Wings and the Physics of Flight

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Ornithology: Ecol484/584
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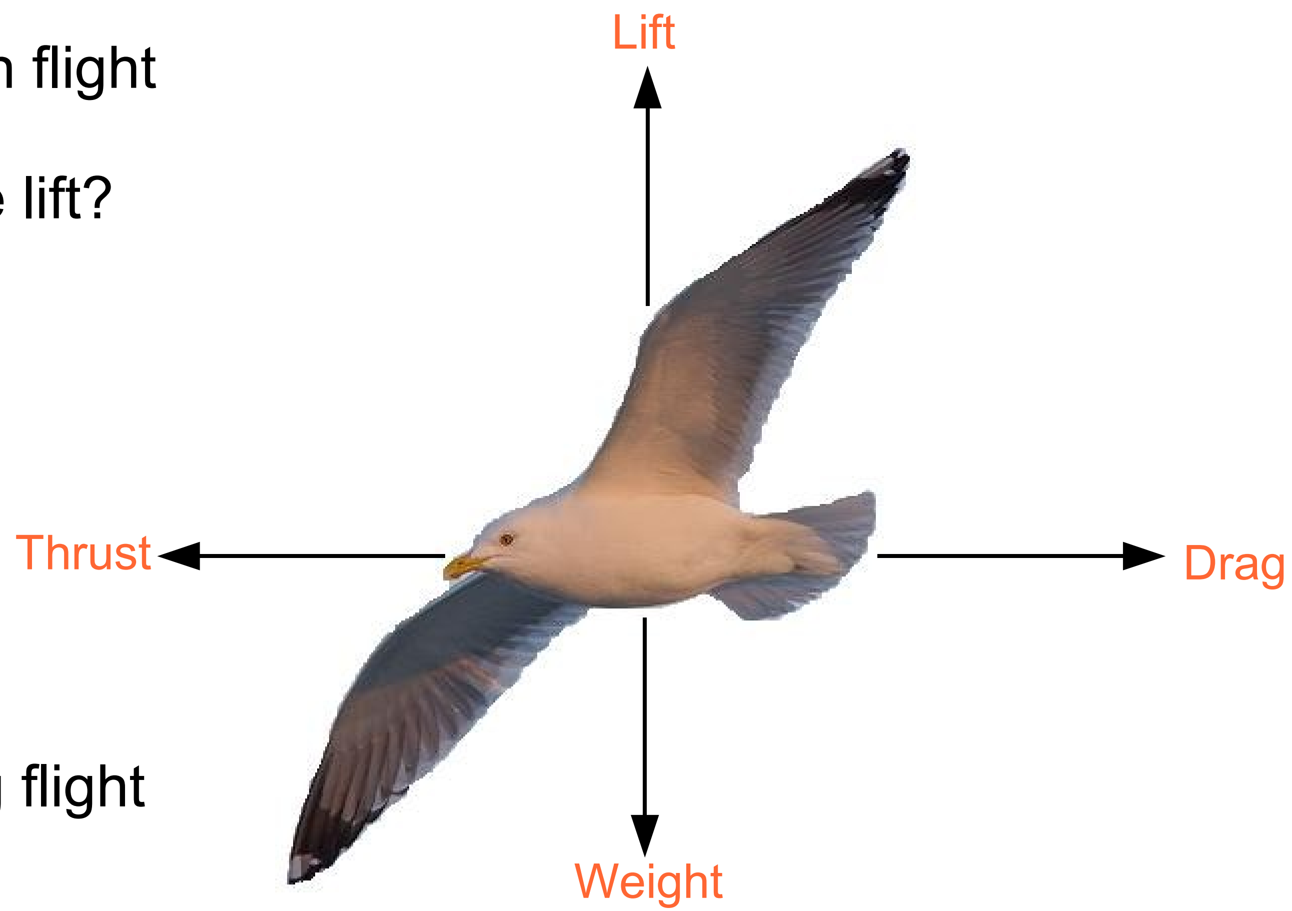
Photo credit:
Richard Bledsoe


Calvin and HOBBES
by WATTERSON
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.
HEAVE!
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.
WATTERSON

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



Physics Primer

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

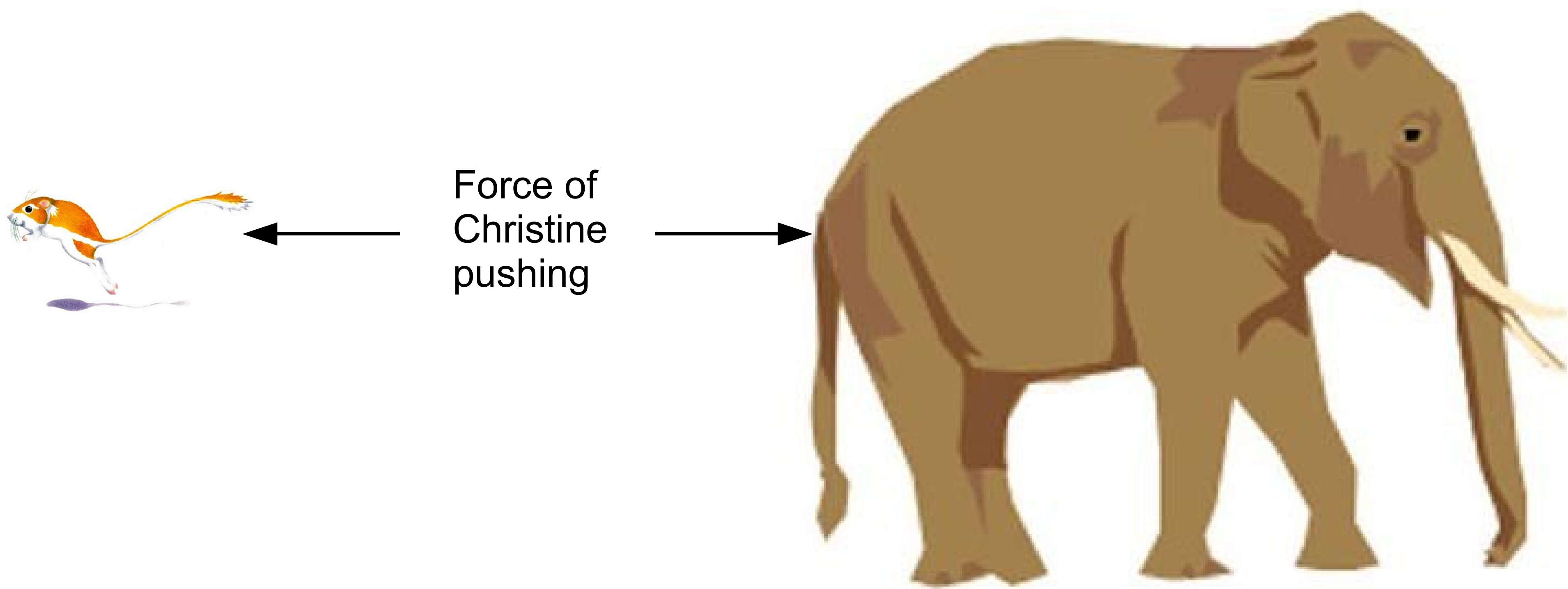
What are some everyday forces?

Physics Primer

From Newton's Second Law of motion:

Force = mass x acceleration

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

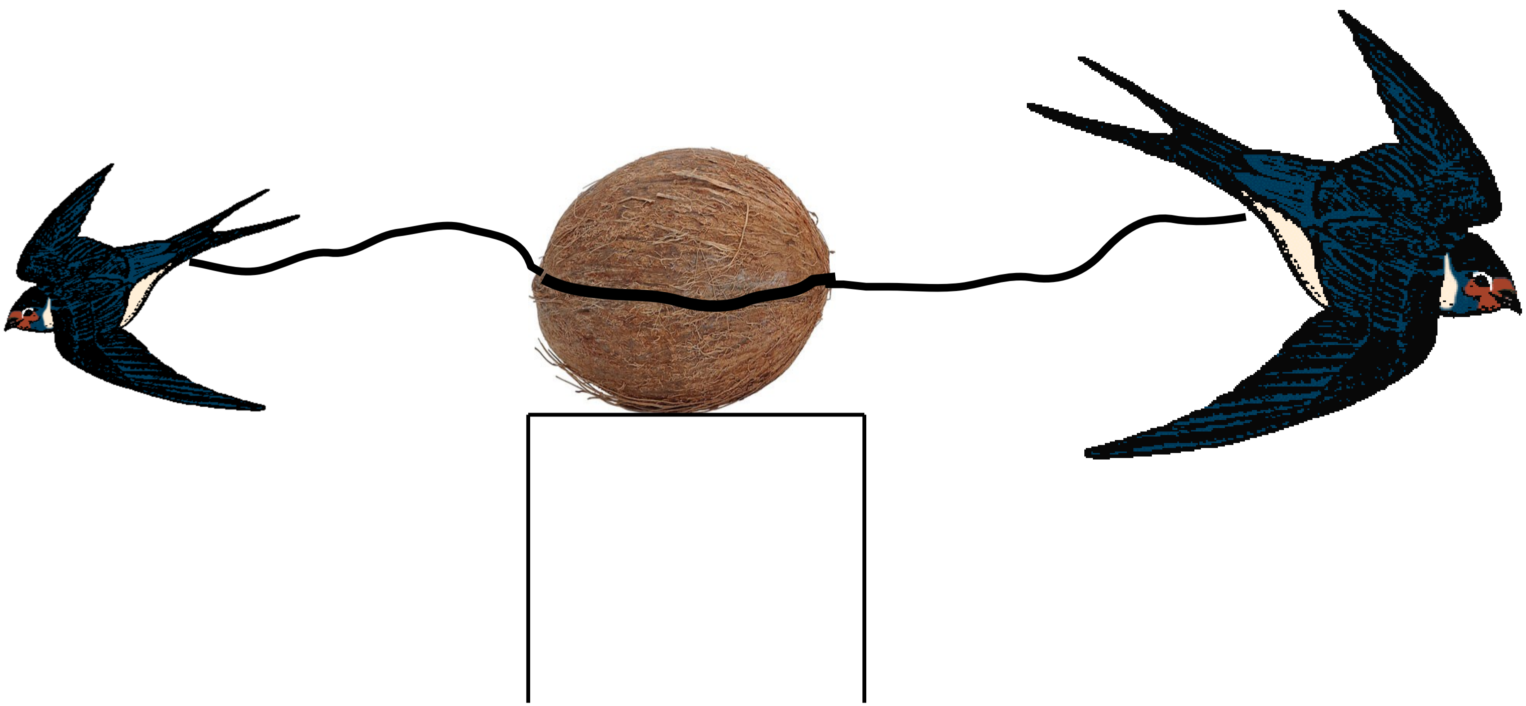


Physics Primer

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

Net Force → Change in Motion

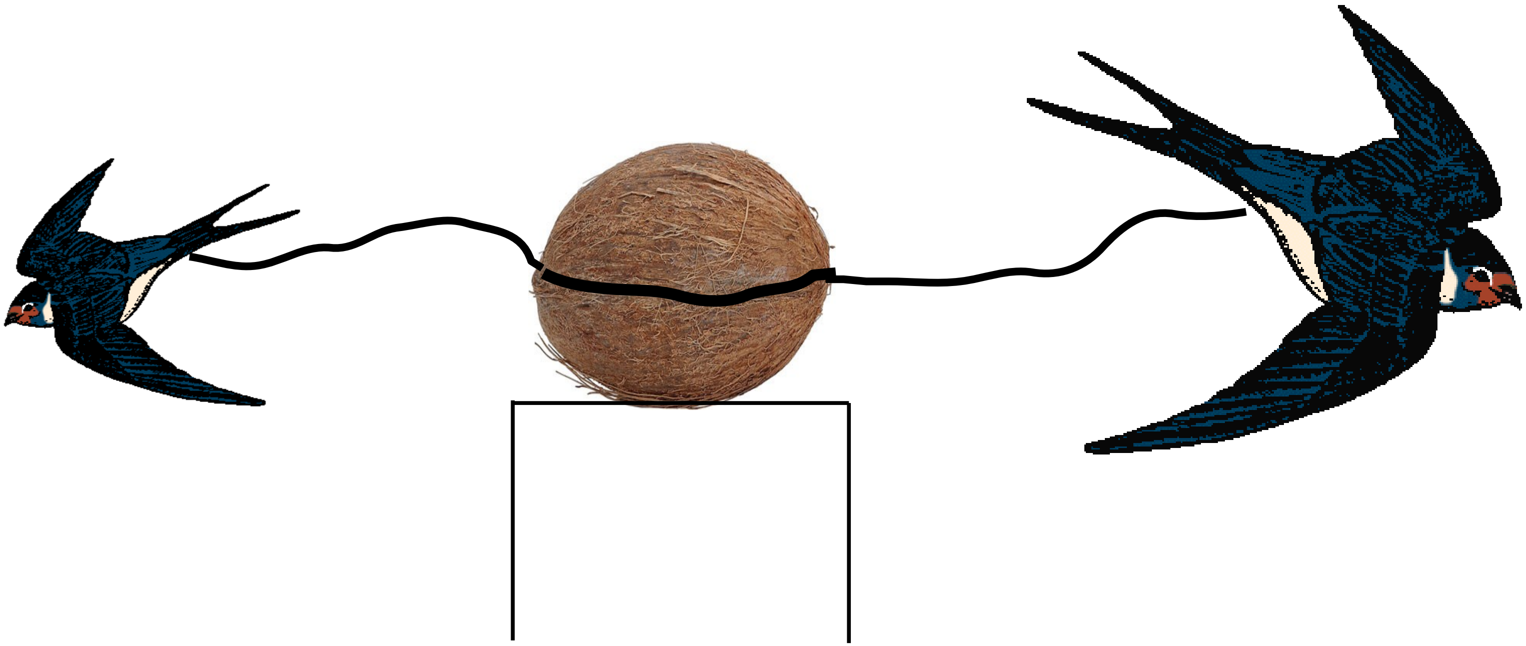
Which way will the coconut move?



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

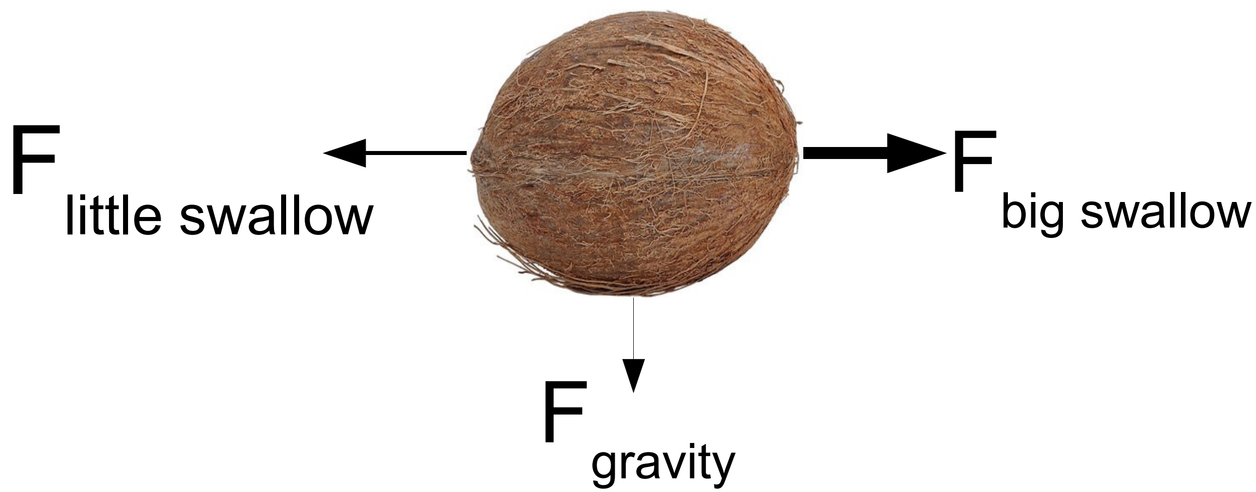
Physics Primer

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*

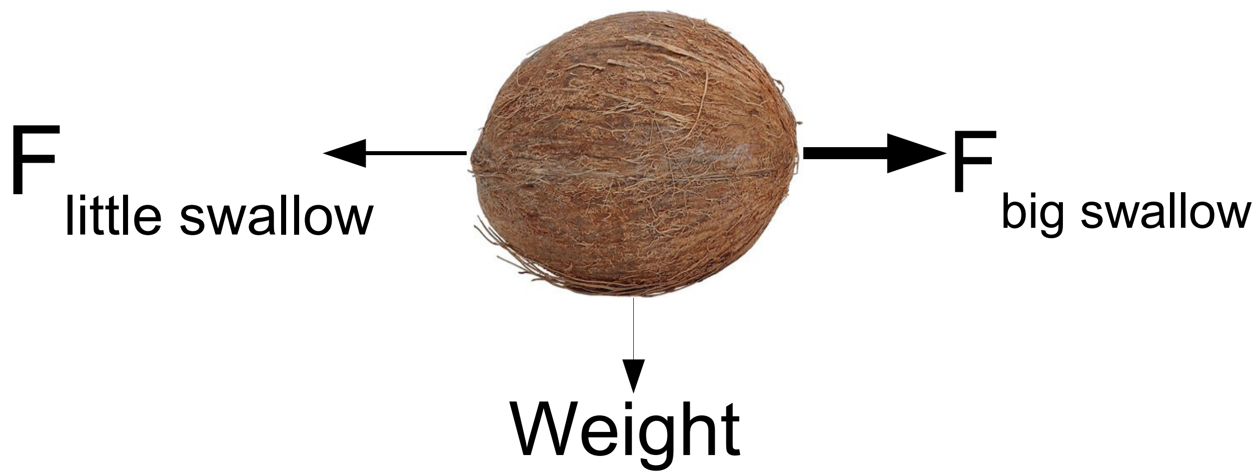


The Force of gravity on the coconut is proportional to the coconut's mass.
We generally call this force **weight**

