Biomimetic Flight

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Outline

- Background
  - What is biomimetics?
  - Why study biological flight?
- The case for flapping flight
  - The problem of scale
  - Does engineered flapping flight ever make sense?
  - Kinematics of flapping flight
  - Flow control issues
- Unsteady aerodynamics
- Marine drag reduction
- Summary

Biomimetics

The examination of natural systems
for
inspiration in engineering design

Why Study Biological Flight?

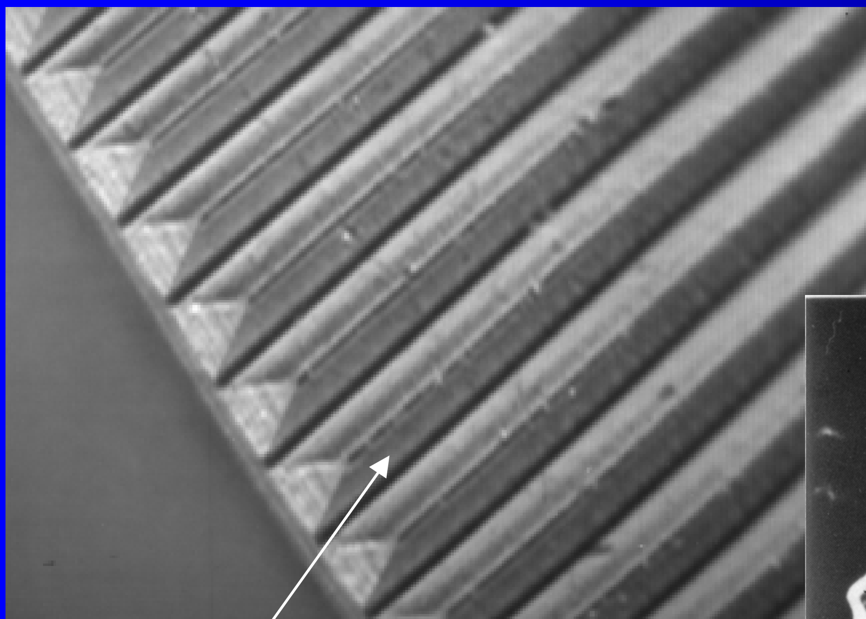
- Several known engineering solutions are also found in nature

Aerodynamic problem	Engineering solution	Biological solution
turbulent drag reduction	riblets	shark skin
high lift	multi-element airfoils	hand wing (alula)
tip vortex management	winglets	slotted wingtip (tip feathers)
separation control	vortex generators	leading edge comb pop-up feathers

