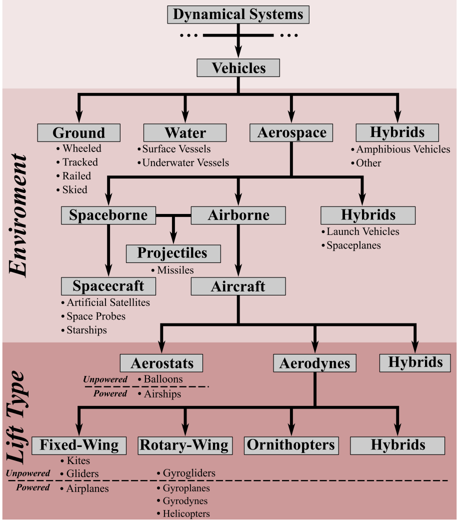
Lecture 3: Aerospace Vehicles and Reference Frames

Dr. Jordan D. Larson

Textbook Sections 7.1 and 7.2

Vehicles

- **Vehicle**: dynamical system that transports payload, e.g., cargo, people, munitions, sensors
  - Typically classified by environment, i.e., ground, water, flying, or hybrids



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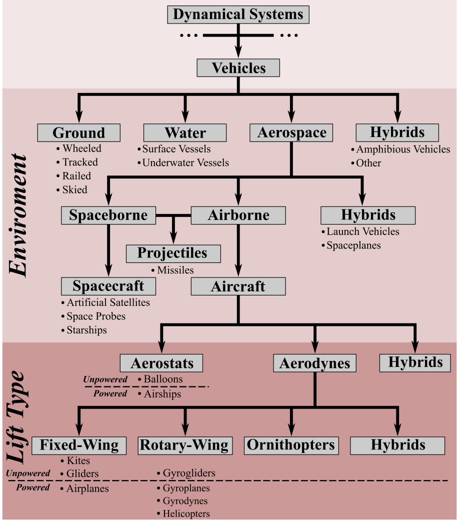

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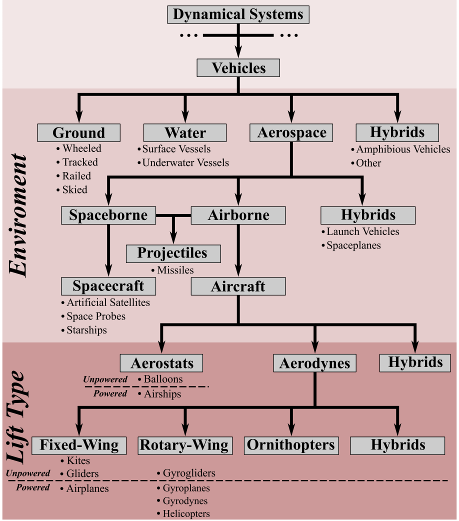
  - A.k.a. **aerospace vehicles**
    - Aerostats (balloons, airships)
    - Fixed-wing (gliders, airplanes)
    - Rotary-Wing (gyrogliders, helicopters, autodynes, gyrodynes)
    - Spacecraft (satellites, probes, starships)
    - Hybrid flight vehicles, air & space (launch vehicles, spaceplanes)



Vehicle Dynamics and Control

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- Applied to flight vehicles $\rightarrow$ **flight dynamics and control (FDC)**: subject of course
  - Differentiating factor in FDC: flight vehicles affected by three external forces: gravity, propulsion, and aerodynamics
  - Ground vehicles experience ground forces
  - Water vehicles experience hydrodynamics