Weight = mass x acceleration due to gravity

Physics Primer

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



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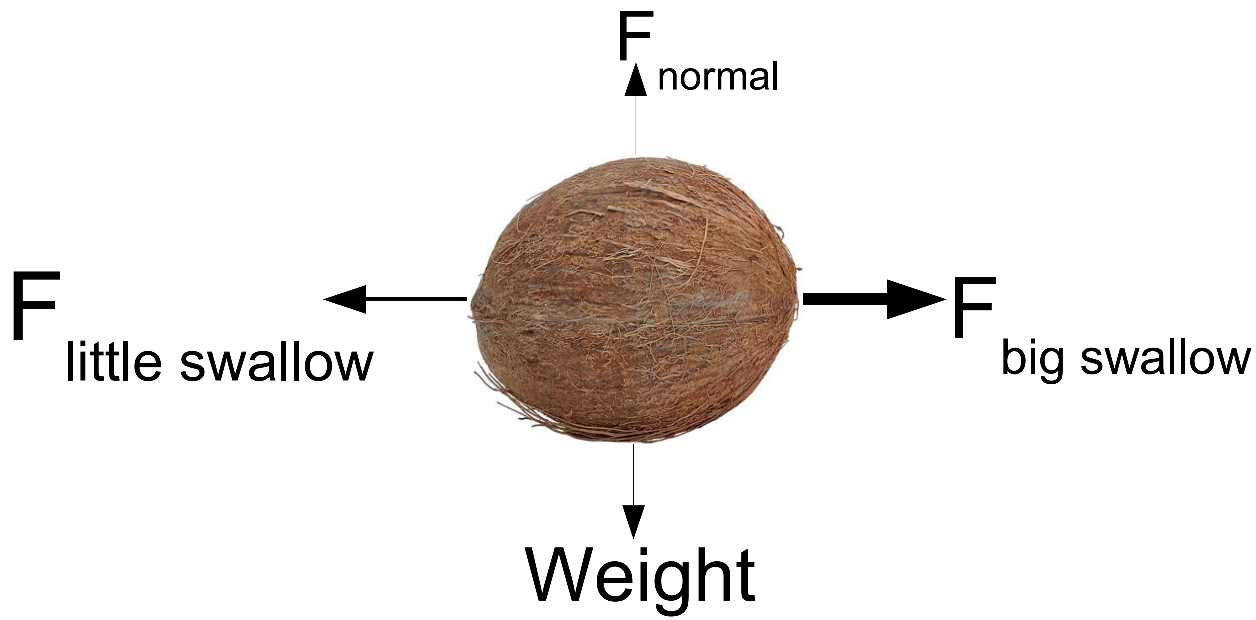
Physics Primer

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

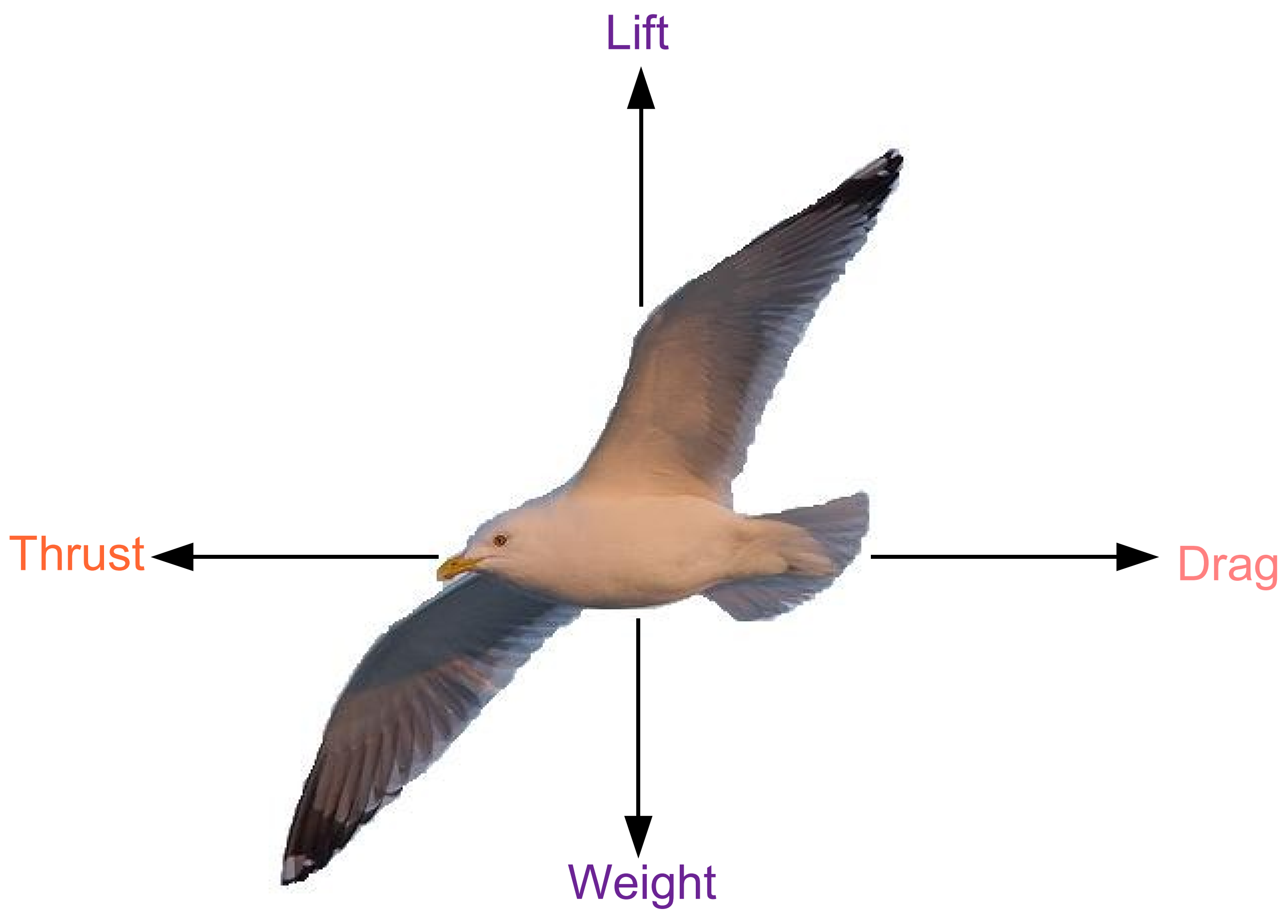
Now imagine a bird in level flight at a constant speed

What forces are acting on this bird?

The Physics of Flight

Now imagine a bird in level flight at a constant speed

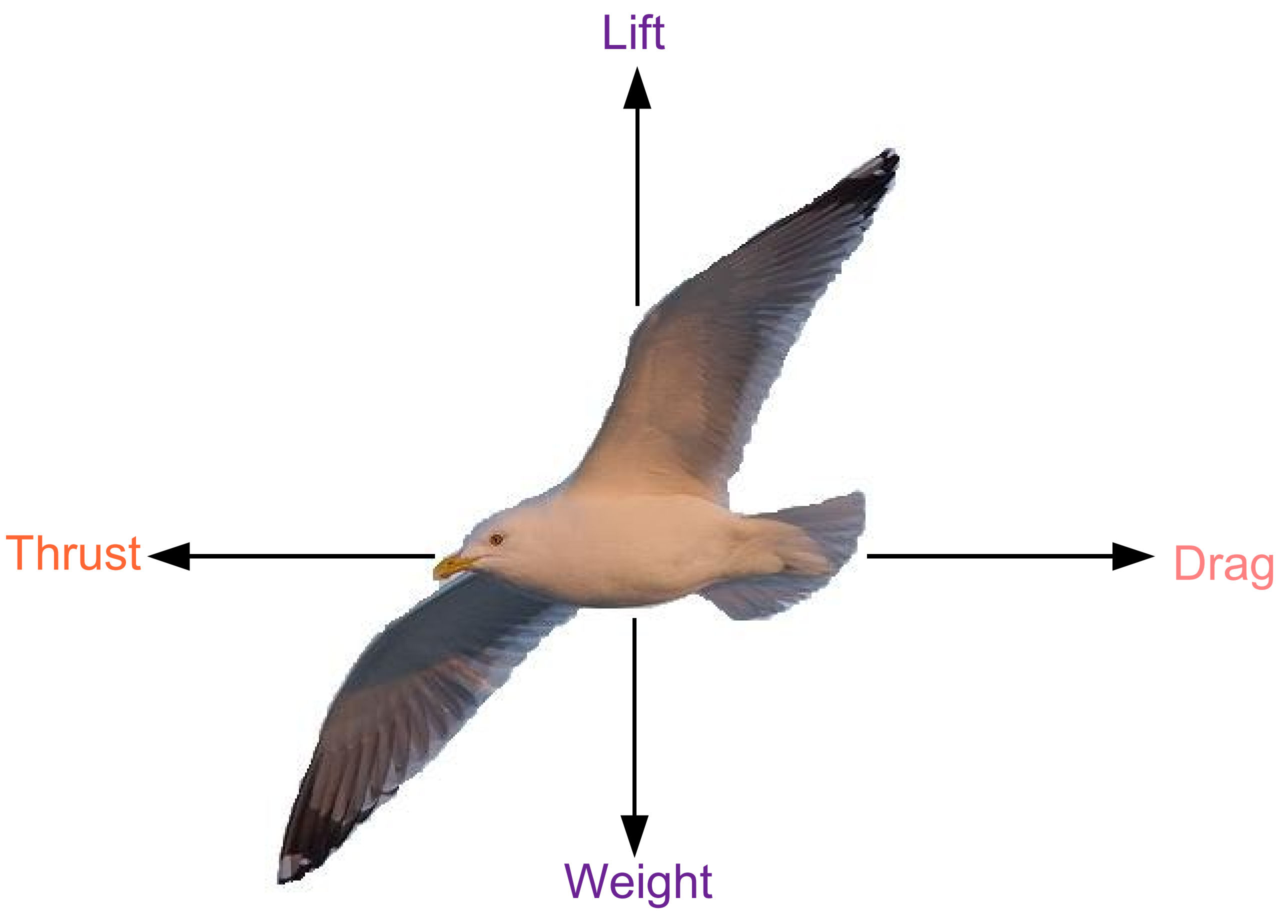
*What is the **net force** on the bird?*



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...

Weight = Lift

Thrust = Drag

The Physics of Flight

Concept-test:

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

Costa's Hummingbird Hovering

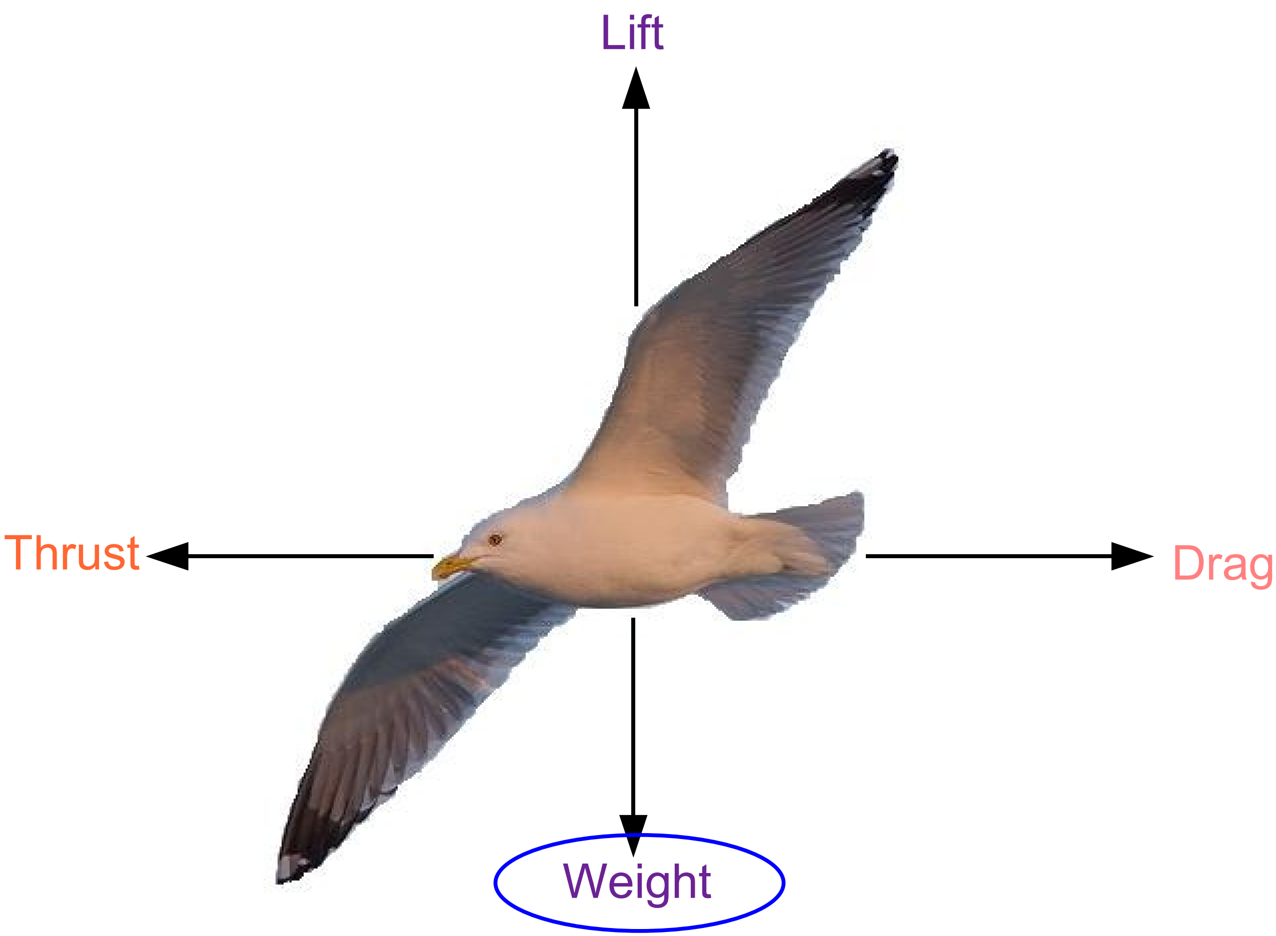
Turkey Vulture soaring at a constant speed