- This suggests the existence of other, unknown biological solutions

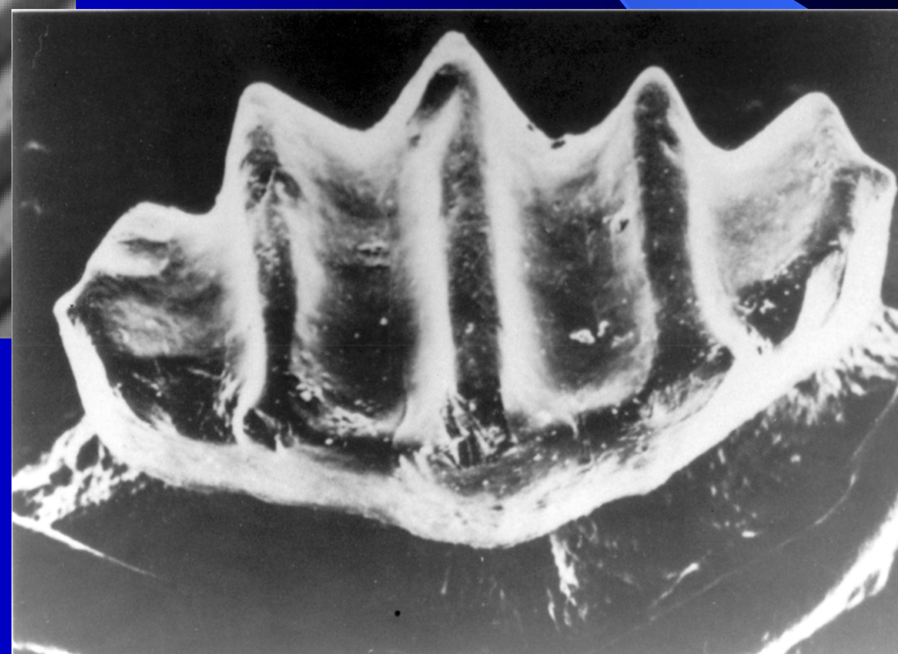
Turbulent Drag Reduction

Riblets

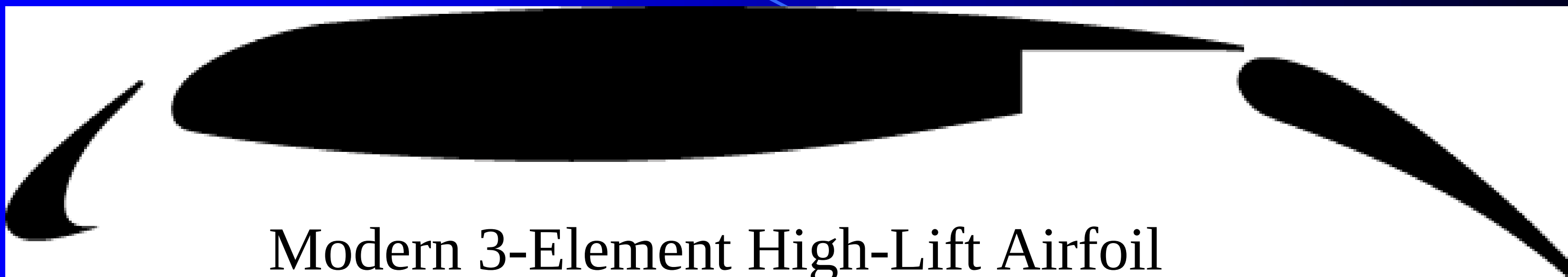


4% - 6% reduction in turbulent C_f

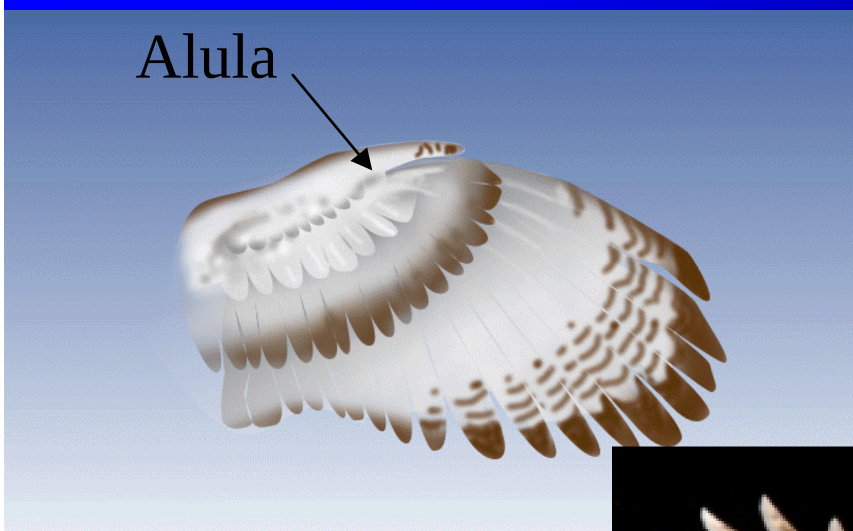
Shark dermal denticle



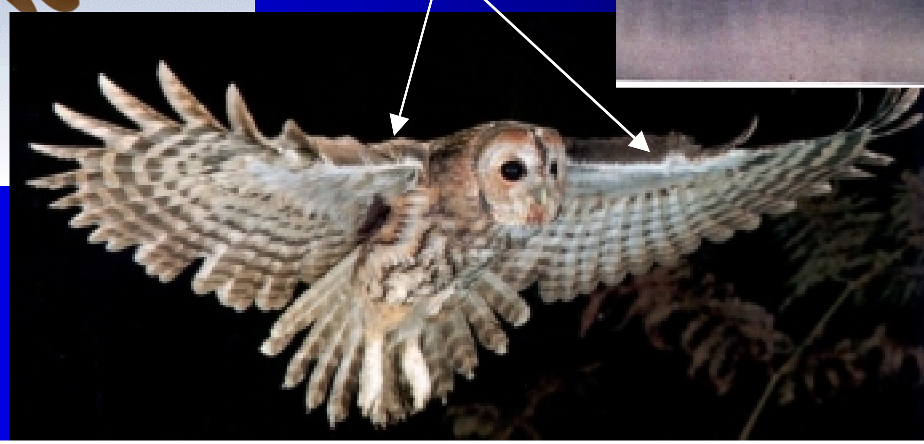
High Lift



Modern 3-Element High-Lift Airfoil



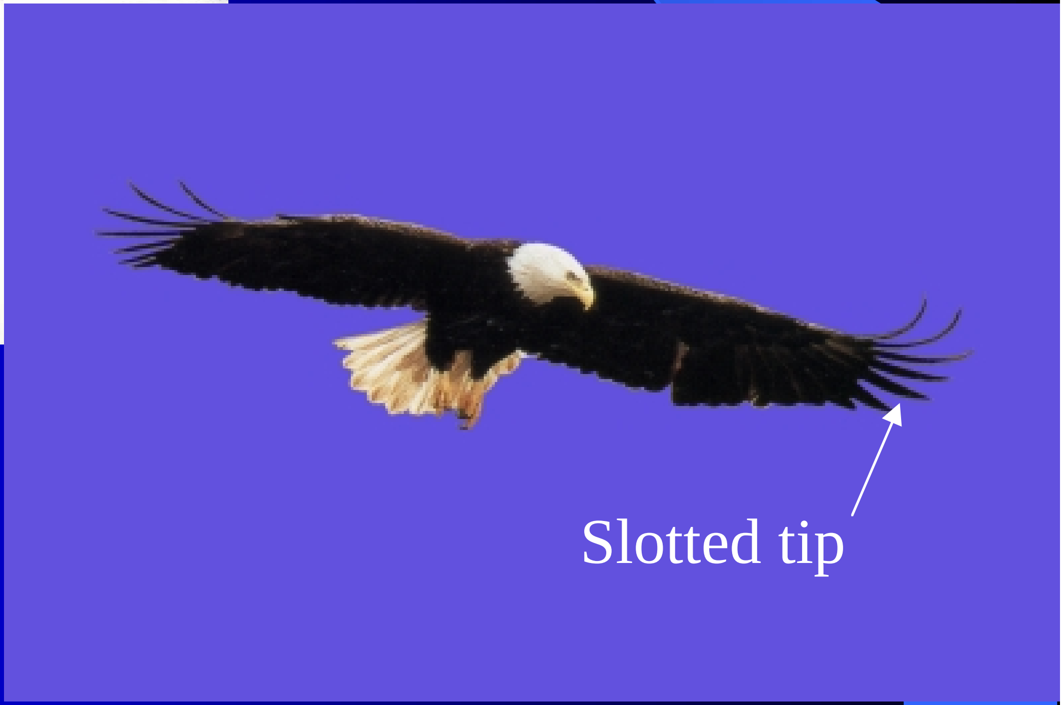
pheasant wing



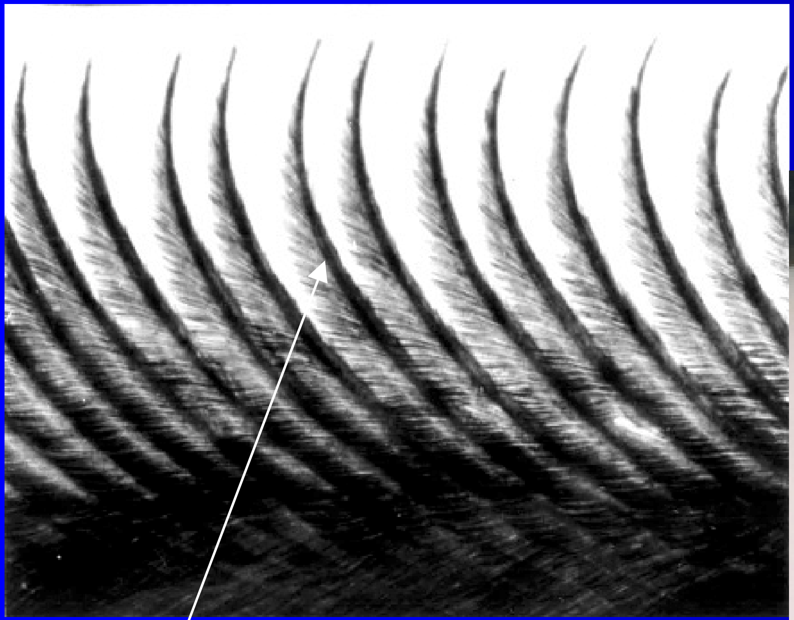
Alula

Tip Vortex Management

• Cone (1964) - 25% computed reduction in induced drag for branched wing tip



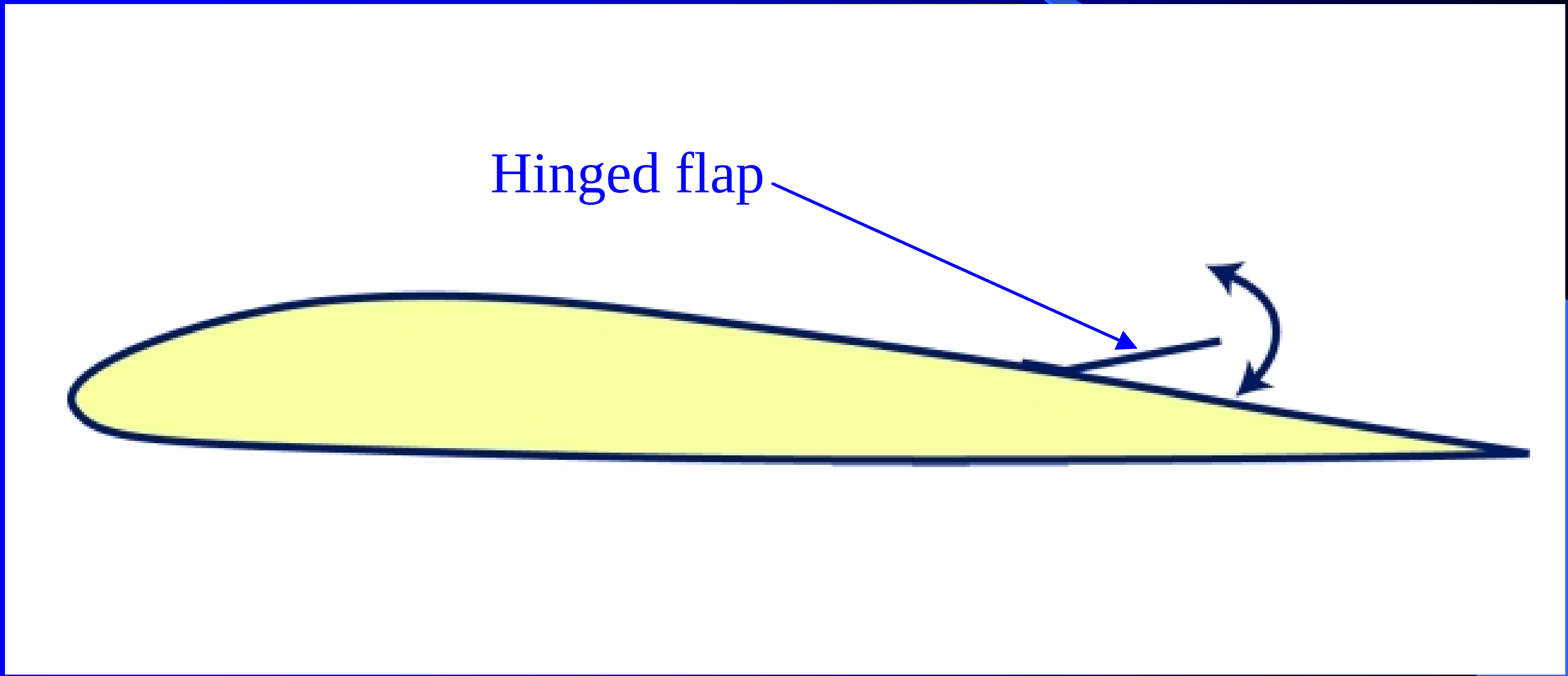
Vortex generators



Leading edge barbules (comb) on an owl wing

Micro vortex generators

Popup Separation Control



Bechert (1997) - 10% increase in max C_l

Why Study Biological Flight?

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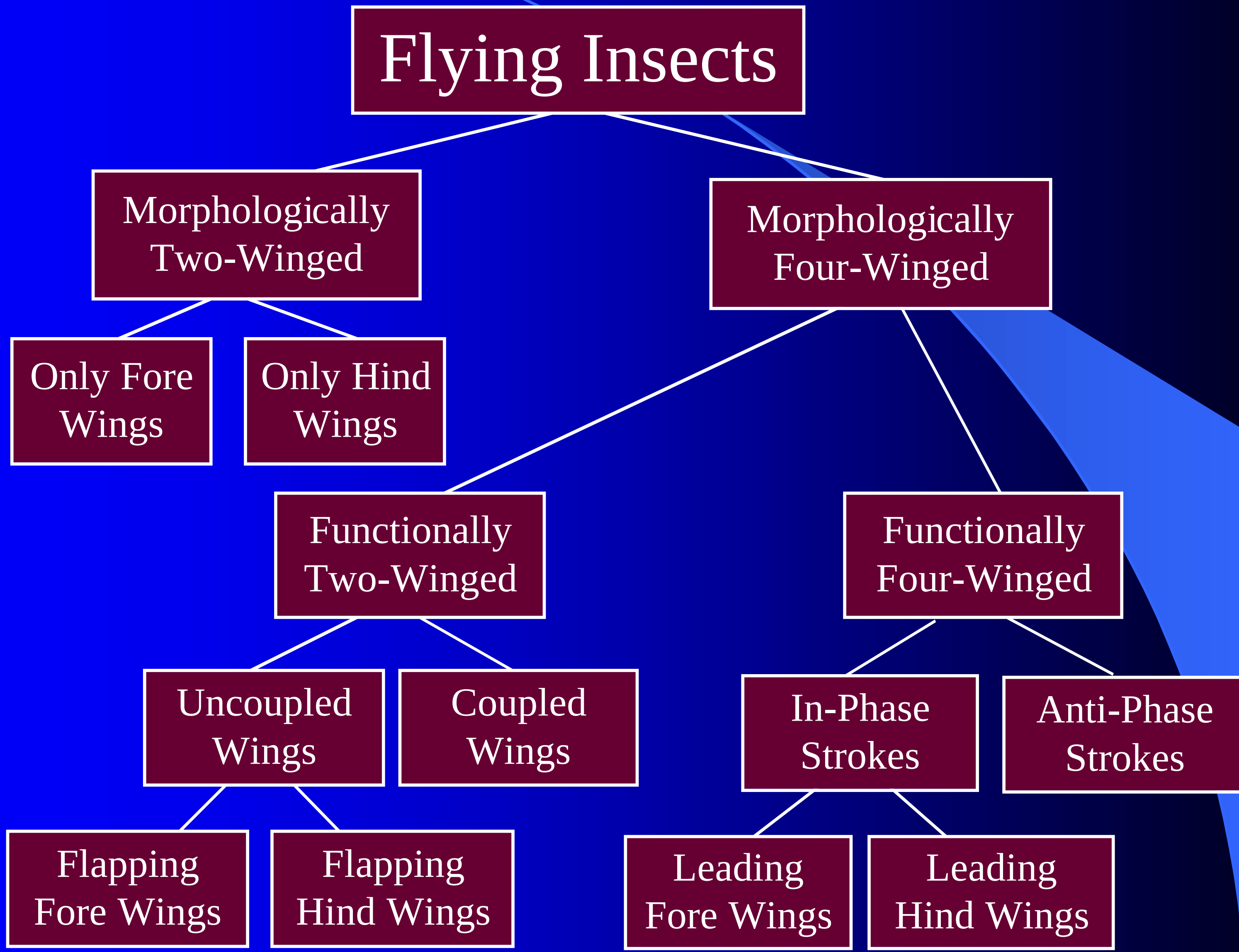
Why Study Biological Flight?

- Most living things fly
  - 1,000,000+ described species of flying insects
  - 43,000 species of vertebrates
    - 23,000 marine
    - 10,000 birds and bats
    - 10,000 all other (230 primates)

Why Study Biological Flight?

- Evolution has conducted a multi-million year optimization experiment
  - Flying insects date from at least 245 MYBP
  - Presumably highly efficient flight systems have evolved
  - Despite this long optimization process diversity in flying systems still exists