Pilot and Control

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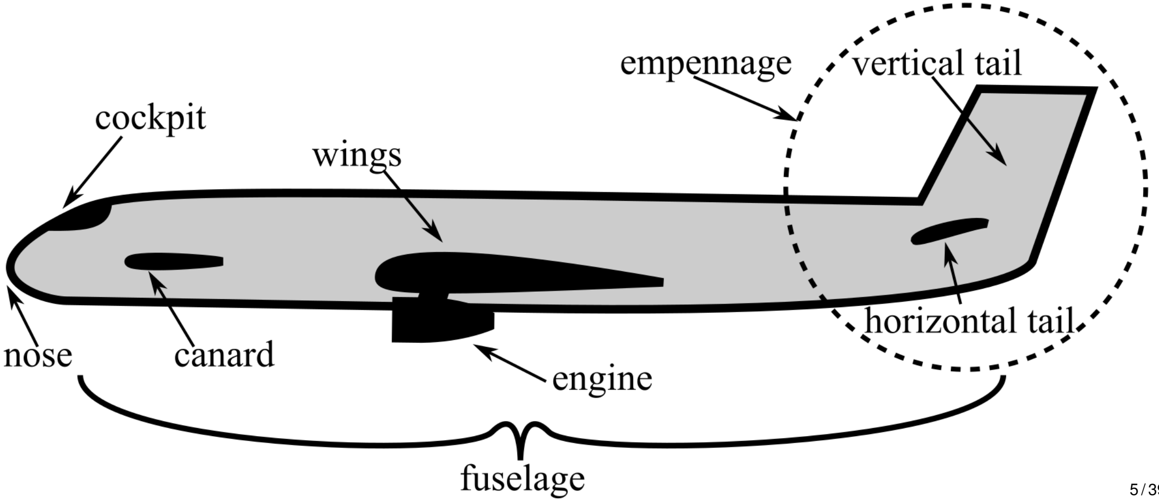
- Control of flight vehicle:
  - **Manual control**: completely performed by human
  - **Automatic control**: completely performed by computer
  - **Semi-Automatic control**: partially performed by human and computer
- Module: classical control theory reviewed and applied to control of flight vehicles
  - Later module: modern control theory introduced and applied to control of flight vehicles

Basic Components of Conventional Airplane

- Powered fixed-wing aircraft



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  - Generate majority of lift force to overcome vehicle's weight and fly
  - May have two wings:
  - **Tandem wings**: front-and-back wings
  - **Biplane**: stacked wings

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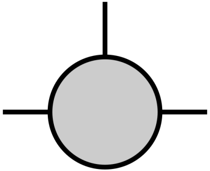
  - **Biplane**: stacked wings
- **Engine/motor** produces thrust forces, controlled by pilot
  - Mounted on wings, empennage, or nose
  - **Propeller**: rotating airfoil-section blades creating swirling slipstream

Empennage Design

- **Empennage**: rear section of airplane
  - Creates aerodynamic effects to stabilize and steer airplane



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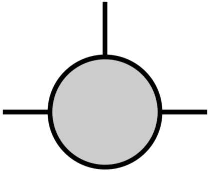

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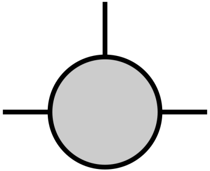

- **Horizontal tail**: produces up or down lift force
  - Static **horizontal stabilizer**: maintain horizontal stability
  - Dynamic **elevator**: steer airplane
- **Vertical tail** produces left or right side force to steer airplane
  - Static **vertical stabilizer**: maintain vertical stability
  - Dynamic **rudder**: steer airplane

Other Designs

- Some airplanes may be **tailless**: no other horozontal lifting surface besides main wing
  - I.e. no horizontal tail, canard or tandem wing
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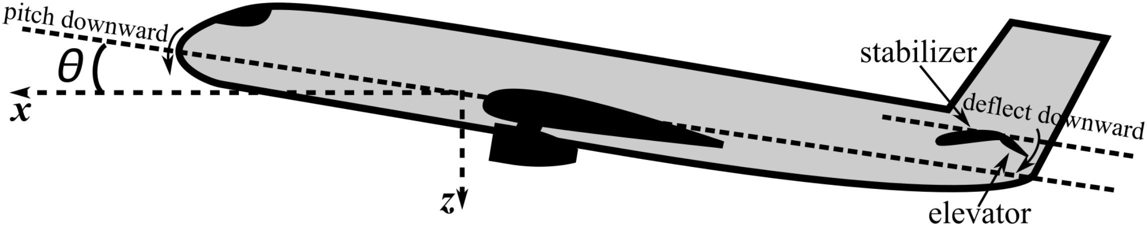
- Some airplanes may use **canard**, i.e. forward horizontal stabilizer and elevator, either in addition or instead of rear horizontal tail

