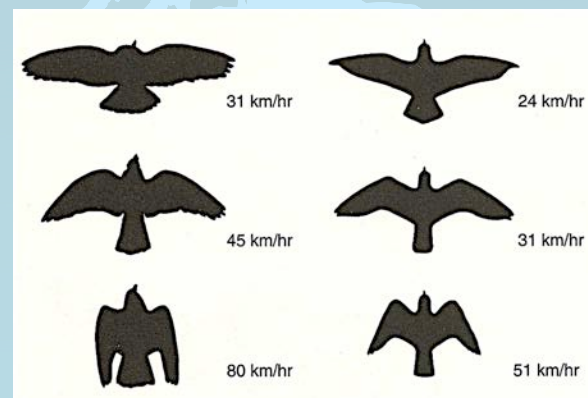






Largest flying animal known. Weighed 700 newtons (150 lbs), wing area of 8 m^2, soaring flight speed 15 m/s (33.5 mph)

Reducing Drag in a Dive

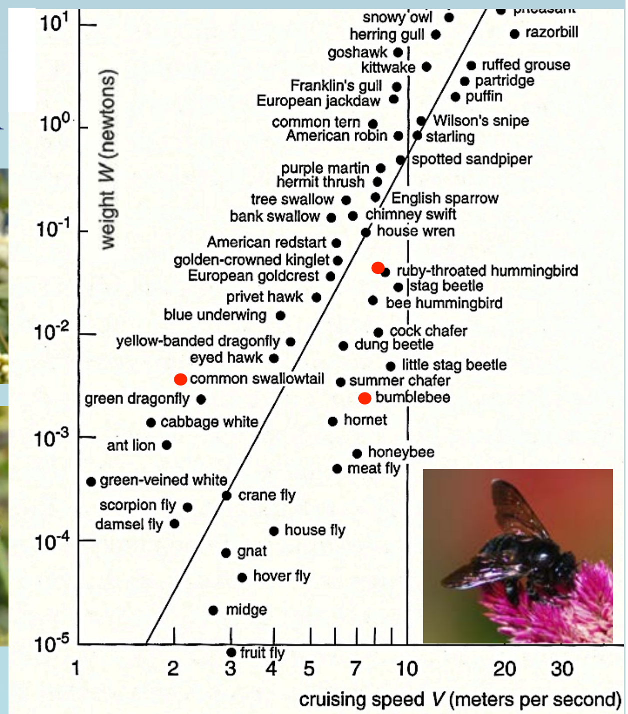


Reducing wing area reduces drag. Peregrin Falcons have been clocked at 242 mph (390 kph).

Increasing Drag for Landing

Humming Birds, Bees and the Trend Line

The Great Flight Diagram

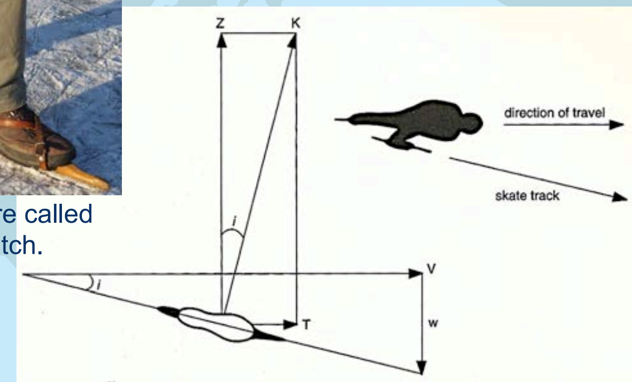


Art of Staying Airborne

The Skater's Edge

Skater's Free Gearbox

Wooden skates are called “doorlopers” in Dutch.



The art of skating produces a fully automatic gear. The motion of the leg generates a large sideways force Z, but also a forward force, thrust T. Proportional triangles show that the ratio T/Z = w/V. Rewriting we see that *TV = Zw;* the power propelling the skater forward equals the power generated by the skater's leg.

