Last updated: November 1, 2026

🗺️ Four-year roadmap · Year 1, Fall · 🧮 Built-in calculator

About this course

This free course has 10 units and 4 labs. Those are the real counts, not a longer syllabus cut short.

A check is one number or code result on a course page that a script recomputes before the page is published. The printed number and the recomputed number have to match.

> This is a free self-study course outline written by Saving Planets. It is not a university course, it carries no academic credit, and no school is involved.
>
> Its scope follows first-year aerospace engineering introductions such as MIT 16.00 and the opening of MIT's Unified Engineering, the introductory aeronautics and astronautics courses at Purdue, Georgia Tech and Embry-Riddle, and the classic textbook Introduction to Flight by John D. Anderson Jr. We link to free materials throughout, especially NASA Glenn's Beginner's Guide to Aeronautics. None of these organizations endorse this page.
>
> What we add: every unit connects to cleaner flight and to the spacecraft that watch our planet, every number on the page is re-computed by a checking script before it goes live, and four labs, including a virtual wind tunnel and a glider you build, make the equations real.
>
> Work through it in order. Each unit has goals, key ideas, equations, step-by-step examples, practice with full answers, common mistakes, flashcards and a quiz. Your progress is saved only in this browser.

How this course helps save the planet

Aerospace engineering builds the satellites that measure Earth's climate, forests, ice and oceans, and it also has to shrink its own footprint: every kilogram of jet fuel burned makes about 3.16 kg of CO_2.

Each unit ends with a short, sourced section showing how its ideas help people and the planet.

For instructors

You can teach this course, or let a student work through it alone. It is free. Saving Planets does not give a grade or school credit.

- This page is the whole course: 10 units and 4 labs (AERO 101).
- Plan on 15 weeks, about 6 to 9 hours a week, including the lab weeks.
- Follow the 15-week schedule. Read the unit, do the practice on paper, then open the answer. In a lab week, do the lab or the home version.
- A check is one number or code result on the page that a script recomputes before we publish. The number you see and the recomputed number have to match.
- Use Print this page, or download the PDF study guide. The formula sheet is near the end.
- Ask: how does this unit help people and the planet? Each unit has a green box with a sourced fact.
- Copy the teacher guide template and write in your class name, the time you have, and the questions you will ask. Open the teacher guide template

Before you start

Prerequisites

- High-school algebra and trigonometry; logarithms and exponentials.
- Physics I mechanics (forces, energy, momentum, circular motion) helps; take it alongside if you can.
- Calculus I is useful for a few derivations but not required for the numbers.

How to study

- Keep units in SI throughout and write them on every line.
- Sketch the forces (lift, weight, thrust, drag) before writing any equation.
- Estimate first; aerospace numbers have familiar sizes (sea-level air ≈ 1.2 kg/m³, low orbit ≈ 7.7 km/s).
- Do every practice problem on paper before opening the answer.
- Use the NASA Glenn simulators to check your intuition.
- Retake the quizzes a few days later. Spaced practice beats one long session.

What you need

- A computer with a web browser and a spreadsheet (FoilSim runs in the browser).
- For the glider lab: card stock or foam board, a ruler, scissors, modeling clay or coins for nose weight, and a tape measure.
- Optional: a smartphone stopwatch.

Suggested 15-week schedule

About 6 to 9 hours a week: reading, practice problems and, in lab weeks, the lab.

Week	Unit	Topics	Reading
1	History of Flight & the Design Process	History of flight; the design process; four forces	MIT 16.00; Smithsonian
2	The Atmosphere	Standard atmosphere; speed of sound	NASA Glenn: atmosphere
3	Basic Aerodynamics: Lift & Drag	Lift and drag equations; Bernoulli	NASA Glenn: lift and drag
4	Basic Aerodynamics: Lift & Drag	Reynolds number and stall speed; Lab D	FAA PHAK
5	Airfoils & Wings	Airfoils, lift curve, finite wings; Lab A	NASA FoilSim
6	Aircraft Performance	Gliding, power required, climb	NASA Glenn: glide angle
7	Aircraft Performance	Range and endurance; midterm practice	FAA PHAK
8	Stability & Control	Stability and control; Lab C	NASA Glenn: rotations
9	Propulsion Basics	Propulsion: jets, fans and propellers	NASA Glenn: propulsion
10	Rockets & the Rocket Equation	Rocket thrust and the rocket equation	NASA Glenn: rockets
11	Rockets & the Rocket Equation	Staging and launch vehicles; Lab B	NASA Glenn: rockets
12	Orbits & Space Missions	Orbits, Kepler’s laws, geostationary orbit	JPL Basics of Space Flight
13	Orbits & Space Missions	Hohmann transfers and mission design	JPL Basics of Space Flight
14	Sustainable Aviation & Space	Sustainable aviation and space	NASA; EPA; DOE
15	Review	Review and final practice set	All units

Your progress

Tick units and labs as you finish them, and take the quizzes. Progress and quiz scores are saved only in this browser, never sent to us.