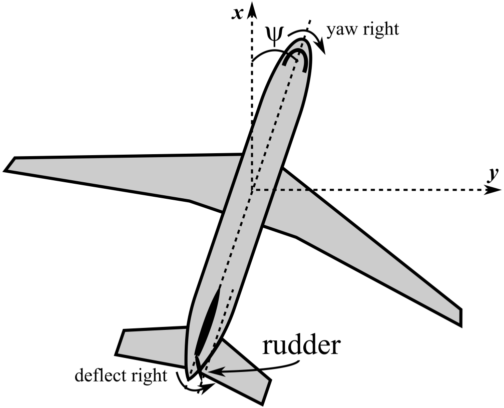
Primary Control Surface: Elevator

- **Elevator**: mounted on trailing edge of horizontal tail
- Primary pitch angle, θ, control input
  - Deflection angle, δ_e: upwards pushes airplane's nose up



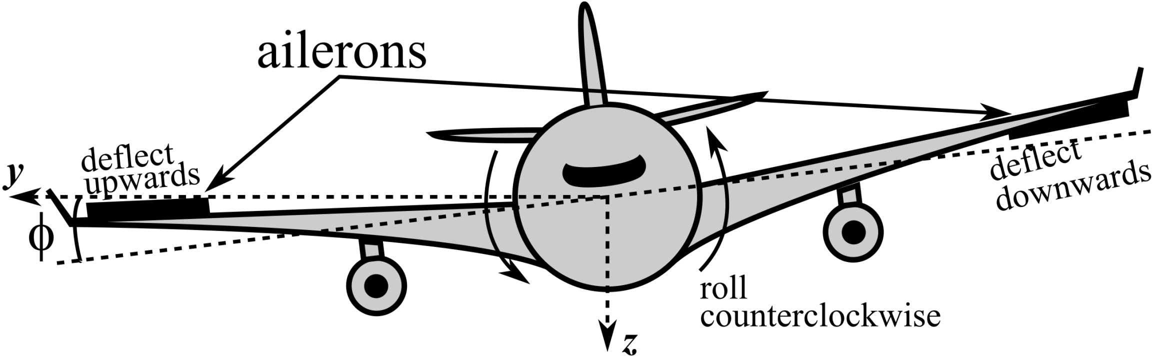
Primary Control Surface: Rudder

- **Rudder**: mounted on trailing edge of vertical tail
- Primary yaw angle, ψ, control input
  - Deflection angle, δ_r: right pushes airplane's nose right



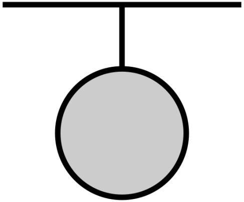
Primary Control Surface: Ailerons

- **Ailerons**: mounted on trailing edge of wings near tips
  - Differential pair of surfaces, i.e. if one deflects up, other deflects down
- Primary roll angle, ϕ, control input
  - Deflection angle, δ_a: airplane rolls to side that deflects up



Other Empennage Configurations

- **T-tail**:



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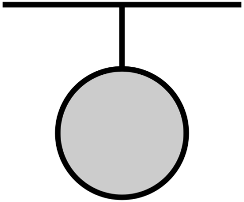
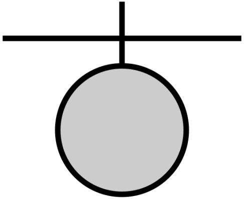


- **Cruciform tail**



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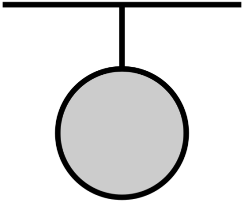

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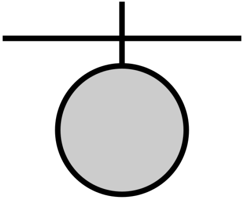
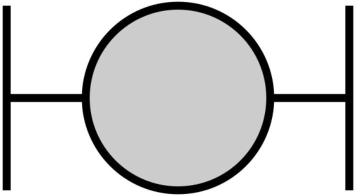


- **H-tail**, a.k.a. **twin tail**
  - Twin tails may be mounted on: fuselage, two booms extending from wing, or wings themselves



Compound Horizontal/Vertical Empennage

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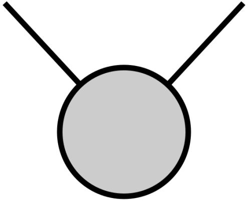

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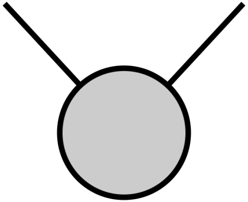

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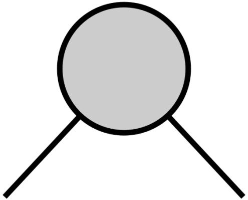

