Calvin and Hobbes

Wipe that grin off your face!

Well, Hobbes, how do I look?

I'm doing my best to bite my tongue.

I cut out construction paper feathers and taped them on my arms so I can fly. Pretty neat, huh?

If paper feathers are all it takes to fly, don't you think we'd have heard about it before?

It takes an uncommon mind to think of these things, Hobbes.

I'd agree with that.

Here's a gorge. This is a good spot.

You're going to jump off this ledge?

Heck no! I need momentum! I want you to toss me over.

You understand I assume no responsibility for this?

Right. I get the patent.

I'm flying! I'm flying!

I'm... uh oh...

Don't sell the bike shop, Orville.

Shut up and go get me some antiseptic.
Wings and the Physics of Flight

1. Physics Primer – forces and force-body diagrams
2. The important forces in flight
3. How do birds generate lift?
4. Drag
5. Thrust
6. Wing shape
7. Types of flight:
   a. gliding and soaring flight
   b. flapping flight
   c. hovering
   d. hummingbirds
What is a force?
Physics Primer

What is a force?

*Something that causes a change in motion*
*a “push or pull” on an object*

By *change in motion* we mean

- speeding up
- slowing down
- changing direction

An object traveling in a straight line at a constant speed is not experiencing a change in motion
Physics Primer

What is a force?

Something that causes a change in motion
a “push or pull” on an object

What are some everyday forces?
Physics Primer

From Newton's Second Law of motion:

**Force = mass \times acceleration**

If the same force is applied to a big object and a small object, which has the higher acceleration?
Physics Primer

An object will move according to the **sum** of all the forces acting on it.

Net Force $\rightarrow$ Change in Motion

*Which way will the coconut move?*
Physics Primer

Which way will the coconut move?

What is the net force on the coconut?
Physics Primer

Which way will the coconut move?

What is the net force on the coconut?

A Force-Body Diagram helps us visualize all of the forces acting on an object.
Physics Primer

Which way will the coconut move?  A Force-Body Diagram

What other forces are acting on the coconut?
Physics Primer

Which way will the coconut move?   A Force-Body Diagram

The Force of gravity on the coconut is proportional to the coconut's mass. We generally call this force **weight**

Weight = mass x acceleration due to gravity
Physics Primer

Which way will the coconut move? A Force-Body Diagram

The Force of gravity on the coconut is proportional to the coconut's mass. We generally call this force **weight**

Weight = mass $\times$ acceleration due to gravity
Physics Primer

Which way will the coconut move? A Force-Body Diagram

The sum of the forces or the **net force** tells us which way the coconut will move!
The Physics of Flight

Now imagine a bird in level flight at a constant speed. What forces are acting on this bird?
The Physics of Flight

Now imagine a bird in level flight at a constant speed

*What is the net force on the bird?*
The Physics of Flight

Now imagine a bird in level flight at a constant speed

*What is the net force on the bird?*

The sum of the forces must equal zero if the bird is in constant motion.

This means that...

\[
\text{Weight} = \text{Lift}
\]

\[
\text{Thrust} = \text{Drag}
\]
The Physics of Flight

Concept-test:

Which of these birds has a net force of zero acting on it?

- Costa's Hummingbird Hovering
- Turkey Vulture soaring at a constant speed
- Lucy's Warbler perching
- Peregrine Falcon diving after prey
Now imagine a bird in level flight at a constant speed.
The Physics of Flight

Now imagine a bird in level flight at a constant speed

Weight = mass x gravity

The heavier the bird, the greater the force of its weight!
The Physics of Flight

Now imagine a bird in level flight at a constant speed

How do birds generate lift to balance their weight in flight?
Need a lift?

How do birds generate lift?

Wing in cross-section:

Wings function as an *airfoil* – a curved surface which produces lift when air passes over it, and minimizes turbulence of airflow behind it.
Need a lift?

What happens to air that passes over a bird's wing?

When air encounters something in its way, such as a wing, it must move around it.

There are two paths around the wing: **over it** and **under it**.

These two paths are not the same – the path over the top of the wing is **longer** than the path under the wing.
Need a lift?

What happens to air that passes over a bird's wing?

The air on top of the wing must move **faster** than the air below the wing.

This difference in speeds results in a lowering of the air pressure above the wing, by

**Bernoulli's Principle**
Need a lift?

What happens to air that passes over a bird's wing?

The air on top of the wing must move faster than the air below the wing. This difference in speeds results in a lowering of the air pressure above the wing, by Bernoulli's Principle: the greater the velocity of a fluid, the less pressure it exerts. The difference in pressures above and below the wing result in LIFT!
Need a lift?

