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Flight Dynamics & Design of Fixed-Wing Drones

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What are the advantages of fixed-wing UAS vs multi-rotors?

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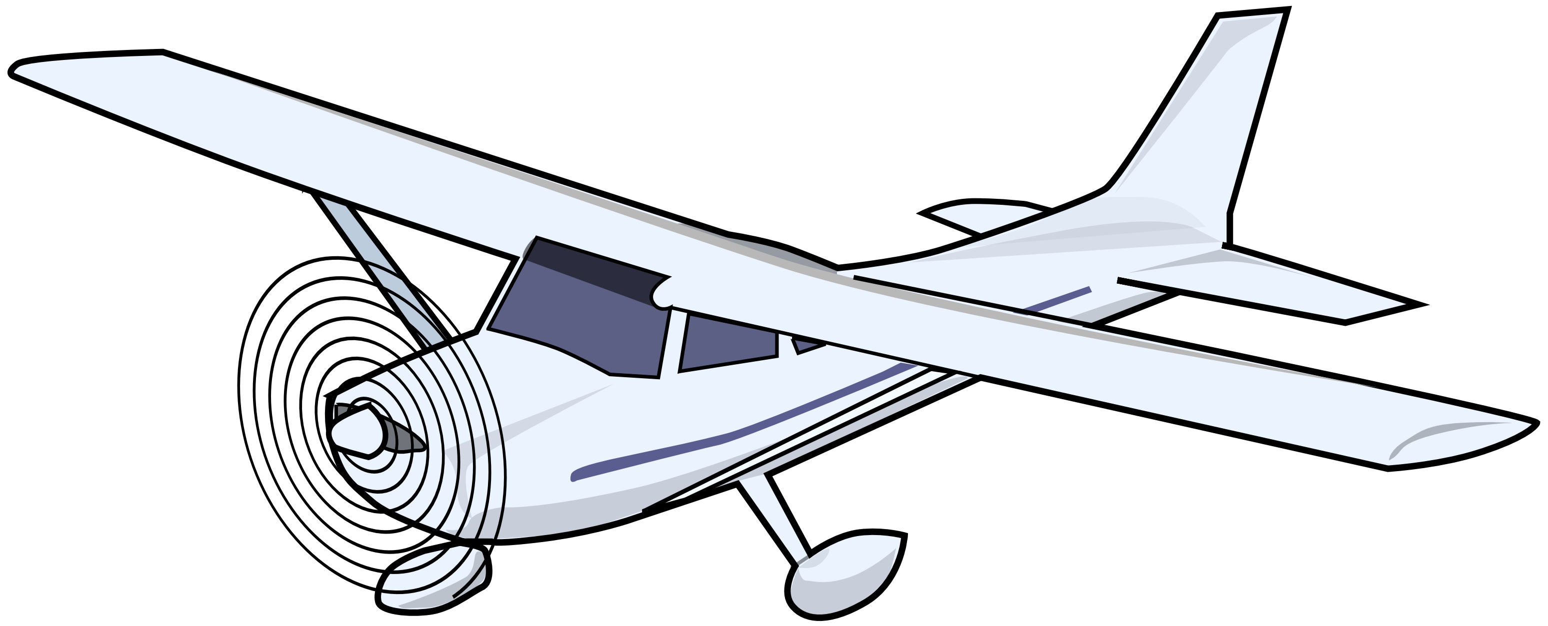
What are the advantages of fixed-wing UAS vs multi-rotors?

SECTION 1

Flight Dynamics & Control

The Four Forces of Flight

Can you guess the 4 forces of flight?



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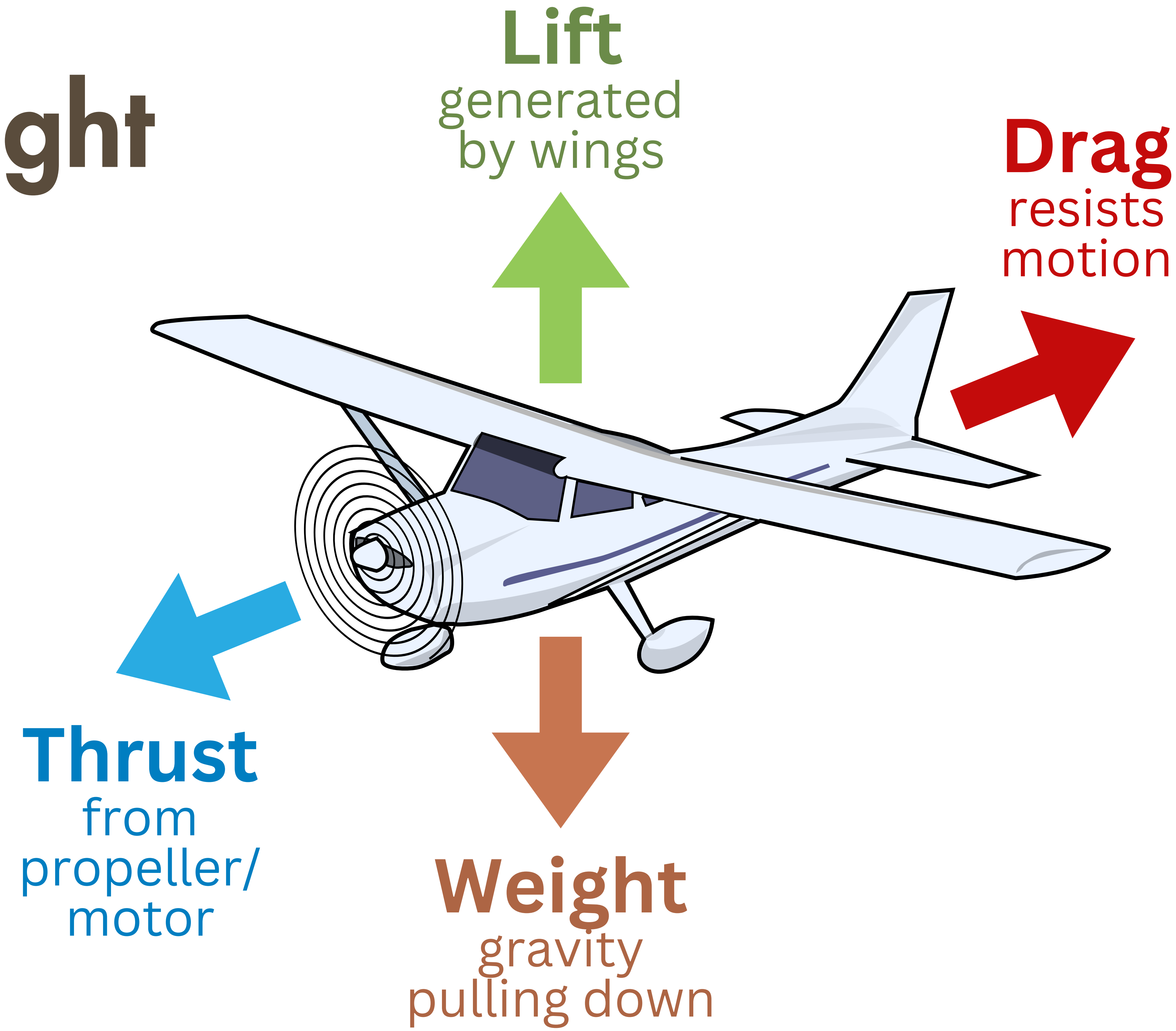
The Four Forces of Flight

- **Lift:** Generated by the wings, acts upward and opposes weight.
- **Weight:** Gravity pulling the aircraft down through its center of gravity.
- **Thrust:** Produced by the motor/propeller, pushes the aircraft forward.
- **Drag:** Air resistance opposing motion (form, friction, induced).



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The Six Degrees of Freedom

Can you place the 6 Degrees of Freedom (DoF)?

1) Pitch

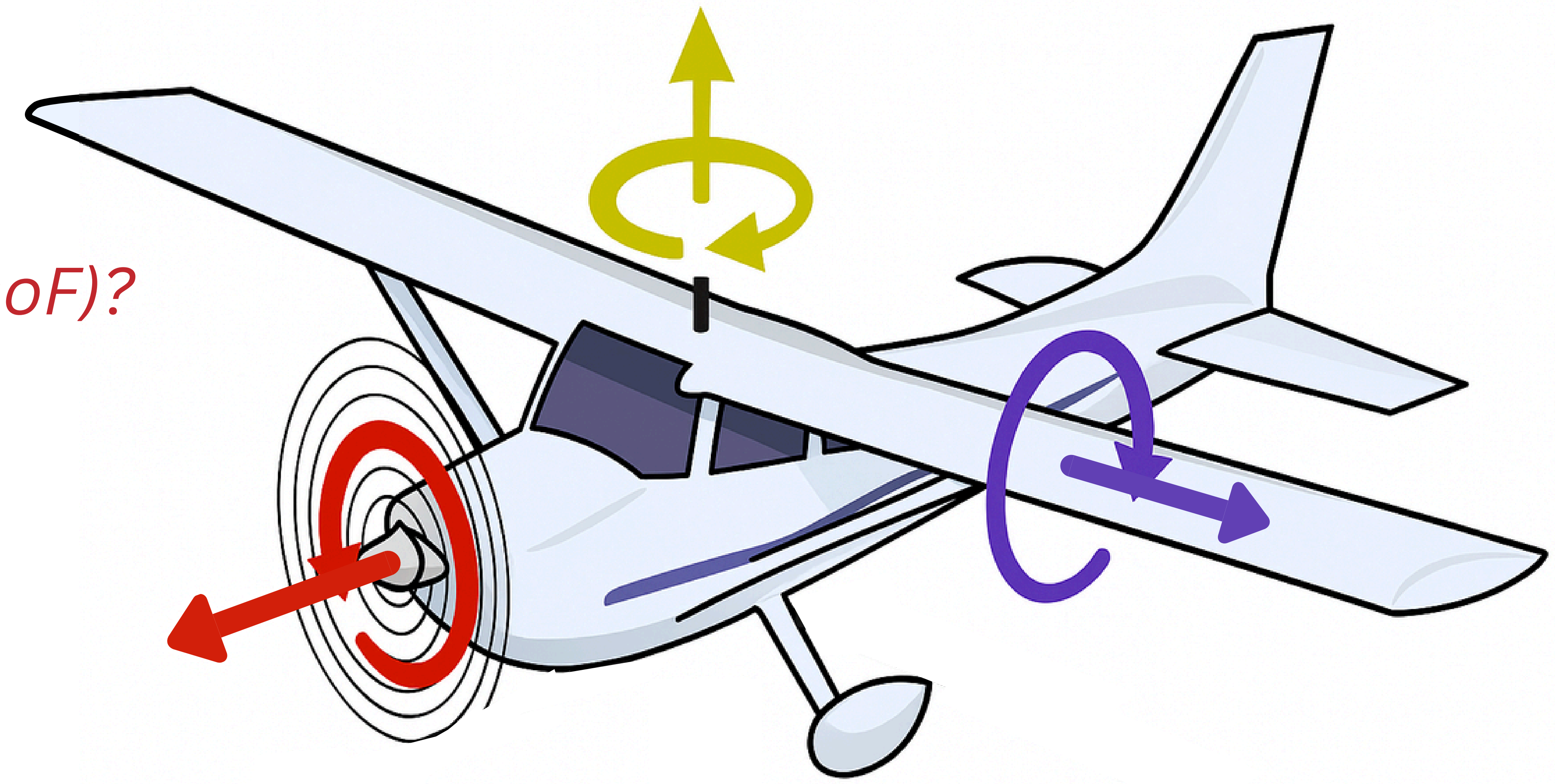
2) Roll

3) Yaw

4) translation-x

5) translation-y

6) translation-z



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The Six Degrees of Freedom

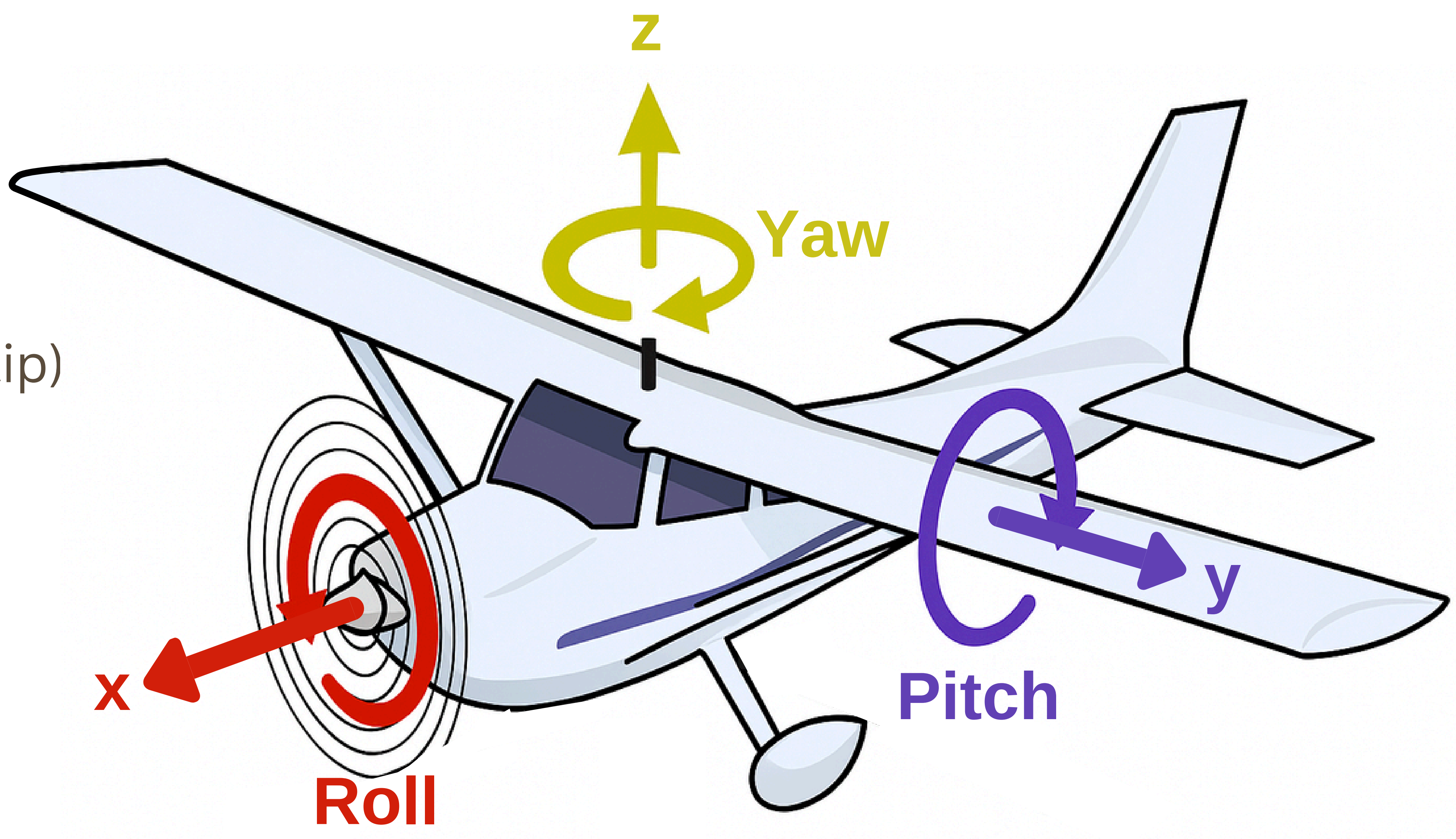
Aircraft motion can be described by 6 Degrees of Freedom (DoF), 3 rotations and 3 translations:

Rotations (Attitude changes):

- **Roll** – about the longitudinal axis (wingtip to wingtip)
- **Pitch** – about the lateral axis (nose up or down)
- **Yaw** – about the vertical axis (nose left or right)

Translations (Linear motion):

- **x** – forward and backward movement
- **y** – side-to-side motion
- **z** – up and down motion



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Control Surfaces

Can you guess which is which?