Classification of Wing Strokes



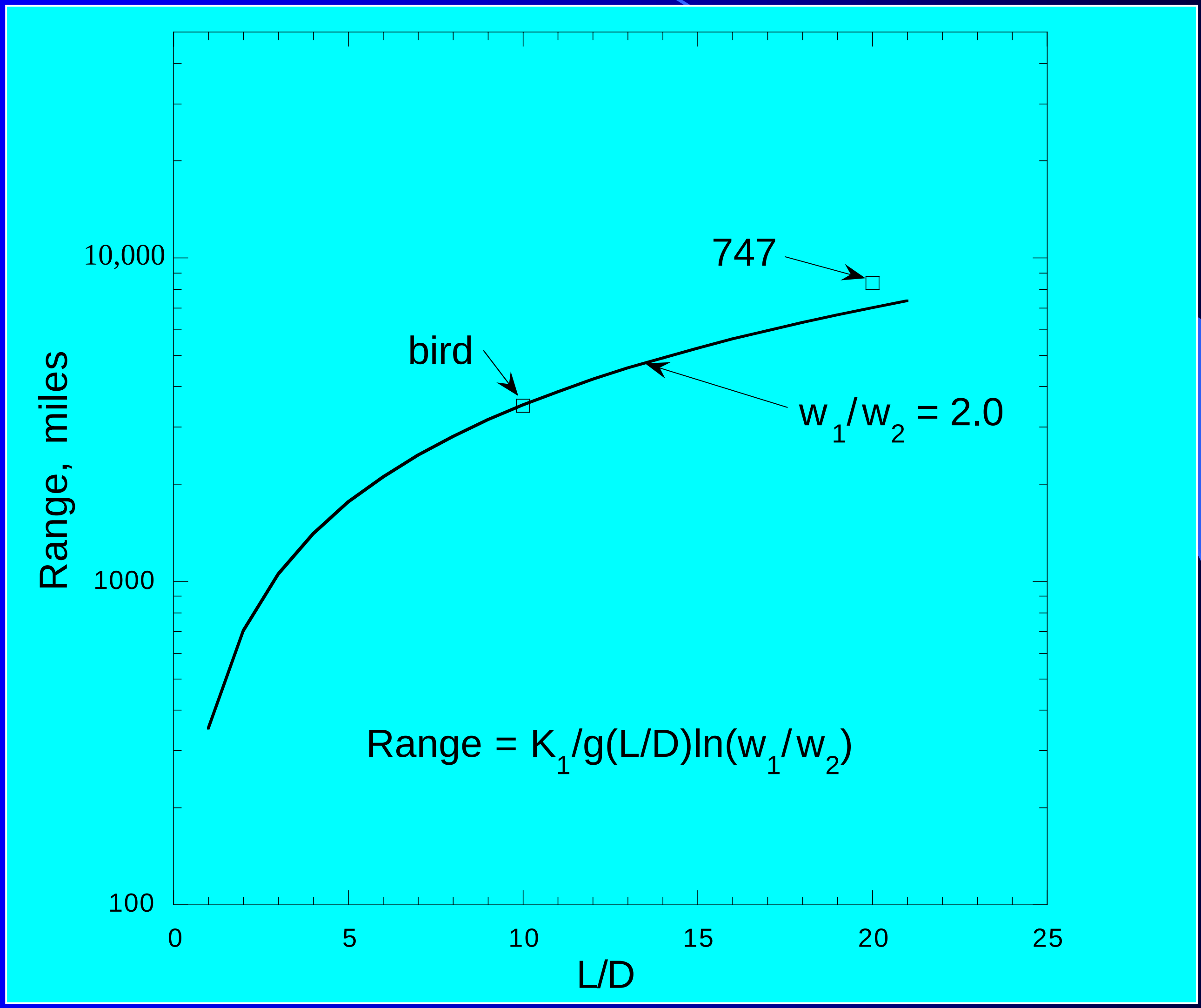
Flight Diversity

- The evolution process did not converge to a single flight solution
  - Wings are used for more than flying
  - Competition among species requires specialization
  - Evolution is a random process with many solutions based on local conditions
- All biological flight must be energy efficient

Long Range Flight of Birds

- Range = $(K_1/g)(L/D)\ln(w_1/w_2)$
- Migrating birds can store and lift 50% body fat ($w_1/w_2=2$)
- L/D ranges from 3 (starling) to 17 (swift)

Simplified Range Equation



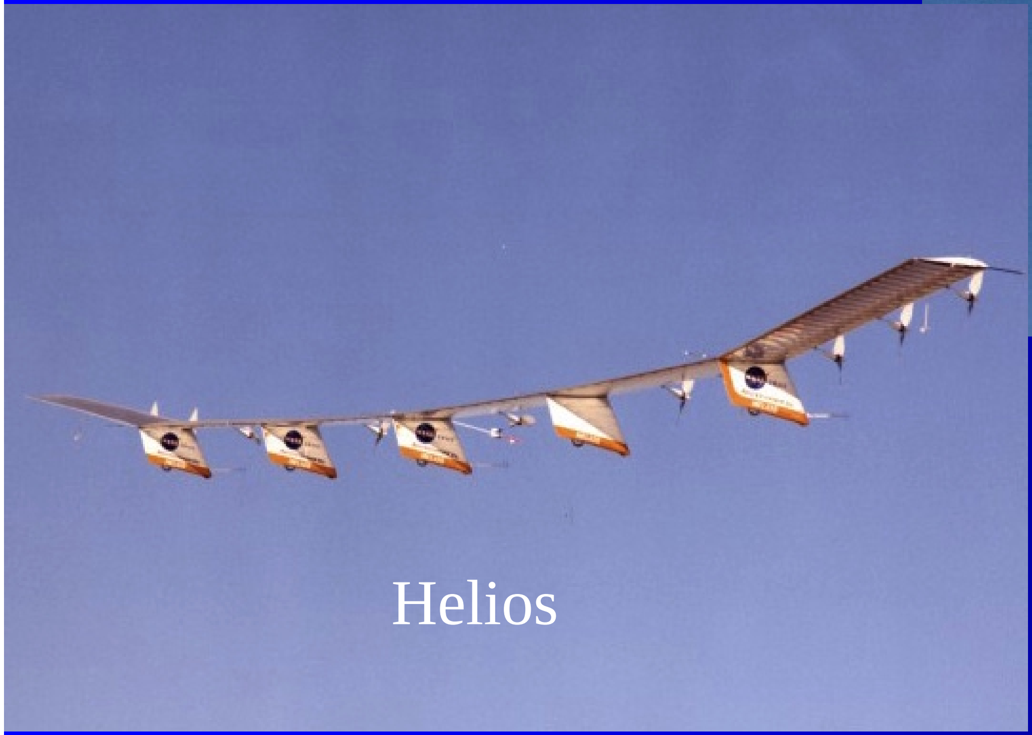
Why Study Biological Flight?

- Biological flight systems are superior to engineered flight systems <u>at small scales</u>
  - Better power supply
  - Better stability and control system
  - Better sensors
  - Use of atmospheric dynamics
  - Better low Reynolds number aerodynamics?
- Current interest in Macro/Micro UAVs

Micro Airplanes

Long Endurance Airplanes (Mega UAVs)

Pathfinder



Helios

UAVs

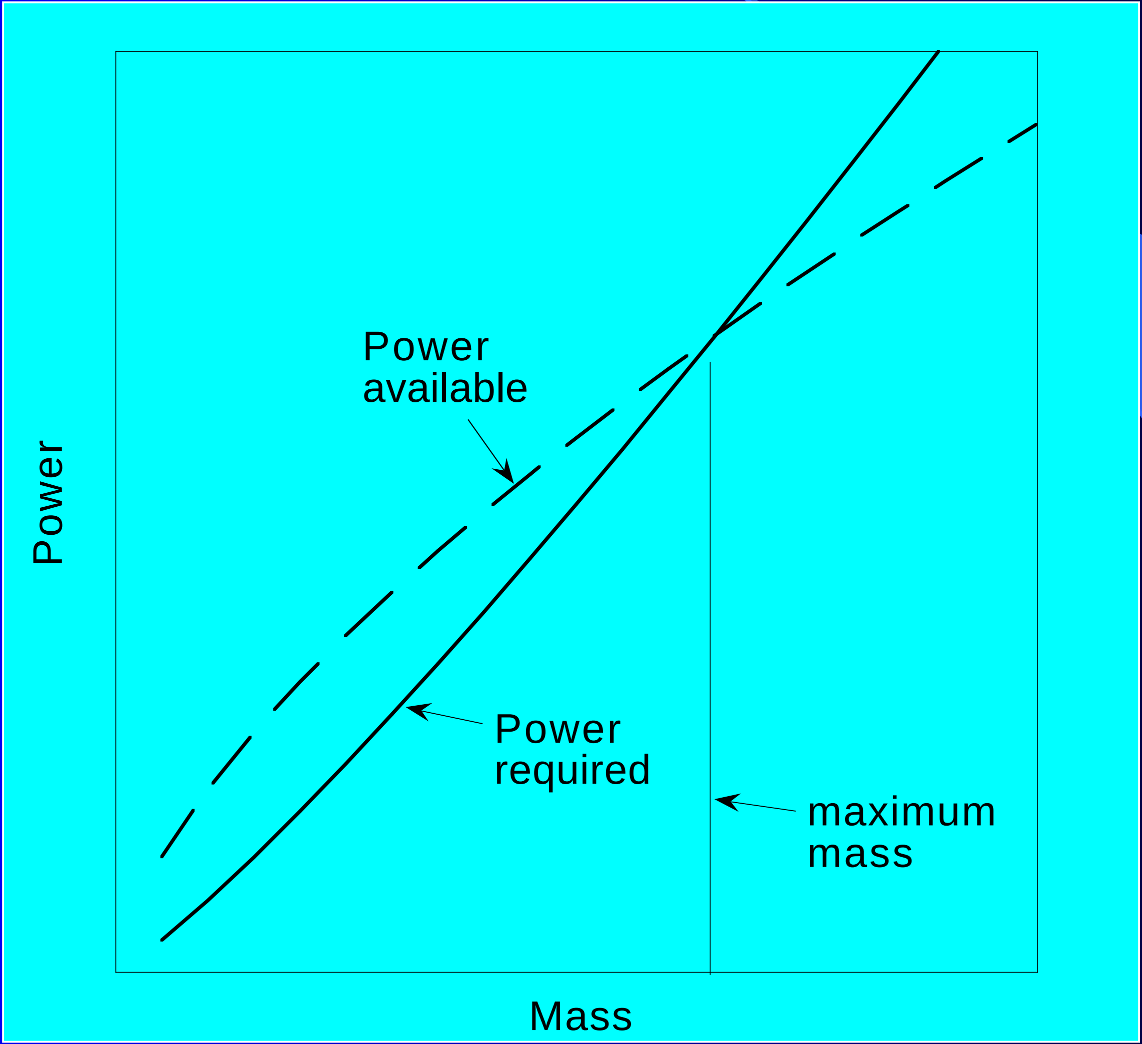
- Micro UAVs
  - Small designs (6 inch wingspan) have limited endurance and stability problems in gusty conditions
- Mega UAVs
  - Large designs (250 foot wingspan) have long endurance, but are .large

Flapping Flight

- The problem of scale
- Does engineered flapping flight ever make sense?
- Kinematics of flapping flight
- Flow control