Lucy's Warbler perching

Peregrine Falcon
diving after prey

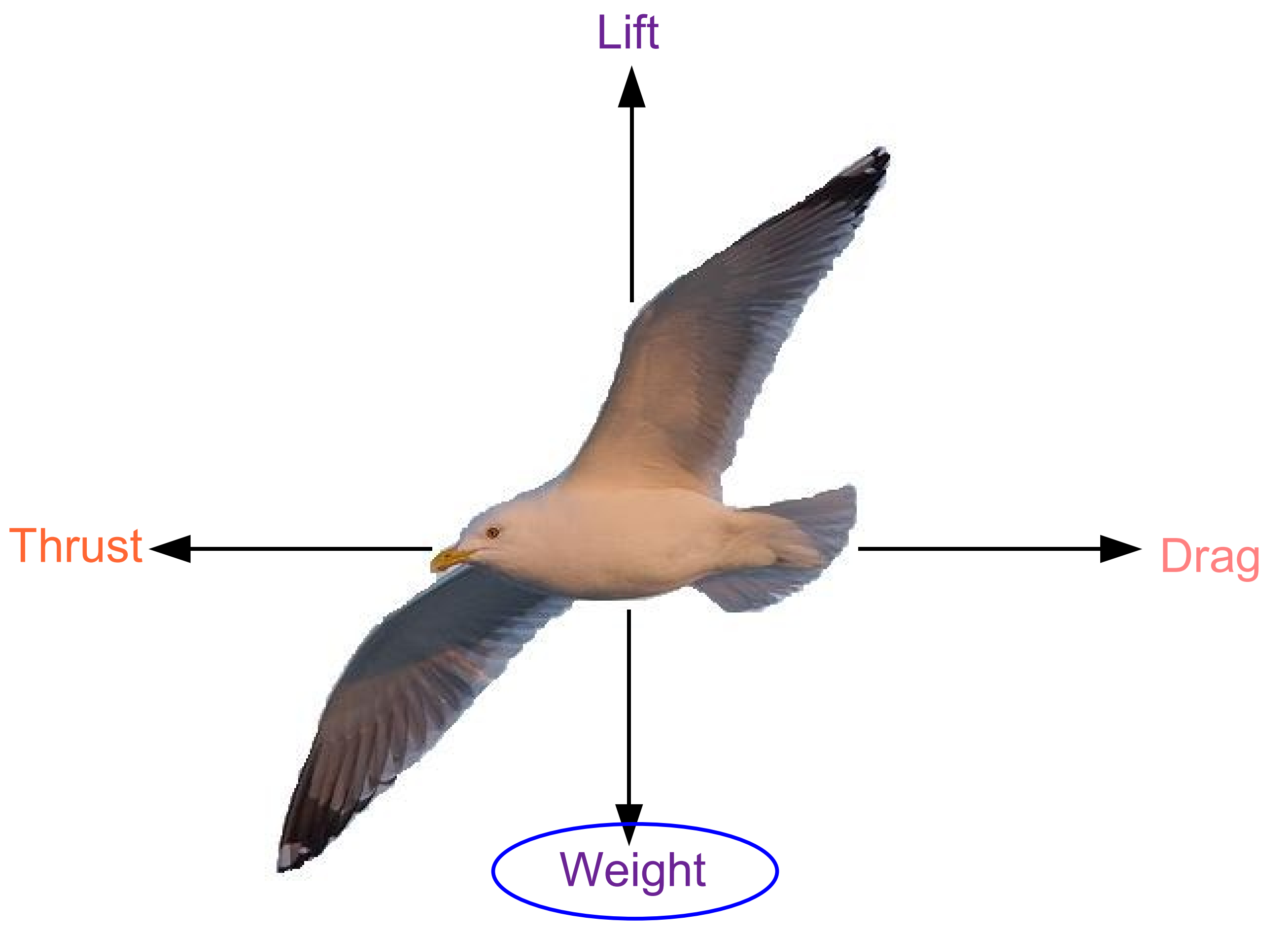
The Physics of Flight

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

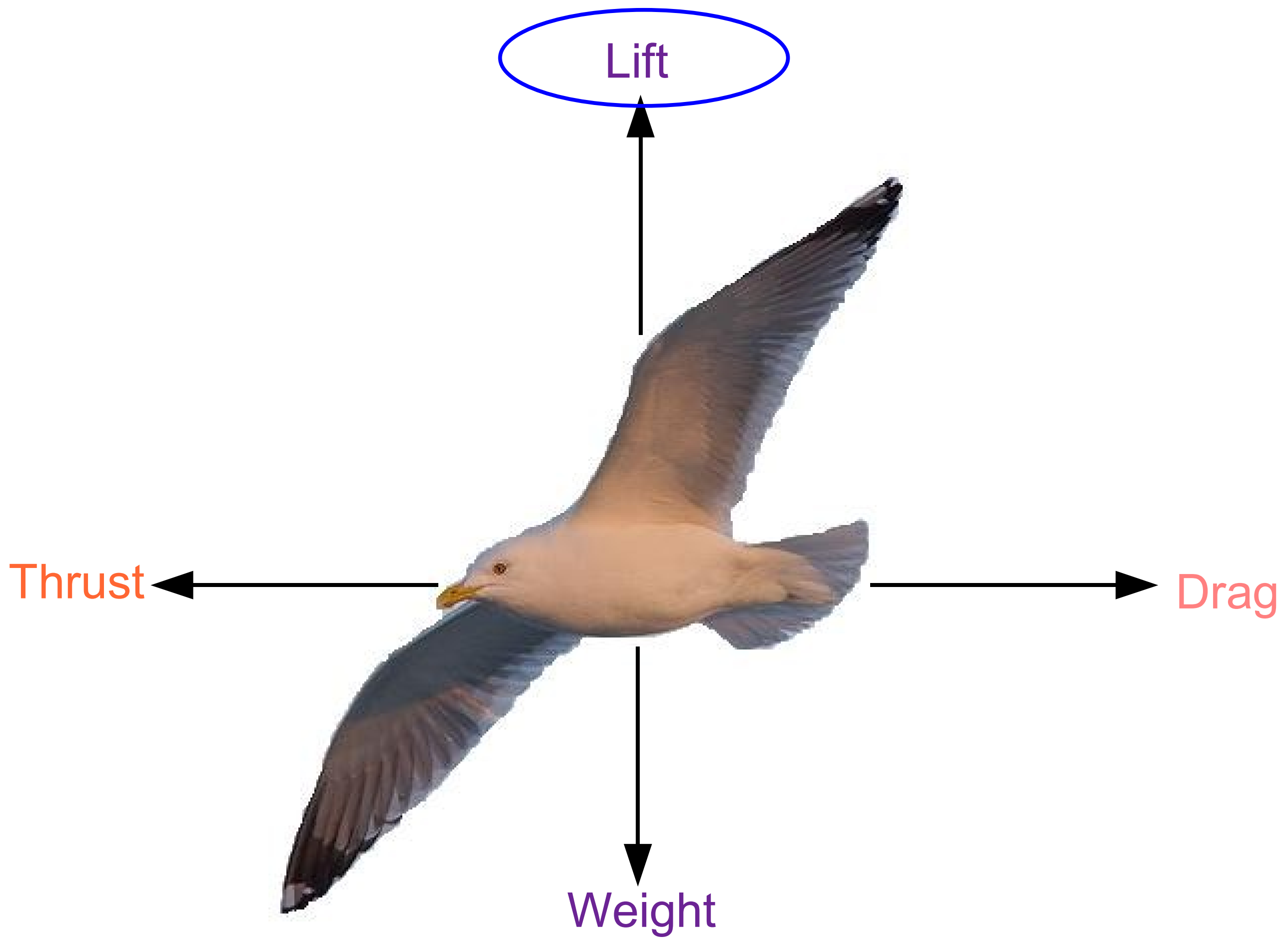


Weight = mass x gravity

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

The Physics of Flight

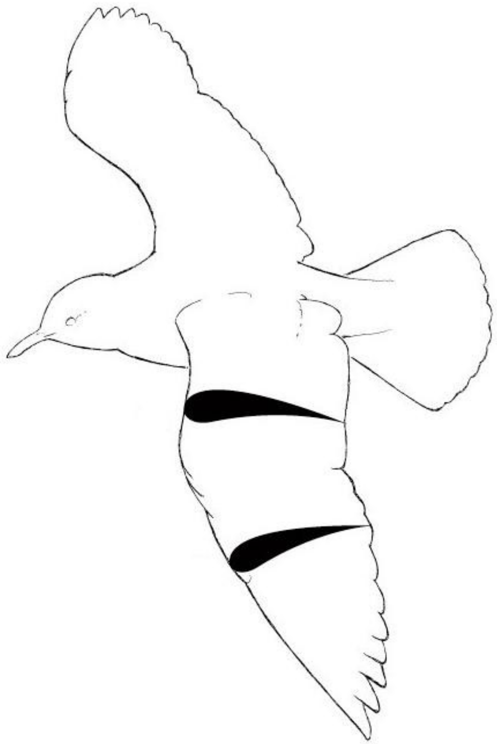
Now imagine a bird in level flight at a constant speed



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

Need a lift?

How do birds generate lift?

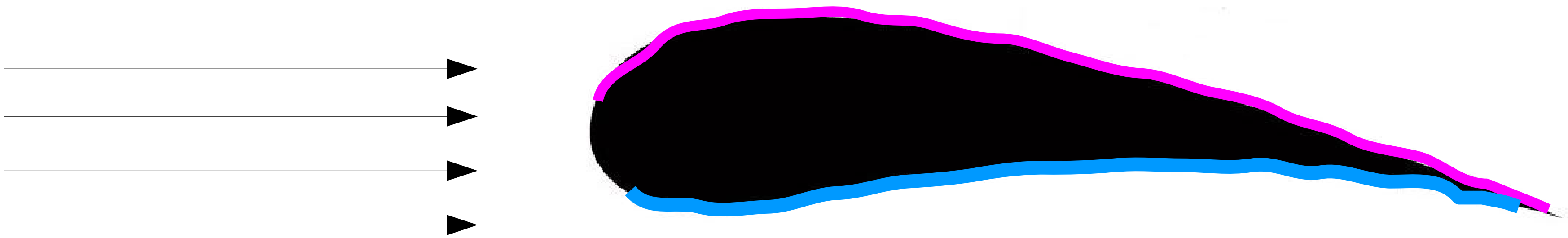


Wing in cross-section:

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 birds wing?



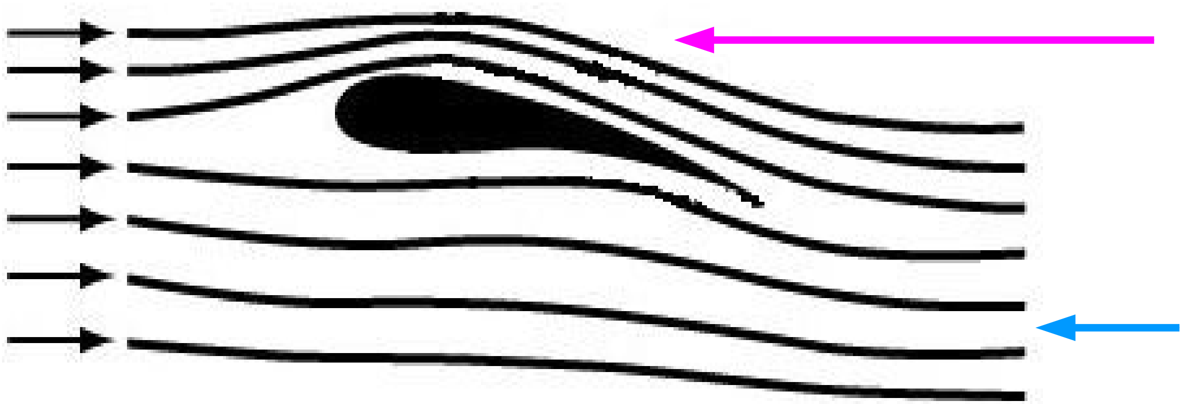
When air encounters something in its way, such as a wing, it must move around it.

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 birds wing?



Airflow is faster over the top

Airflow is slower under the wing

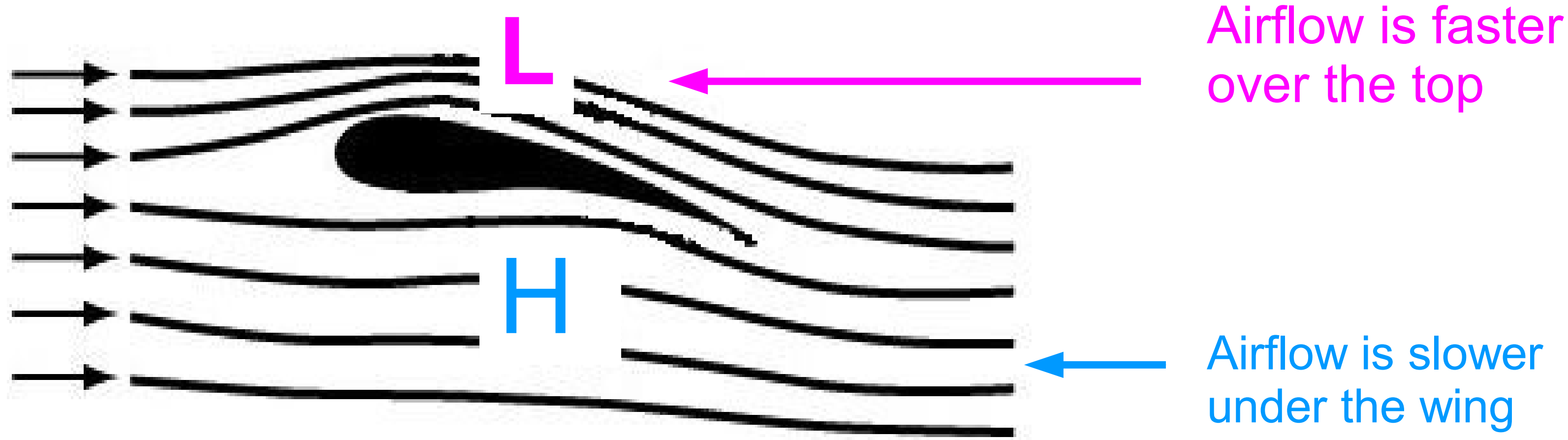
The air on top of the wing must move **faster** than the air below the wing

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 birds wing?



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

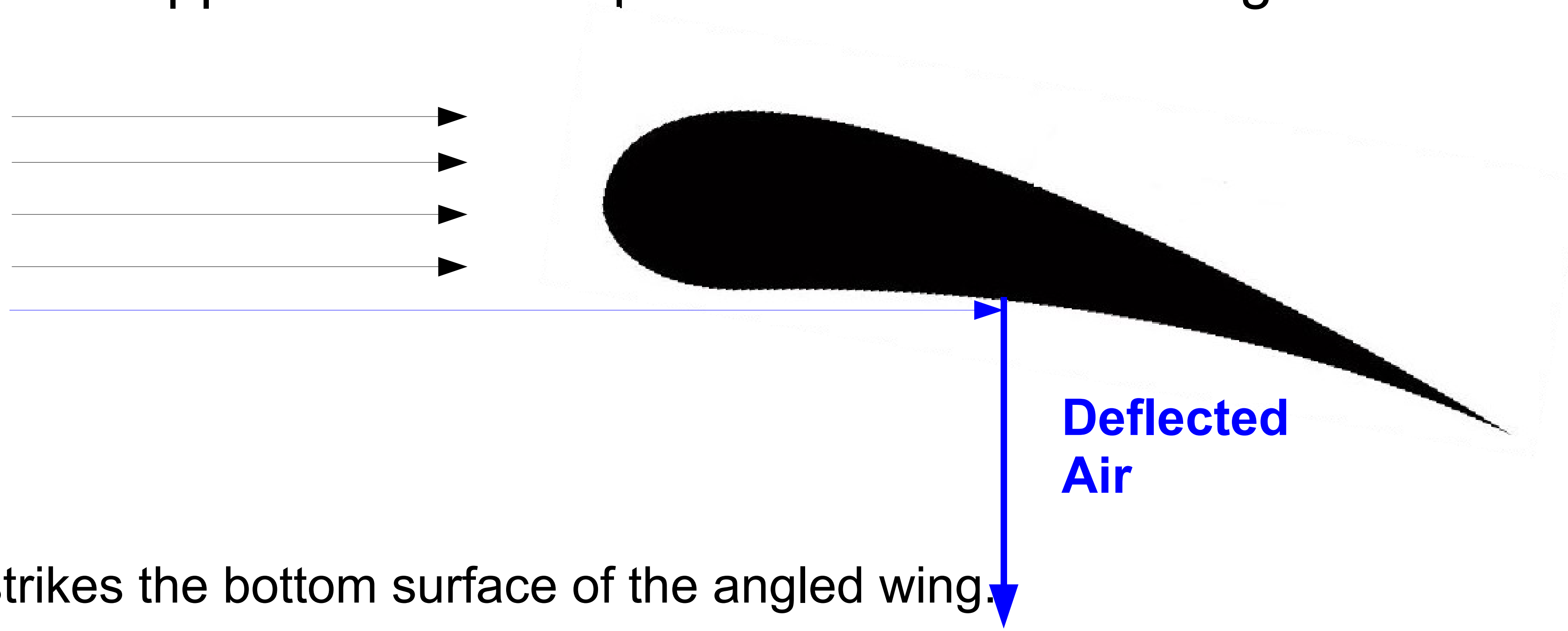
This difference in speeds results in a lowering of the air pressure above the wing, by

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 birds wing?