1) Throttle

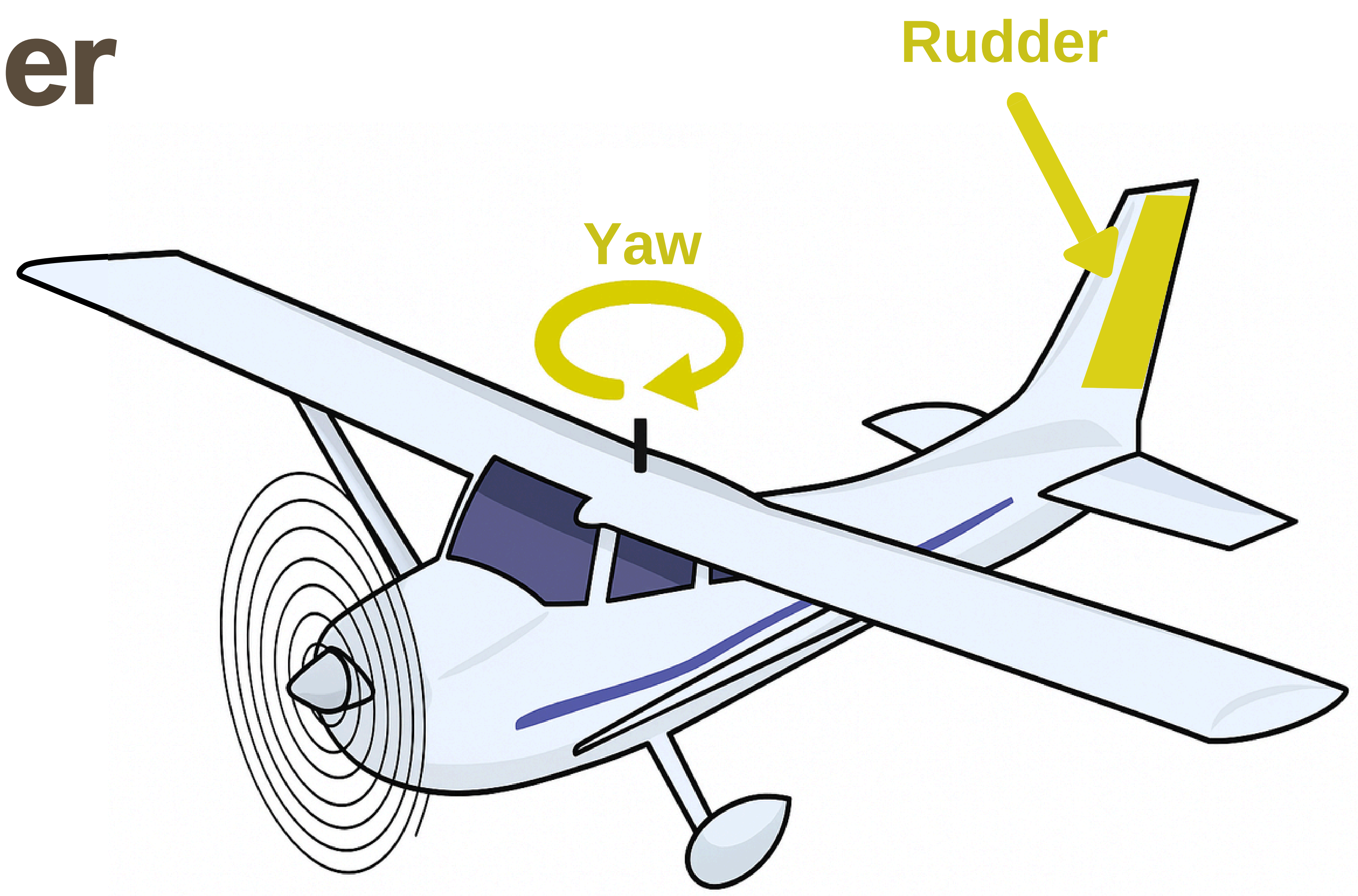
2) Ailerons

3) Elevators

4) Rudder

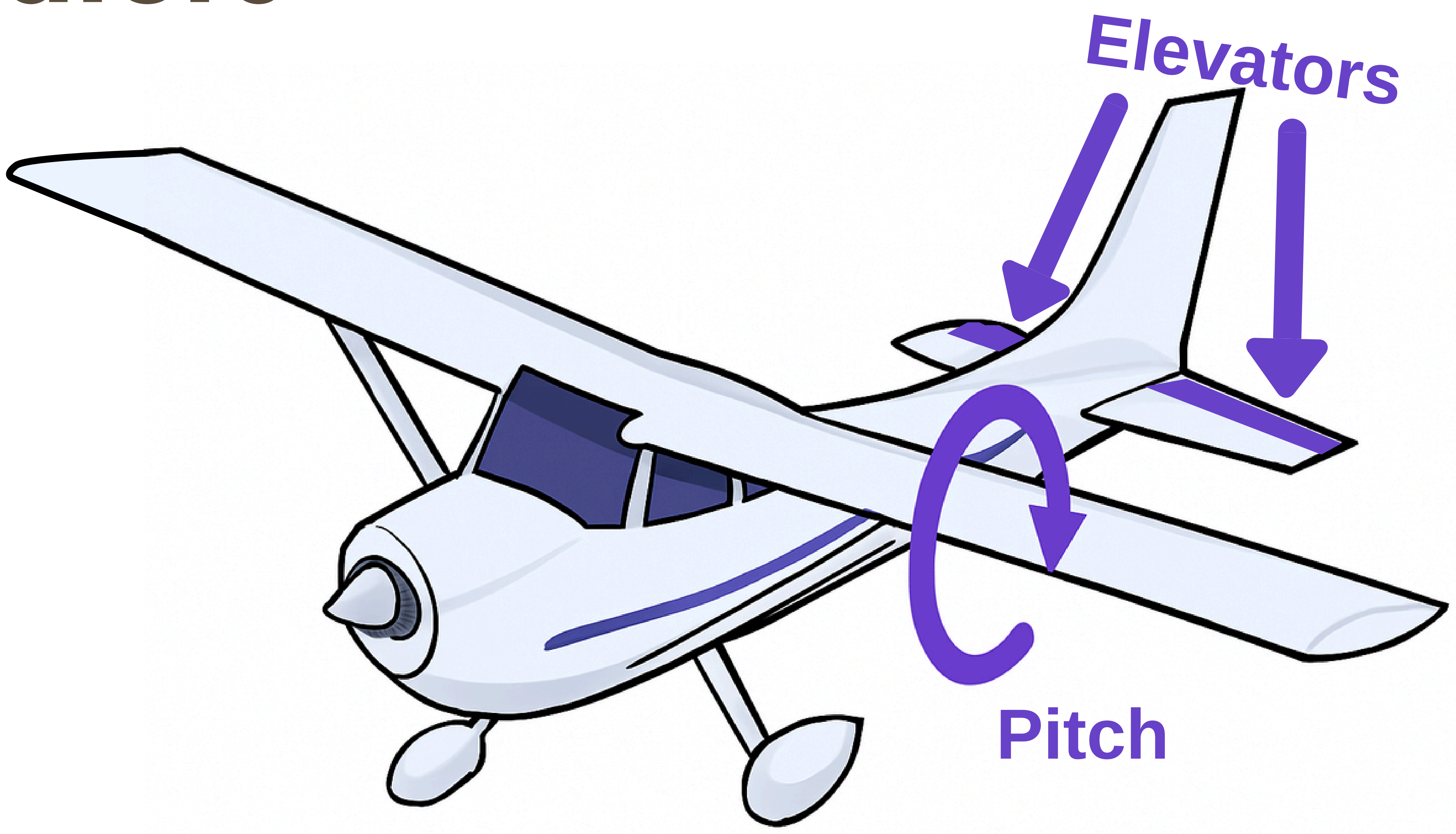
Control Surface - Rudder

DoF	Control Surface
Yaw	Rudder



Control Surfaces - Elevators

DoF	Control Surface
Yaw	Rudder
Pitch	Elevators



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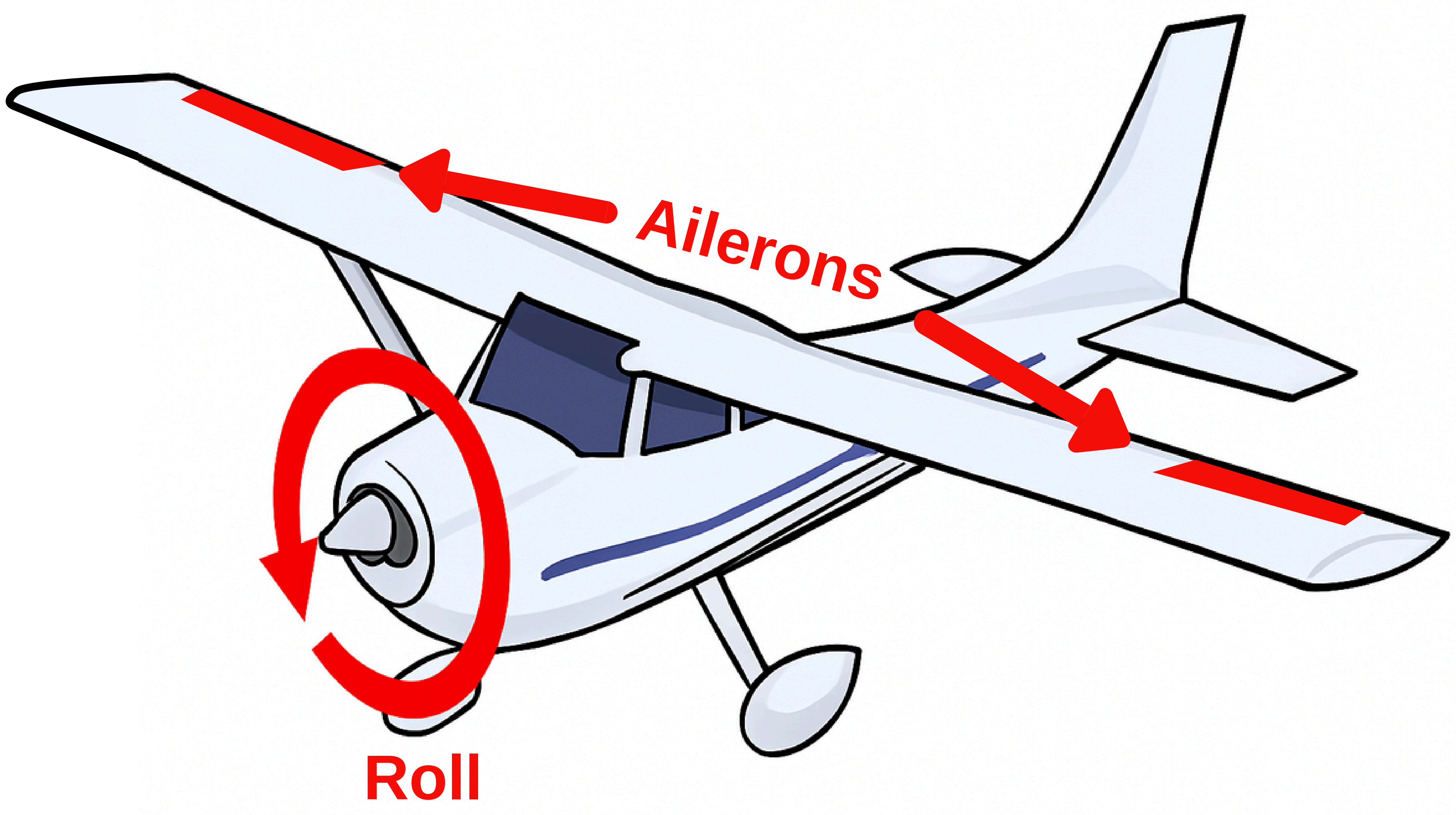
Control Surfaces - Ailerons

DoF	Control Surface
Yaw	Rudder
Pitch	Elevators
Roll	Ailerons



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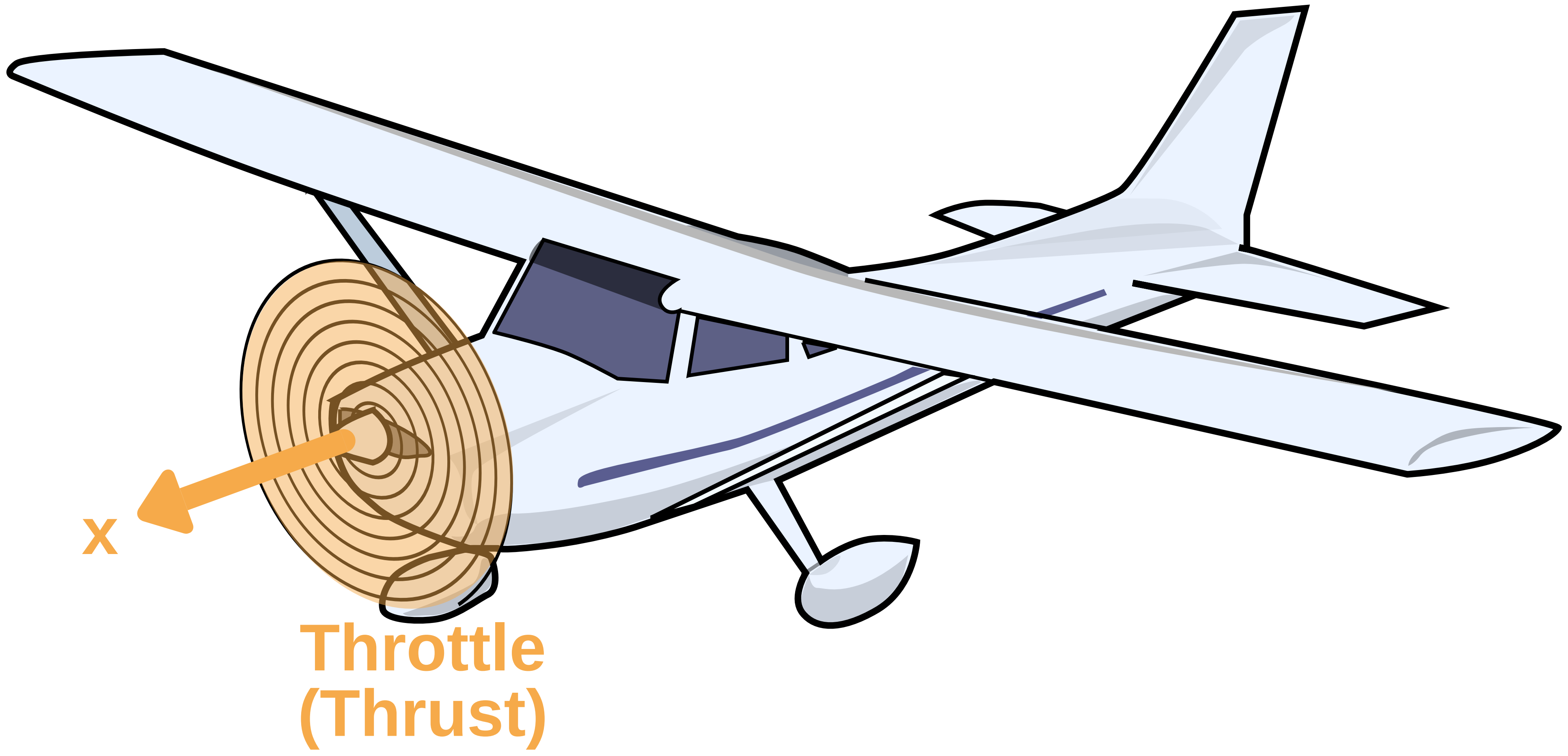
Control Surfaces - Throttle

DoF	Control Surface
Yaw	Rudder
Pitch	Elevators
Roll	Ailerons
translation-x	Throttle (Thrust)



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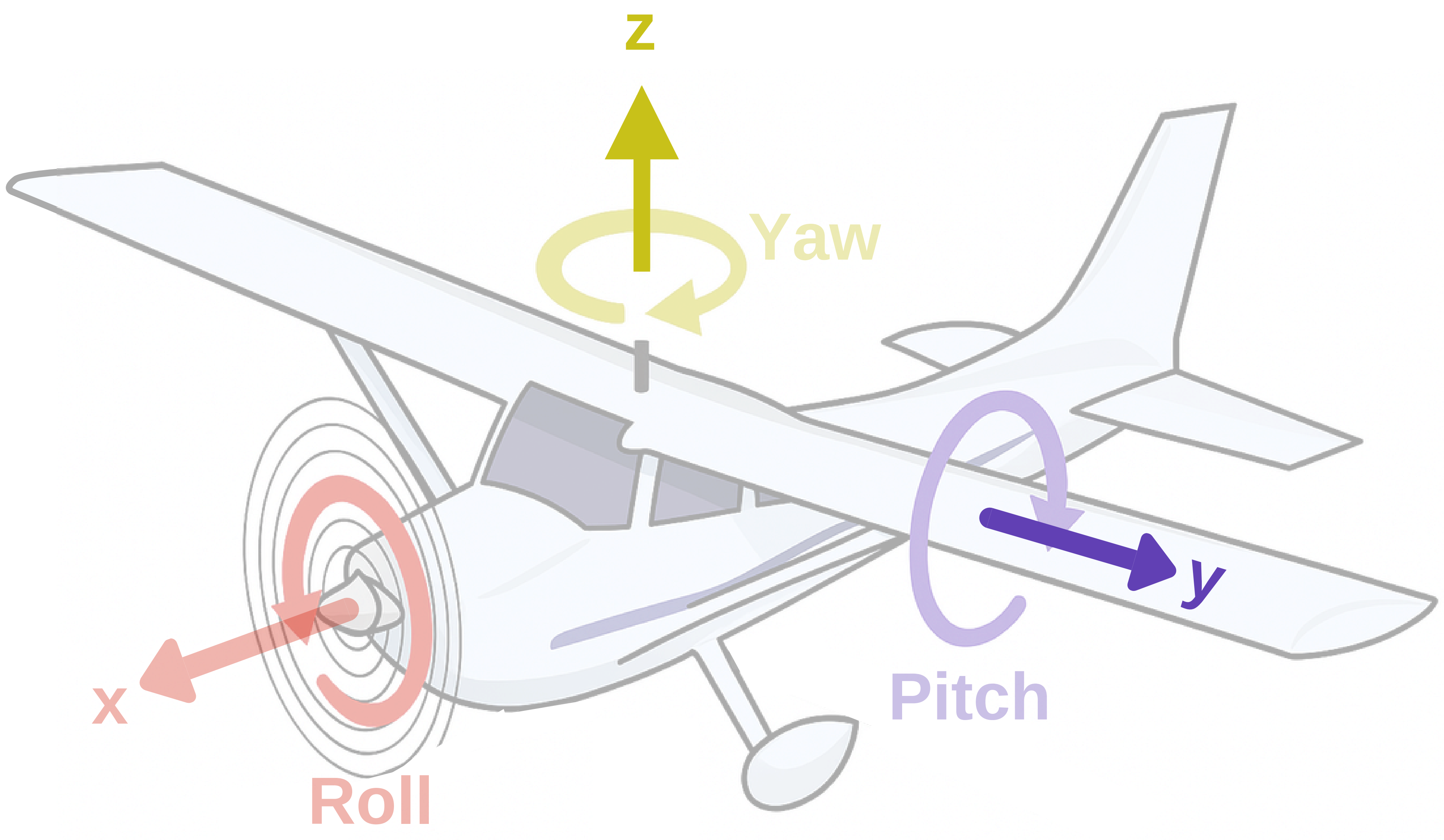
Control Surfaces

We've controlled 4 out of the 6 DOFs

How can we control the other two?