What happens to air that passes over a bird's wing?

Air strikes the bottom surface of the angled wing.

Some of the air striking the wing is deflected at a 90 degree angle from the wing.
Need a lift?

What happens to air that passes over a bird's wing?

Air strikes the bottom surface of the angled wing. This means that the AIR is deflected DOWN, while the WING is deflected UP! This generates LIFT via Newton's Third Law of Motion.
Need a lift?

What happens to air that passes over a bird’s wing?

Air deflected above the wing leaves a gap of air above the wing — LOW P

Air deflected below the wing piles up — HIGH PRESSURE
Need a lift?

What happens to air that passes over a bird's wing?

Air is deflected by the leading edge of the wing.

The difference in pressures above and below the wing creates LIFT.
Bernoulli vs. Newton

So, what really generates lift?
Bernoulli vs. Newton

So, what really generates lift? Well...

Differential pressure creates lift!

The reaction force from air hitting the wing creates lift!

Bernoulli's principle describes the conservation of energy as air flows around a wing.

Newton's laws describe the conservation of momentum.

In physics, we also need to conserve mass ...
So, even though we don't know the exact mechanism by which lift is generated, we can still achieve flight!
Need a lift?

How much lift is generated by the wings?

*It depends on how much air is deflected, the more air that is deflected downwards, the more lift is generated.*

More wing area = more lift

\[
\text{Lift} \propto \text{Area} \\
L \propto A
\]
Need a lift?

How much lift is generated by the wings?

*It also depends on how fast the airspeed over the wings is.*

Lift is proportional to velocity squared $L \alpha v^2$

*Thus, if the airspeed is twice as fast, you generate four times the lift!*
Concept-test:

Two birds, an african and a european swallow (both unladen), begin their spring migration. If the african swallow has only half the wing area of the european swallow, but flies twice as fast, which swallow generates the most lift? Assume the swallows are the same weight.

a. The european swallow, b/c it has twice the wing area
b. The african swallow, b/c it flies twice as fast
c. They generate the same amount of lift
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While lift is proportional to the wing area, it is proportional to the speed SQUARED.

$L \sim A v^2$
The Physics of Flight

Now imagine a bird in level flight at a constant speed

Drag is the resistance of air to movement of an object through it
Resistance is such a drag

Air striking the wing also produces **drag**, or resistance to the forward motion of the wing.

Just like with lift, the more air that hits the wing, the more drag is produced.

More air hits the wing when the **area** is larger or

More air hits the wing when the **velocity** is higher

\[ \text{Drag} \propto Av^2 \]
Angle of Attack

Lift and Drag also depend on the orientation of the wing to the airflow – or the **angle of attack**

Lift and Drag do not depend on AA in the same way
Angle of Attack

Lift and Drag also depend on the orientation of the wing to the airflow – or the **angle of attack**

When AA is greater than about 15, drag >> lift, and the bird STALLS
So now we have some expressions for weight, lift and drag. What about thrust?

**Thrust** is the force which propels a bird forwards through the air
Thrust

Airplanes generate thrust with engines – how do birds do it?

Flapping!

[Diagram showing flapping birds with stages labeled: Downstroke (Generates Power) and Upstroke (Recovery Stroke)]
Thrust

DOWNSTROKE - air collides with the underside of the wing
Thrust

DOWNSTROKE - air collides with the underside of the wing

The air that hits the wing is deflected behind the wing
Thrust

DOWNSTROKE - air collides with the underside of the wing

The air that hits the wing is deflected behind the wing

Just as pushing water backwards with a canoe paddle propels the canoe forwards, the downstroke of the wing propels the bird forwards through the air.
Thrust

UPSTROKE – for most birds, and in slow flight, this is a “recovery” stroke, where no forces are generated... Except DRAG

To reduce drag:

Wings are partially folded

The primaries are held apart
Thrust

Thrust generates **airspeed**, which effects both lift and drag.

When airspeed is low  
**Lift** is very small

When airspeed is high  
**Drag** is very big

It is easiest for birds to fly at intermediate speeds of 30-60 kmph (or 19-37 mph).
Thrust

*Thrust generates airspeed*, which effects both lift and drag.

When airspeed is low  
*Lift* is very small

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It is easiest for birds to fly at intermediate speeds of 30-60 kmph (or 19-37 mph).

To fly faster, birds don't flap more quickly – *this would create too much turbulence*

Instead, they *increase the depth of each stroke*!
Turbulence

Turbulence is the loss of smooth flow in a fluid or air.