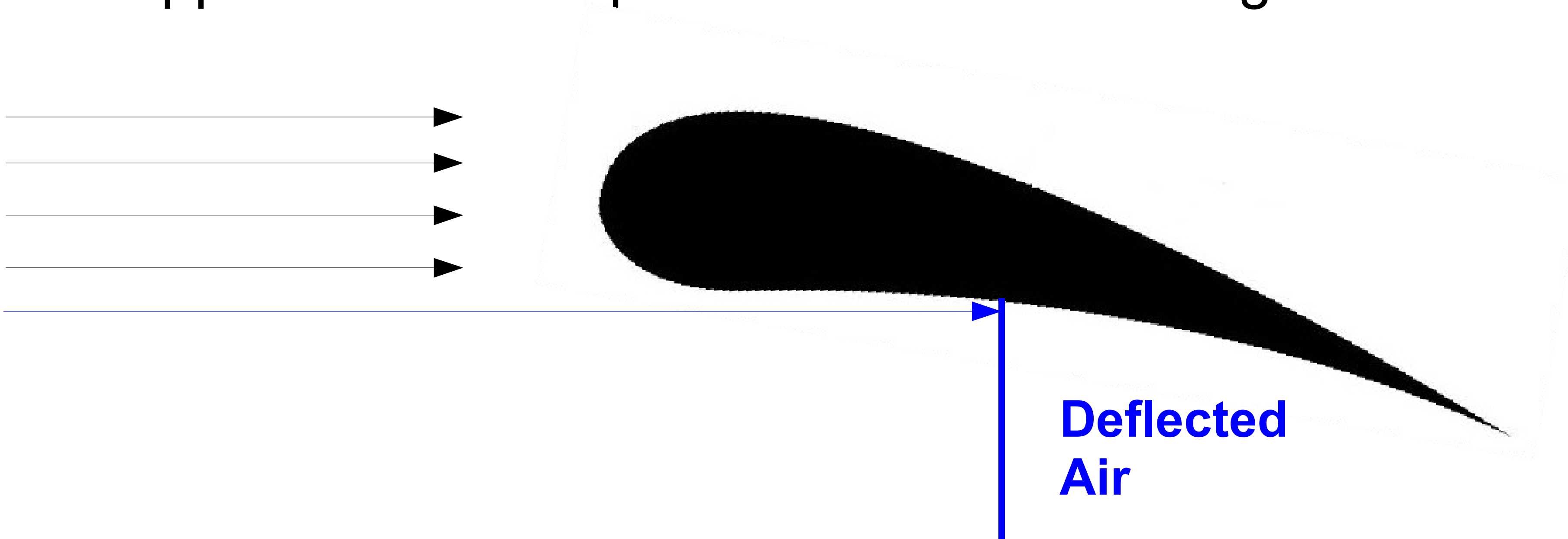


Air strikes the bottom surface of the angled wing.

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 birds wing?



Air strikes the bottom surface of the angled wing.

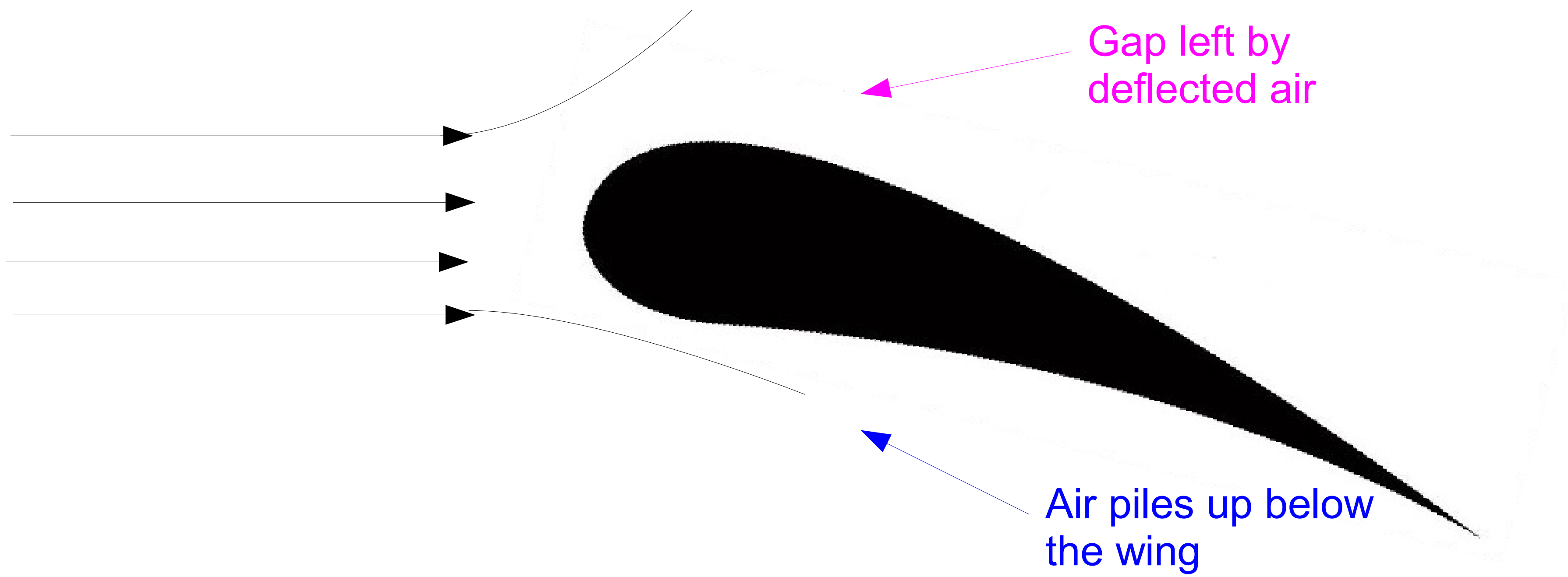
This mean that the AIR is deflected DOWN, while the WING is deflected UP!

This generates LIFT via

Newton's Third Law of Motion

Need a lift?

What happens to air that passes over a birds wing?

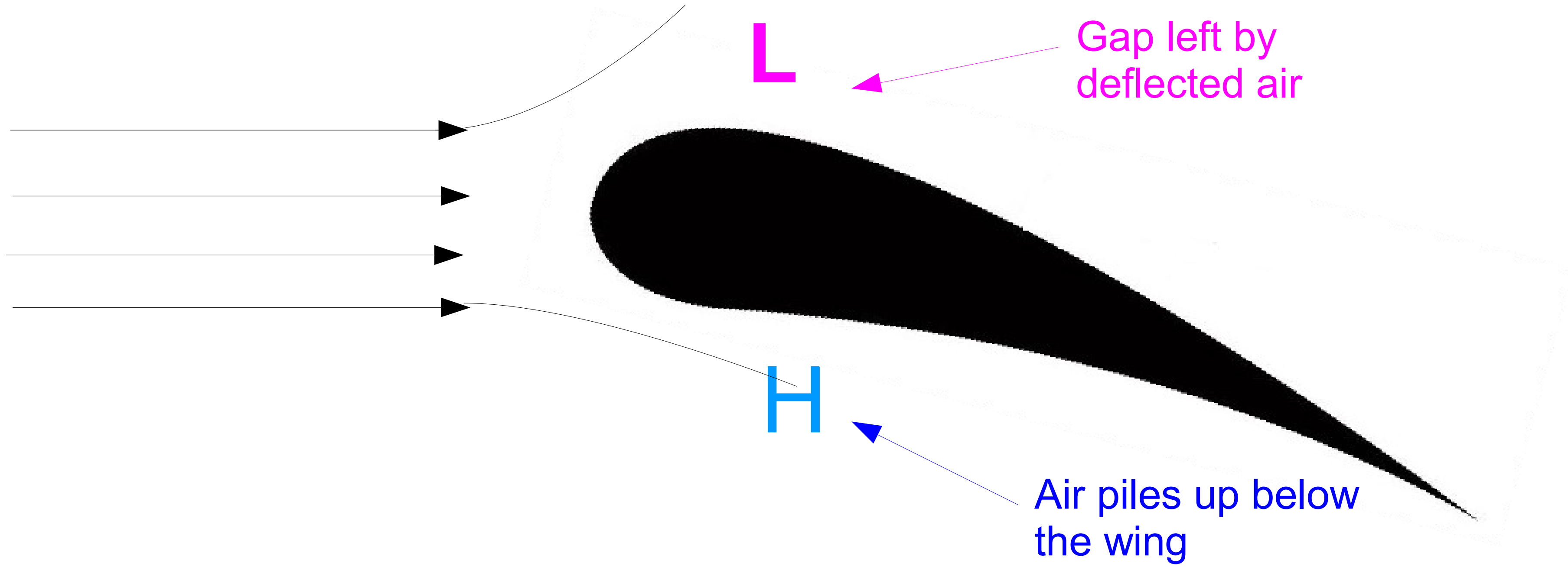


Air deflected above the wing leaves a gap of air above the wing – LOW P

Air deflected below the wing piles up – HIGH PRESSURE

Need a lift?

What happens to air that passes over a birds 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...

Daniel Bernoulli

Differential pressure creates lift!

The reaction force from air hitting the wing creates lift!

Sir Isaac Newton

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 ...

~~Bernoulli vs. Newton~~
Navier-Stokes

Continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X – Momentum:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right]$$

Y – Momentum:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right]$$

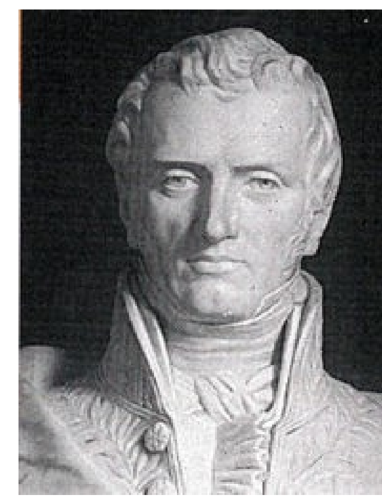
Z – Momentum

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right]$$

Energy:

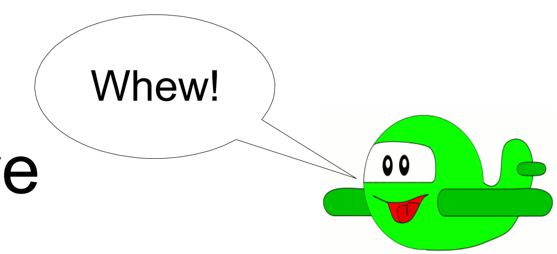
$$\frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right]$$
$$+ \frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\,\tau_{xx} + v\,\tau_{xy} + w\,\tau_{xz}) + \frac{\partial}{\partial y}(u\,\tau_{xy} + v\,\tau_{yy} + w\,\tau_{yz}) + \frac{\partial}{\partial z}(u\,\tau_{xz} + v\,\tau_{yz} + w\,\tau_{zz})\right]$$

George Stokes



Claude-Louis Navier

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

Lift α Area

L α A

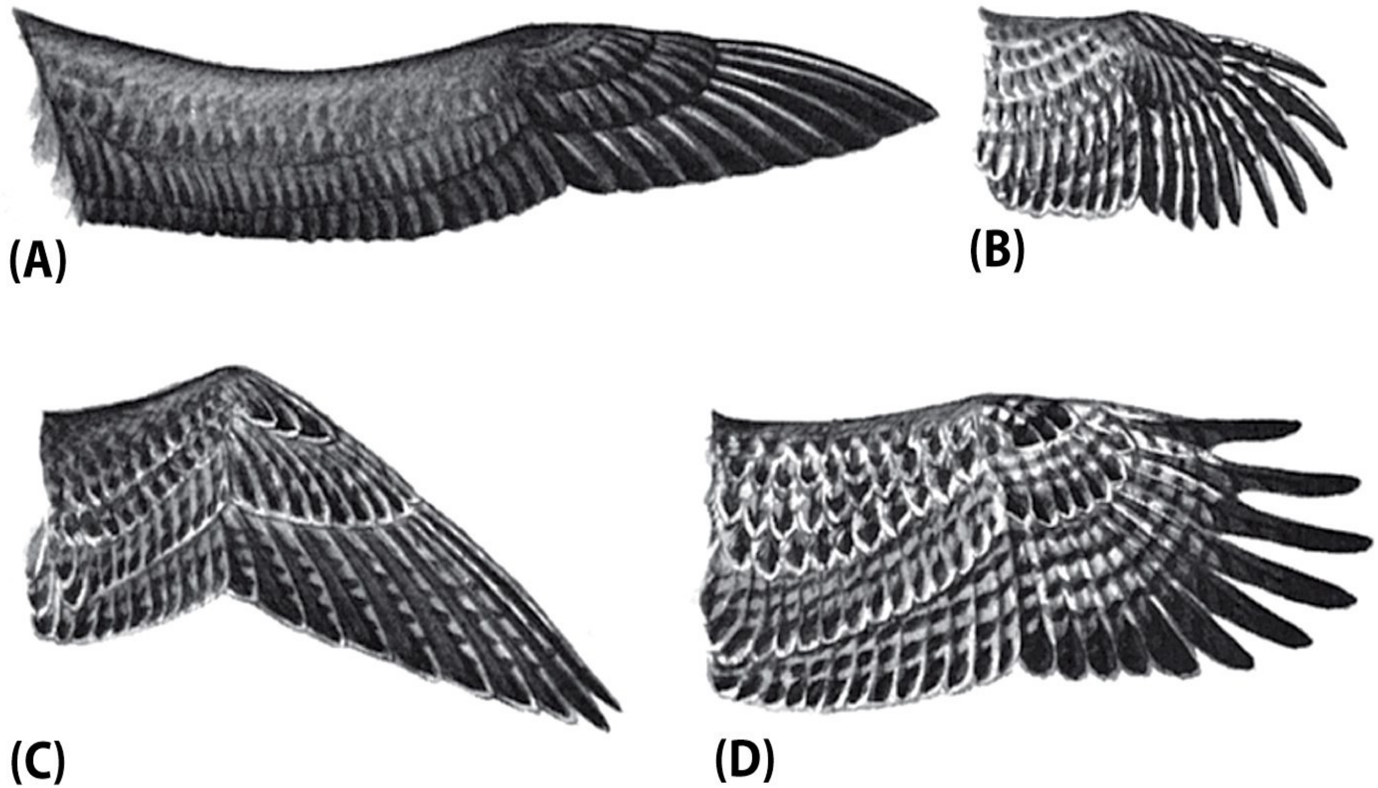


Figure 5-14
Ornithology, Third Edition

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!*

Need a 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*

Need a lift?

Concept-test:

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a. The european swallow, b/c it has twice the wing area

b. The african swallow, b/c it flies twice as fast

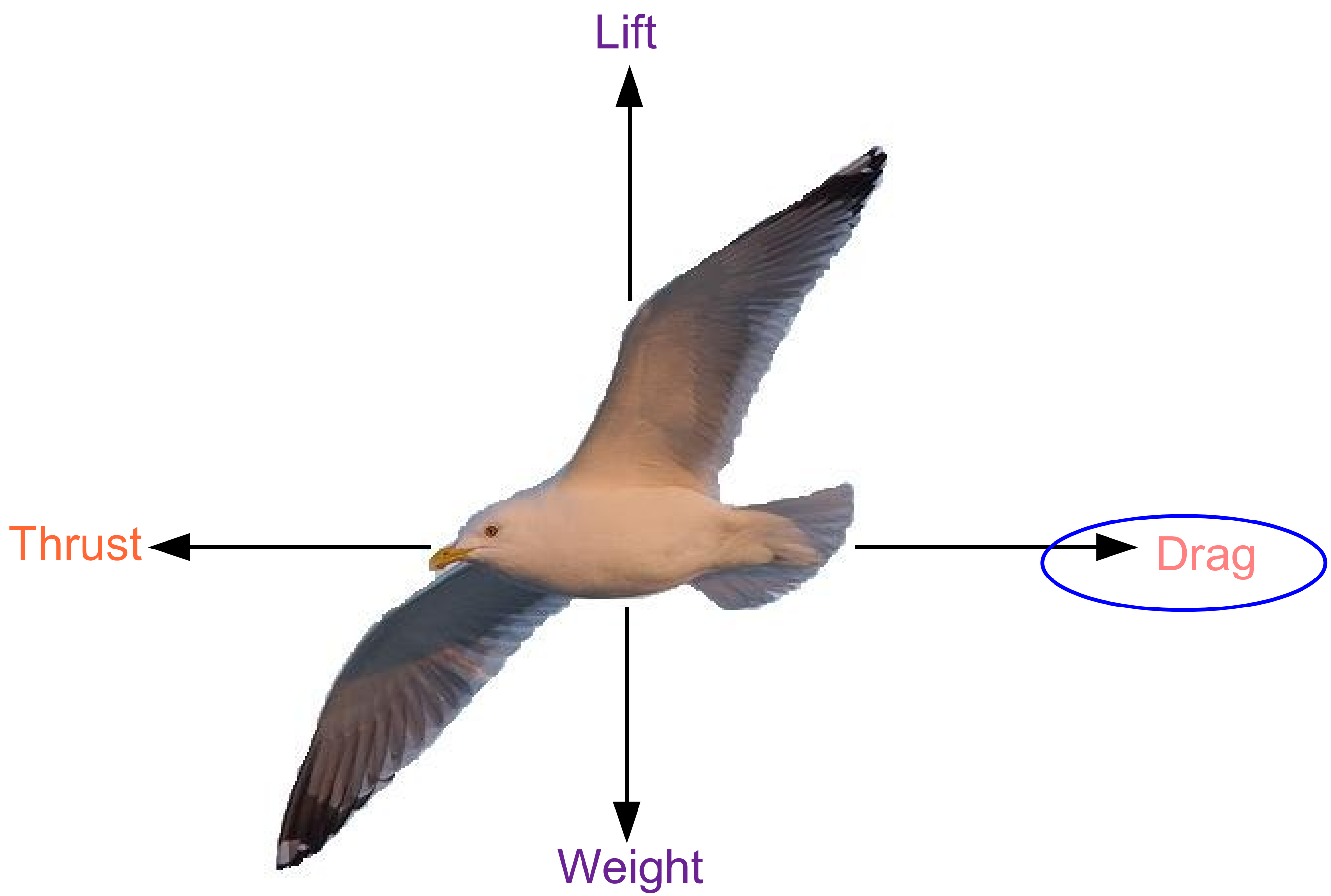
c. They generate the same amount of lift

While lift is proportional to the wing area, it is proportional to the speed SQUARED.