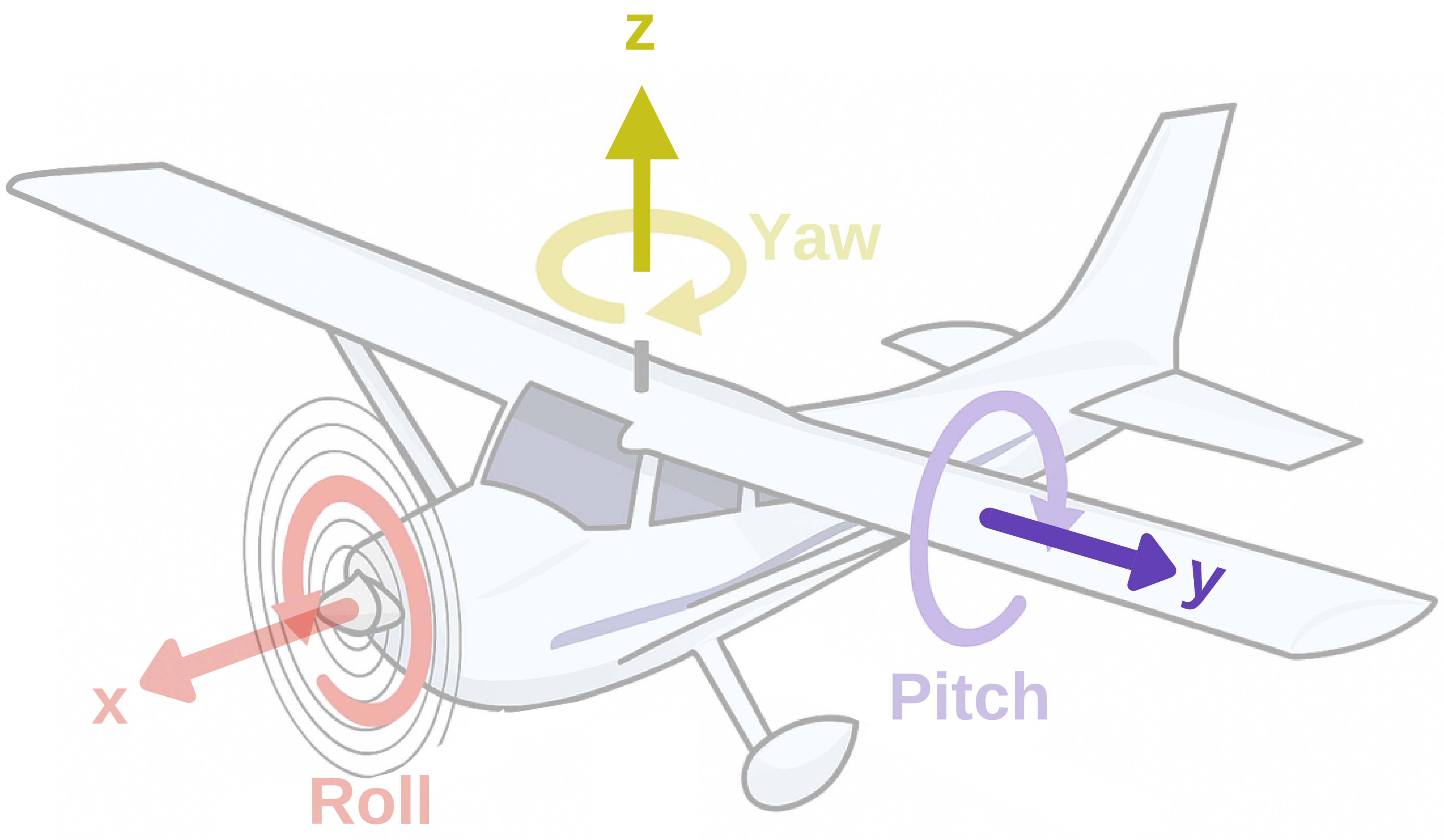
DoF	Control Surface
Yaw	Rudder
Pitch	Elevators
Roll	Ailerons
translation-x	Throttle (Thrust)
translation-z	?
translation-y	?



Control Surfaces

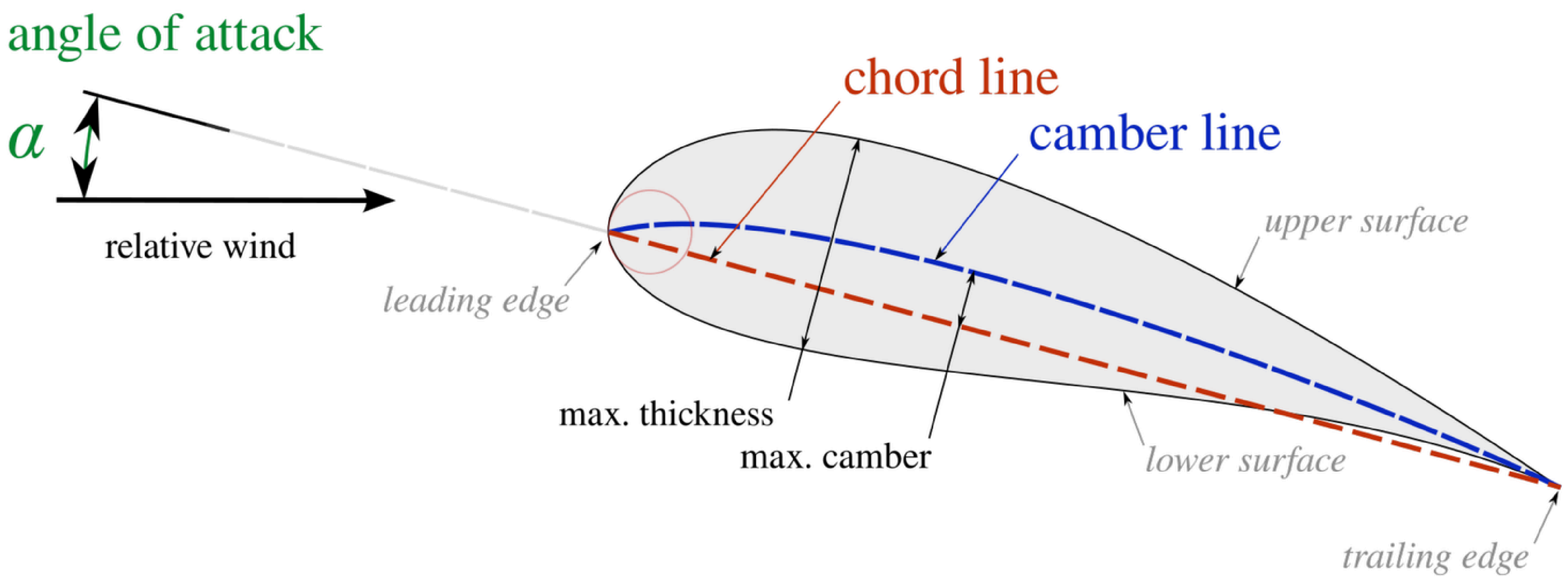
DoF	Control Surface
Yaw	Rudder
Pitch	Elevators
Roll	Ailerons
translation-x	Throttle (Thrust)
translation-z	Wing (Lift*)
translation-y	Side Slip (Rudder + Ailerons)

*Lift is produced by the wings and controlled by the elevator (angle of attack) and throttle (airspeed).



How Wings Generate Lift: The Airfoil

- **Chord line:** The straight line connecting the leading edge and trailing edge of the airfoil. It serves as a reference for defining other geometric angles.
- **Camber line:** The curve passing midway between the upper and lower surfaces of the airfoil. Its shape indicates how much the airfoil is curved, influencing lift and pitching moment.
- **Angle of attack (α):** The angle between the chord line and the relative airflow. Increasing the angle of attack increases lift up to the stall point, after which airflow separates and lift drops sharply.



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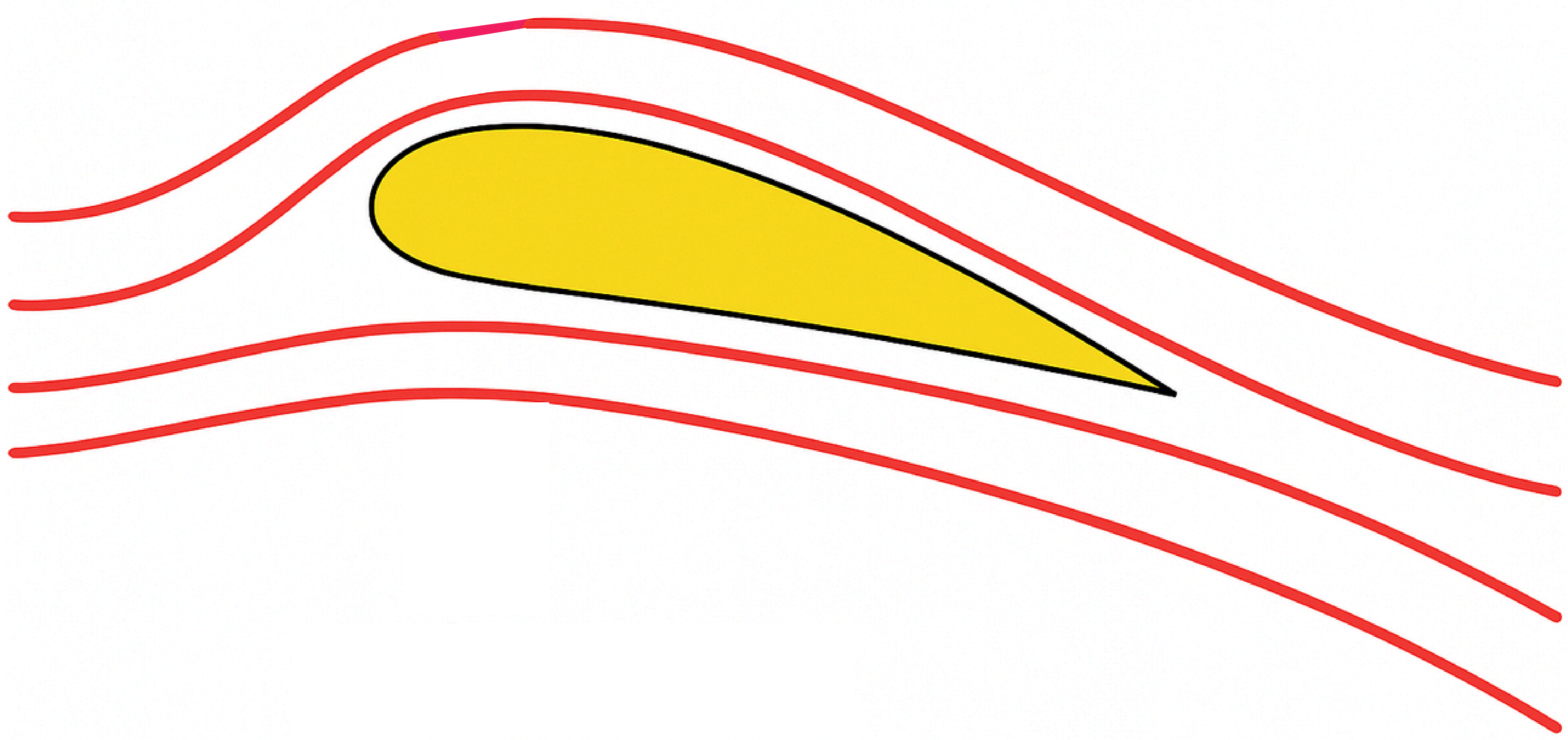
How Wings Generate Lift: The Airfoil

How does an airfoil generate lift?



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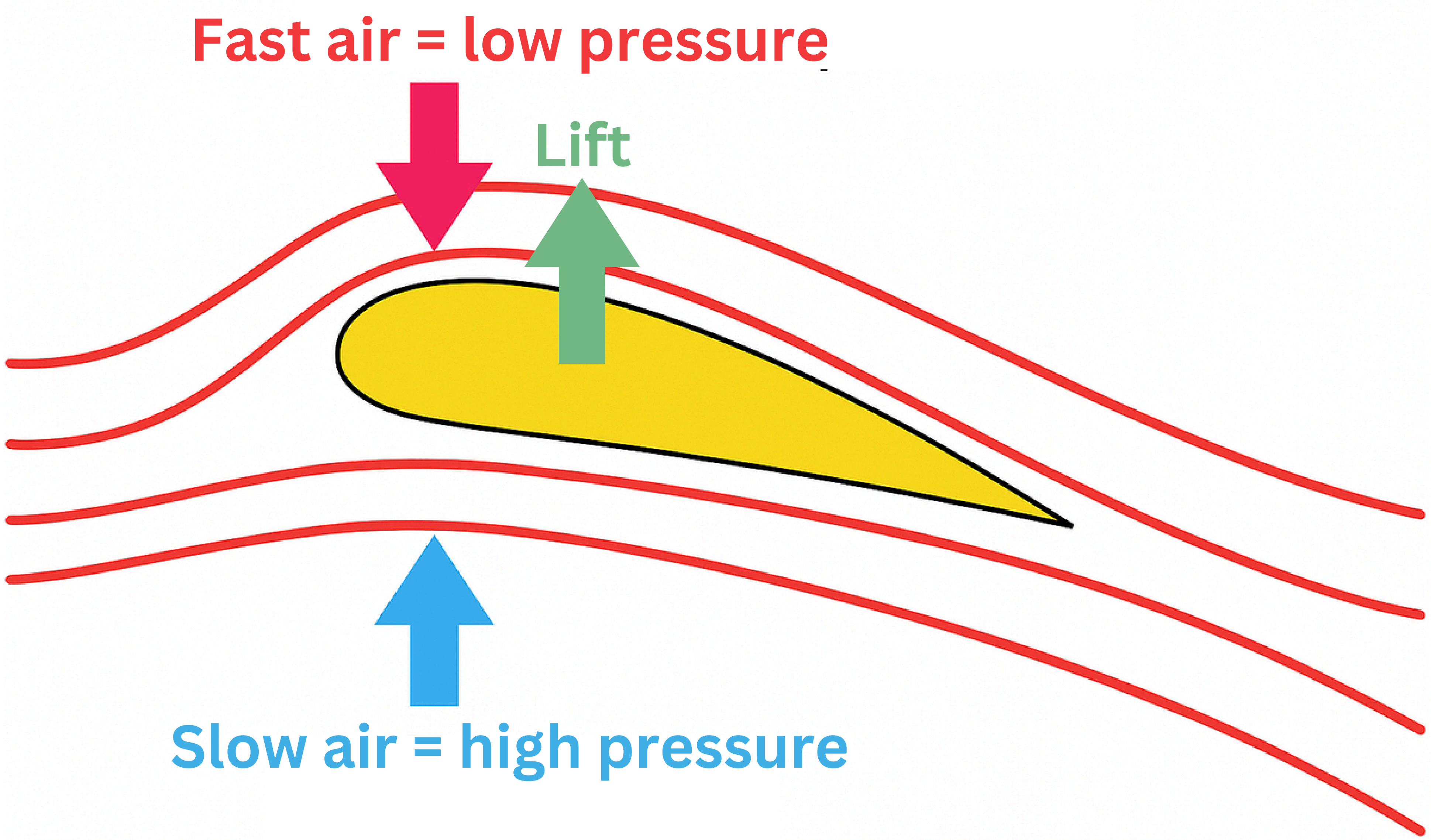
How Wings Generate Lift: The Airfoil