Size Limitation for Biological Flight

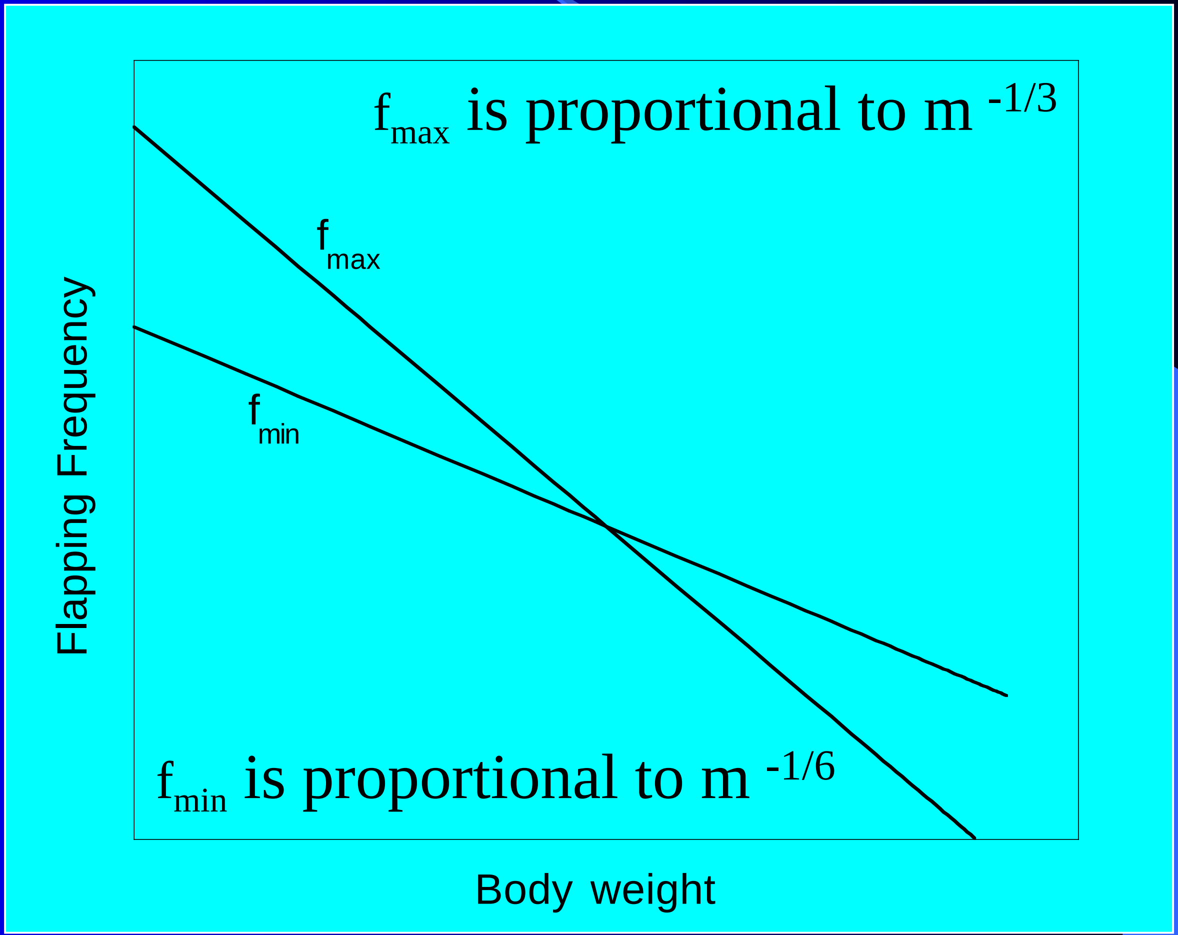
- Power required is proportional to mass$^{7/6}$
- Power available is proportional to mass$^{2/3}$



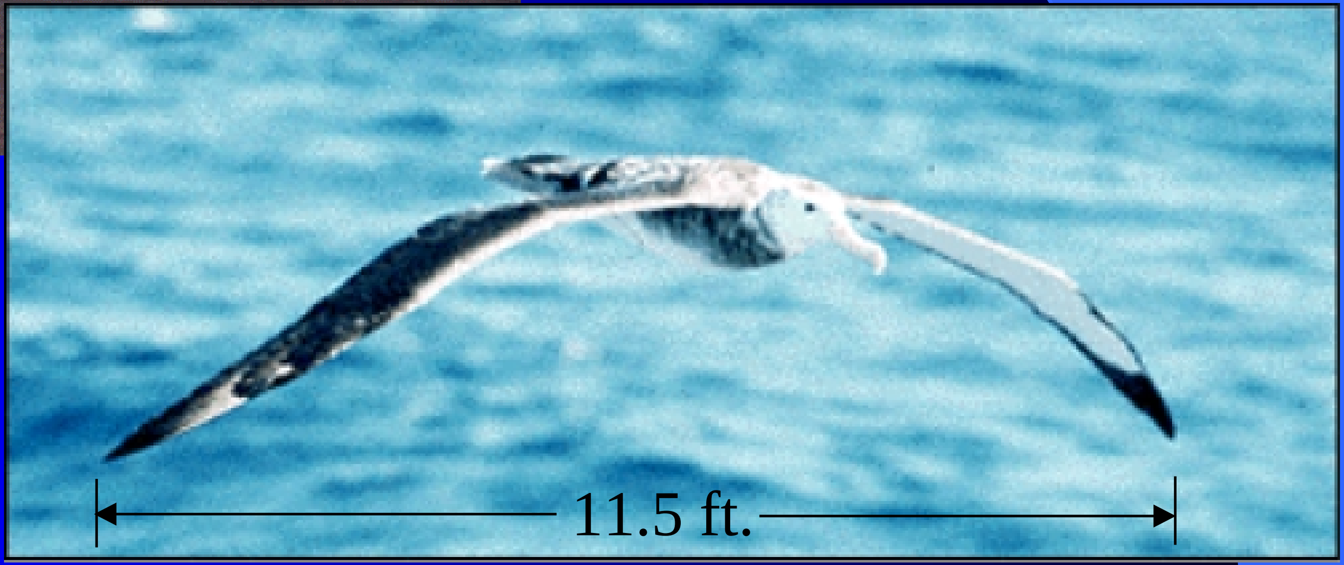
Flapping Frequency

- Smaller birds have a greater range of frequencies available

- Wandering Albatross (11. 5 ft. wingspan) can barely flap at all



High Aspect Ratio Wings



The Problem of Scale

- Biological power available limits size
- High aspect ratio flapping wings limit size
  - Inertial effects
  - Structures/materials
- Low Reynolds number effects

Reynolds Number Range

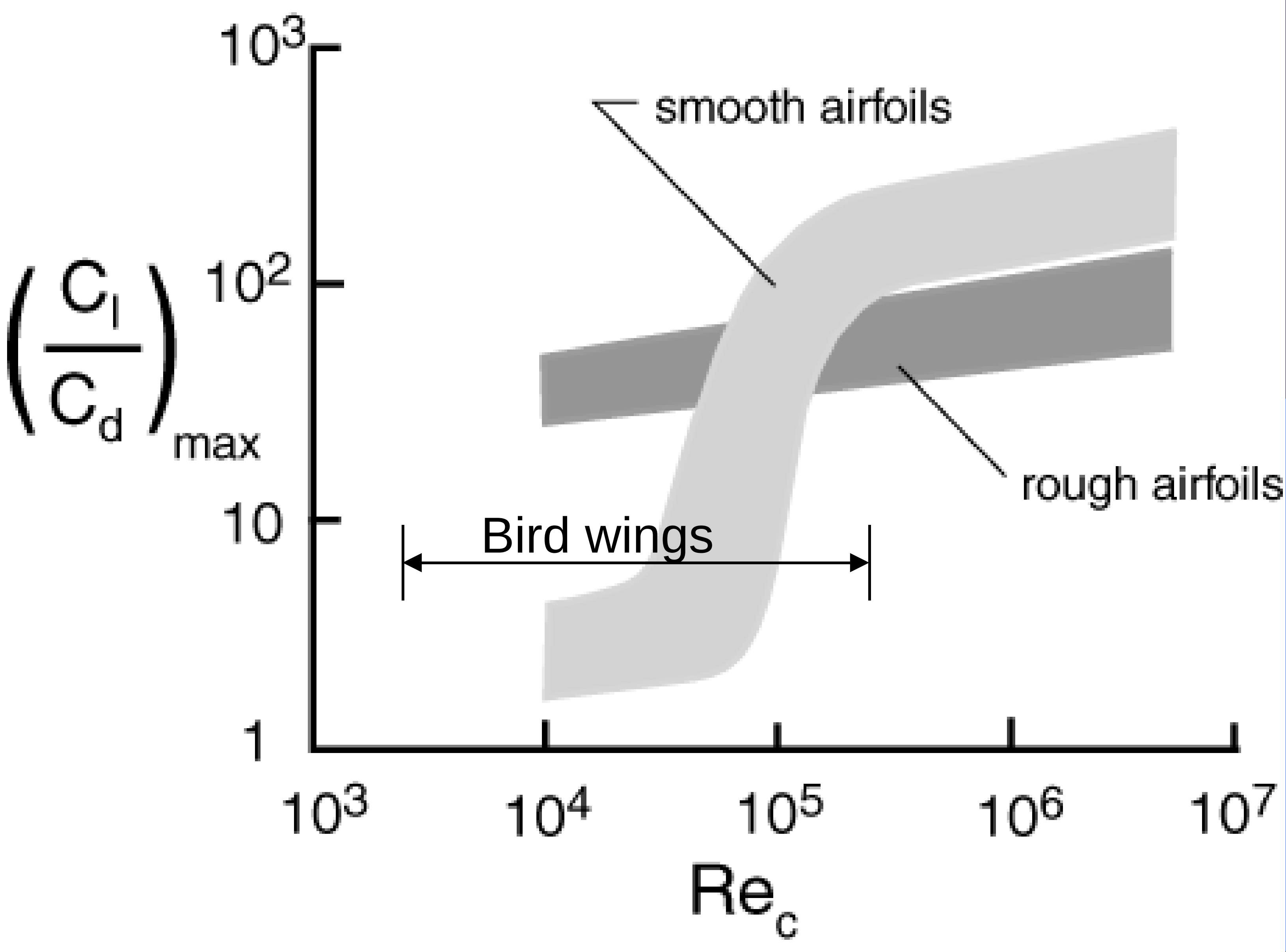
Small insects

- Wing chord Reynolds numbers ≈ 10^1-10^2
- Use unsteady effects to stay aloft
- Wings are corrugated, curved plates

Large, fast flying birds

- Wing chord Reynolds numbers up to ≈ 10^5
- Use conventional airfoil circulation
- Sensitive to transition/separation

Low Reynolds Number Airfoils



The Case for Flapping Flight

- Flapping flight must be small scale!
- Flapping flight may be a viable solution when VTOL/STOL/hover capability must be combined with high-speed forward flight capability
- May be more efficient than helicopter in forward flight
- Stealth
- More agile and maneuverable
- More flow control knobs to turn

Flow Control Knobs Available In Flapping Flight

- Gait selection
- Flapping frequency
- Wing beat amplitude
- Stroke angle
- Wing planform
- Angle-of-attack
- Twist
- Camber

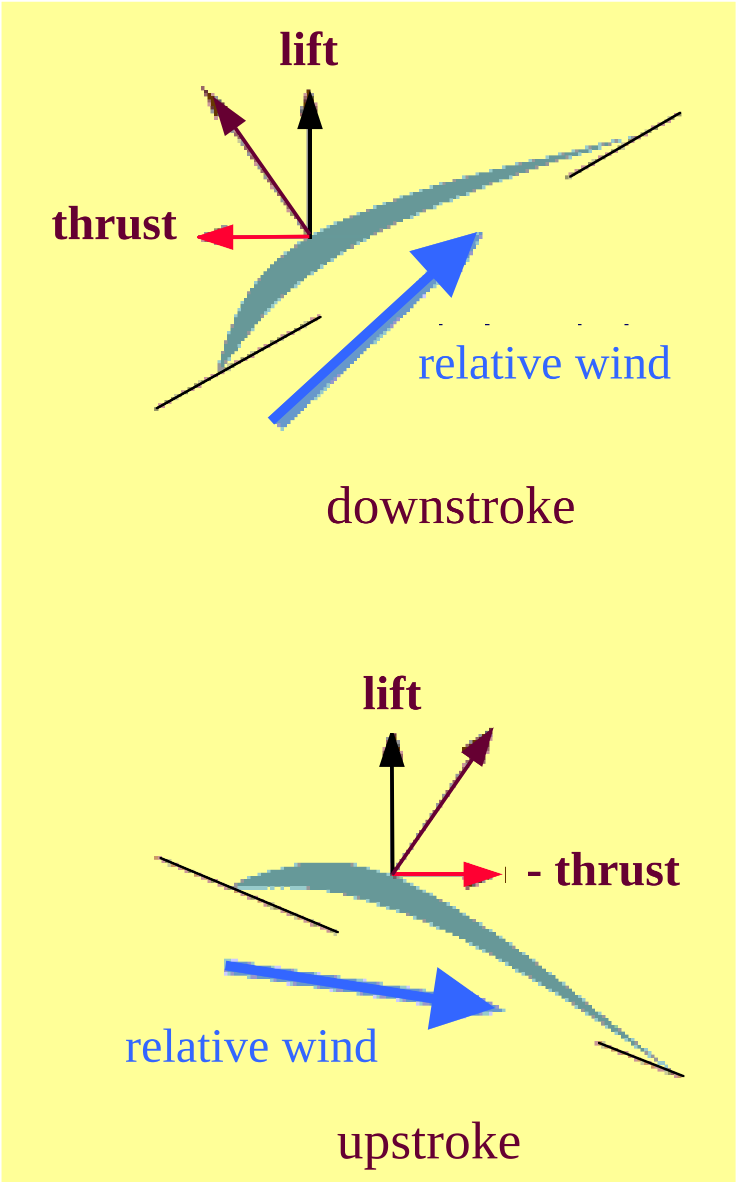
Birds can change most of these within a single wing beat!