$L \sim Av^2$

The Physics of Flight

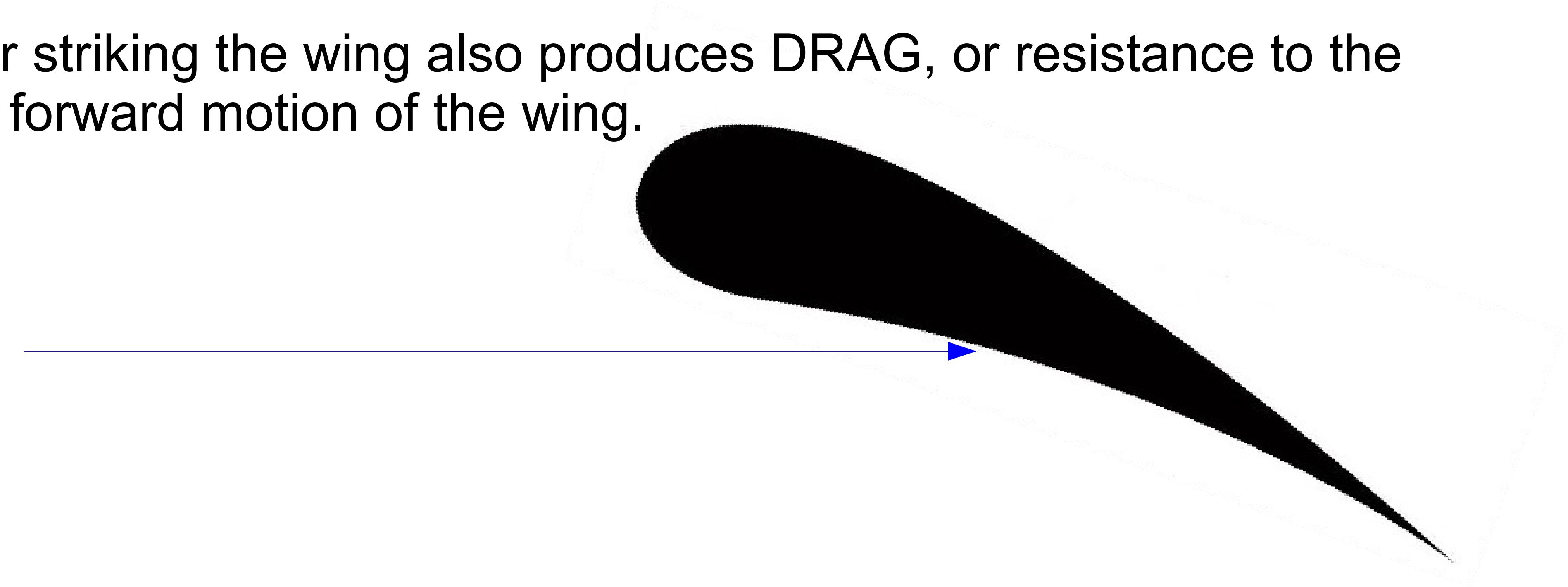
Now imagine a bird in level flight at a constant speed



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

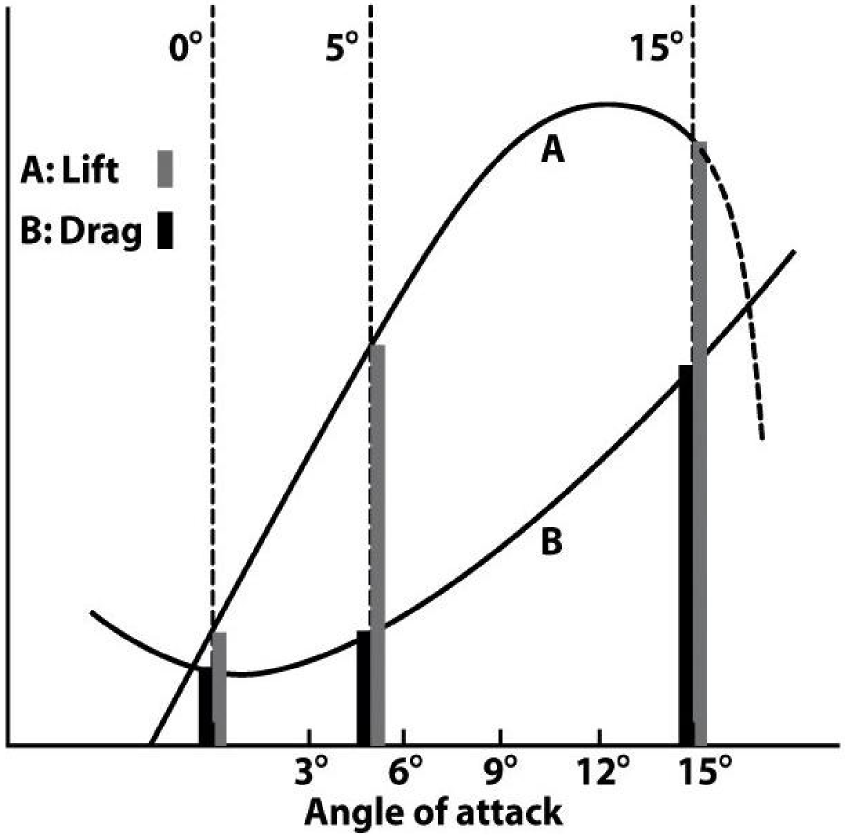
More air hits the wing when the VELOCITY is higher

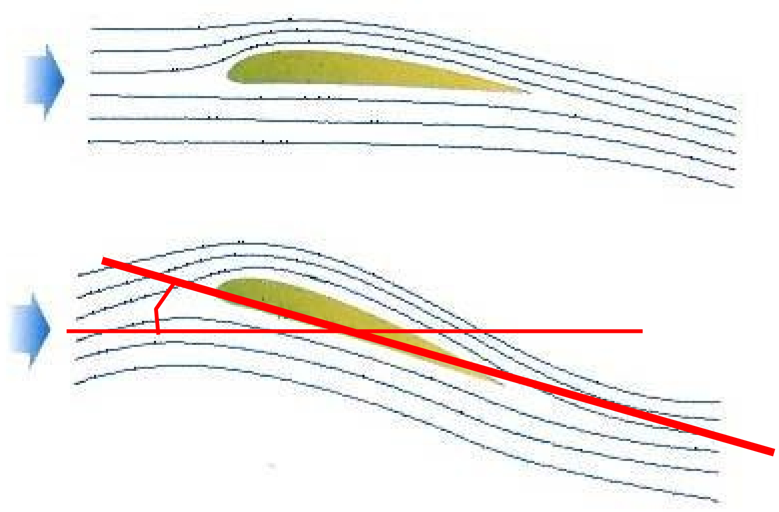
$$\text{Drag} \propto Av^2$$

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

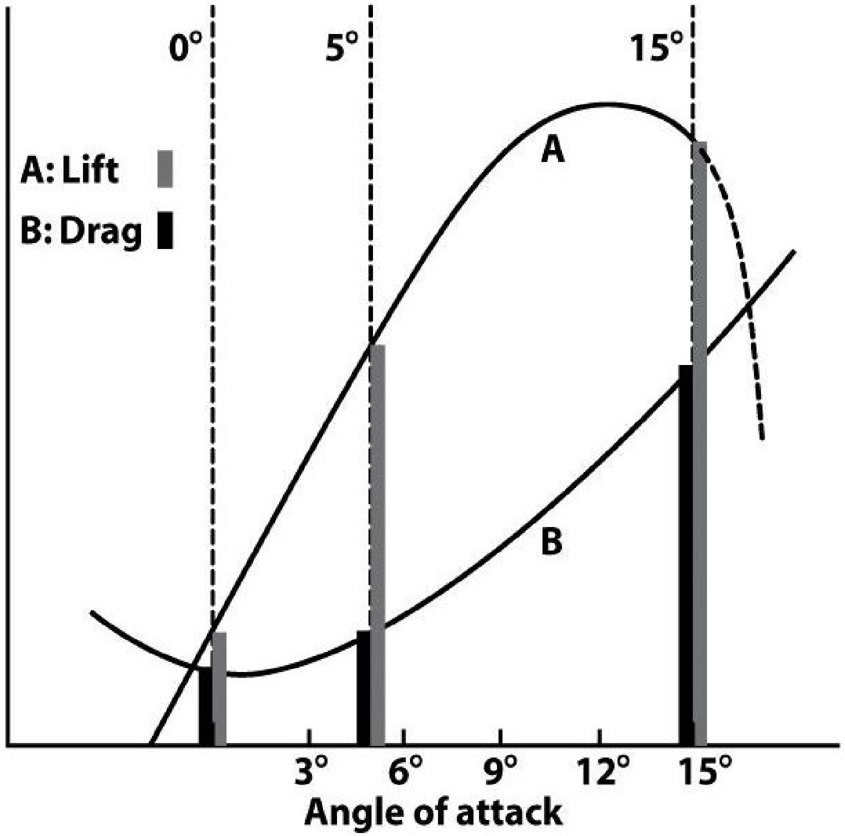




Angle of Attack

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

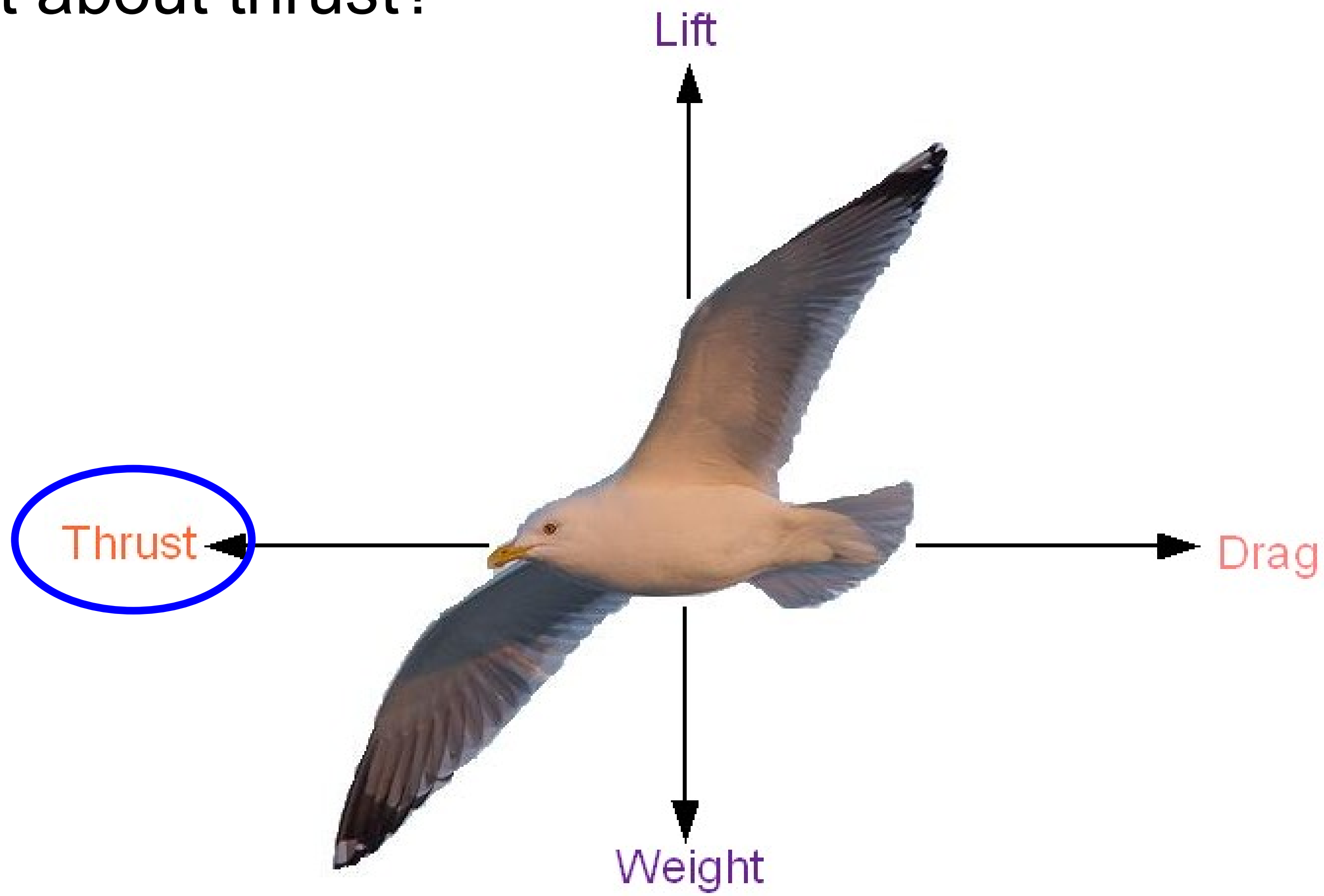
When AA is greater than about 15, drag >> lift, and the bird STALLS



Force Body Diagram revisited

So now we have some expressions for weight, lift and drag.

What about thrust?