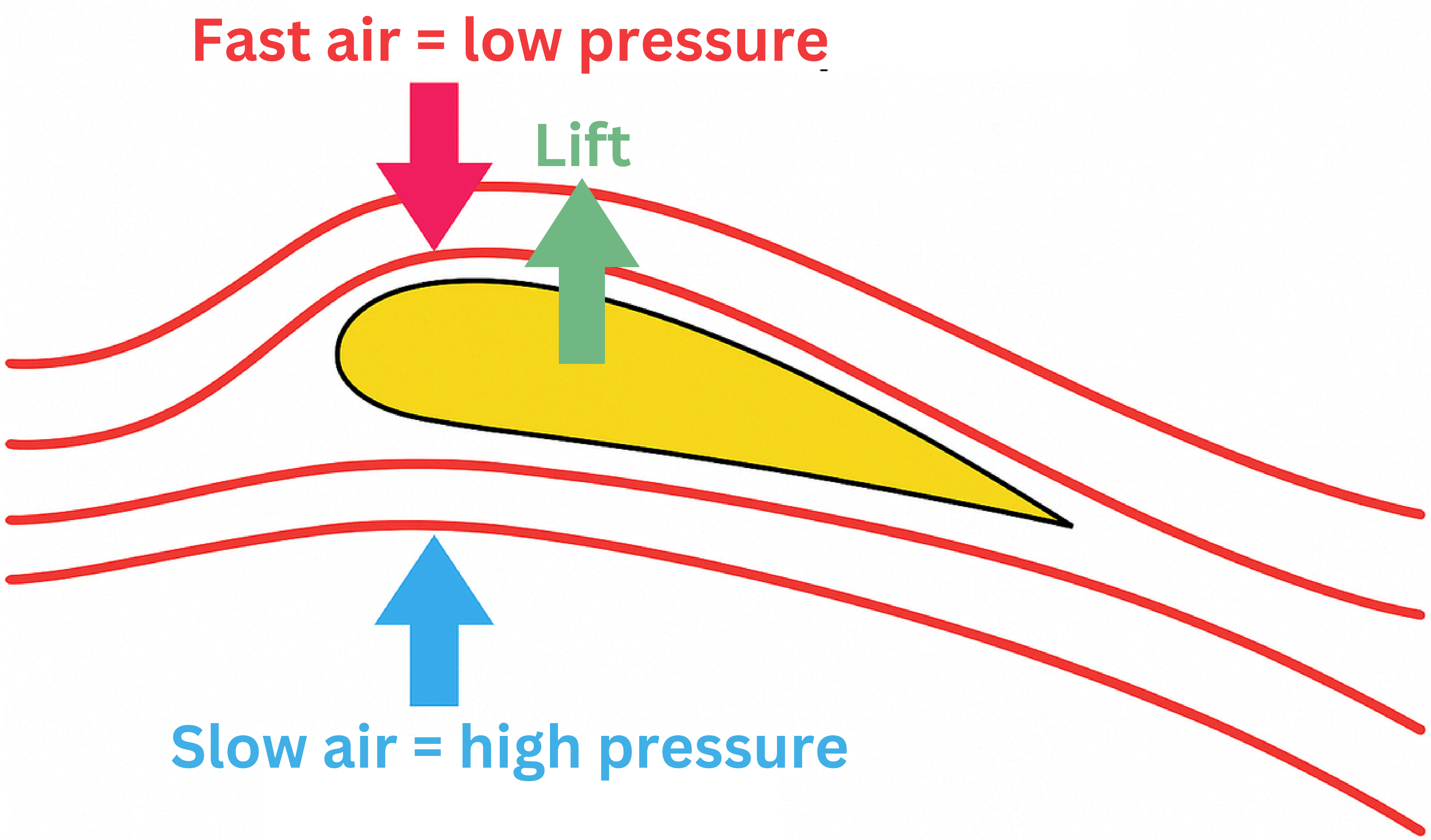
- As air flows around the wing, it moves **faster over the curved upper surface and slower underneath.**
- Faster airflow means **lower pressure on top**; slower airflow means **higher pressure below**.
- The **pressure difference** creates an upward force — **lift.**
- The **angle of attack (α)** also increases the downward deflection of airflow, further adding lift.
- Too high an angle → airflow separates → **stall** (sudden loss of lift).



How Wings Generate Lift: The Airfoil

$$L = \frac{1}{2}\rho V^2 S C_L$$

L – Lift force (Newtons)
ρ – Air density (kg/m³), depends on altitude and temperature
V – True airspeed (m/s), relative to the airflow
S – Wing planform area (m²)
C_L – Coefficient of lift (dimensionless), depends on airfoil shape and angle of attack



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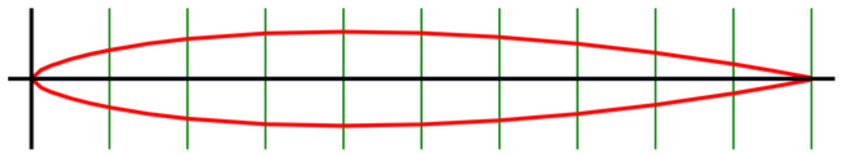
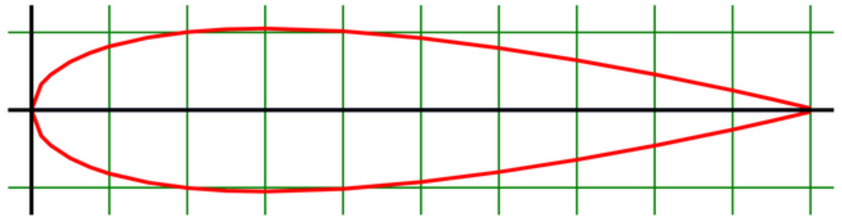
Airfoil Geometry & Selection

Thickness



Thin

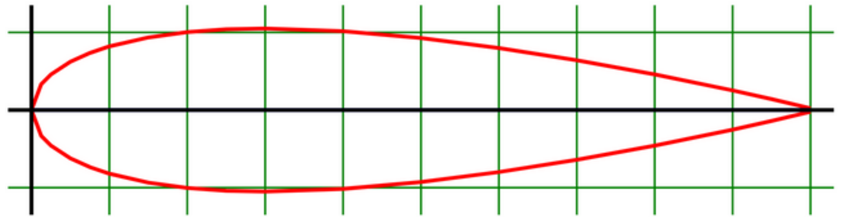
- **Lift:** Low at small angles of attack.
- **Drag:** Very low.
- **Stall:** Early and abrupt.
- **Stability:** Less forgiving, highly responsive.
- **Use:** Fast or agile aircraft.



Thick

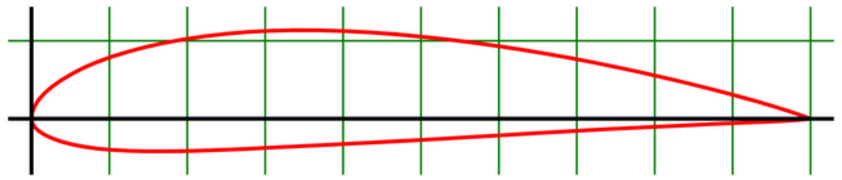
- **Lift:** Higher due to greater thickness.
- **Drag:** Moderate, less efficient at high speed.
- **Stall:** Later and smoother.
- **Stability:** More stable and forgiving to pitch changes.
- **Use:** Gliders, trainers, endurance-focused UAVs.

Camber



Symmetrical

- **Lift:** Zero at zero angle of attack, changes with pitch.
- **Drag:** Low, efficient for high-speed and bidirectional flight.
- **Stall:** Predictable and balanced.
- **Stability:** Neutral, no inherent pitching moment.
- **Use:** Aerobatic aircraft and control surfaces.



Cambered

- **Lift:** Produces lift even at zero angle of attack.
- **Drag:** Slightly higher than symmetrical at high speed.
- **Stall:** Occurs earlier but with a smoother transition.
- **Stability:** Generates a nose-down pitching moment.
- **Use:** General aviation, efficient low-speed flight.

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Reynolds Number (Re)

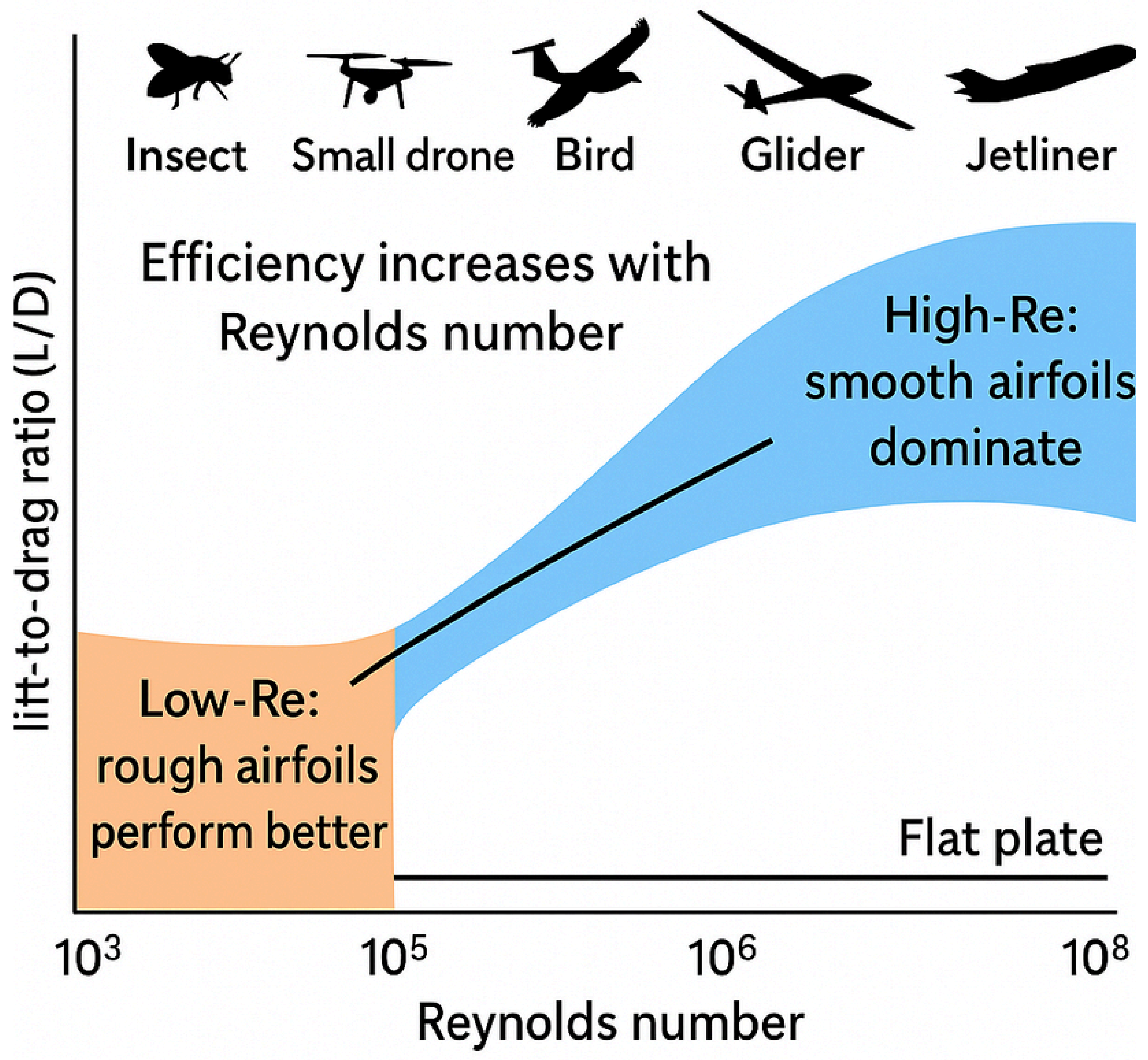
Describes the **flow environment an aircraft operates in,** it's a result of your flight conditions:

- **Faster speeds** and **larger wings** → higher Re (air behaves smoothly, efficient flow).
- **Slower speeds** and **smaller wings** → lower Re (air feels "thicker," more viscous).

You choose your airfoil to perform well at the Reynolds number range your aircraft naturally operates in.

$$Re = \frac{\rho V c}{\mu}$$

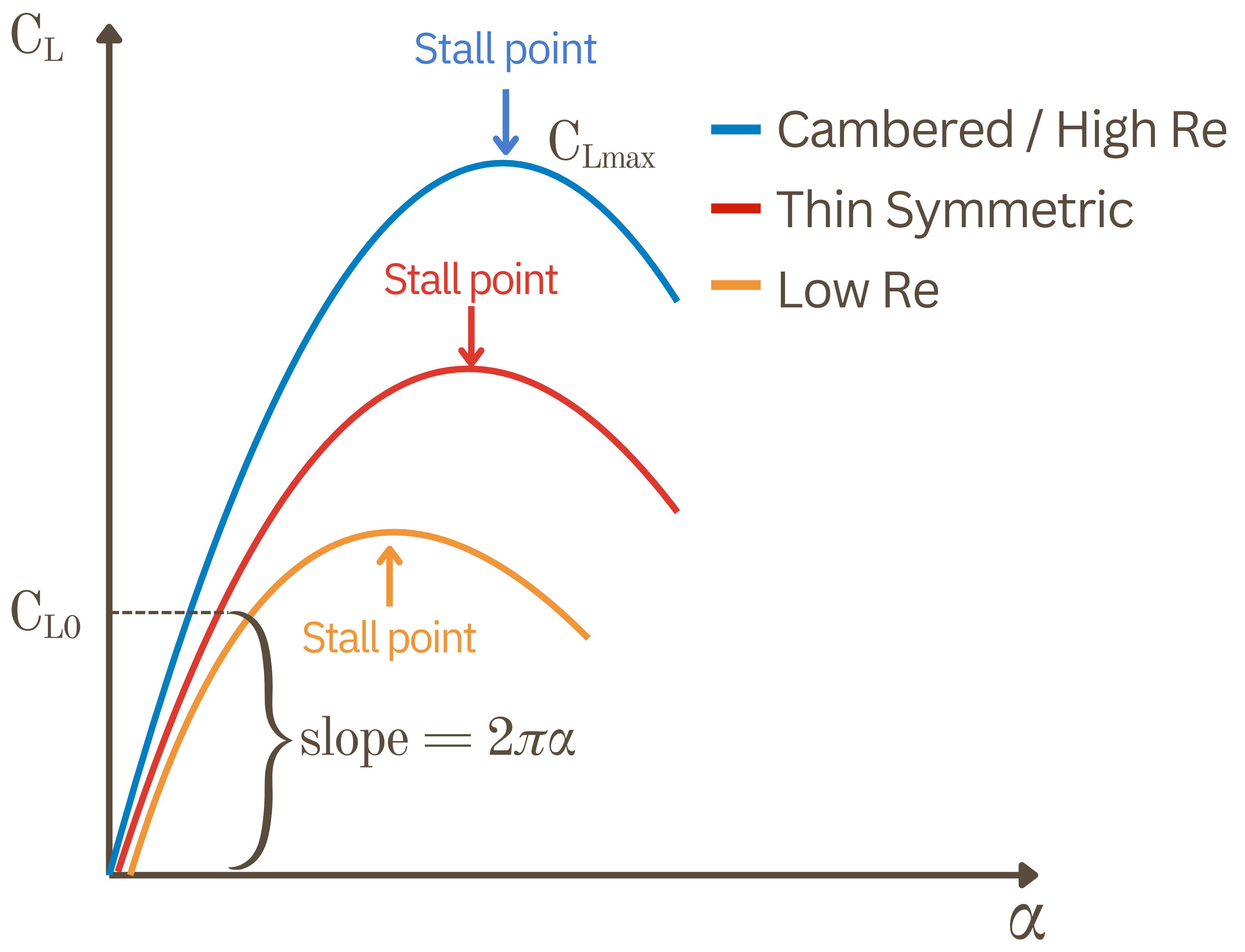
Re – Reynolds number (dimensionless).
ρ – Air density (kg/m³).
V – True **airspeed** (m/s).
c – Mean aerodynamic **chord** (m).
μ – Dynamic **viscosity of air** ($kg \cdot m^{-1} \cdot s^{-1}$).



Lift Curve and Stall Behaviour

- As **angle of attack (α)** increases, **lift coefficient (CL)** rises almost linearly until a maximum value (CLmax).
- Beyond CLmax, **airflow** starts to **separate**, leading to **stall** and a sharp **drag increase**.