Units

History of Flight & the Design Process

From the Wright brothers to Artemis: how aerospace engineers turn a mission into requirements, trade-offs and a design that flies.

Learning objectives

By the end of this unit you can:

- Outline key milestones of aviation and spaceflight.
- Describe the design cycle: requirements, concept, preliminary and detailed design, test.
- Explain trade studies and why weight drives everything.
- Name the four forces of flight.

Key concepts

- On December 17, 1903, the Wright Flyer made a 12-second flight covering 36 m (120 ft); the best flight that day covered 260 m (852 ft) in 59 seconds. The Wrights succeeded by testing: they built gliders and their own wind tunnel before adding an engine.
- Every design starts with a mission: payload, range or orbit, cost, safety. Requirements turn the mission into numbers the design must meet.
- Design is iterative: concept sketch, sizing, analysis, test, redesign. A trade study compares options against weighted criteria.
- Four forces act on an aircraft: lift, weight, thrust and drag. In steady level flight, lift = weight and thrust = drag.
- Weight compounds: extra structure needs more lift, a bigger wing, more drag, more fuel, and more weight again.

Key equations

$$L = W, \quad T = D$$

`L=W, T=D`

Steady, level, unaccelerated flight

$$W = mg$$

`W=mg`

Weight

$$\text{Score} = \sum_i w_i \, s_i$$

`Score=_i w_i s_i`

Weighted trade-study score

Worked examples, step by step

Example 1.1 A 1,100 kg light airplane cruises level. How much lift must its wing produce?

1. Level flight: L = W = mg.
2. L = 1,100 × 9.81.

Answer: 10,791 N ≈ 10.8 kN.

Example 1.2 Two wing concepts are scored out of 10 on cost (weight 0.3), efficiency (0.5) and ease of building (0.2). Concept A scores 8, 6, 9; B scores 5, 9, 6. Which wins?

1. A: 0.3(8) + 0.5(6) + 0.2(9) = 7.2.
2. B: 0.3(5) + 0.5(9) + 0.2(6) = 7.2.

Answer: A tie at 7.2: the team should test both or revisit the weights it trusts least.

Example 1.3 The Wright Flyer's first flight covered 36 m in 12 s. What was its average ground speed?

1. v = 36/12.

Answer: 3 m/s over the ground. It flew into a strong headwind, so its airspeed was much higher.

Practice problems

Work each on paper first, then check.

1. An airliner of mass 70,000 kg cruises level. Find its lift.

   L = 70,000 × 9.81 = 686,700 N ≈ 687 kN.

2. In level cruise an aircraft's engines give 30 kN of thrust. What is its drag?

   30 kN, since thrust balances drag in steady flight.

3. Why did the Wright brothers build a wind tunnel?

   Published lift data were unreliable, so they measured many wing shapes themselves: testing before building is the heart of the design process.

Common misconceptions

Myth: Engineers design the aircraft first and then find a mission for it.

Actually: The mission and its requirements come first.

Myth: In level flight thrust must balance weight.

Actually: Thrust balances drag; lift balances weight.

Myth: Shaving a little weight saves only that weight.

Actually: Weight savings compound through wing size, drag and fuel.

Flashcards

Four forces

Lift, weight, thrust, drag.

Requirements

Measurable targets a design must meet.

Trade study

Weighted comparison of design options.

Design cycle

Concept → preliminary → detailed design → test → iterate.

Wright Flyer

First powered, controlled airplane flights, Dec. 17, 1903.

Weight spiral

Extra weight grows the whole design.

Self-check quiz

1. In steady level flight, lift equals...

thrust

drag

weight

zero

weight. Vertical forces balance.