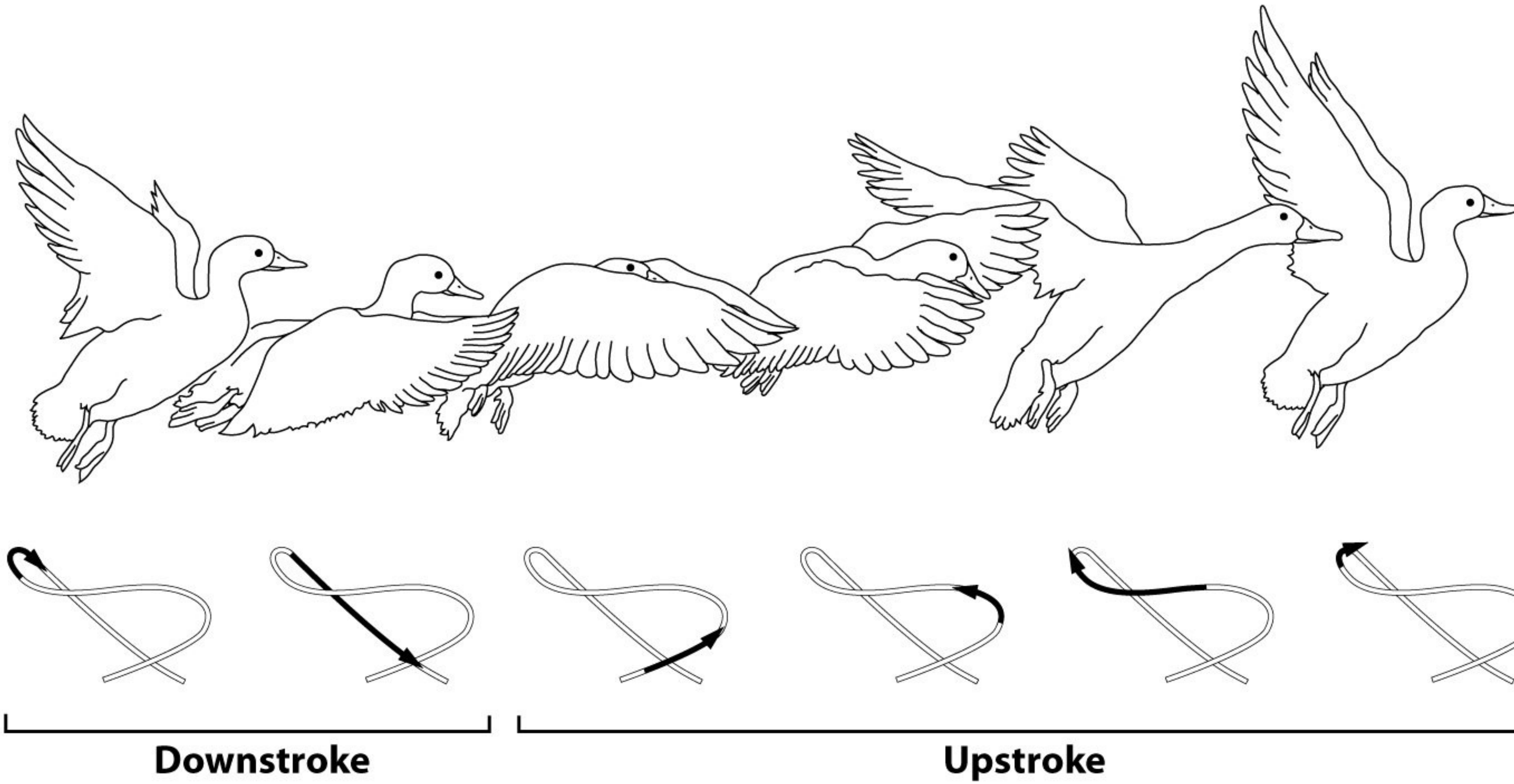


Thrust is the force which propels a bird forwards through the air

Thrust

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

Flapping!

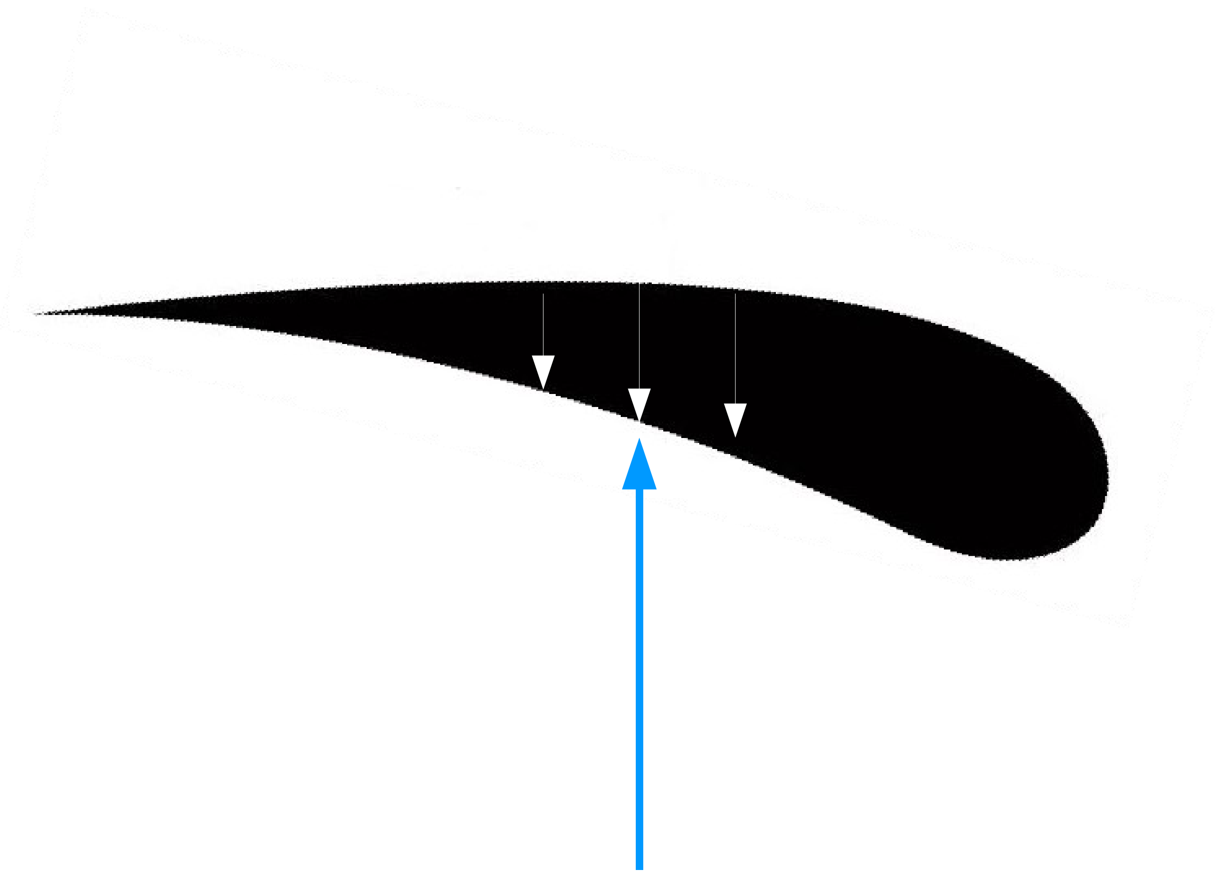


Generates Power

Recovery Stroke

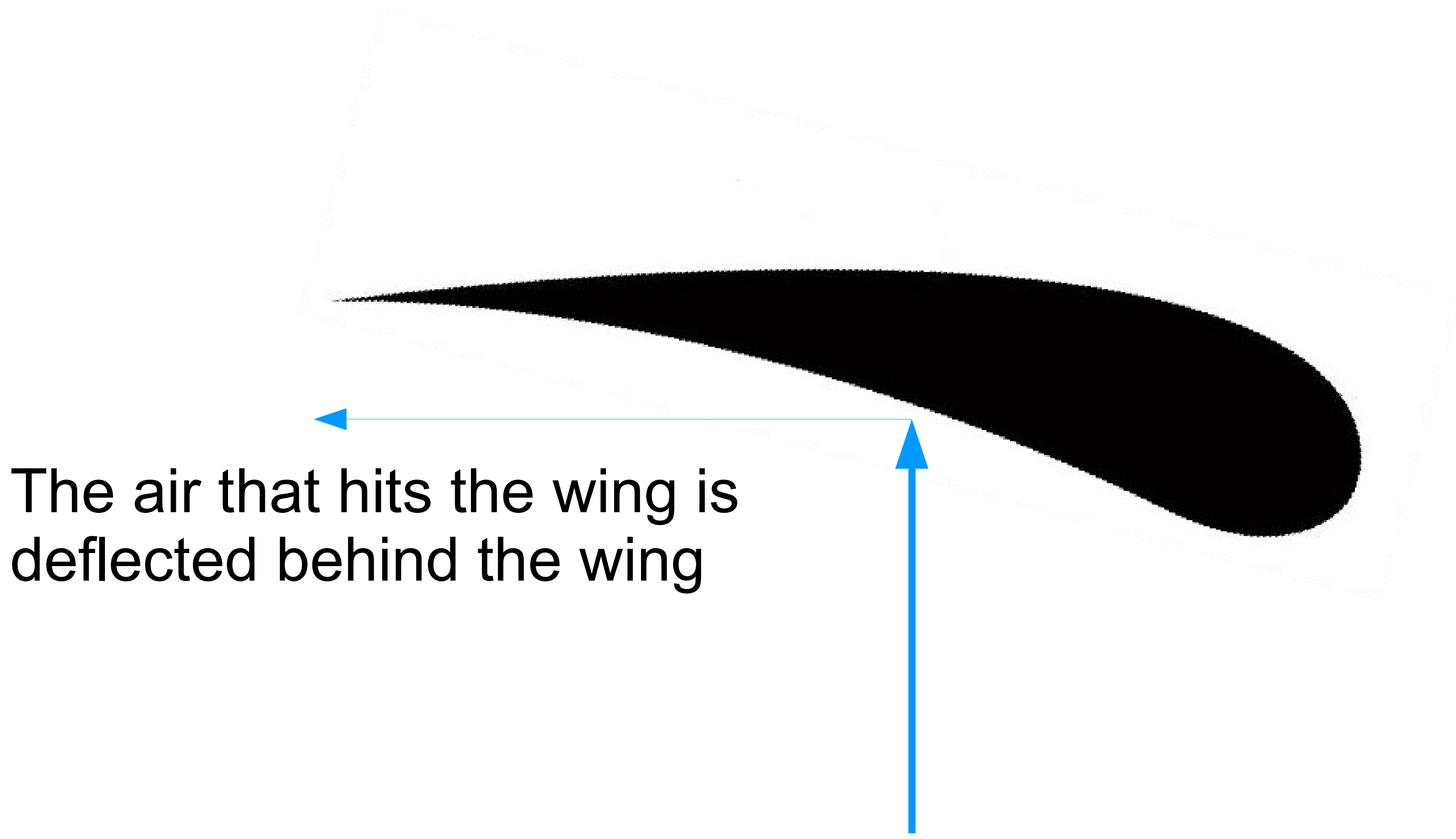
Thrust

DOWNSTROKE - air collides with the underside of the wing



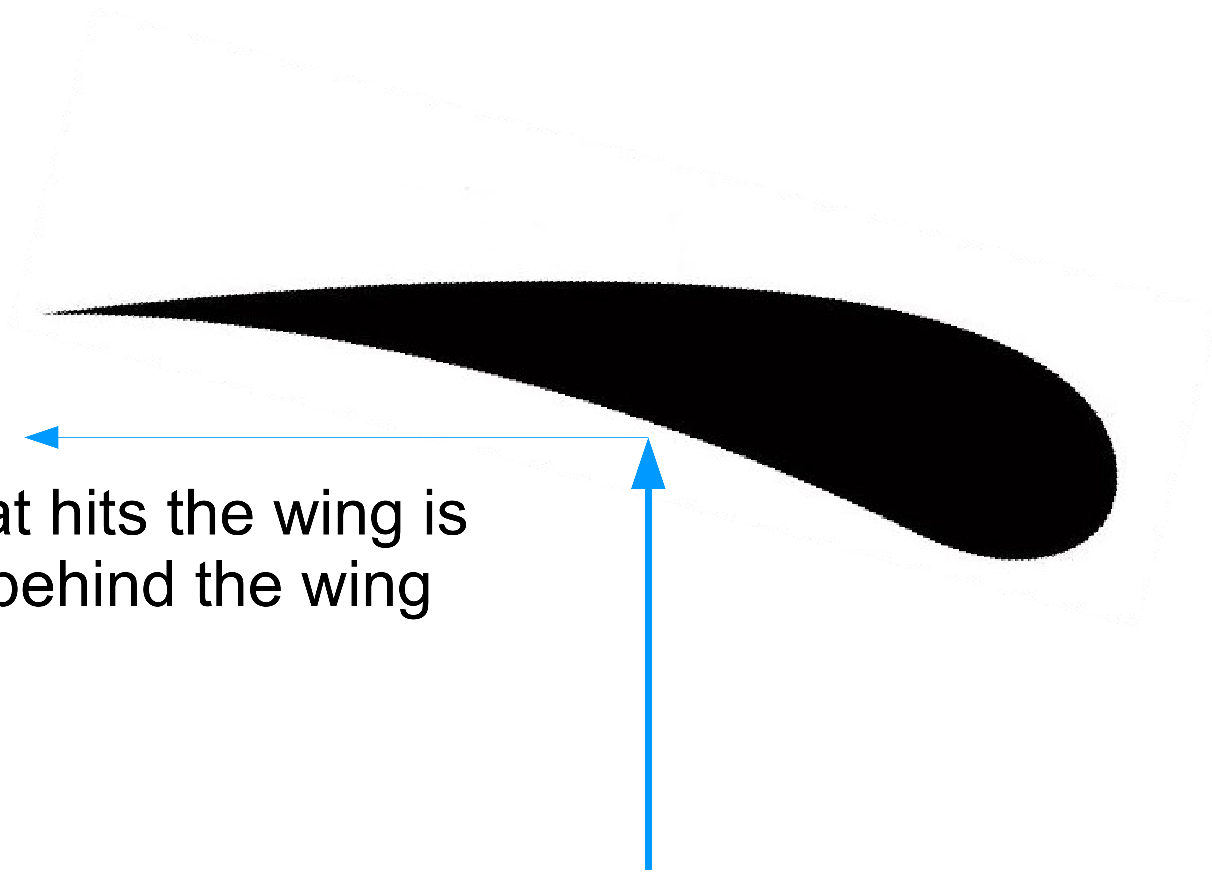
Thrust

DOWNSTROKE - air collides with the underside of the wing



Thrust

DOWNSTROKE - air collides with the underside of the wing



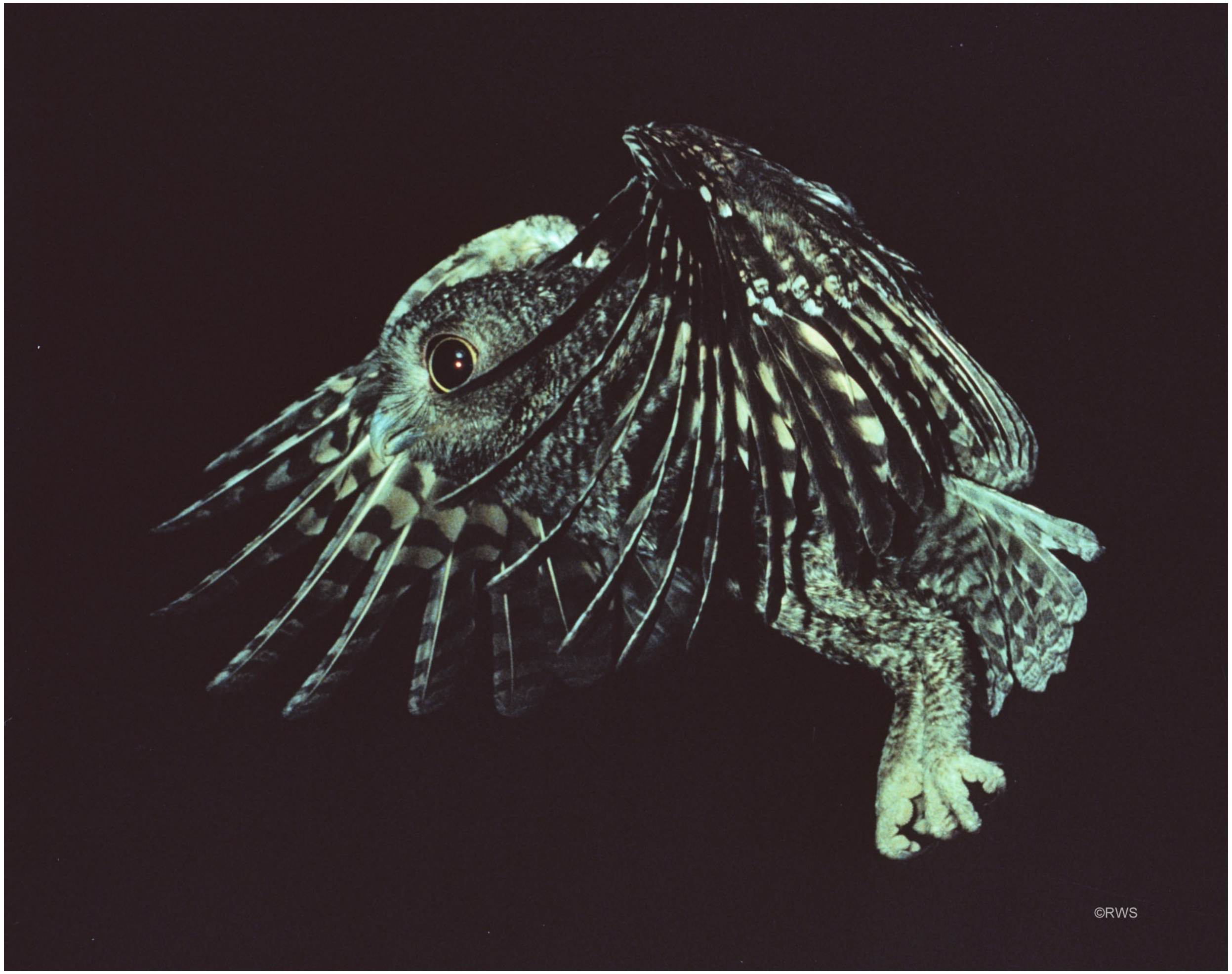
The air that hits the wing is deflected behind the wing

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

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).