Can be generated by a steep angle of attack, or by flapping.

Vee-formation – reduces and utilizes turbulence.

Alula can control turbulence over the top of the wing.
Turbulence can also be used to generate extra lift!

Air moves from areas of high pressure to areas of low pressure.
This creates a rising mass of air along the wingtips of the bird.
By flying at the wingtips of a preceding bird, that extra lift can be used to save energy!
Thrust

Concept-test:

Assuming that they could breathe, would birds be able to fly (i.e. powered, directional flight) in space??
Concept-test:

Assuming that they could breathe, would birds be able to fly (i.e. powered, directional flight) in space??

NO!

Birds generate lift and thrust by moving and deflecting air masses with their wings. In the vacuum of space, birds wouldn't be able to generate these forces.
Wing Shapes

How much weight must the wings support?

Wing loading = body mass / wing area
Birds vary from ~ 3 g/cm² to 0.1 g/cm²

if wing loading is low, gliding is possible
Wing Shapes

*How much weight must the wings support?*

Wing loading = body mass / wing area

Birds vary from ~ 3 g/cm² to 0.1 g/cm²

As wing loading increases....
Wing Shapes

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Wing Shapes

How much weight must the wings support?

Wing loading = body mass / wing area
Birds vary from ~ 3 g/cm² to 0.1 g/cm²

As wing loading increases....

Lift is more difficult to generate, especially at low speeds
Wing Shapes

How much weight must the wings support?

Wing loading = body mass / wing area

Birds vary from ~ 3 g/cm² to 0.1 g/cm²

Species with high wing loading tend to be powerful short distance fliers, and need a lot of speed to take off.

Loons (Gaviidae)
Fowl (Galliformes)
Alcids (Alcidae)
Wing Shapes

**Aspect Ratio** = wing length / wing width

It measures the relative amount of lift and drag produced by the wing.

- **Length >> Width**
  - High aspect ratio = high lift to drag ratio

- **Length ~ Width**
  - Low aspect ratio = low lift to drag ratio
Wing Shapes

**Aspect Ratio** = wing length / wing width

Birds with a high aspect ratio are good gliders and soarers, but they have poor agility, and poor take-off power.

(A) (B) (C) (D)
Types of Flight

- Soaring or gliding
  - Some of the lift is generated by rising air masses
  - Without thrust, drag decreases $v$, which decreases lift at a predictable rate – this is how gliders work
Types of Flight

- Soaring or gliding
  - Critical to migration of raptors
  - Long distance, slow migration, with minimal energy
Types of Flight

- **Flapping**
  - The downstroke deflects air backwards and down, generating lift and thrust.
  - How do birds maintain control while they fly?

Warrick et al. 2002
Types of Flight

- Hummingbirds

Ability to completely rotate the wing allows for different combinations of lift and thrust, resulting in the following types of flight:

- Forward 26 miles per hour (top speed)
- Forward 8.6 miles per hour
- Hovering
- Backward flight
Types of Flight

- Hovering
  - Must generate lift on both the down and upstrokes
  - Extremely taxing to the bird, very few are true hoverers

Physics and Conservation

The Marbled Murrelet (Alcidae)

mass ~ 220 g
wing area ~ 75 cm²

Compare to Mourning Dove

mass ~ 130 g
wing area ~ 257 cm²

High wing loading, and feet positioned for diving

Physics and Conservation

The Marbled Murrelet (Alcidae)

Cannot take off unless it is in the water or at a significant height.

On the ground it will walk to a suitable takeoff site, and has been known to nest very rarely on the ground – usually on a cliff edge.
Wing Shapes

Concept-test

Two diurnal raptors (Falconiformes) have equal wing areas. The Peregrine Falcon (family Falconidae) has a higher body mass, but also a higher aspect ratio than the Gray Hawk (family Accipitridae). What can't you say about the flying ability of these two birds?

a. The Gray Hawk has lower wing-loading, so it should fly with more flapping

b. The Peregrine Falcon has a higher aspect ratio, so it should be a better glider

c. The Gray Hawk has a lower aspect ratio, so it should be able to maneuver better in the forest
Two diurnal raptors (Falconiformes) have equal wing areas. The Peregrine Falcon (family Falconidae) has a higher body mass, but also a higher aspect ratio than the Gray Hawk (family Accipitridae). Which statement about the flying ability of these birds is wrong?

a. The Gray Hawk has lower wing-loading, so it should fly with more flapping

b. The Peregrine Falcon has a higher aspect ratio, so it should be a better glider

c. The Gray Hawk has a lower aspect ratio, so it should be able to maneuver better in the forest