Skater's Free Gearbox

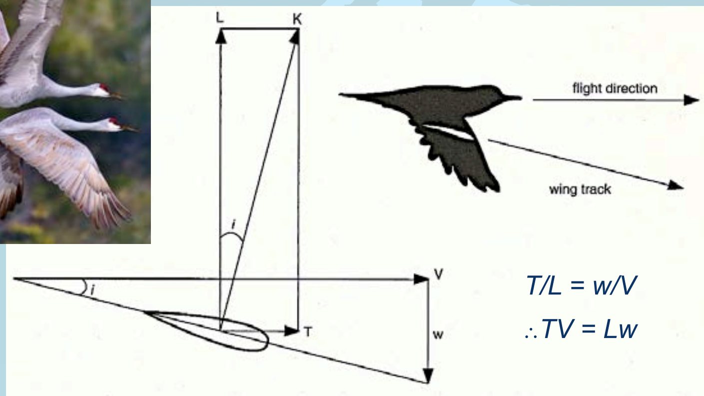
The free gearbox: 100% of the work done by the large force Z at the small speed w is converted into the work done by the small thrust T at the high forward speed V. To gain more speed V, simply push off harder to increase Z, without changing the frequency of the strokes.

Beating Wings

Black Turnstones

A bird in flapping flight faces essentially the same problem as a skater, because beating its wings too rapidly as its speed increases will cause a buildup of lactic acid in its muscles, the bird must find a way of flapping that limits the frequency of its wing strokes.

The Flier's Edge

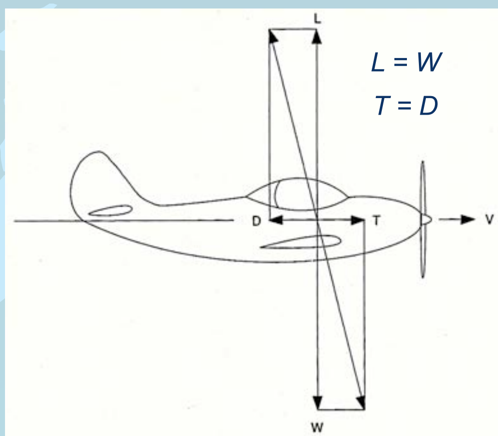


As the wing moves down, the lift force generates power. This power, the product of L and w, is transmitted in its entirety to the propulsive effort, the product of T and V.

Beating Wings

Birds don't row with their wings, rather the wing is brought forward and down. To keep the wing-beat frequency down, a bird simply maintains a small angle between the wing stroke and the direction of flight, thus minimizing the loss of energy to the air..

Thrust vs Drag

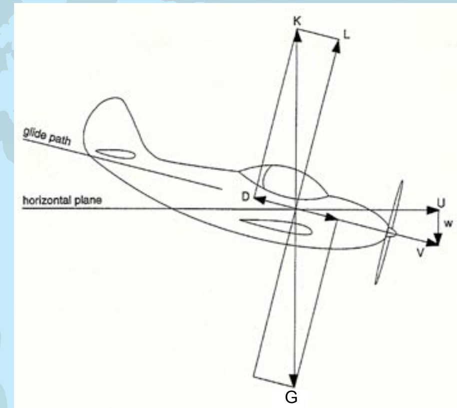


The force balance in horizontal flight – The weight *W* is balanced by the aerodynamic lift L, and the aerodynamic drag *D* is overcome by the thrust *T*. Power is force times speed, so the product of *T* and *V* is the work that must be performed per second to maintain horizontal flight against drag. $P = TV$

Gliding

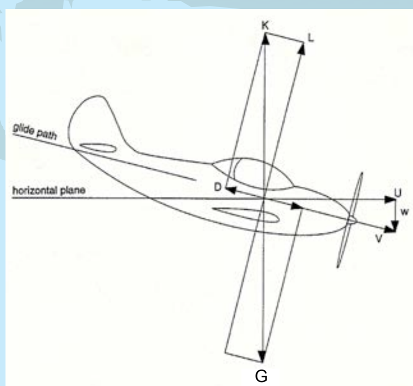
In the absence of thrust, a bird or plane cannot maintain the balance of forces required for horizontal flight; it will inevitably lose altitude. When an airplane or bird descends a new balance is obtained.