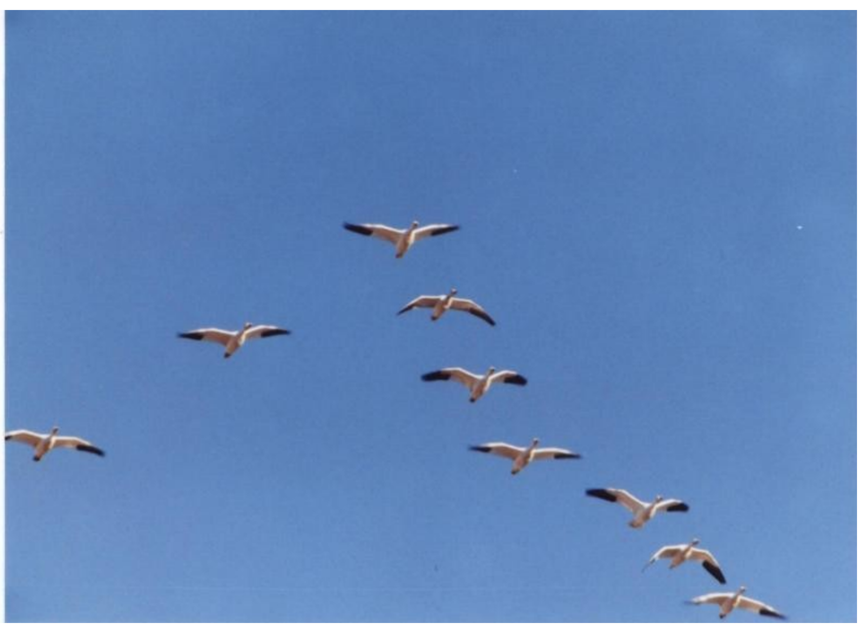
To fly faster, birds don't flap more quickly – this would create too much turbulence
Instead, they increase the depth of each stroke!

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

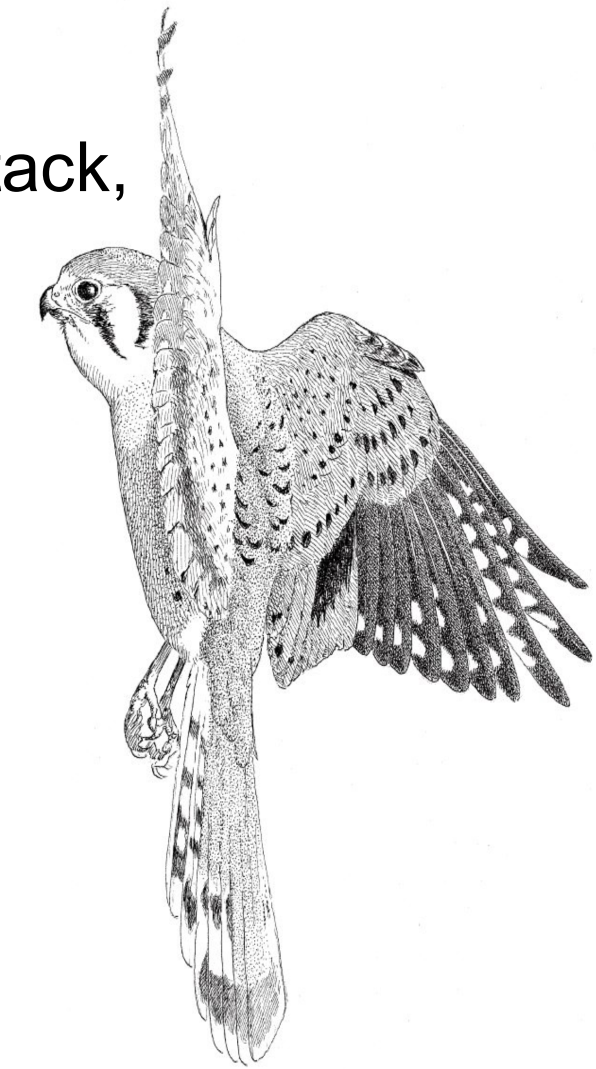


Figure 5-5a
Ornithology, Third Edition

Turbulence

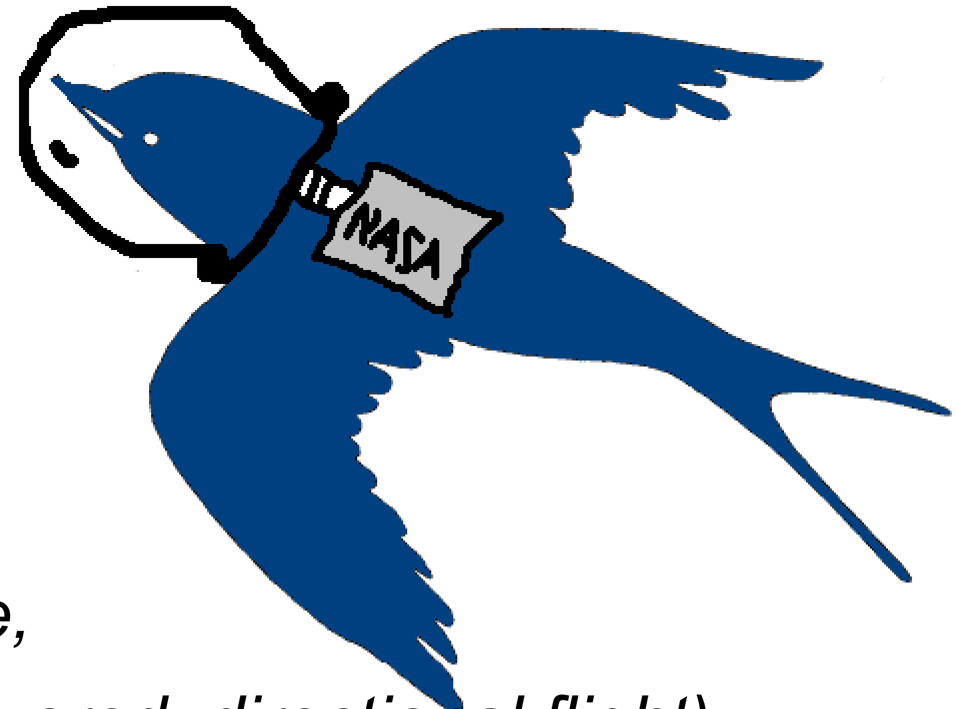
Turbulence can also be used to generate extra lift!

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

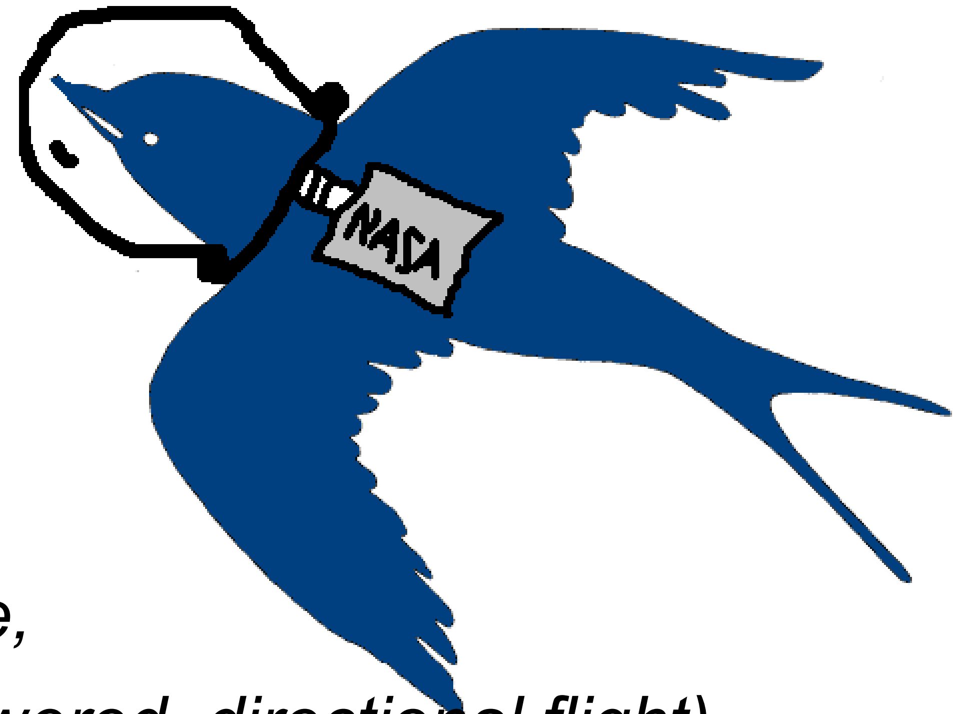


Concept-test:

Assuming that they could breathe,

would birds be able to fly (i.e. powered, directional flight) in space??

Thrust



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 vaccuum 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

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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

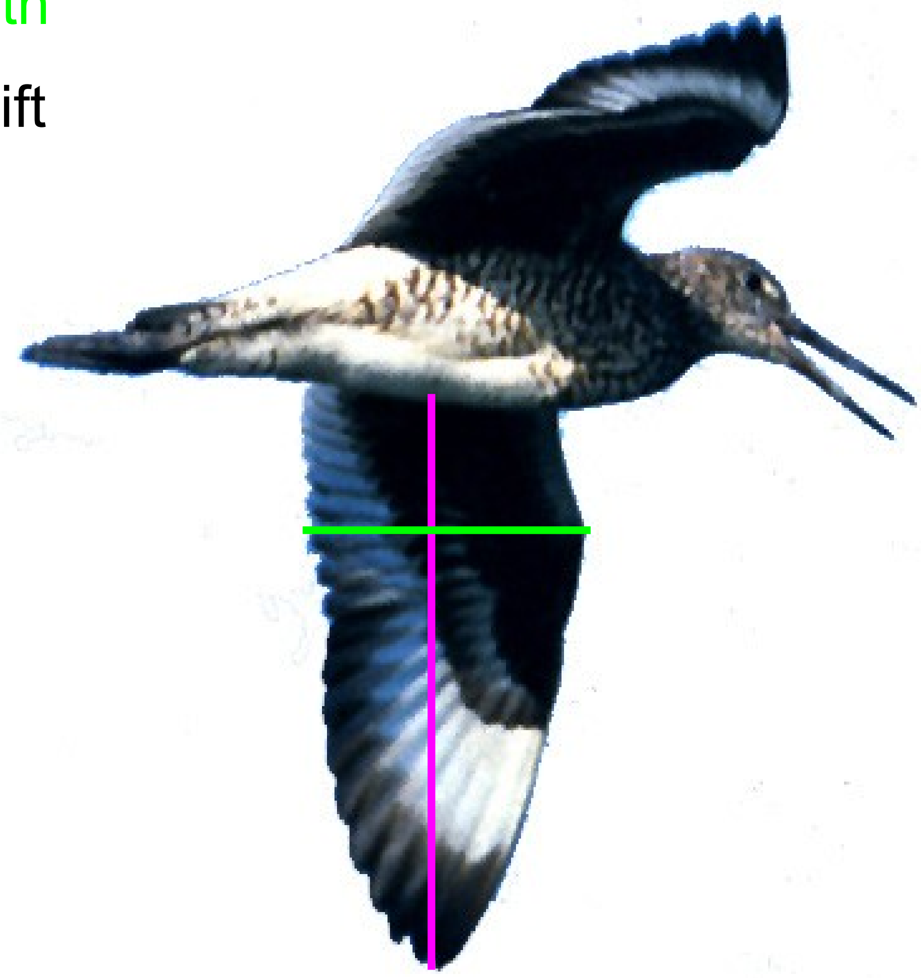
Species with high wing loading tend to be powerful short distance fliers, and need a lot of speed to take off.