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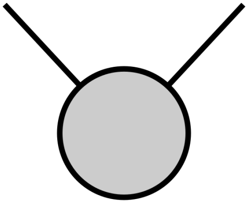

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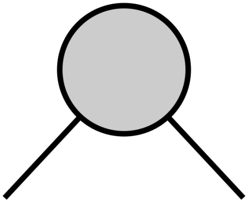
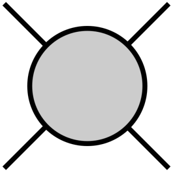


- **X-tail**



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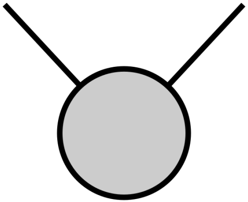

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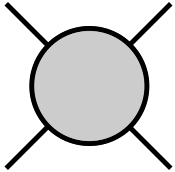

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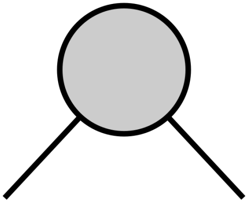
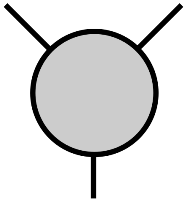
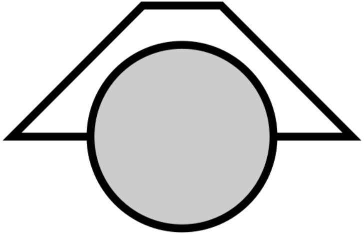


- **Y-tail**



Compound Horizontal/Vertical Empennage (continued)

- **A-tail**
  - Typically mounted on twin booms



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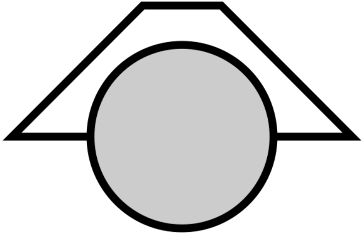

- Empennage configurations use compound rudder and elevator control surfaces: **ruddervator**

Secondary Control Surfaces

- **Spoilers**: hinged flat plates attached to wing facing oncoming airflow
  - “Spoil” lift on wing when rotated up from surface of wing
  - Typically used as speed brake, sometimes for roll control with or without ailerons

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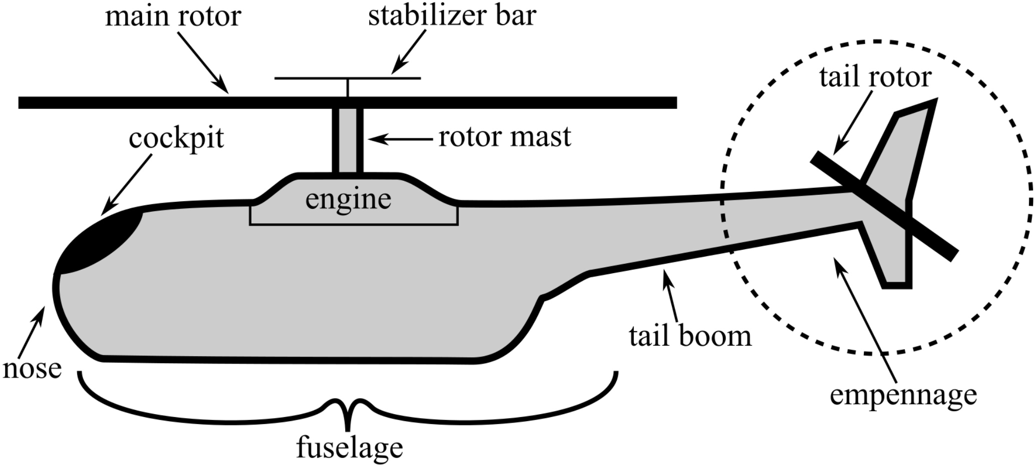
- **Slats** & **Flaps**: mechanized leading & trailing edges of wings
  - Extended/retracted from nominal wing shape, changing airfoil cross-sectional shape and effectively increasing/decreasing lift potential of wing with higher/lower induced drag
  - Primarily extended during takeoff and landing, not dynamically active control surfaces

Basic Components of Conventional Helicopter

- Powered rotary-wing aircraft without propellers:



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- Second **tail rotor** allows for directional control of helicopter
  - Required to negate angular momentum produced by main rotor blades on helicopter