	Lift Behaviour	Stall Behaviour
Thin / Symmetric Airfoil	Flow separates early (Low CLmax)	Stalls earlier (smaller α)
Low Reynolds Number		
Cambered Airfoil	Flow stays attached longer (High CLmax)	Stalls later (larger α)
High Reynolds Number		



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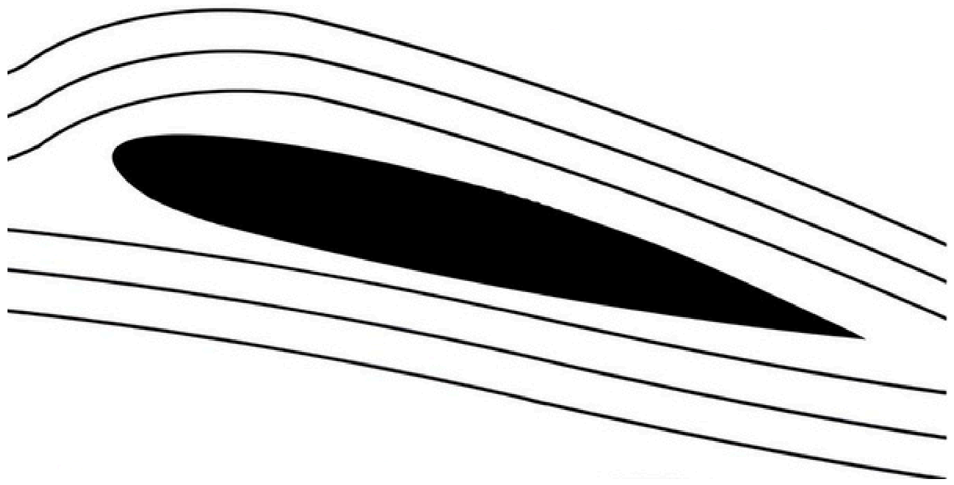
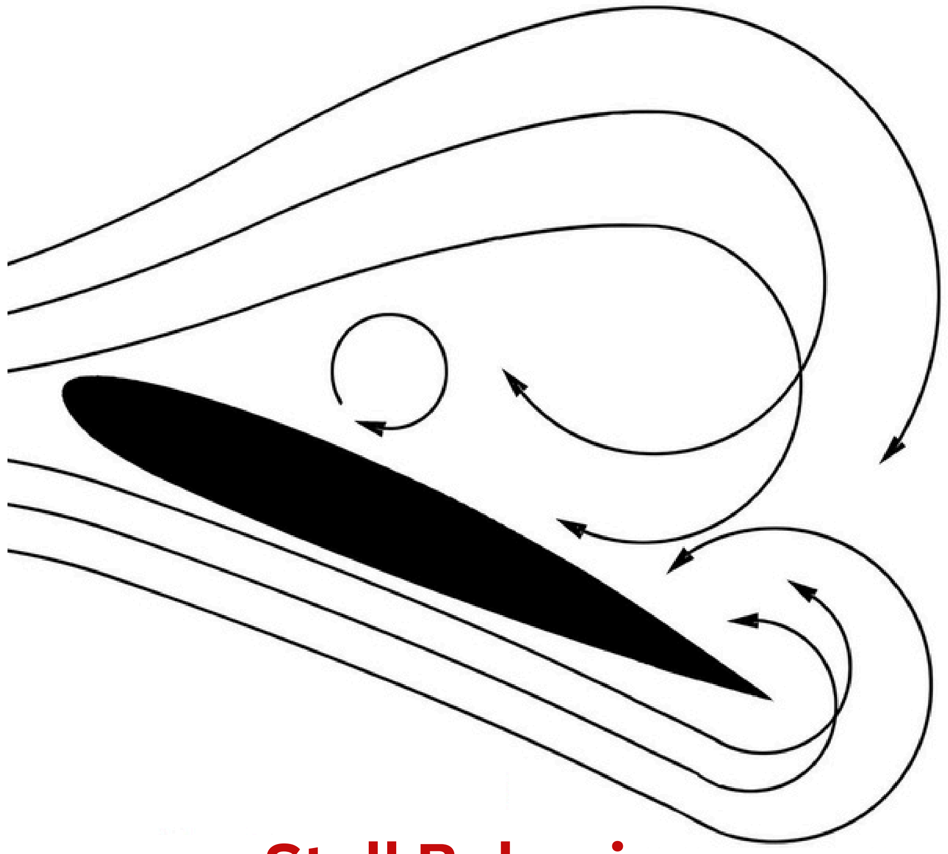
Visualisation of Stall Behaviour

- Occurs when **airflow separates** from the upper surface of the wing.
- Flow becomes **turbulent and detached**, forming a low-pressure wake.
- Results in:
  - **Sharp loss of lift.**
  - **Sudden increase in drag.**
- Stall angle depends on:
  - **Airfoil geometry.**
  - **Surface roughness.**
  - **Reynolds number.**



Normal Flight



Stall Behavior

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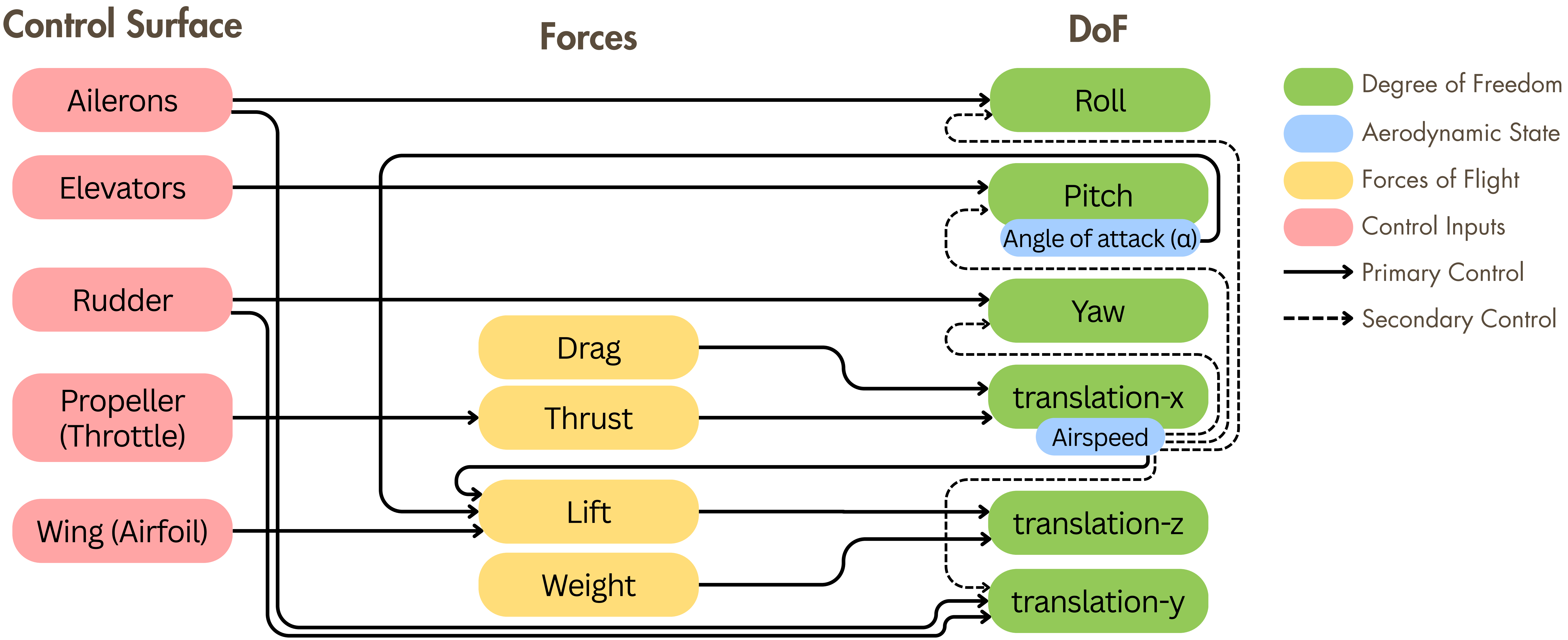
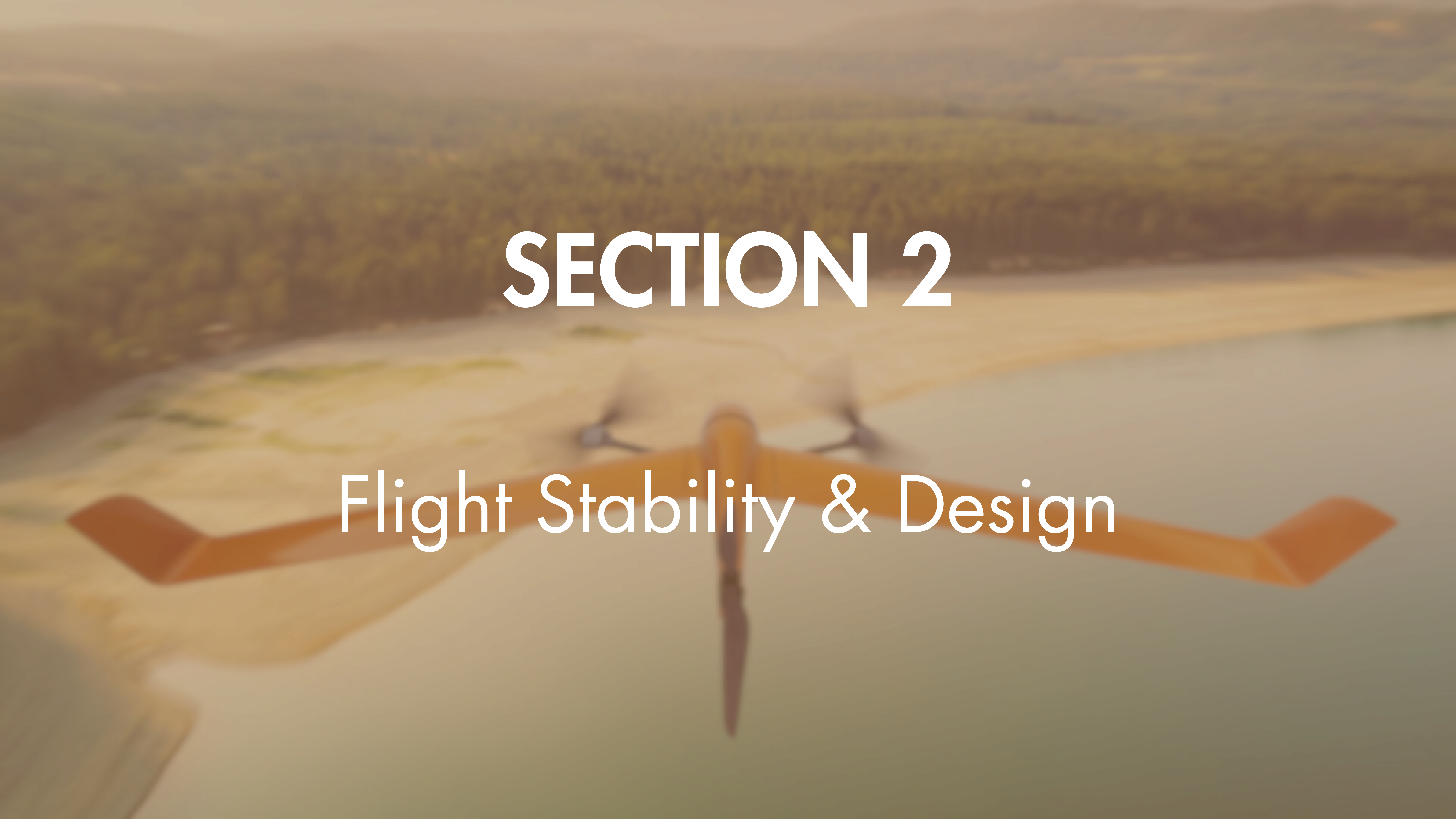
The Flight Control Loop (Simplified)





SECTION 2

Flight Stability & Design

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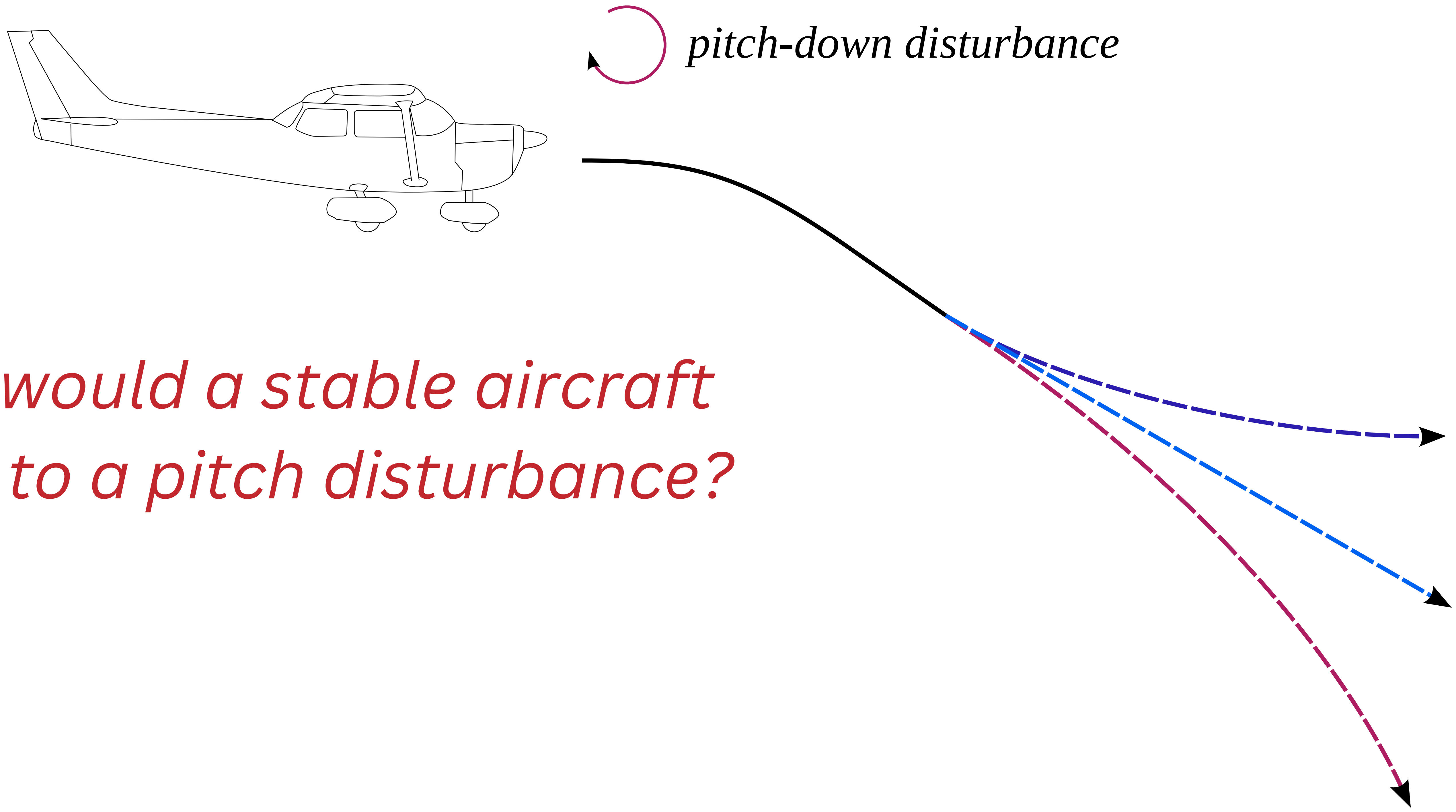
What is Stability?



How would a stable aircraft react to a pitch disturbance?