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

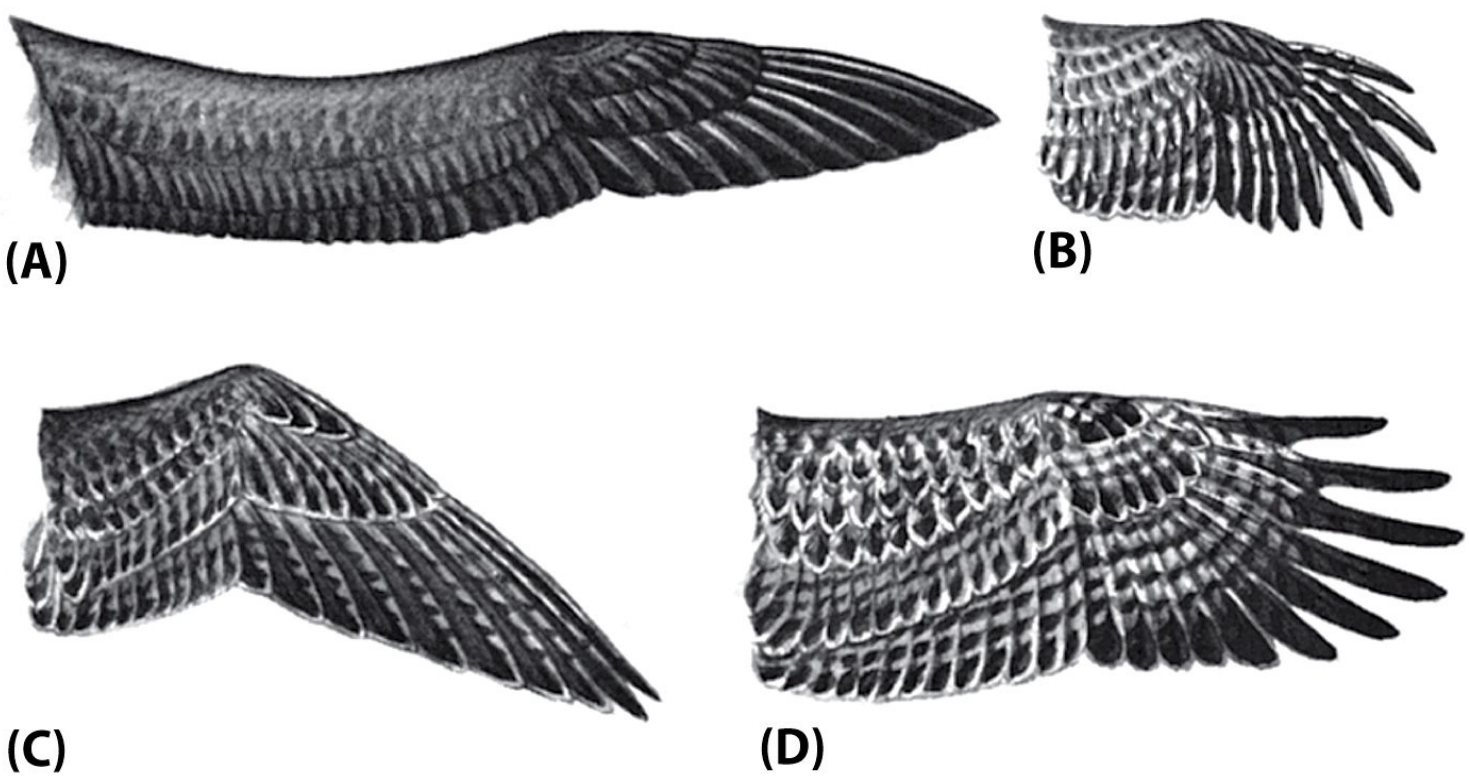


Figure 5-14
Ornithology, Third Edition

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

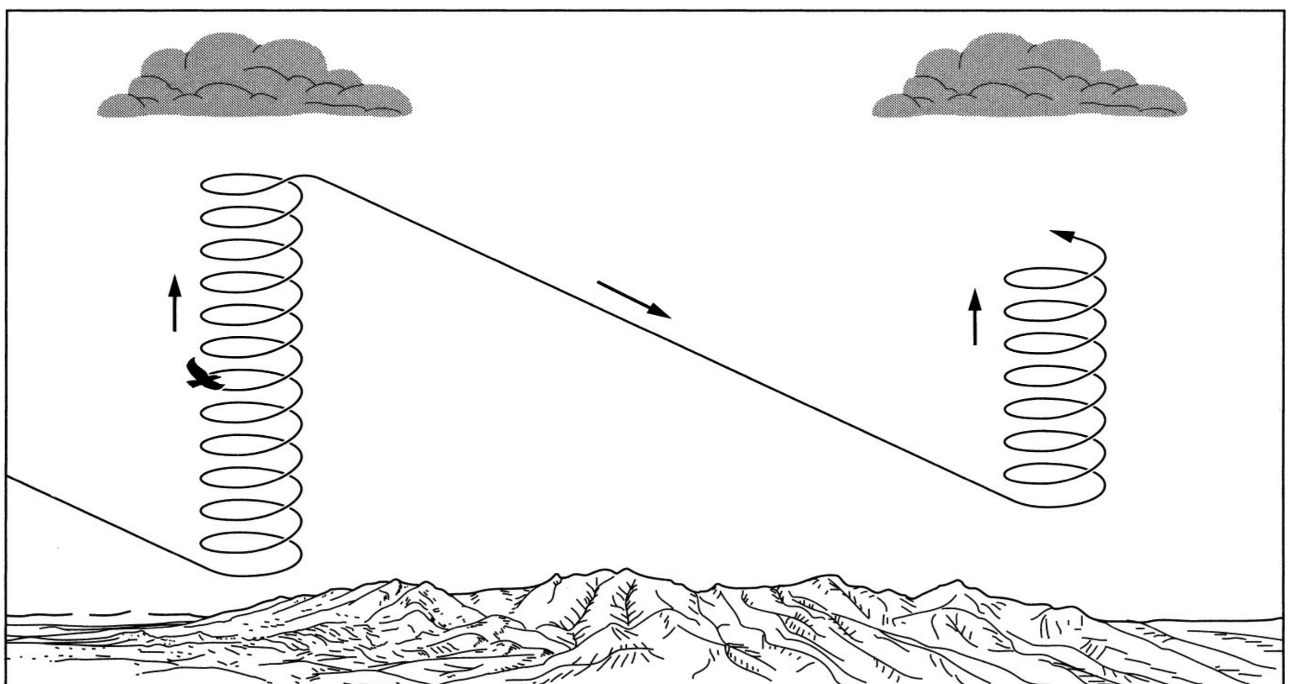
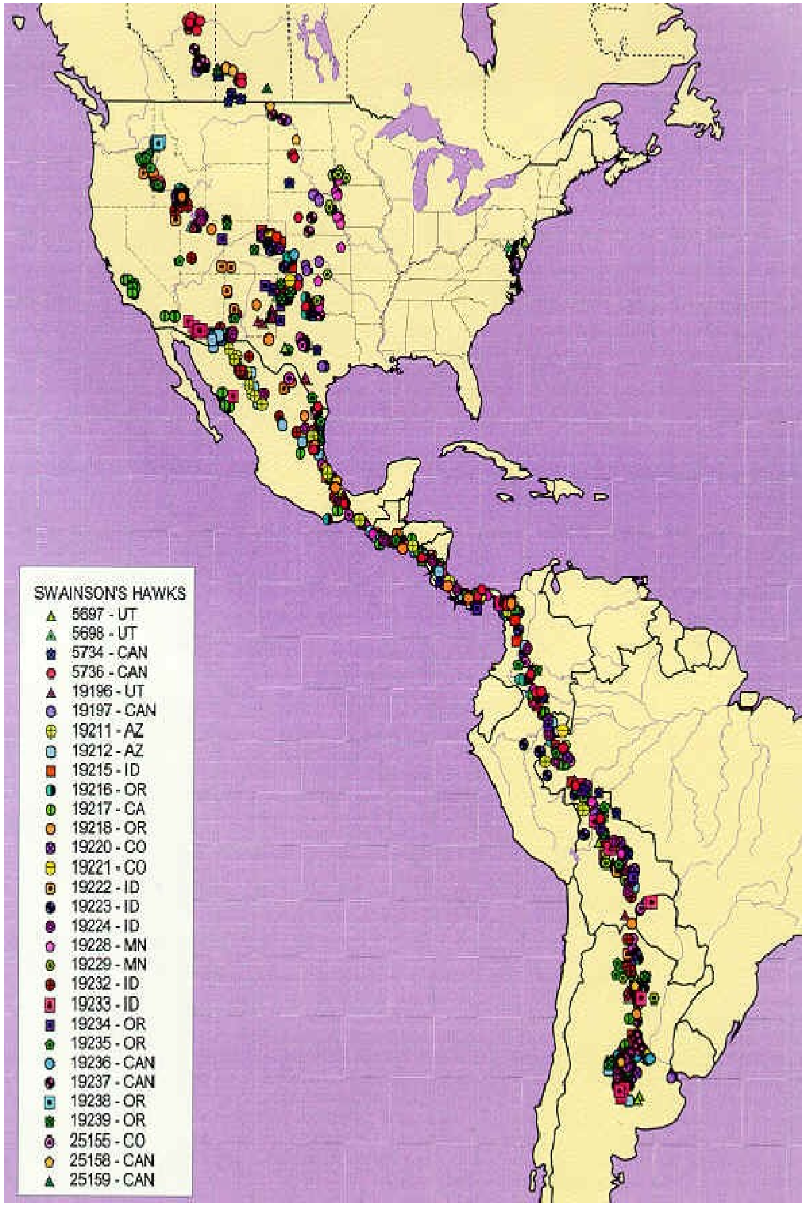


Figure 5-7
Ornithology, Third Edition

Types of Flight

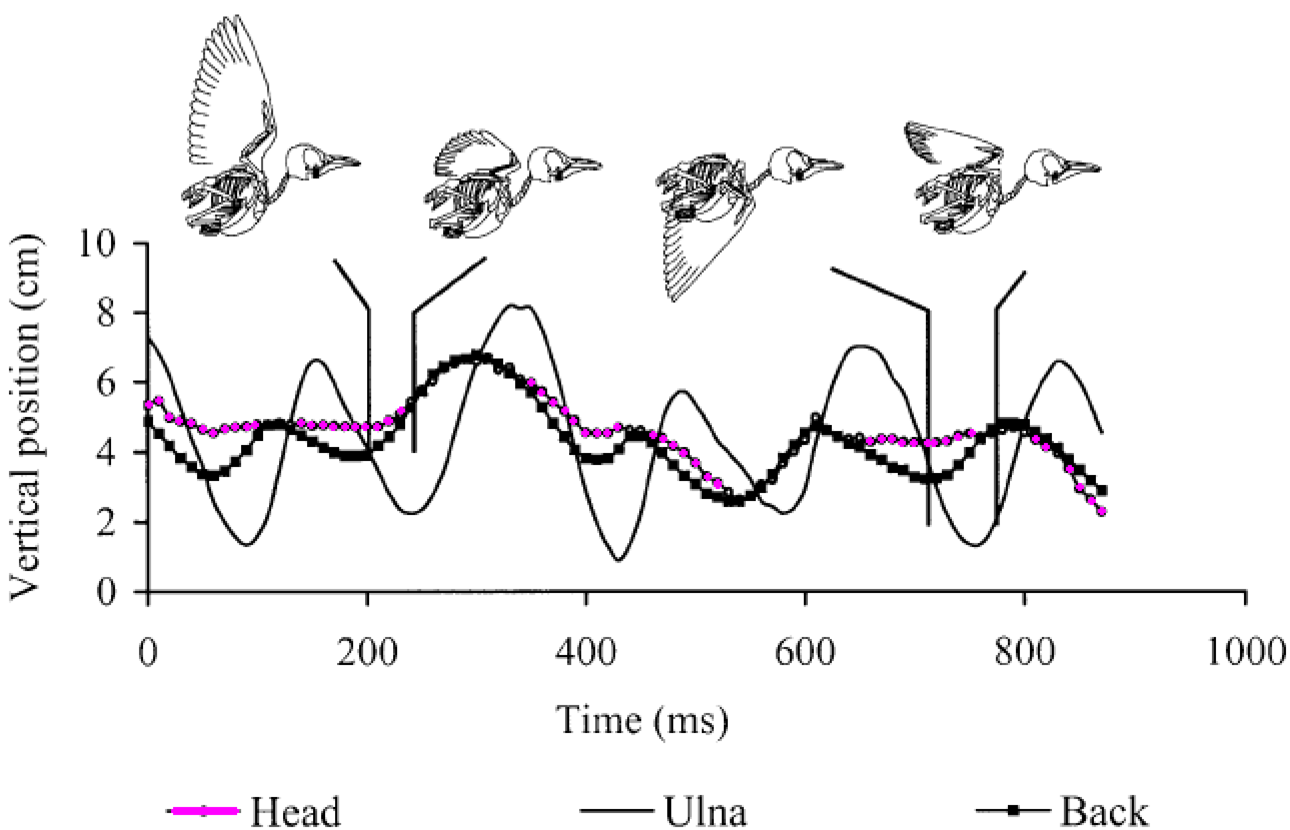
- Soaring or gliding
  - Critical to migration of raptors
  - Long distance, slow migration, with minimal energy



Types of Flight

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

video



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

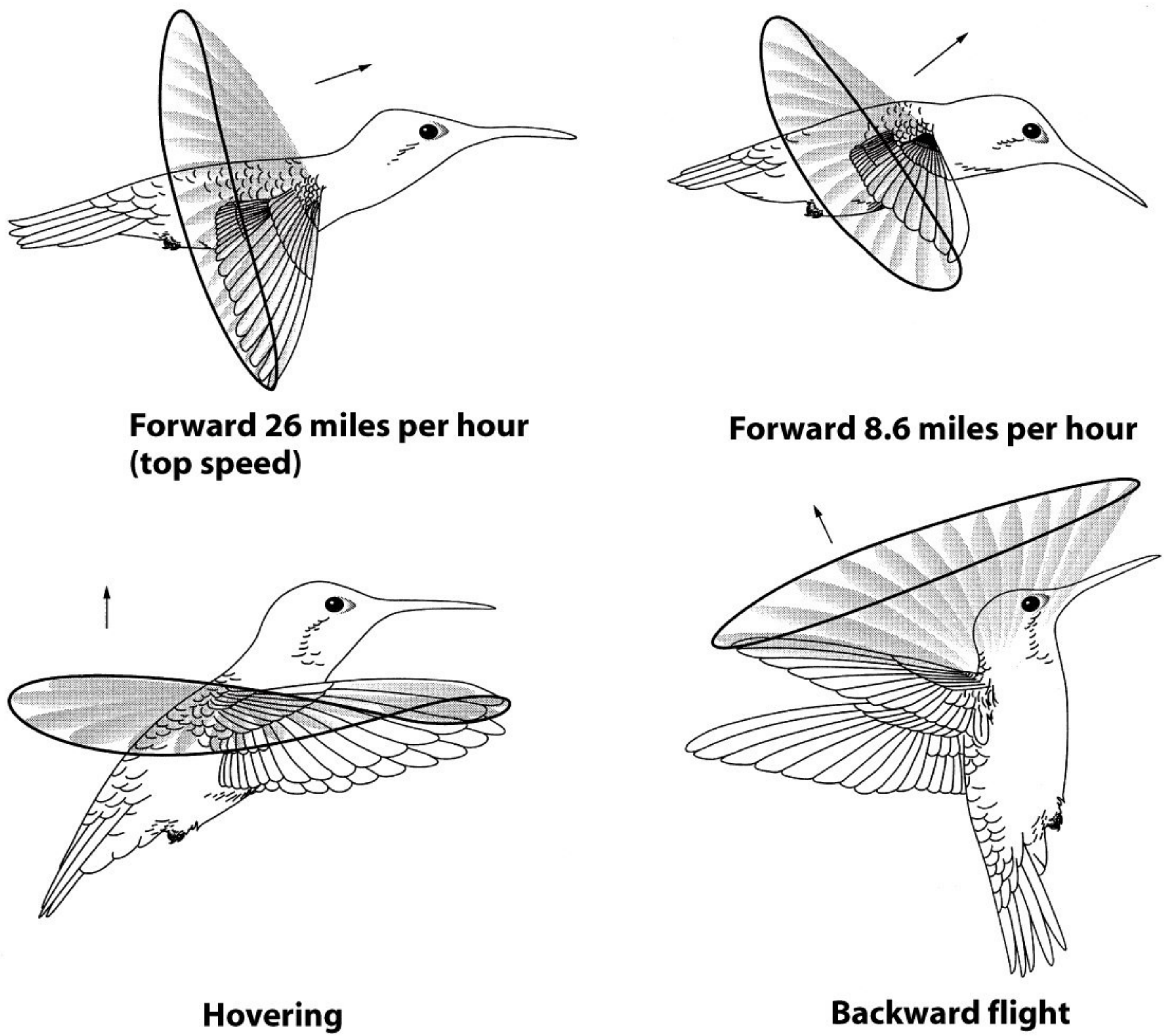
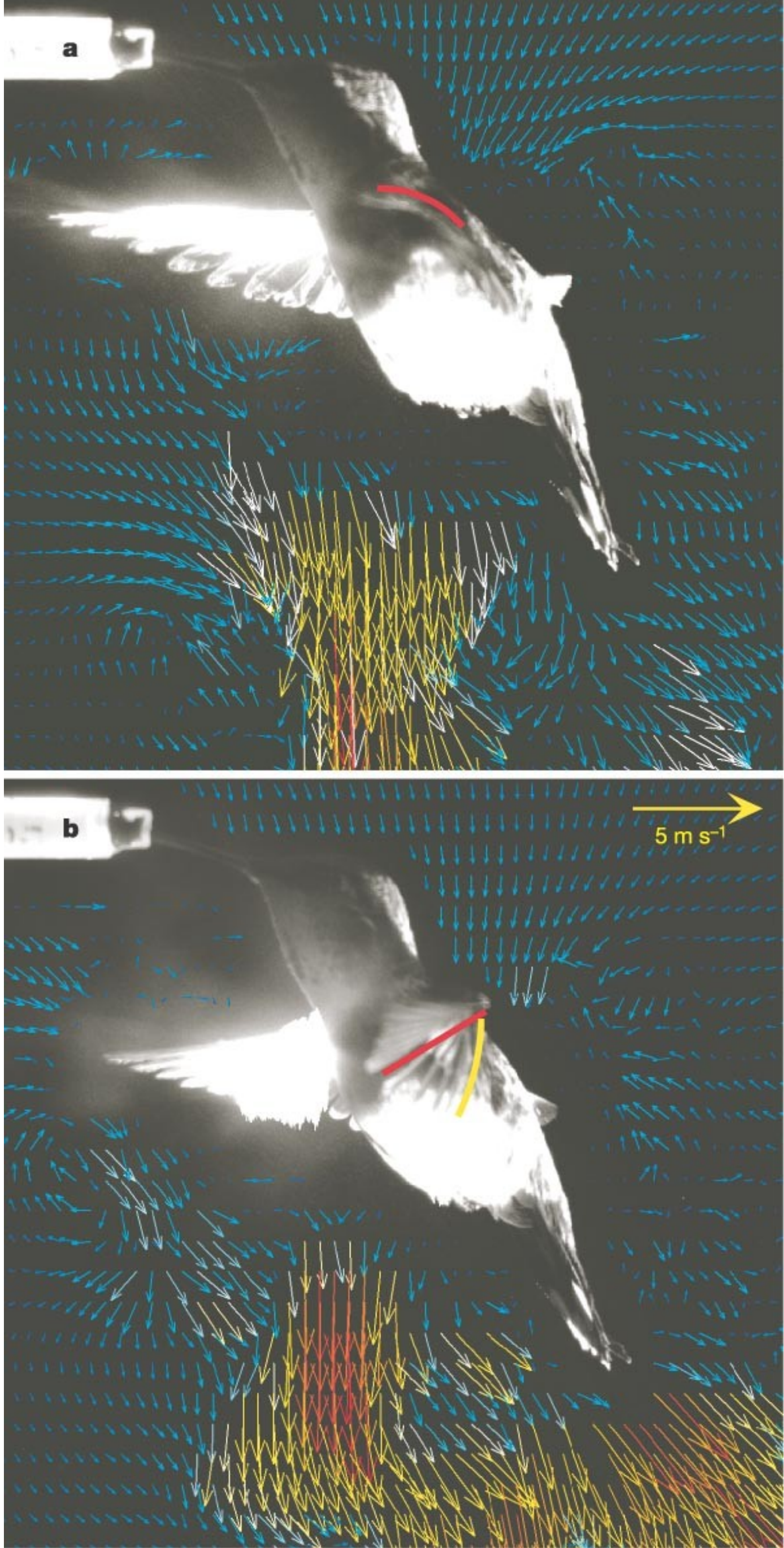


Figure 5-9
Ornithology, Third Edition

Show hummer video

Types of Flight

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



Warrick, et al. *Nature* **435** (2005).

Physics and Conservation

The Marbled Murrelet (Alcidae)

mass ~ 220 g

wing area ~ 75 cm^2

Compare to Mourning Dove

mass ~ 130 g

wing area ~ 257 cm^2

High wing loading, and feet positioned for diving

MAMU stats from *Elliott et al. Can. J. Zoo 2004, and The Birds of North America*

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 Acciptridae). 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

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 Acciptridae). 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