Gliding with Finesse



The force and speed triangles again have the same proportions. Thus, w/V = D/W, and Gw = DV. The power DV required to overcome the aerodynamic drag is supplied by the large force of gravity G acting on the small downward speed w.

Finesse



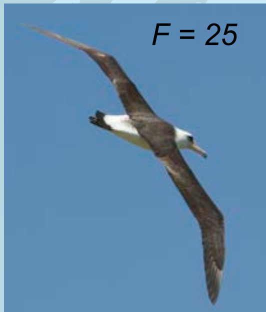
The force and speed triangles also provide useful information on the distance that can be covered in a glide. If U equals the horizontal component of the airspeed, the ratio between it and the rate of descent w must be equal to the ratio of the lift L to the drag D. L/D = U/w, determines how many meters a gliding bird or plane can travel for each meter of descent.

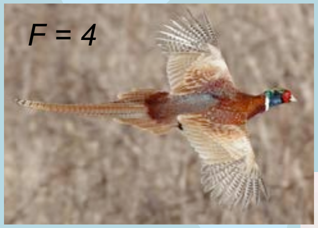
Finesse

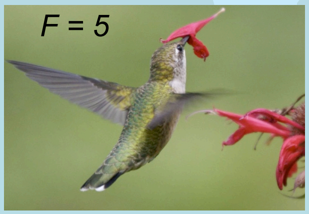
The French call the ratio of the lift L to the drag D of a bird or plane its *finesse (F).* Aeronautical engineers speak of the *glide ratio* when they talk about the finesse of an airplane.

Finesse

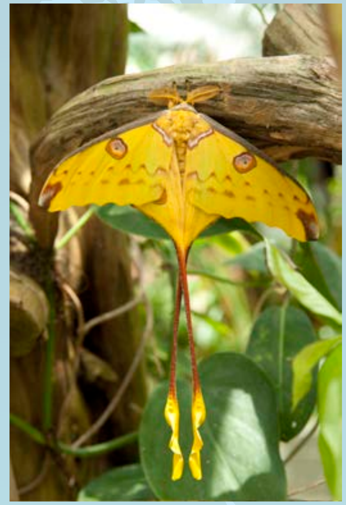
or glide ratio



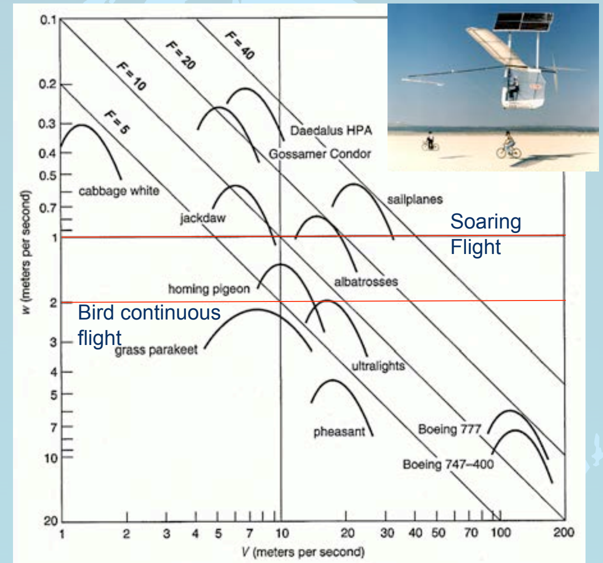




The Great Gliding Diagram



Madagascan Comet Moth



Gliding on Wind Shear

An albatross glides just above the waves for long distances without flapping their wings. How do they do this?