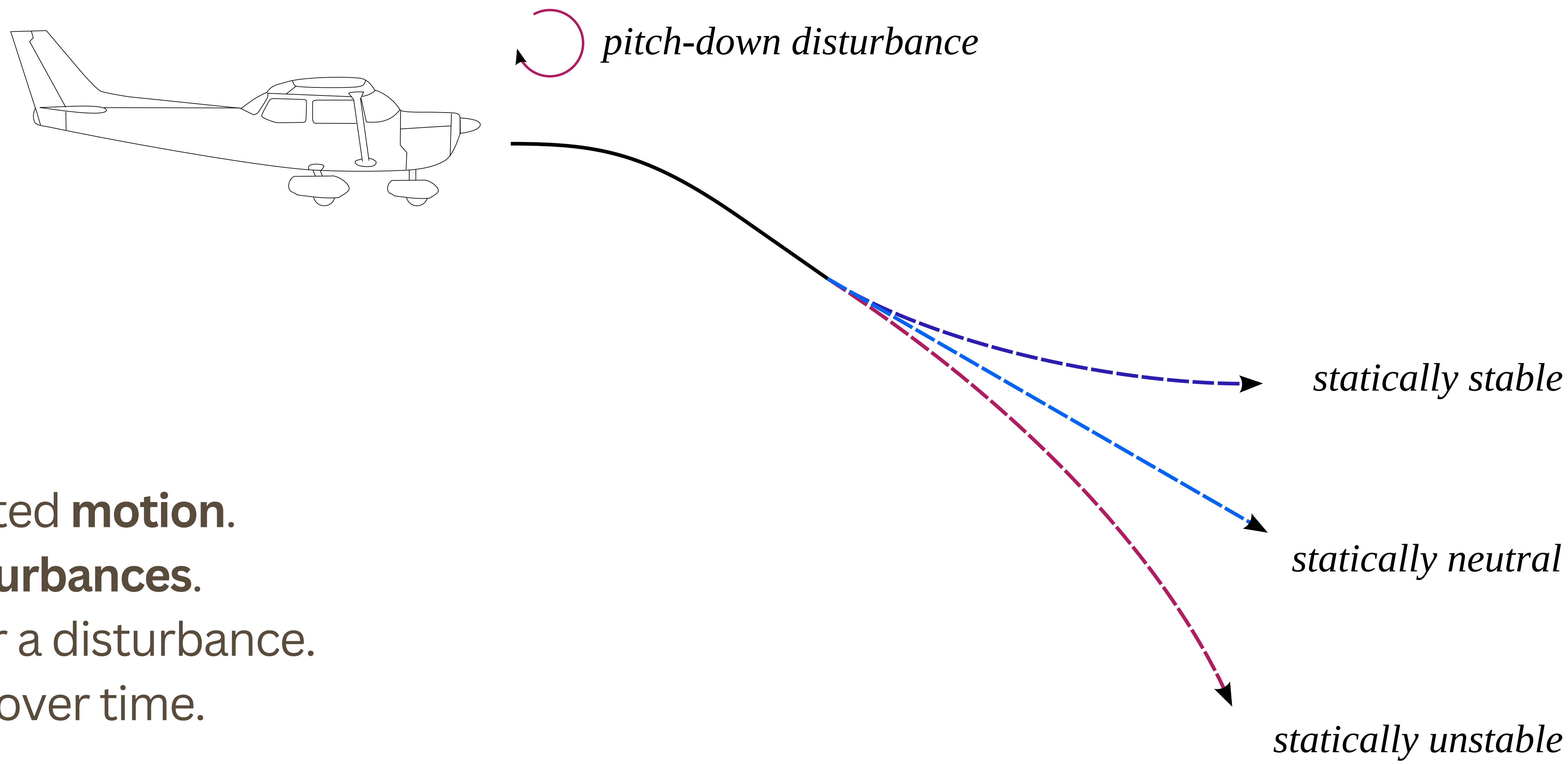
What is Stability?

*"**Stability** in a fixed-wing aircraft refers to its **ability to return to a steady flight** condition after a disturbance **without continuous pilot input.**"*

Key points:

- A **stable** aircraft naturally **resists** unwanted **motion**.
- An **unstable** aircraft **amplifies** small **disturbances**.
- **Static stability:** immediate reaction after a disturbance.
- **Dynamic stability:** long-term behaviour over time.

Examples of static stability



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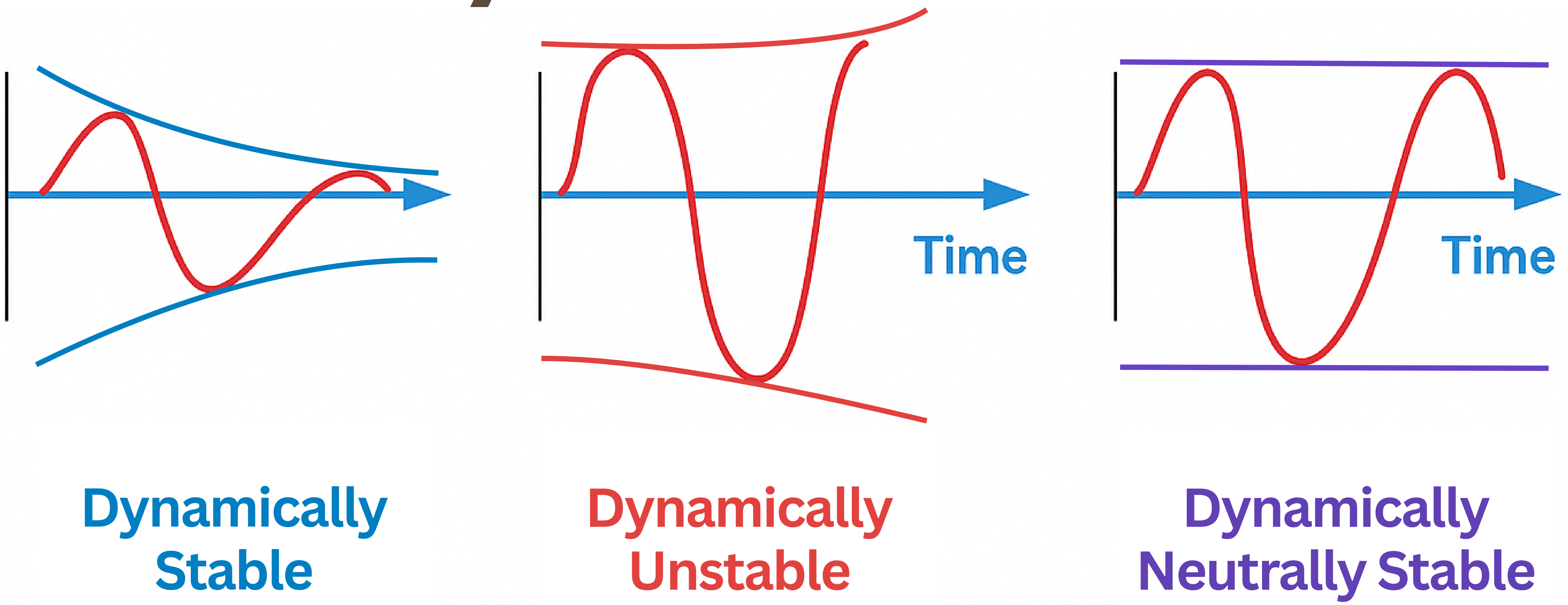
Dynamic Stability



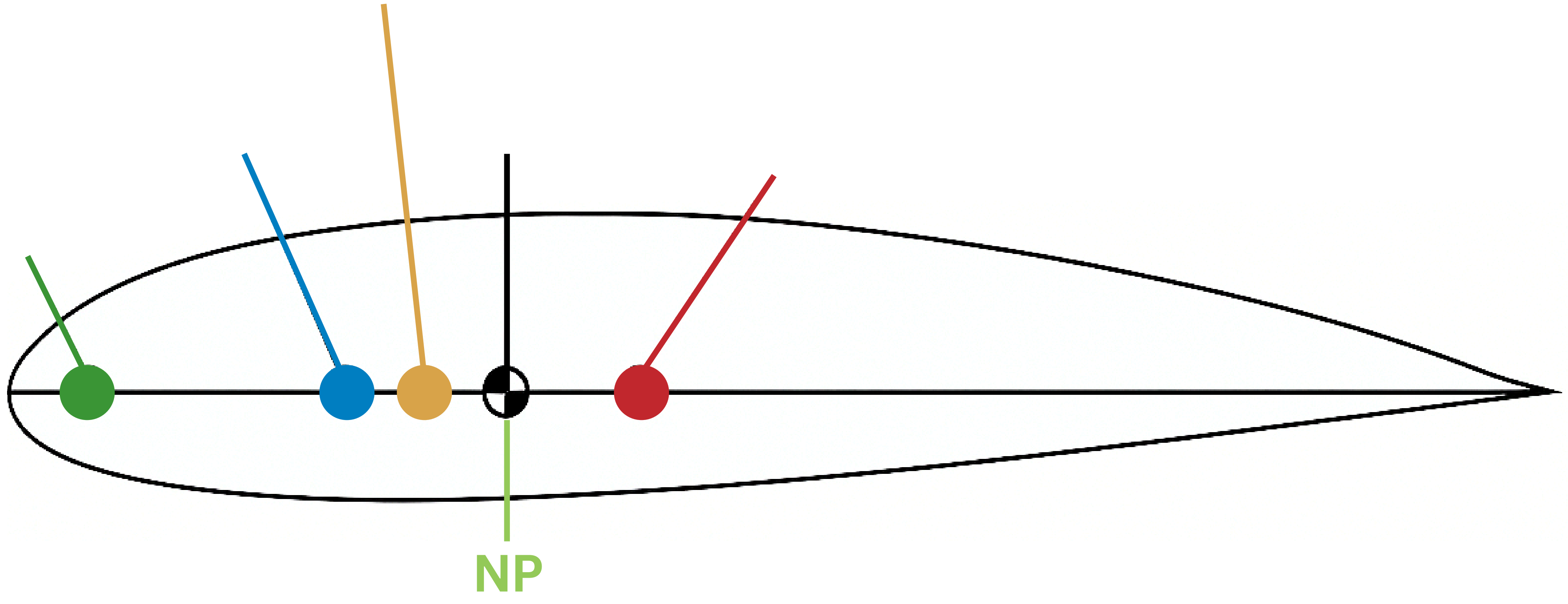
Dynamic stability describes **how the motion evolves over time** after that initial reaction.

Even if the aircraft is **statically stable**, the resulting motion could:

- Return smoothly to equilibrium (damped),
- Oscillate before settling (underdamped), or
- Oscillate with growing amplitude (divergent).

Longitudinal (Pitch) Stability

Where should the CG be relative to the Neutral point (NP) to get the most stability?



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Longitudinal (Pitch) Stability

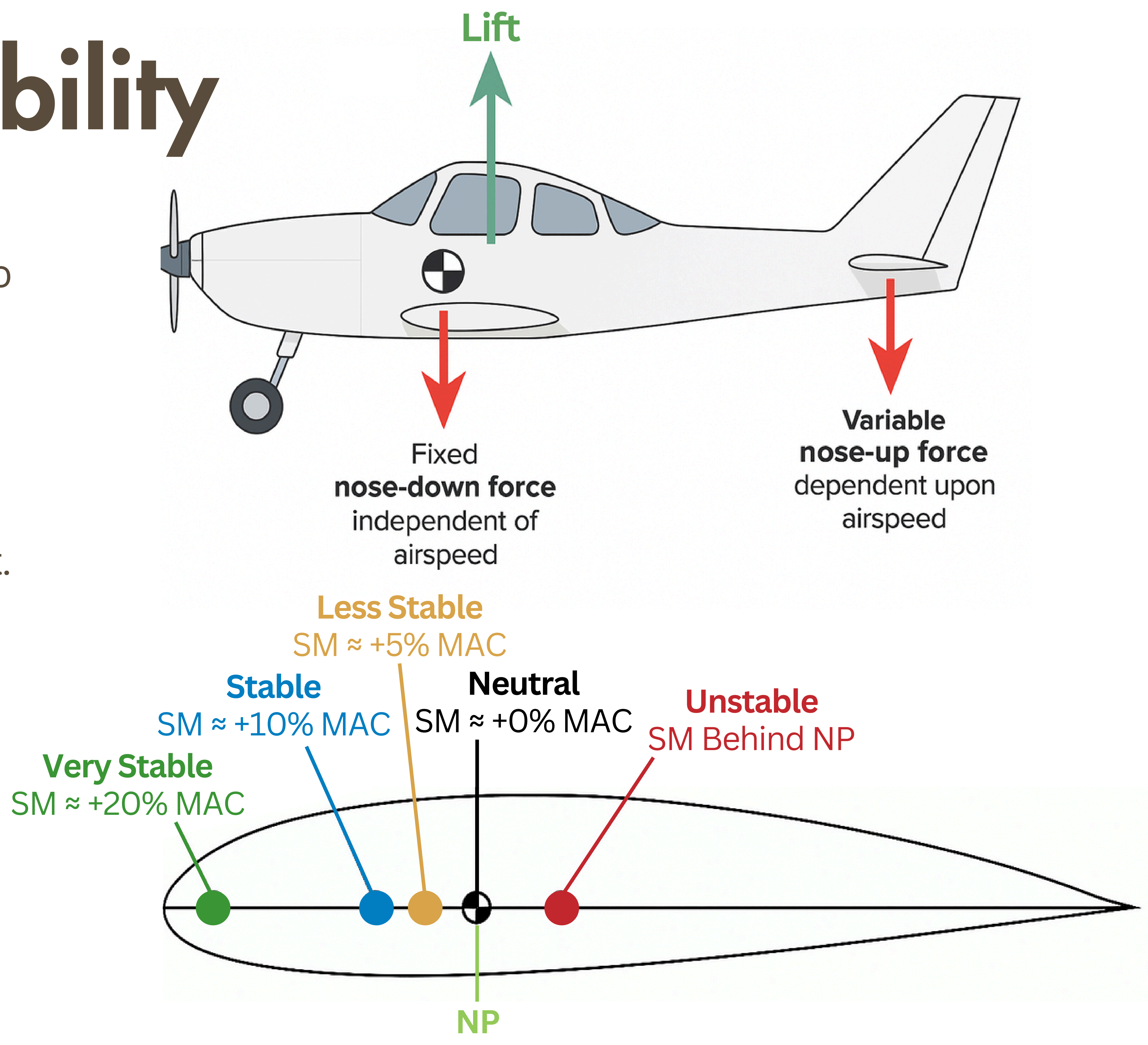
Longitudinal stability concerns how the aircraft responds to **changes in pitch**.

It is mainly influenced by:

- The **centre of gravity (CG)** relative to the **aerodynamic centre (AC)**.
- The **horizontal tail**, which provides a balancing moment.

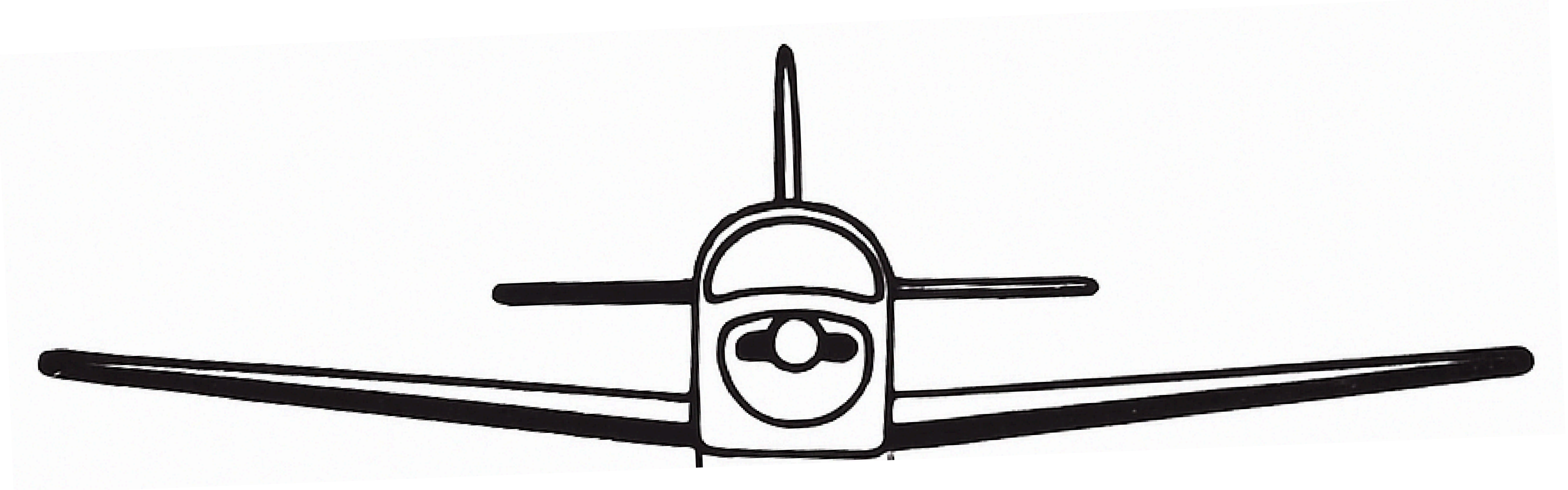
Key points:

- If the **nose pitches up**, the tail **produces a downward force**, pitching the nose back down.
- The **further back the CG**, the **less stable** (but more maneuverable) the aircraft becomes.



Roll Stability

How can we ensure roll stability?