Gait Selection

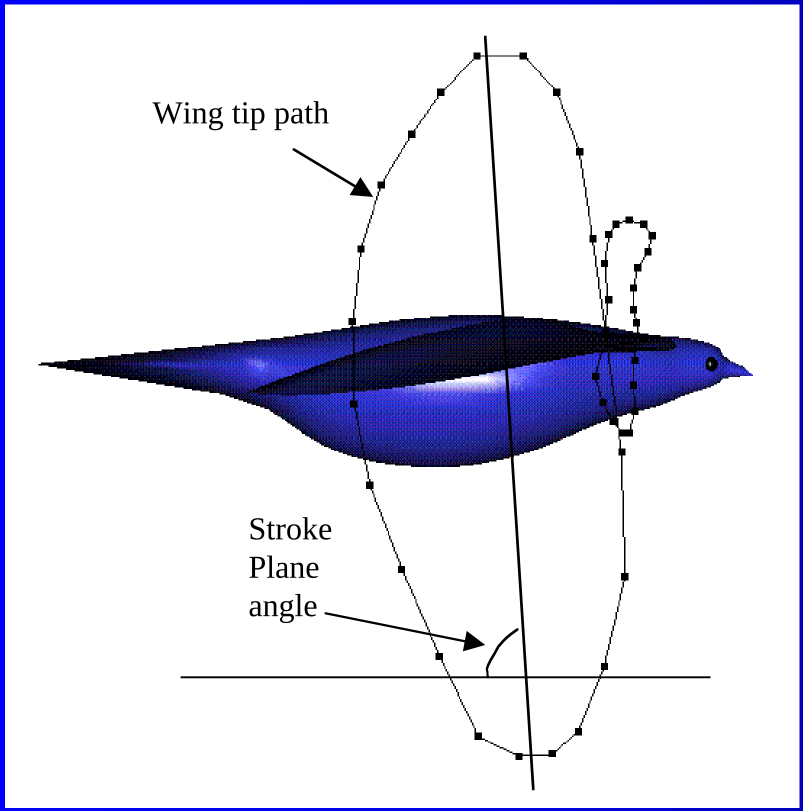
- Vortex ring gait
  - All lift produced on downstroke
    - Starting and stopping vortices merge to form ring
    - Wing highly flexed on upstroke - little or no lift is produced
  - Leaves behind a series of ring vortices
  - All birds use this at low speeds
  - Birds with low aspect ratio wings use this exclusively (so-called fixed gear)

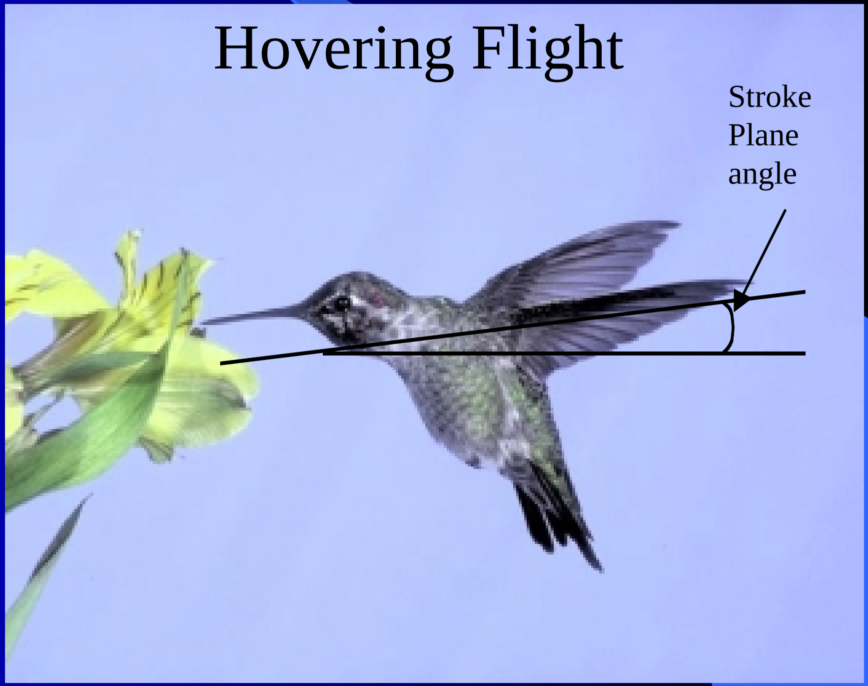
Gait Selection

- Continuous vortex gait
  - Lift produced on downstroke and upstroke
    - trailing vortex pattern similar to fixed wing aircraft
  - Birds with high aspect ratio wings shift to this gait at high speeds (second gear)
  - Produces negative thrust on upstroke