Other Helicopter Configuration

- Helicopters designed to cancel out rotary-wing angular momentum through tail rotors as shown

  Or **counter-rotating rotors**, i.e. pairs of rotors which rotate in opposite directions to counter each other's angular momentum

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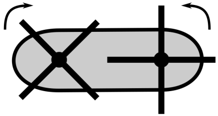

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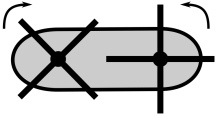
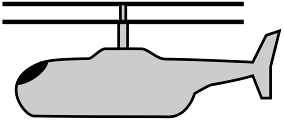


- Coaxial rotors configuration:



Other Helicopter Configuration (continued)

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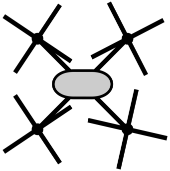

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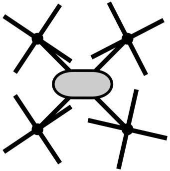

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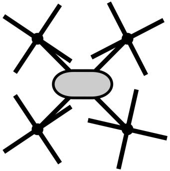

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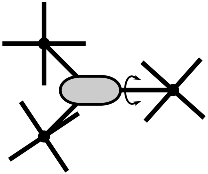
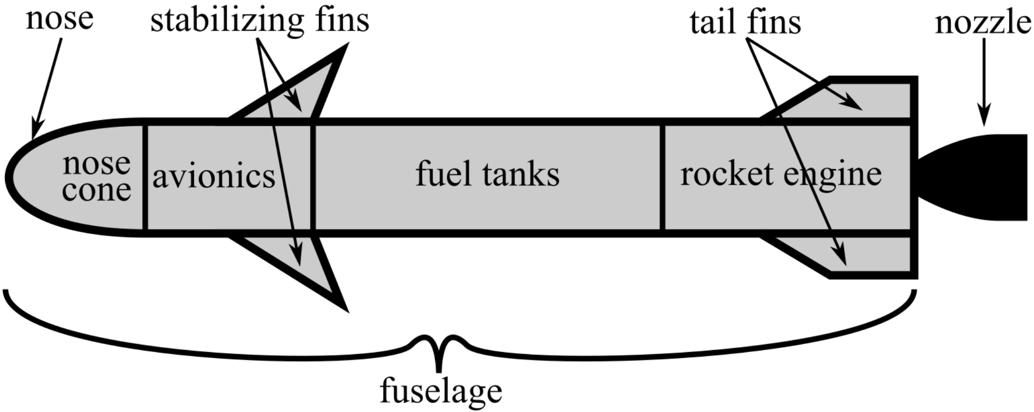
- **Tricopter**: 3-rotor configuration, one rotor allowed to rotate about arm to provide thrust force with some horizontal component



Basic Components of Launch Vehicle



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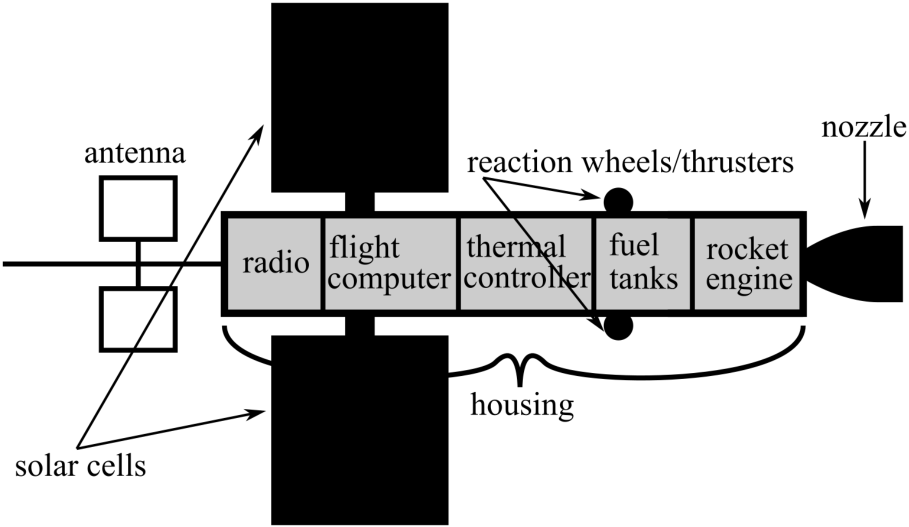
- **Fuselage**: tubular structure of launch vehicle
  - Houses avionics, fuel, oxidizer, rocket engine
- **Fins**: both stabilizing and tail, produce up or down lift force to steer launch vehicle
  - Some may have only tail fins
  - Some may have control surfaces: rudders