They extract energy from the wind shear in the MBL. Consider the balance between kinetic energy and gravitational potential energy of the bird;

$1/2mv^2 + mgz$ = constant

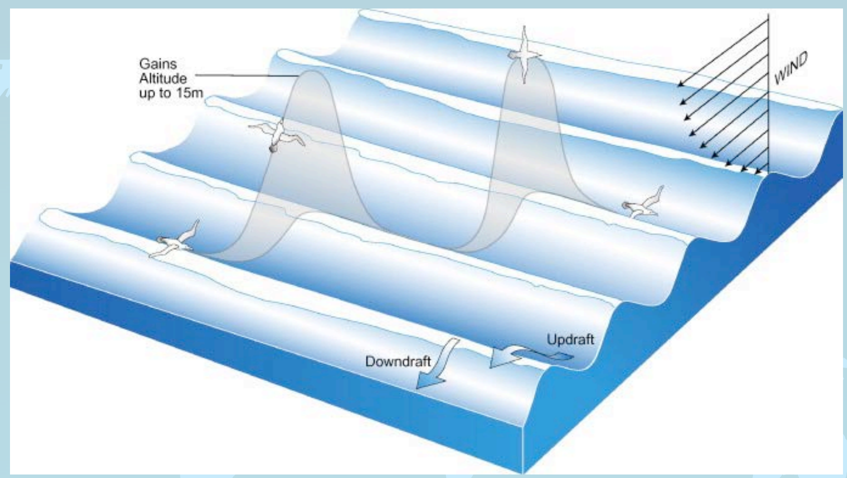
in differential form: $vdv = -gdz$

or $dv/dz = -g/v$

For a gliding bird to remain airborne, the wind speed in the MBL must increase by a factor of g/v plus drag.

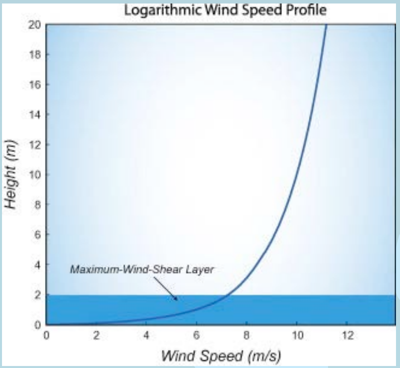
A large gliding velocity *V* is very helpful in this. And the albatross is perfectly adapted.

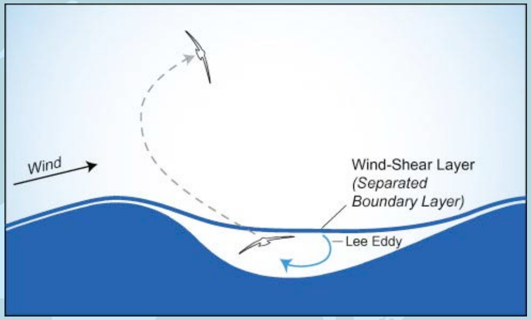
Dynamic Soaring



In dynamic soaring the albatross turns into the wind to gain height (~15 m) and turns away from the wind to gain speed (~25 m/s).