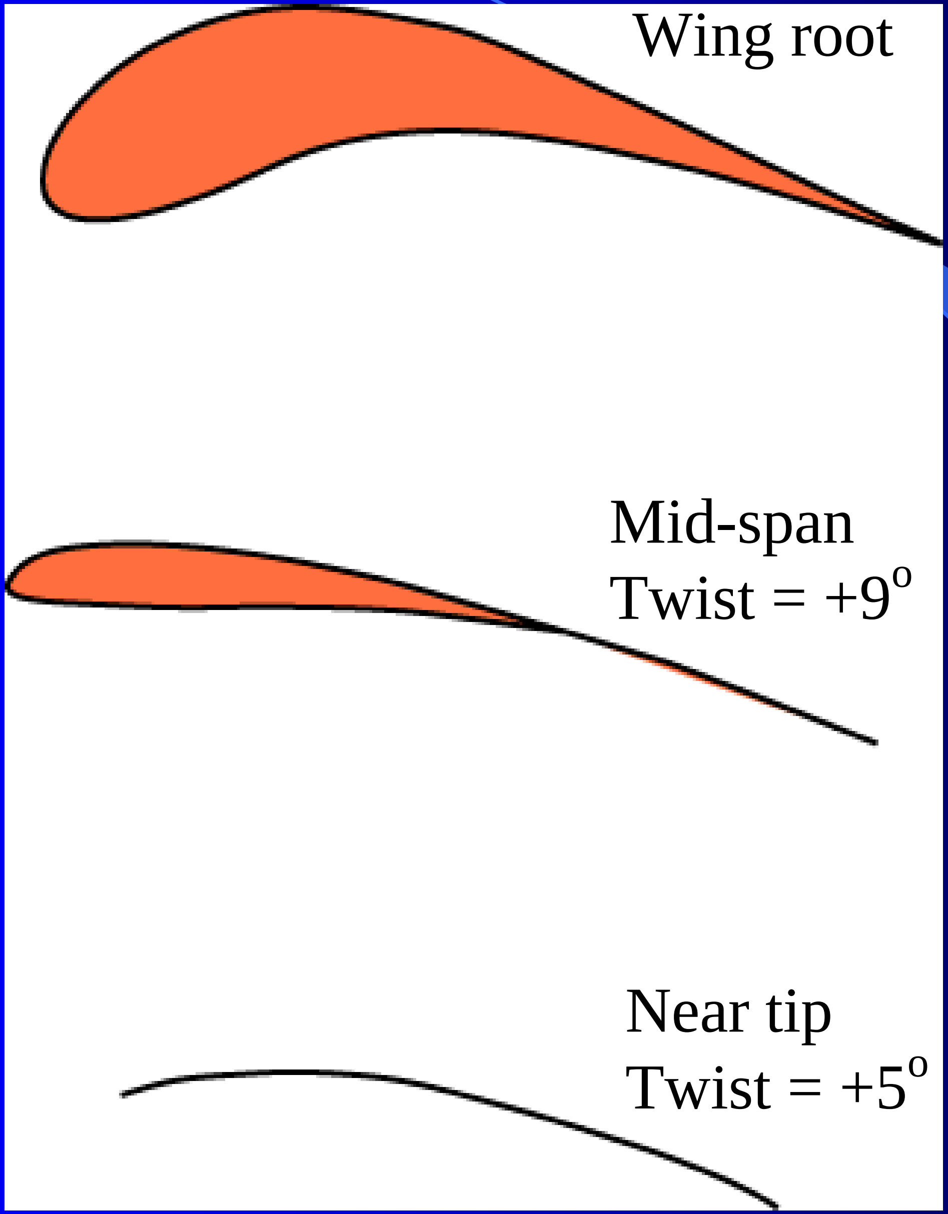
Stroke Plane Angle



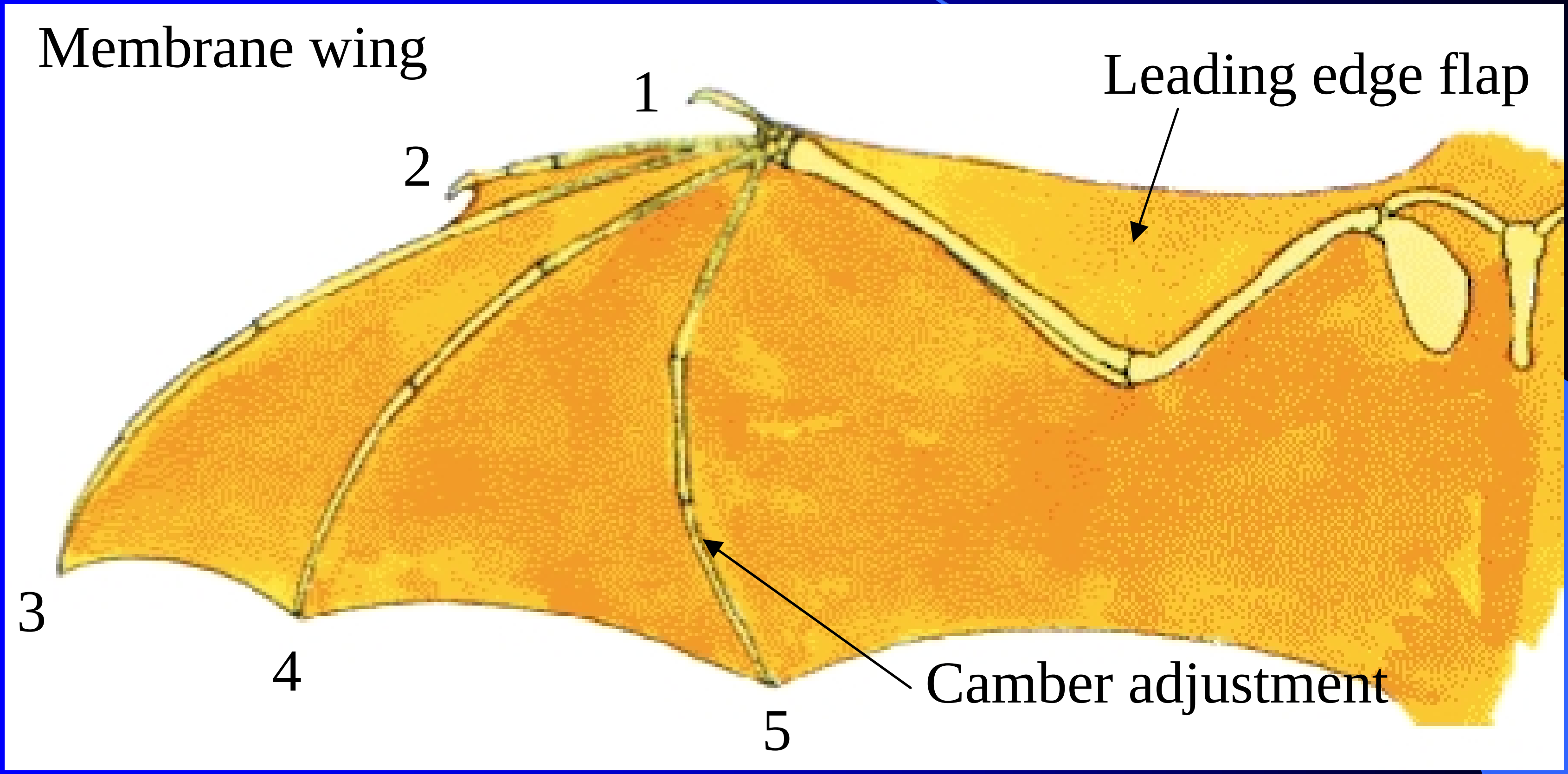


Wing Camber/Twist

Idealized pigeon wing



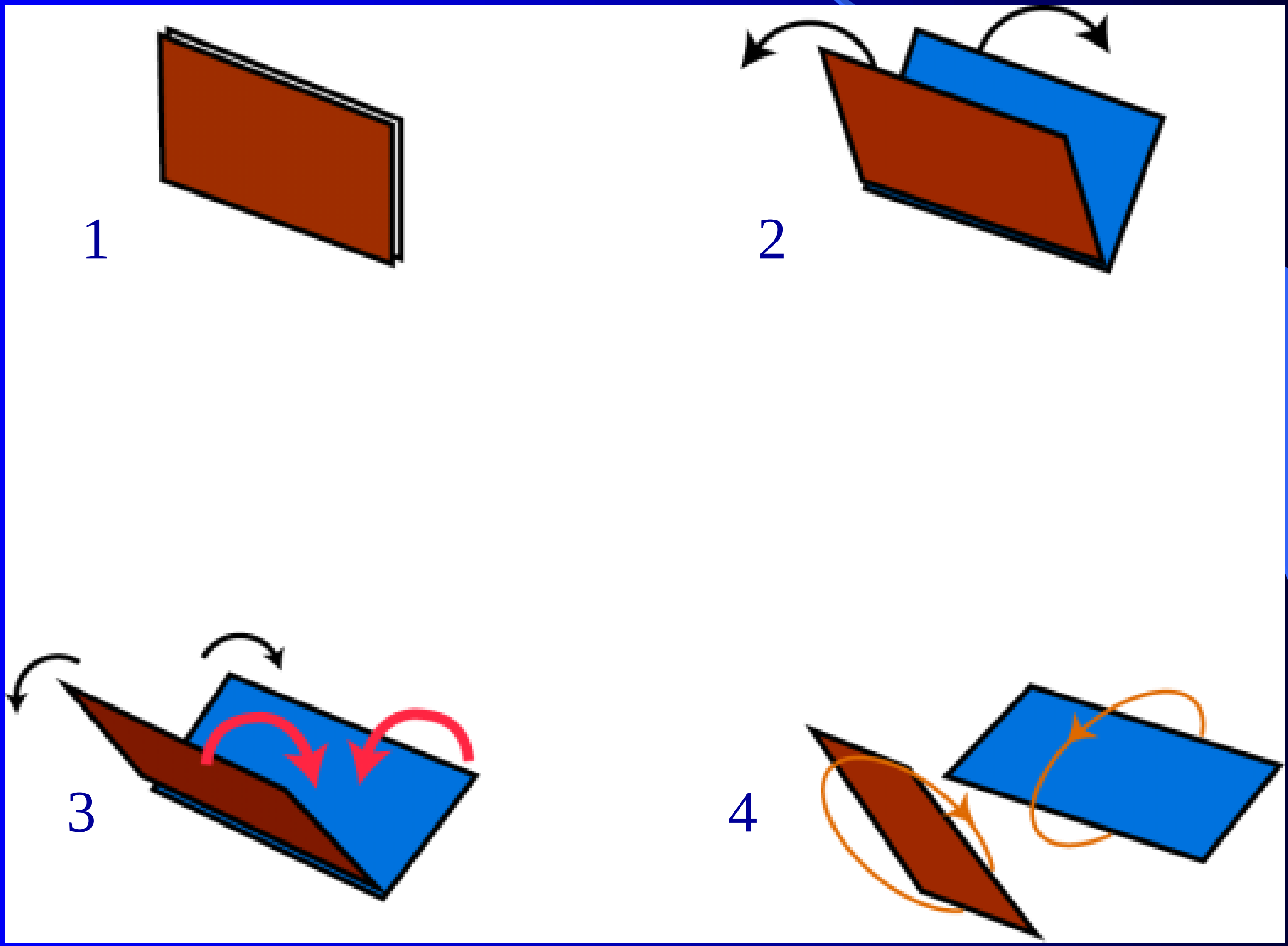
Bat Wing Morphology



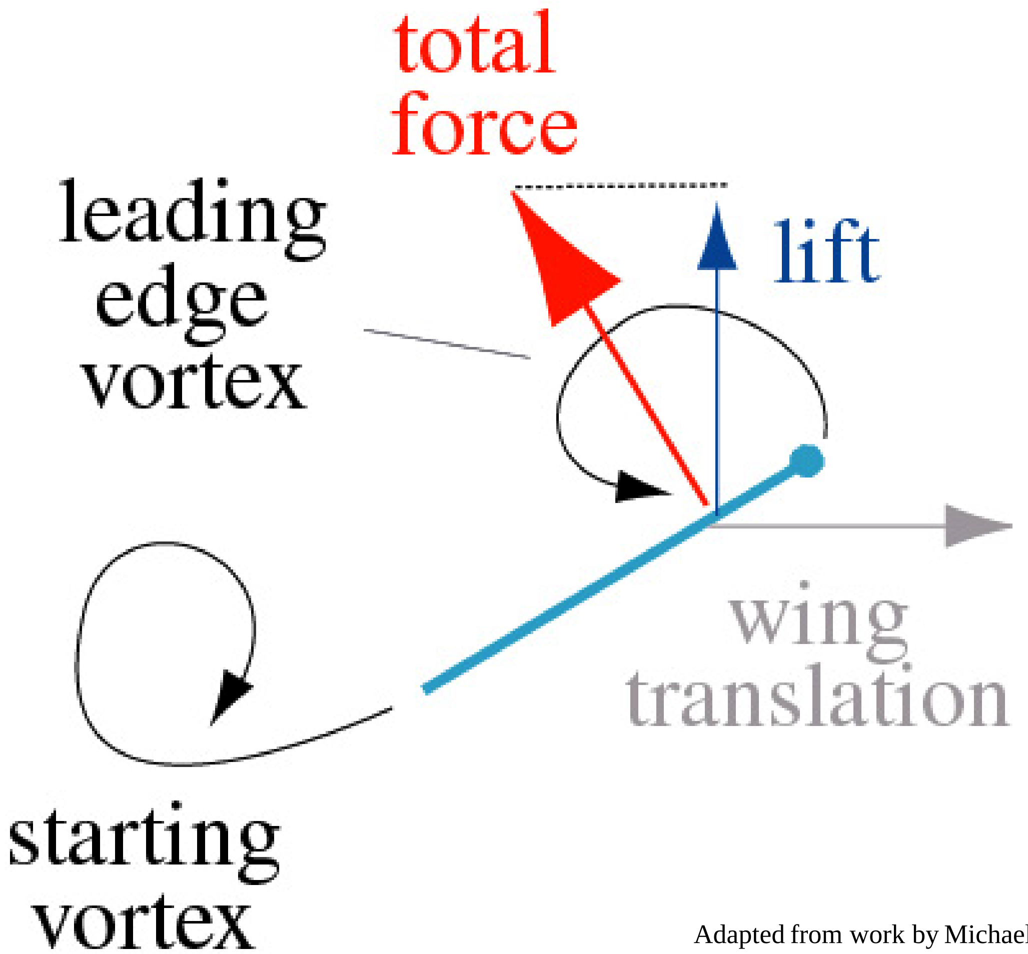
Unsteady Aerodynamics

- Clap and fling
- Delayed stall
- Rotational circulation
- Wake capture

Clap and Fling



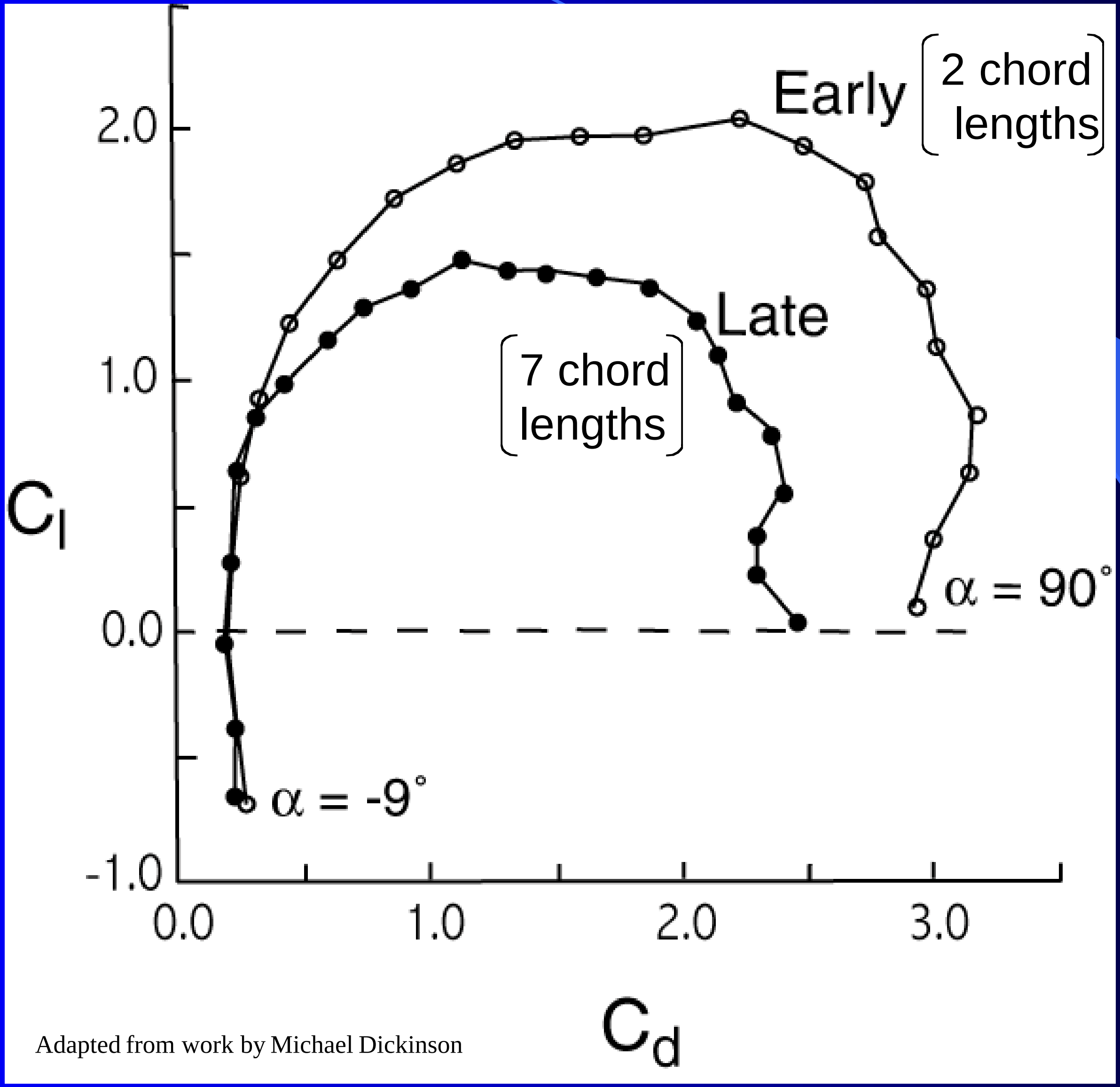
Delayed Stall



Adapted from work by Michael Dickinson

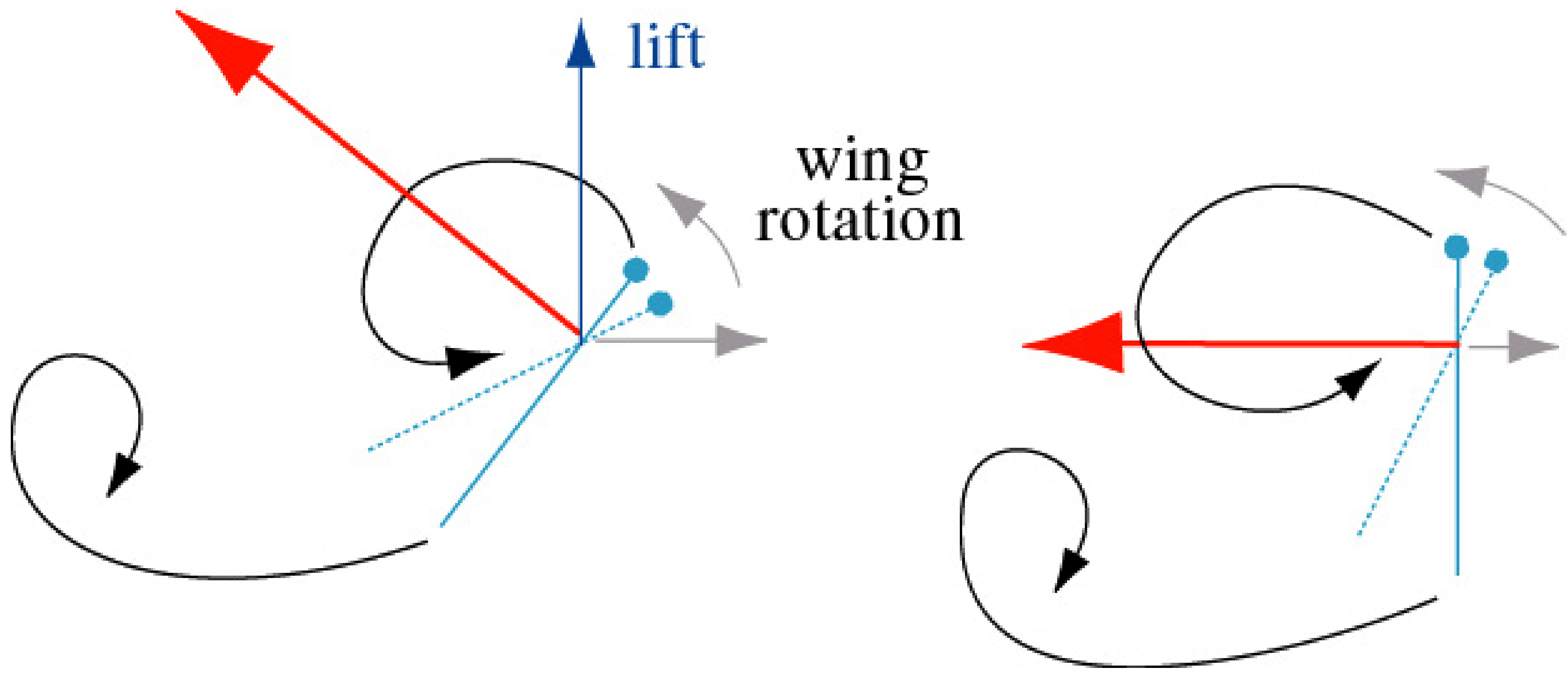
Delayed Stall

2-D impulsively started airfoil



Nearly 80% increase in lift at high AOA