Roll Stability

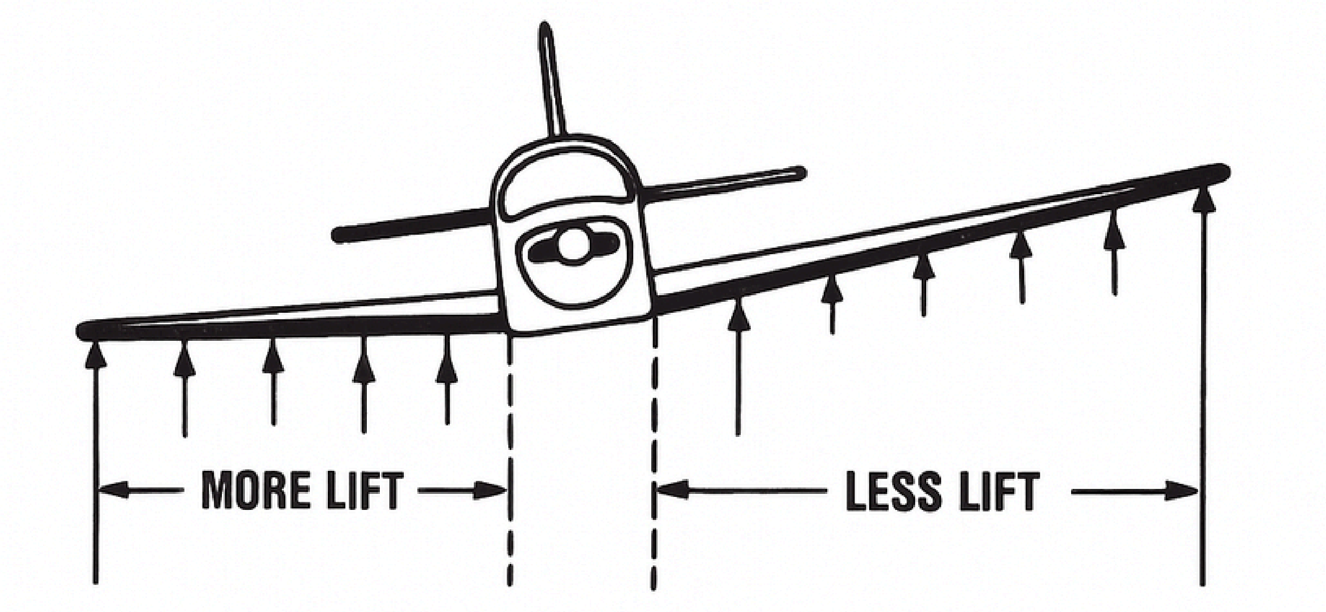
Roll stability is the aircraft's tendency to **return to level wings after being rolled**.

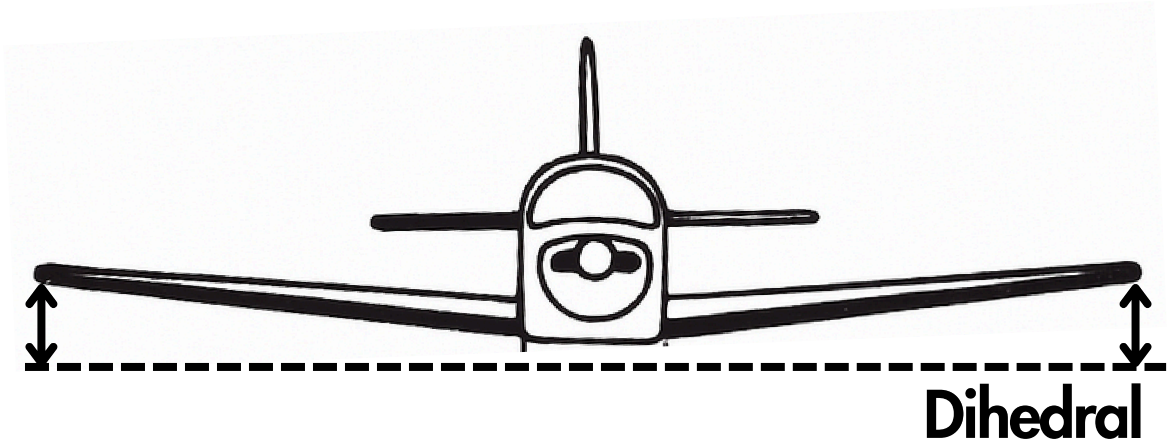
It is mainly governed by:

- **Dihedral angle** (wings angled upward).
- **Sweepback** and **wing position** (high-wing aircraft are more stable).

Key points:

- When one wing drops, it generates more lift due to sideslip, rolling the aircraft back upright.
- Too much dihedral can make the aircraft sluggish in turns.





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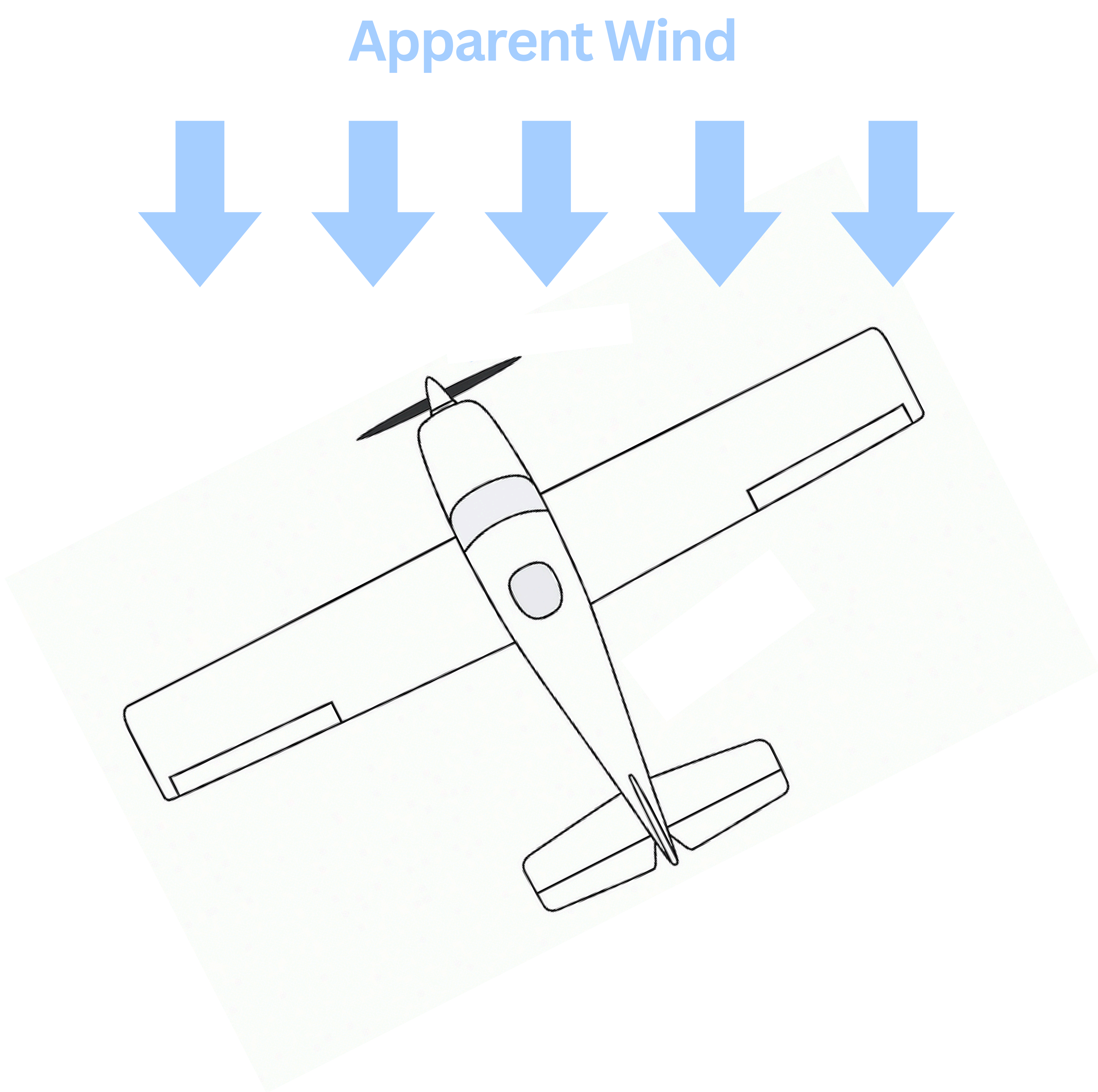
Yaw Stability

What about yaw stability?



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Yaw Stability

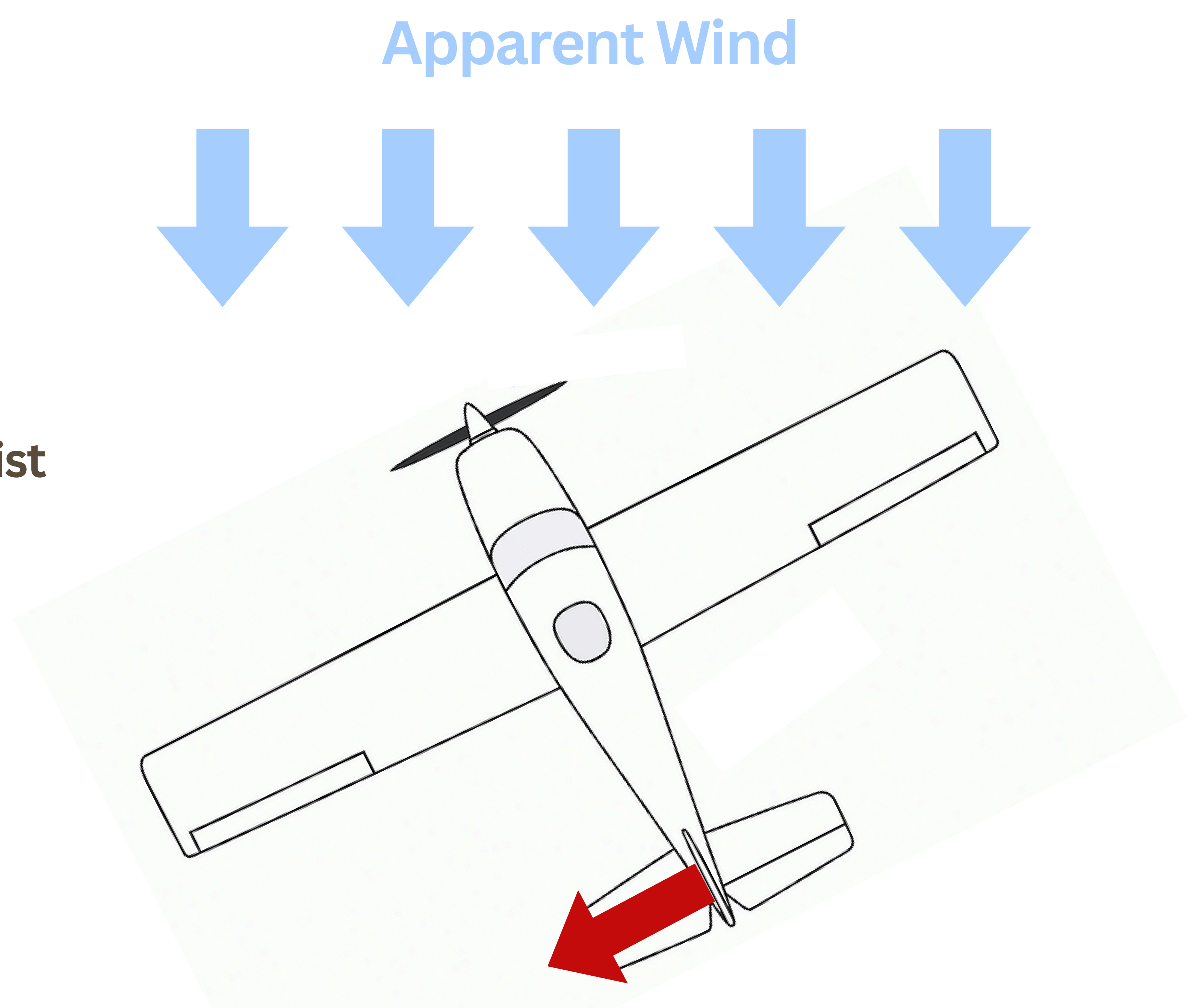
Directional stability (or yaw stability) is the aircraft's ability to **resist unwanted yaw motions.**

It depends primarily on:

- The **vertical stabiliser** (fin) and rudder area and placement.

Key points:

- A sideslip causes **airflow to hit the fin at an angle**, creating a restoring yawing moment.
- The aircraft naturally **aligns itself with the relative wind**.



Sideslip causes the vertical tail to develop an **angle-of-attack** and **generate a yawing moment** which acts to **align the aircraft** with the apparent wind.

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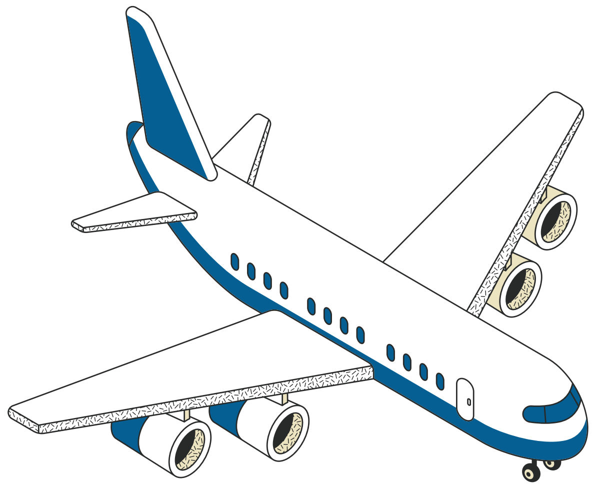
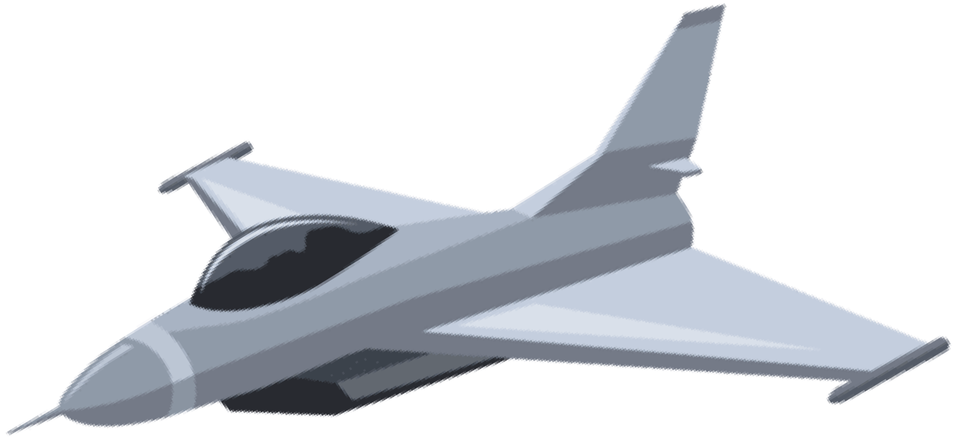
Stability vs. Maneuverability

Stability and maneuverability are opposite ends of a design spectrum.



Stable Aircraft
Naturally resists disturbances
Easier to control, safer
Lower control authority
Common in general aviation



Maneuverable Aircraft
Responds quickly to pilot input
Requires active control or fly-by-wire
High control authority
Common in fighter jets or acrobatic drones

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What Is Drag?

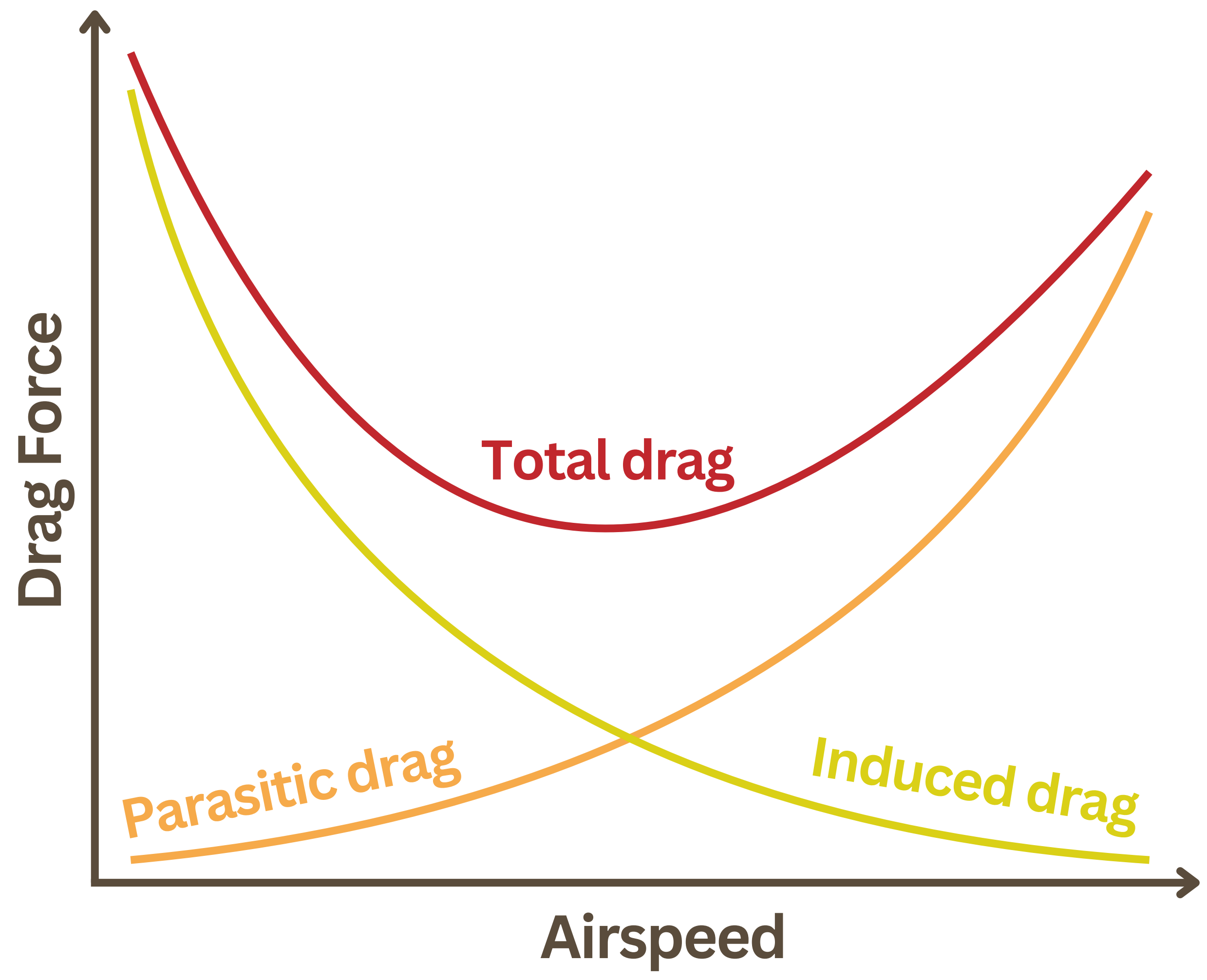
Drag is the ***aerodynamic force opposing motion*** *through air.*
It acts ***opposite to the direction of flight*** *and limits speed and efficiency.*