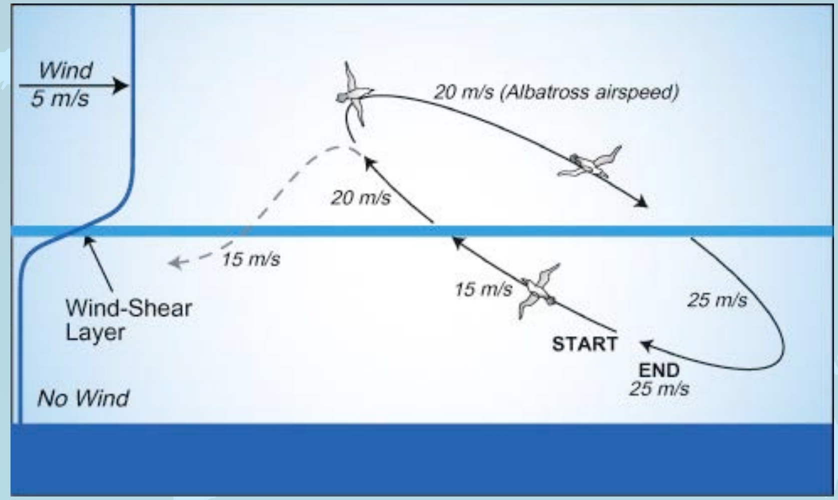
Dynamic Soaring





Most (72%) of the increase of wind speed within the lowest 10 m of the profile is located in a ~2 m thick wind–shear boundary layer near the surface (shaded layer). On crossing the wind–shear layer, the bird's airspeed abruptly increases. The increase in airspeed can be used to climb up to heights of 10–15 m by trading airspeed (kinetic energy) for height (potential energy)

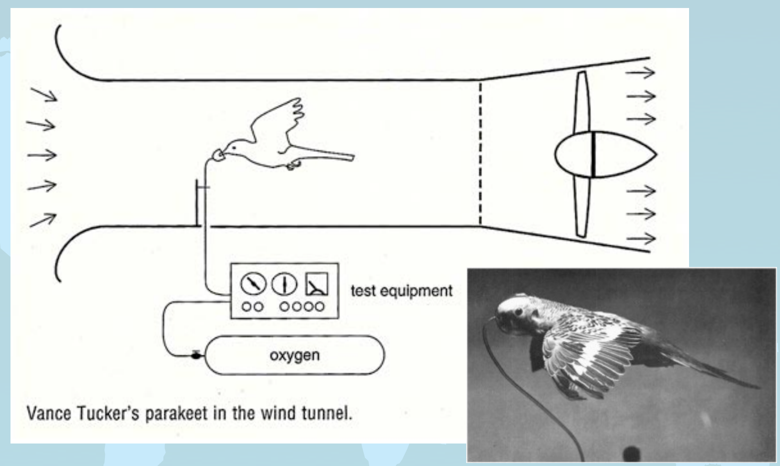
Dynamic Soaring



Rayleigh (1883) first suggested that a bird could continuously soar in nearly-circular flight on an inclined plane that crosses a thin wind–shear layer.

Powered Flight

Power: A Hard Days Flight



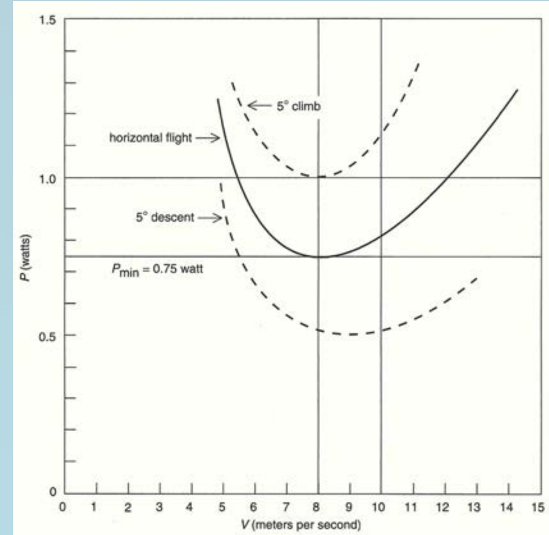
Vance Tucker's parakeet in the wind tunnel.

Wind tunnel tests show that a bird can generate ~100 watts per kilogram of muscle mass (a human can manage only 20). The lungs of birds have air sacs behind them, so they are ventilated twice during each respiration cycle. The pectoral muscles of a bird account for about 20% of its total mass.