Basic Components of Launch Vehicle (continued)

- **Nose cone**: front of launch vehicle
  - Houses **fairing**
  - Typically for payload, may include crew
- **Fuselage**: tubular structure of launch vehicle
  - Houses avionics, fuel, oxidizer, rocket engine
- **Fins**: both stabilizing and tail, produce up or down lift force to steer launch vehicle
  - Some may have only tail fins
  - Some may have control surfaces: rudders
- **Rocket engine** projects reaction mass through **nozzle** to produce thrust force to overcome vehicle's weight and fly
  - May have thrust vectoring capabilities for control

Basic Components of Artificial Satellite



Basic Components of Artificial Satellite (continued)

- **Housing**:
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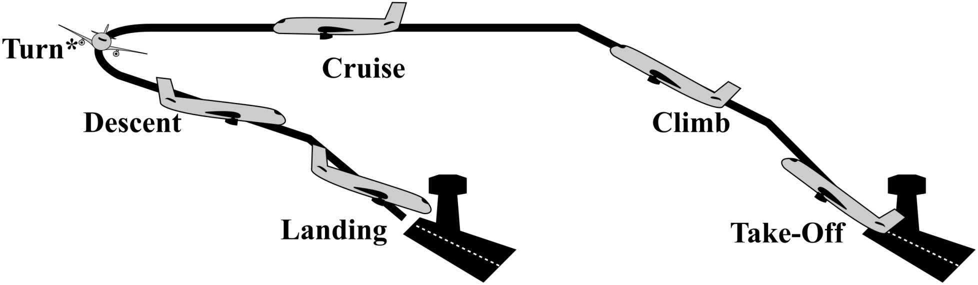
- Powered using batteries and **solar cells** mounted on satellite

Aircraft Flight Phases

- Five phases of flight: takeoff, climb, cruise, descent, landing
  - Each phase: different flight conditions including potential turns during climb, cruise, and/or descent
  - Aircraft may be configured differently at each phase, directly impacts aerodynamic forces and moments
    - E.g., for airplane takeoff/landing: flaps may be deployed and landing gear extended down



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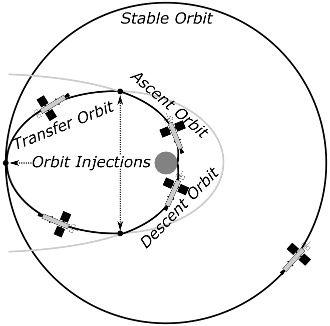
- Four phases of flight: boost, orbit(s), reentry, optional landing
- Types of orbits: ascent orbit, transfer orbit, stable orbit, descent orbit
  - Orbit changes: **orbit injection**, a.k.a. **orbit insertion**, type of orbital maneuver
  - **Orbital maneuver**, a.k.a **burn**, use of propulsion system to change orbit of spacecraft
  - Not undergoing orbital maneuver, spacecraft in **coast**



Types of Orbital Maneuvers

- Orbital maneuvers cause some amount of change in velocity: Δv
  - **Impulsive manuever**: use burn to generate particular Δv almost instantaneously
    - E.g., **Oberth maneuver**: use burn close to gravitational bodies to increase final velocity
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- **Rendezvous maneuver**: coordination of two spacecraft called the "chaser" and "target" arriving at same orbit and approaching to very close relative distance
  - Often accompanied by other maneuvers, e.g., coordinated operations in close proximity, docking, undocking: **rendezvous, proximity operations, docking, and undocking (RPODU)** procedures
  - **Low-thrust relative transfer**: chaser covers specific distance relative to target using continuous low-thrust propulsion

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- Modern missile systems: exhibit more elaborate flight plans
  - **Skip** phase: additional atmospheric exit and reentry
  - **Glide** phase: Long duration of unpowered atmospheric flight

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- ICRF origin: barycenter of Solar System, not center of sun
- ICRF axes: “show no global rotation with respect to set of distant extragalactic objects”