Rotational Circulation



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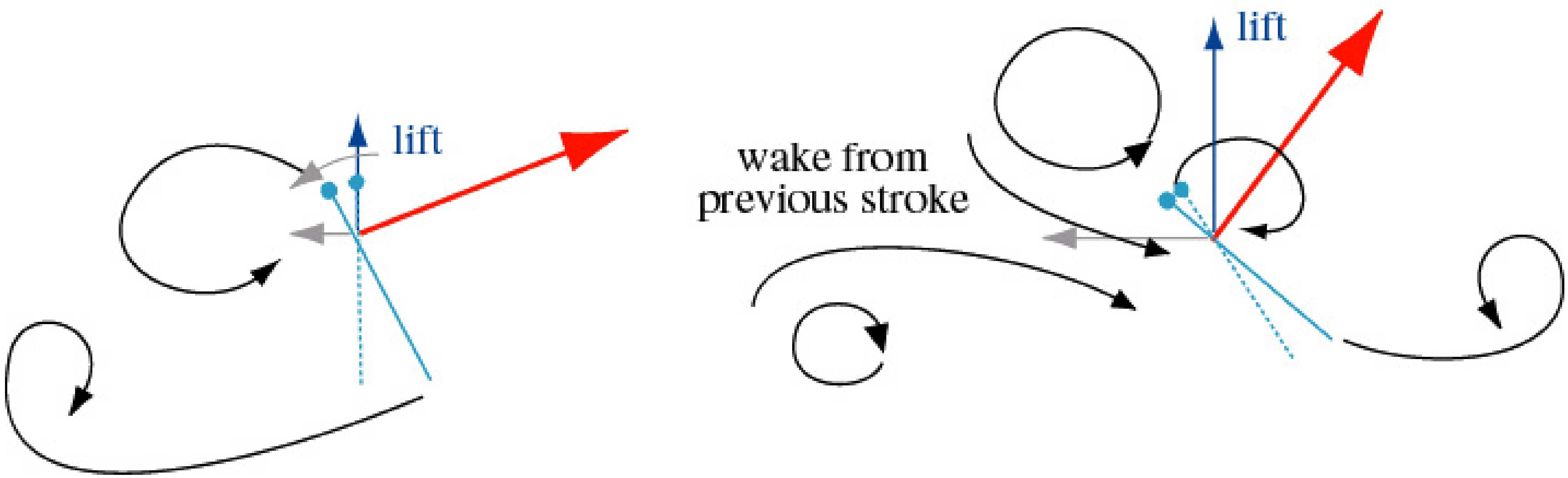
Wake Capture



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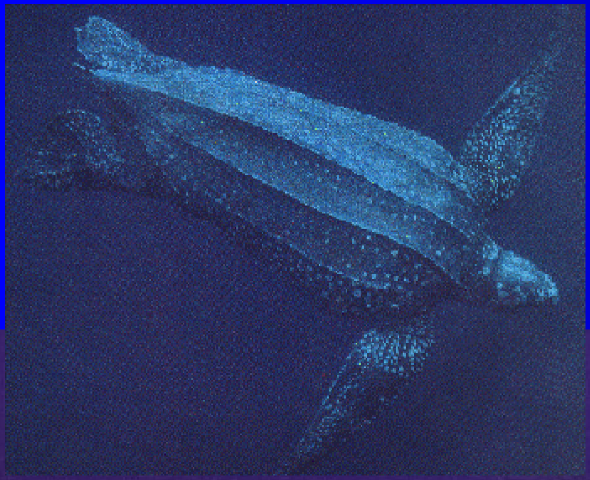
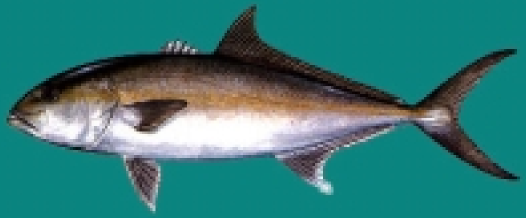
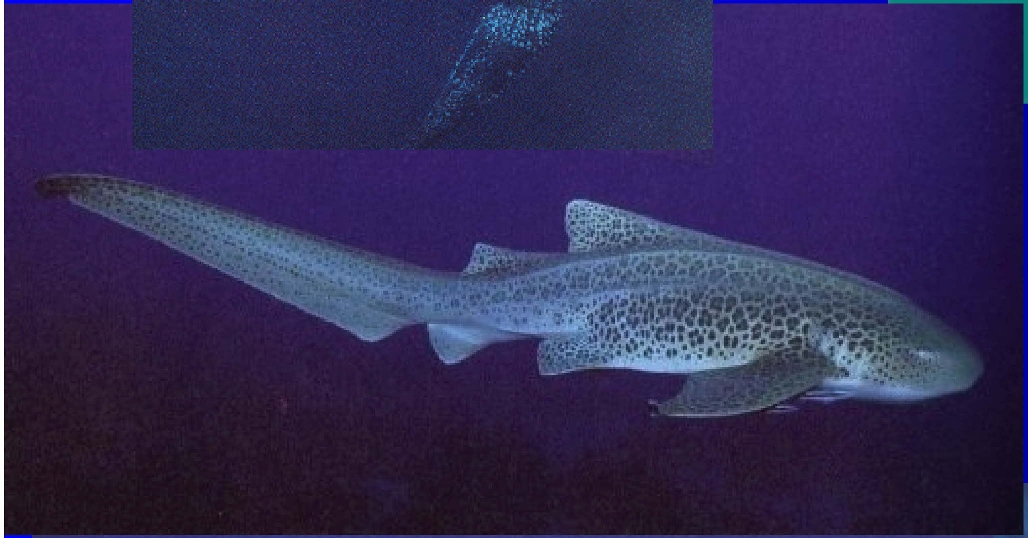
Unsteady Aerodynamics

- Insects use unsteady effects to generate the necessary lift to stay aloft (i.e., this is why the bumblebee can fly)
- Small birds (e.g.,hummingbirds) use unsteady effects to some degree
- Large, soaring birds use conventional circulation-based lift from airfoil-shaped wings