A Hard Days Flight

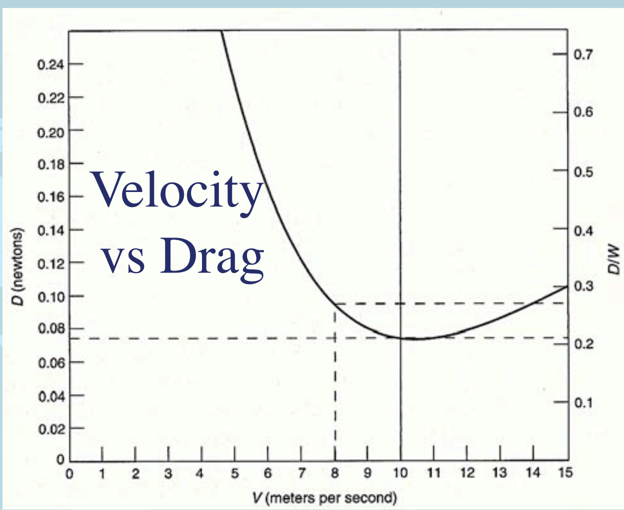
The tests show the parakeet ‘s most economical speed was~8 m/s (18 mph). At that speed the parakeet required 0.75 watt (0.001 horse power) to remain airborne. At lower and higher speeds more power was needed.

A Hard Days Flight



The flight muscles of a 35 gram parakeet weigh about 7 g, corresponding to a continuous output of about 0.7 watt, close to the minimum power in the curve above. The maximum continuous power is about twice the normal rate, or 1.4 watt, corresponding to a minimum flight speed of 5 m/s.

Velocity vs Drag



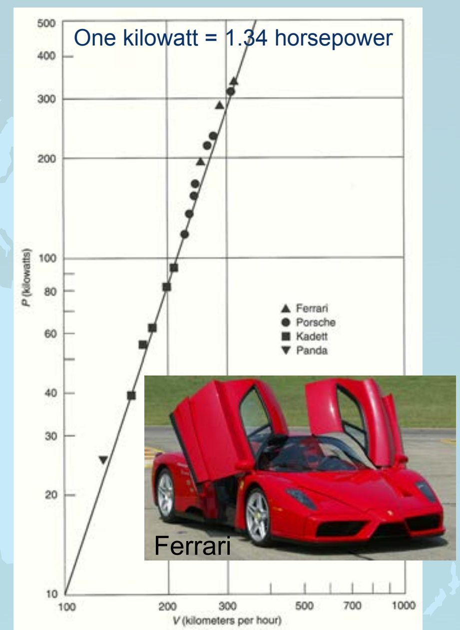
To fly at constant speed a bird or a plane must develop enough thrust *T* to overcome aerodynamic drag *D*. Power equals force times speed: $P = TV = DV$. And $D = P/V$. For our parakeet the speed at which the drag is a minimum (~11 m/s, 25 mph) is higher than the speed at which the power is a minimum (8 m/s, 18 m/s).

How do Cars Match up?

Engine power plotted vs maximum speed for four makes of car.

Power required increases as the third power of the speed.

Cars have awful aerodynamic properties caused by turbulence around the wheels and in the wheel wells.



To go twice as fast requires an eight-fold increase in engine power.

For the Speed Demon

A sport plane with a Porsche engine and retractable landing gear can easily attain speeds of 250 mph (~400 kph)

Energy and Migration

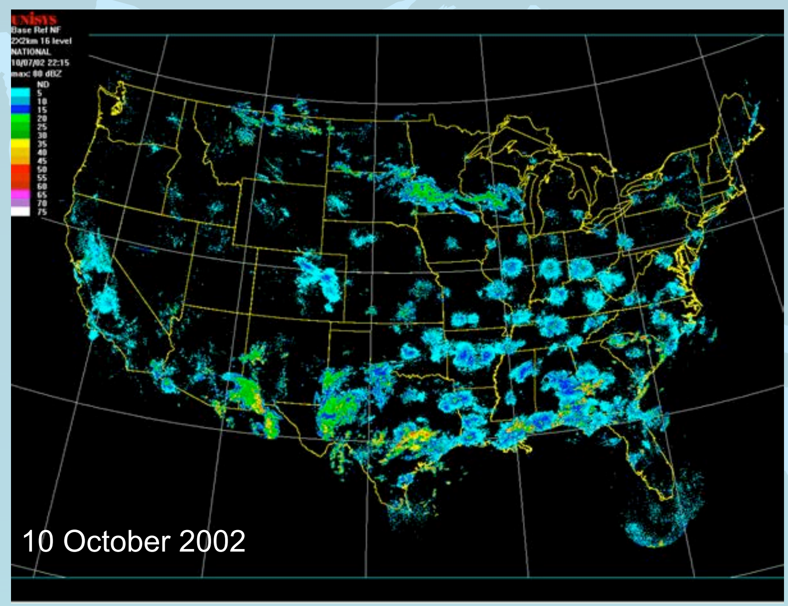
Starling Murmuration

http://vimeo.com/50014387

Migration

How much food do birds need when they migrate south in the autumn?