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- x_E-axis passes through intersection of prime meridian and equator
  - Located just south of west Africa
- y_E-axis: orthogonal to both x_E- and z_E-axes according to right-hand-rule located just south of India along the equator.
- z_E-axis passes through true north
  - Does not coincide with Earth's instantaneous rotational axis because of Earth's wobble, but average

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- **Geoid**: idealized equilibrium surface of Earth's gravitational potential
  - Varies according to crust formation
  - A.k.a. **International Terrestrial Reference Frame (ITRF)**

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- Geodetic coordinates $=$ ellipsoidal coordinates, require ellipsoidal trigonometry
  - Latitude angle does not define angle between Earth's center and point on surface
  - Altitude does not align with Earth's center unless at equator or pole
  - Both have analytical offset

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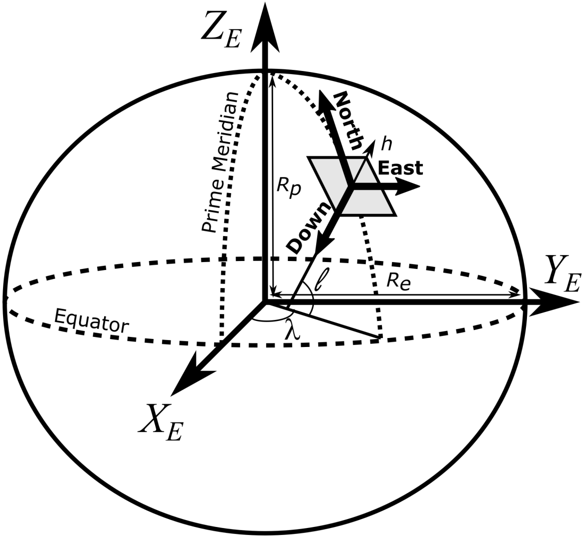
- Two common right-handed LTP axes:
  - East-North-Up (ENU) frame
  - **North-East-Down (NED)** frame

Relationship between ECEF, LLA, LTP



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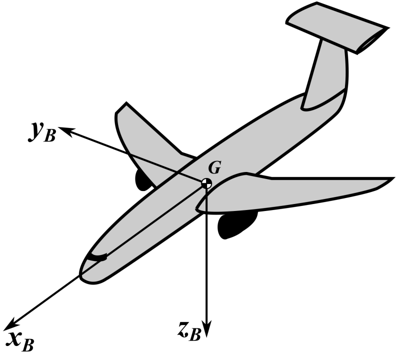
  - Vertical axes of navigation and LVLH frames differ because down for LTP does not always intersect Earth's center of mass

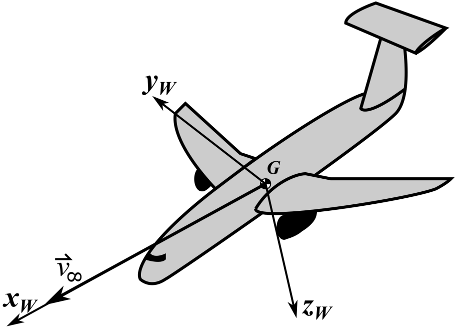
Body-Fixed Frame

- **Body-fixed frame** (subscript B): attached to flying vehicle's body structure
  1. Origin: flying vehicle's center of gravity G
  2. x_B axis: points out front of flying vehicle, typically "along" the nominal path of travel, a.k.a. **longitudinal axis**
  3. y_B axis: points out the right side of flying vehicle, a.k.a. **lateral axis**
  4. z_B axis: points straight beneath flying vehicle, a.k.a. **vertical axis**
  5. Ideal for geometric configuration and structural modeling



Wind Frame

- **Wind frame** (subscript W): relates **free-stream airflow** that aircraft encounters as it flys
  1. Origin: aircraft's center of gravity G
  2. x_W axis: colinear with free-stream airflow $\vec{v}_\infty$
  3. z_W axis: plane of symmetry of aircraft, positive below aircraft
  4. y_W axis: perpendicular to both
  5. Ideal for aerodynamics modeling (particular to aircraft dynamics and control)



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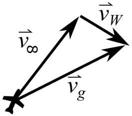
- Velocity vectors related through **wind speed** vector, $\vec{v}_w$:

$$\vec{v}_g = \vec{v}_\infty + \vec{v}_w \tag{1}$$

  - A.k.a. **wind triangle**
  - $\vec{v}_w$: velocity of air mass relative to ground



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