Marine Morphologies







Drag Reduction Morphologies

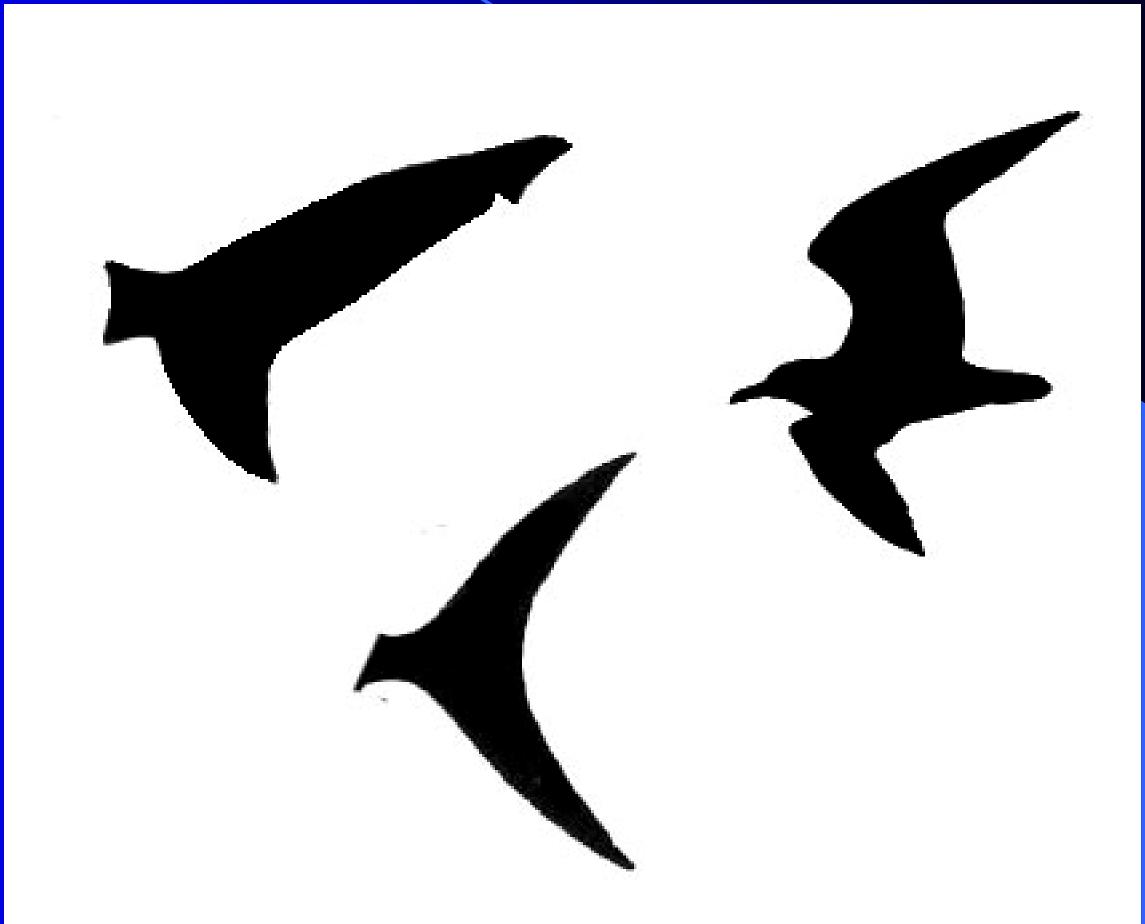
- Swept, tapered tips
- Shark tail
- Leading edge bumps
- Trailing edge serrations
- Fillets
- Bluff body grooves
- Passive, porous bleed (subsurface canals)
- Compliant surfaces
- Boundary layer blowing (gill slots)
- Micro vortex generators
- Vortex management (caudal finlets)
- Surface heating
- Mucus

Swept, Tapered Tips

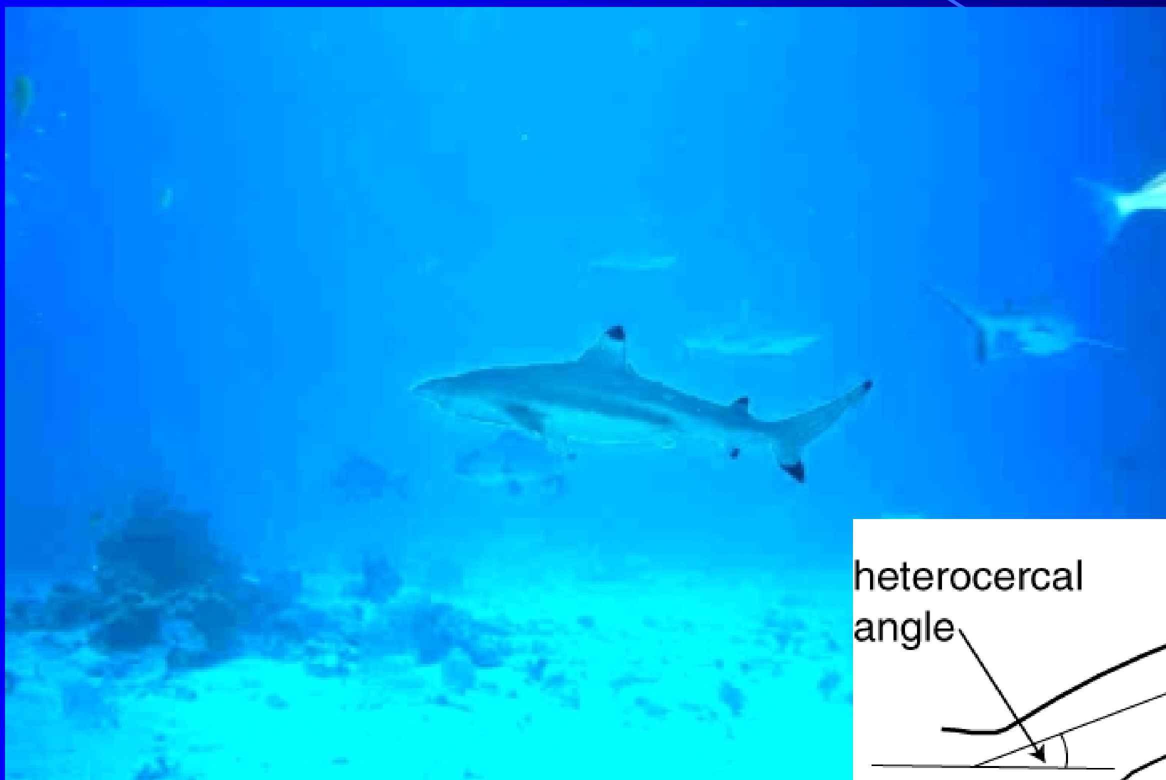
Crescent Wing

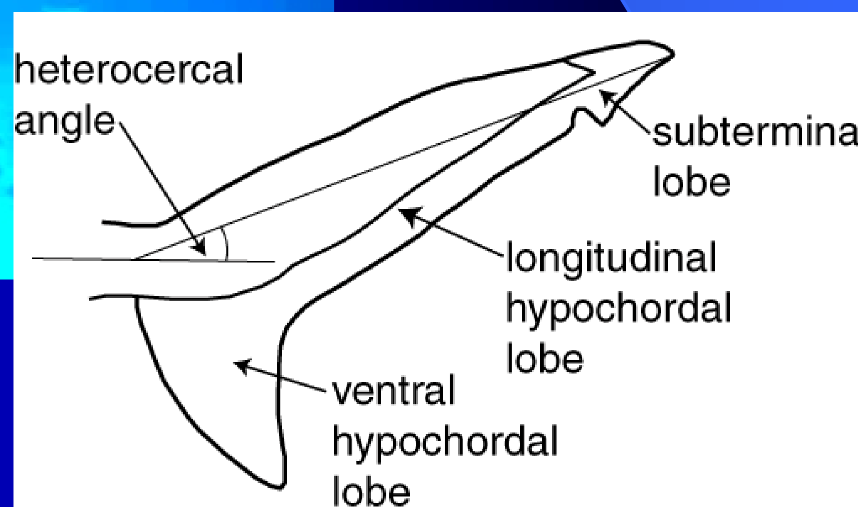
- Burkett (1989) 4% reduction in induced drag

- Van Dam (1991) less induced drag than elliptic wing



Shark Tail



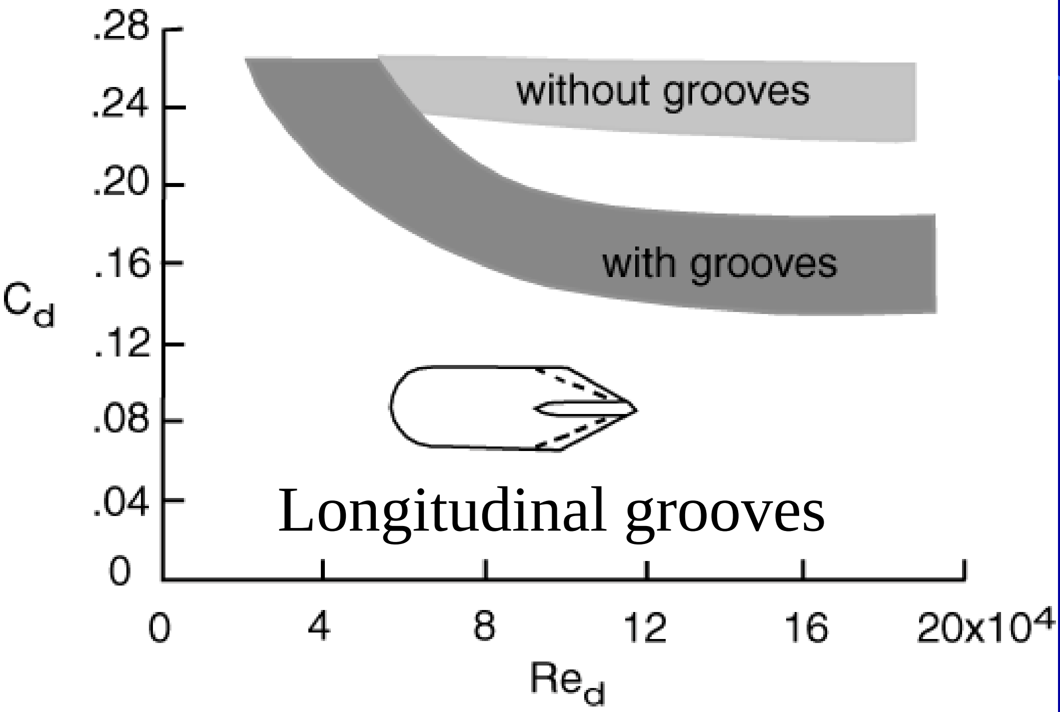

heterocercal angle
subterminal lobe
longitudinal hypochordal lobe
ventral hypochordal lobe

Leading Edge Bumps

Trailing Edge Serration

Fin-Body Intersections

Bluff Body Grooves



Concluding Remarks

- Birds and insects display a wide range of flight systems
  - tailored for low Reynolds numbers
  - Flapping wing flight allows an extraordinary amount of control
  - Unsteady aerodynamics plays a central role in insect flight
- Birds and marine animals have a variety of morphologies to minimize drag and enhance efficiency
- Engineered flight systems (especially small scale) may benefit from an improved understanding of biological flight