Total drag mainly comes from:

- **Induced drag:** generated by lift.
- **Parasitic drag:** due to the aircraft's shape and surface.

$$D = \frac{1}{2}\rho V^2 S C_D$$

D – Drag force (Newtons)
ρ – Air density (kg/m³)
V – True airspeed (m/s)
S – Wing planform area (m²)
C_D – drag coefficient (dimensionless)



Note: This graph is representative of level flight

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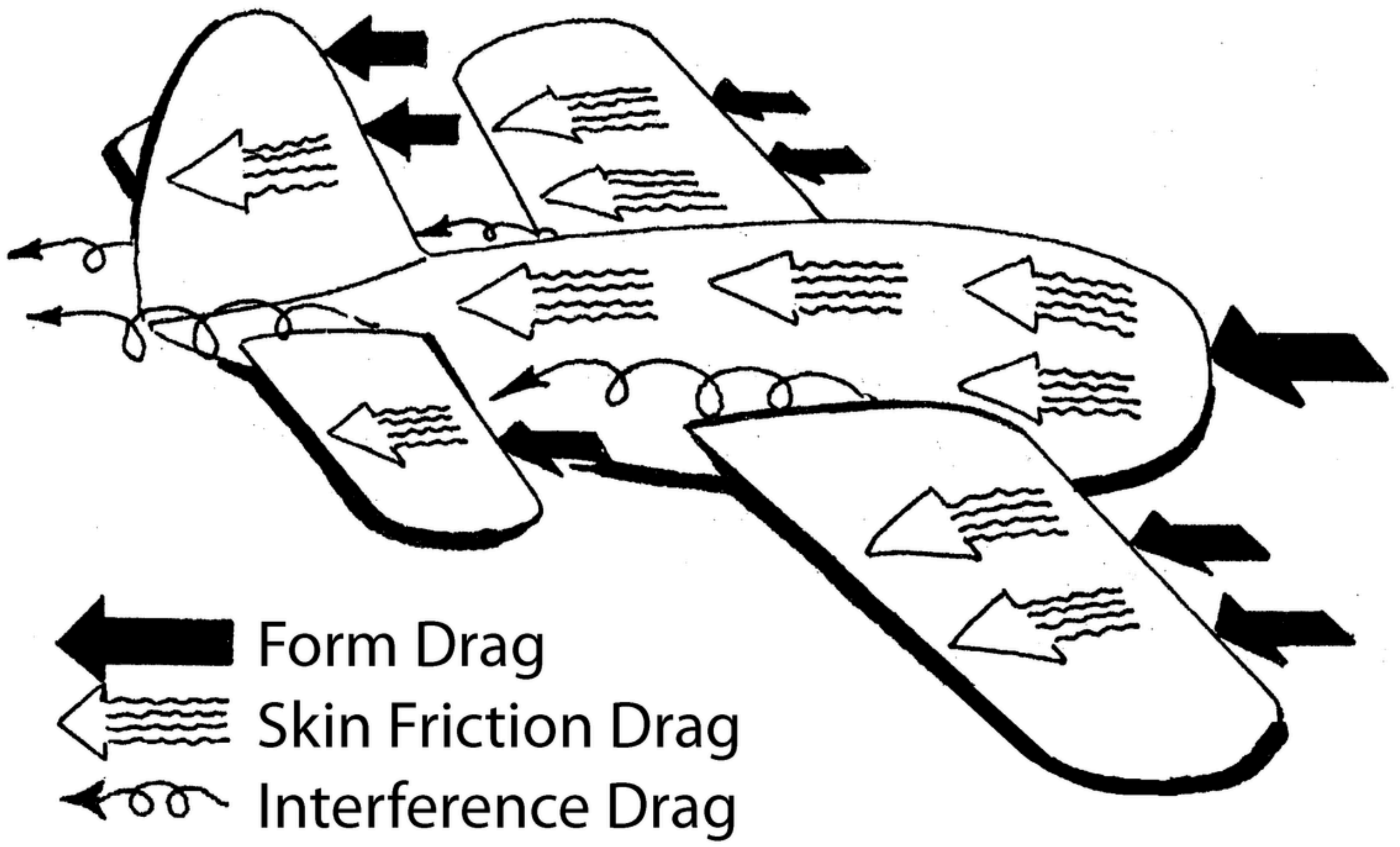
Parasitic Drag

Parasitic drag is the **resistance from motion through air,** and increases rapidly with airspeed ($\propto V^2$).

Divided into:

- **Form drag:** due to the aircraft's shape and frontal area.
- **Skin friction drag:** due to air rubbing along surfaces.
- **Interference drag:** caused where components meet (e.g. wing–fuselage junctions).



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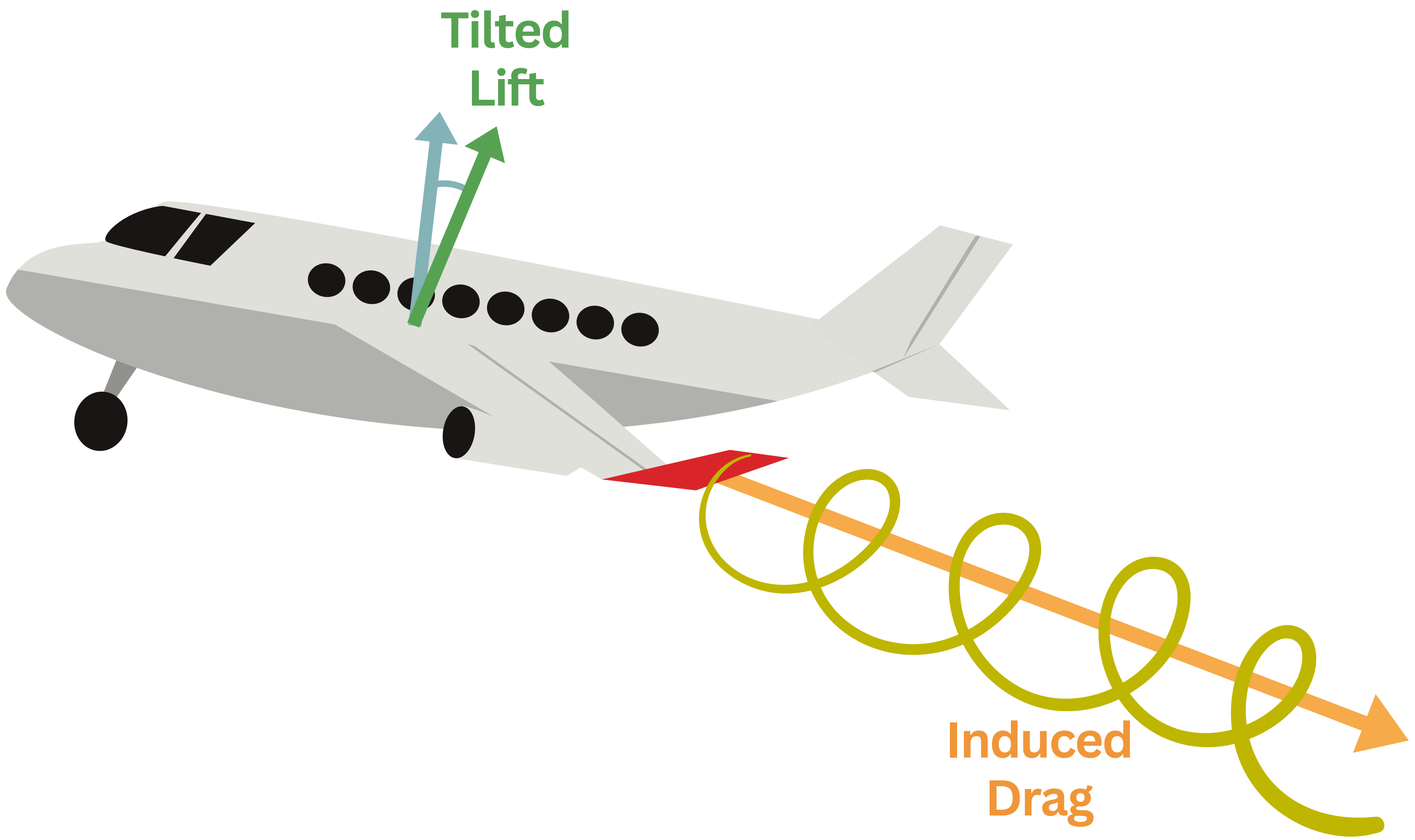
Induced Drag

Induced drag is generated as a **by-product of lift.** Airflows around the wingtips **create vortices**, tilting the total lift rearwards.

High at low speeds and **high angles of attack**, lower at cruise speeds.

Decreases with **increasing airspeed** and higher aspect ratio wings.



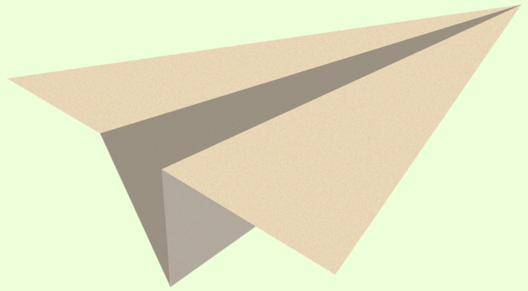
The Design Trade-off

1. Define the mission

What does the aircraft do?

→ Long endurance, fast mapping, short take-off, heavy payload…

Your **mission defines speed, range, and environment**, which then **sets the Reynolds number** and **performance targets**.



2. Choose the aerodynamics profile

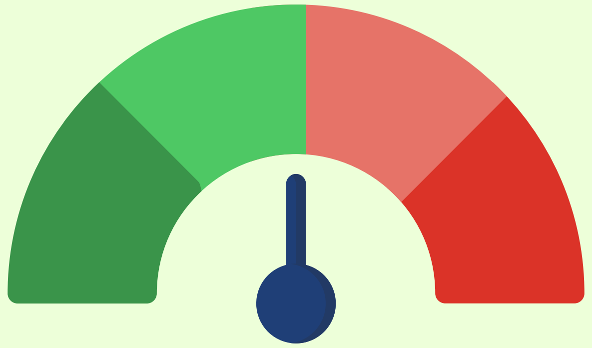
Pick the **cruise speed** and **airfoil type** that fit your flight profile.

- Slow flyers use thick, cambered airfoils for efficiency.
- Faster aircraft use thin, smooth airfoils for low drag.

3. Size the wing

Decide the **aspect ratio (AR)** and **wing loading (W/S)**:

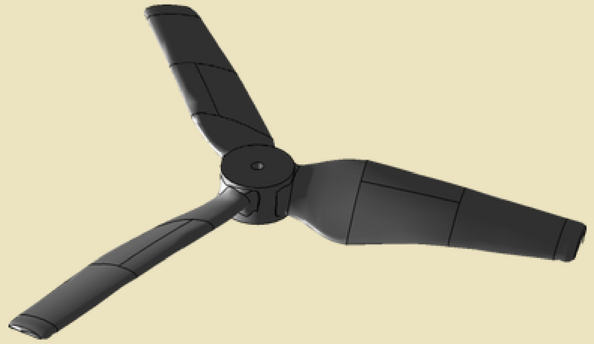
- High AR: less induced drag, more structure.
- Low AR: more drag, more compact, easier to build.
- Low W/S: better take-off and endurance, but slow.



4. Balance stability and control

Set the **CG position** and **tail sizes** to match **how stable or agile you want** it to feel.

- Forward CG = more stable, less responsive.
- Aft CG = more agile, harder to control.
- Bigger tails = more stability, more drag.



5. Match propulsion to performance

Pick the **propeller** and **motor** to deliver the needed thrust.

- Larger prop = better efficiency at low speeds.
- Smaller prop = higher top speed, less drag.

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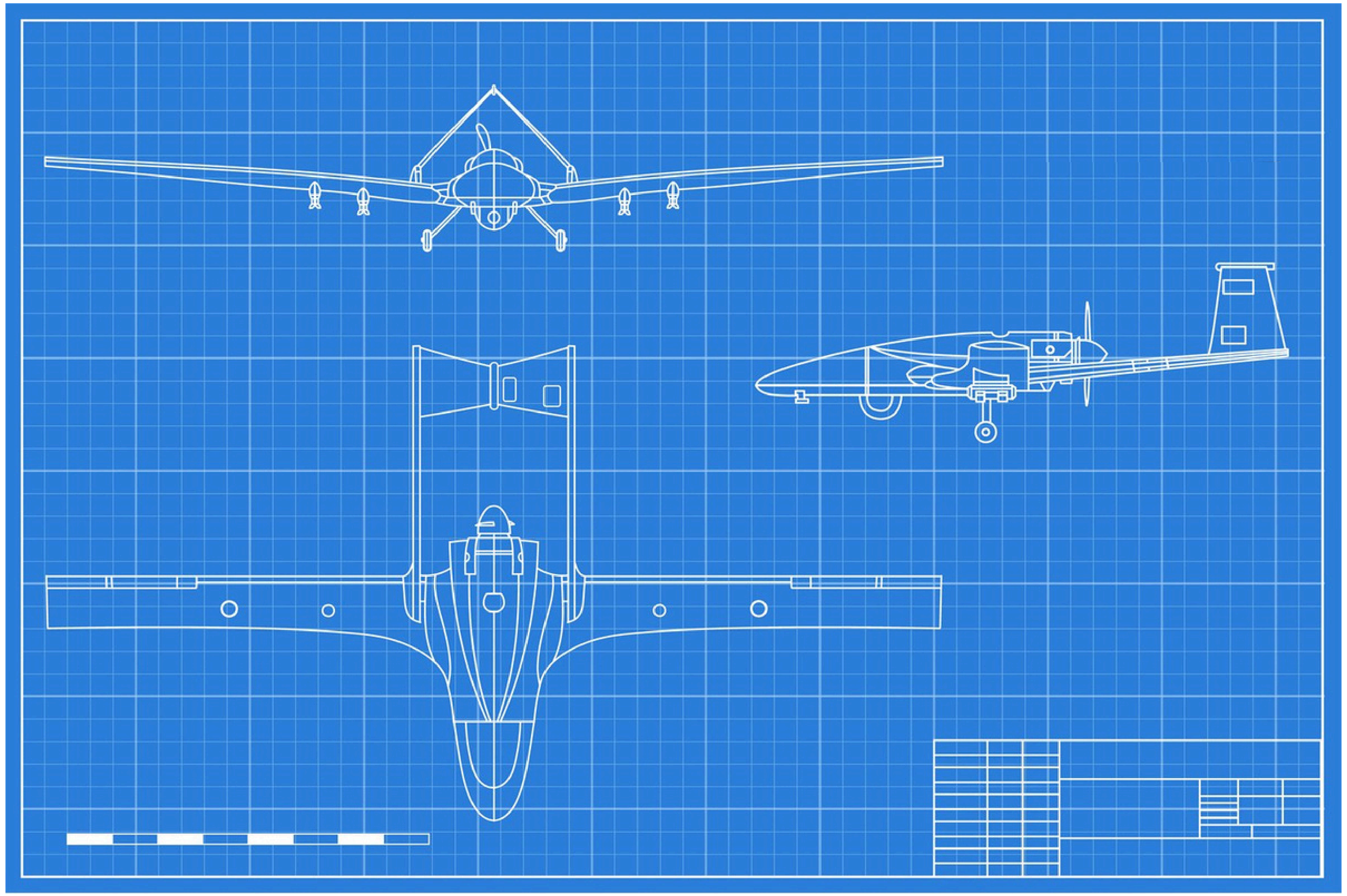
Any Questions?



SECTION 3

Hands-on Exercise

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Hands-On Exercise

Design a **fixed–wing UAV** for **mapping in a wildlife conservancy**.

You will **define the mission,** select an **airfoil**, estimate **flight speed** and **Reynolds number**, compute basic **drag** and **power**, and propose **stability** choices that match the mission.