Radar is used in Migration Studies



Mute Swan

Mute Swan

A mute swan cruises at ~20 m/s. It weighs 10 kg, 2 kg of which constitute its flight muscles. In cruising flight, the power output of these flight muscles is ~100 watts/kg, or about 200 watts mechanical power during migration.

Migration

Snow Geese

Because the conversion efficiency of nutrient energy is only about 25%, the swan needs 800 watts of nutrient energy. At a speed of 20 m/s this corresponds to an energy consumption of 40 J/m.

Migration

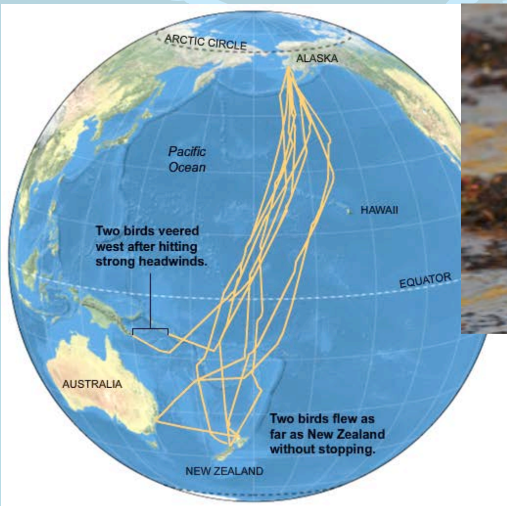
Flamingos

This energy is supplied by the spare fat on the bird's chest. The nutritional value of bird fat is ~32 J/gm. Since a swan requires 40 J/m, it consumes 1.2 gm of fat per km. After 12 hours of cruising at 20 m/s, the swan has traveled 870 km and lost more than 1 kg of body weight. The swan will not only be exhausted, but also famished. A light snack will not suffice. Thus, it is easy to understand the importance of bird sanctuaries.

The Amazing Bar-Tailed Godwit

Bar-Tailed Godwits are large wading birds that cross the entire Pacific Ocean without refueling.

Bar-Tailed Godwit Migration



Bar-tailed godwits are powered migrants—which means that they must flap their wings the whole way, without the luxury of soaring or gliding. Not only this, but unlike arctic terns or sooty shearwaters, powered migrants can never stop to feed or rest at sea.

Bar-Tailed Godwit Migration

Their takeoff weight is 500 g, wingspan 0.73 m, wing area is . 0.57 m^2, leading to a cruising speed of 15 m/s. Their flight muscle mass is 70 gm at takeoff, providing 7 watts of power. To overcome their drag, they need about 6 watts, so they are cutting it close.

Do They Violate the Laws of Physics?

Upon their arrival in New Zealand, their weight has dropped to 220 gm. The metabolic energy consumed is about 9000 kilojoules. With a conversion efficiency of 25%, this becomes ~2,300 kilojoules mechanical. On average during the trip their lift to drag ratio (finesse) is 14 and their drag is 0.26 newton, resulting in a flight range of 8,800 km — 2,200 km short of their goal of 11,000 km. How do they do it?

Elementary meteorology, dear Watson

1. They take off with a strong tail wind (+ 1700 km)
2. They climb high enough to profit from counter trades in SH (+ 1000 km)
3. Their metabolic efficiency may be closer to 30% *without steroids* (+1500 km)

Now they arrive with 1000 km to spare.

Questions?

Acknowledgement: much of the material in this talk is from:
The Simple Science of Flight by Henk Tenekes

Questions?