2. The Wright Flyer first flew in...

1899

1903

1911

1927

1903. December 17, 1903, at Kitty Hawk.

3. A trade study...

picks the cheapest part

compares options against weighted criteria

tests a prototype to failure

is done after flight test

compares options against weighted criteria. It ranks options systematically.

4. The first step of the design process is...

detailed drawings

the mission and requirements

flight test

choosing an engine

the mission and requirements. Requirements drive everything after.

Try this quiz again

How this helps save the planet

Design priorities change with the times. Requirements for new aircraft now include fuel burn and emissions, so the same trade-study tools weigh climate alongside cost and performance.

NASA lists three main ways to make aviation sustainable: efficient aircraft technology, sustainable aviation fuel, and better operations and infrastructure.

On Saving Planets: Artemis II

Sources: Smithsonian: 1903 Wright Flyer (https://airandspace.si.edu/collection-objects/1903-wright-flyer/nasm_A19610048000) · NASA: Sustainable aviation (https://www.nasa.gov/aeronautics/sustainable-aviation/)

Free learning resources

- Smithsonian: 1903 Wright Flyer (https://airandspace.si.edu/collection-objects/1903-wright-flyer/nasm_A19610048000): The Wright Flyer's story and specifications.
- MIT OpenCourseWare 16.00: Introduction to Aerospace Engineering and Design (https://ocw.mit.edu/courses/16-00-introduction-to-aerospace-engineering-and-design-spring-2003/): MIT's design-centered introductory course.
- NASA Glenn: Beginner's Guide to Aeronautics (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/): Start here for every topic.

☐ **I finished this unit**

The Atmosphere

The air an aircraft flies through: how temperature, pressure, density and the speed of sound change with altitude.

Learning objectives

By the end of this unit you can:

- Use a standard atmosphere model to find T, p and ρ at altitude.
- Apply the ideal-gas law to air.
- Compute the speed of sound and Mach number.
- Explain why airliners cruise near 11 km.

Key concepts

- A standard atmosphere is an average model fitted to measurements. In NASA's model the troposphere runs from the ground to 11,000 m, and temperature falls about 6.5 °C per kilometer.
- From 11 to 25 km (lower stratosphere) the model's temperature is constant at −56.46 °C, while pressure keeps falling exponentially.
- Density follows from the ideal-gas law, ρ = p/(RT). At 11 km air is about 30% as dense as at sea level.
- The speed of sound is a = √(γRT), so it depends only on temperature. Mach number M = V/a.
- Thin air means less drag at a given speed, which is why jets cruise high, but wings and engines still need enough air to work.

Key equations

$$T = 15.04 - 0.00649\,h \;\; (^\circ\mathrm{C},\; h \text{ in m})$$

`T=15.04-0.00649 h\ \ (^,\ h in m)`

NASA troposphere temperature fit

$$p = 101.29 \left(\frac{T + 273.1}{288.08} \right)^{5.256} \;\; \mathrm{kPa}$$

`p=101.29((T+273.1)/(288.08))^5.256 kPa`

NASA troposphere pressure fit

$$\rho = \frac{p}{0.2869\,(T + 273.1)}$$

`ρ=(p)/(0.2869 (T+273.1))`

Density (p in kPa, ρ in kg/m³)

$$a = \sqrt{\gamma RT}, \quad M = \frac{V}{a}$$

a=γ RT, M= Va

Speed of sound and Mach number

Worked examples, step by step

Example 2.1 Find T, p and ρ at 5,000 m with NASA's model.

1. T = 15.04 − 0.00649 × 5,000 = −17.41 °C.
2. p = 101.29 × (255.69/288.08)^5.256 = 54.11 kPa.
3. ρ = 54.11/(0.2869 × 255.69).

Answer: T ≈ −17.4 °C, p ≈ 54.1 kPa, ρ ≈ 0.738 kg/m³ (60% of sea level).

Example 2.2 Find the speed of sound at sea level (15 °C) and at 11 km (−56.5 °C).

1. a = √(1.4 × 287 × 288.15) = 340.3 m/s.
2. a = √(1.4 × 287 × 216.65) = 295.0 m/s.

Answer: 340 m/s and 295 m/s.

Example 2.3 An airliner flies at 230 m/s true airspeed at 11 km. What is its Mach number?

1. M = 230/295.0.

Answer: M ≈ 0.78.

Practice problems

Work each on paper first, then check.

1. Find the air density at 11,000 m with the NASA model (T = −56.46 °C, p = 22.72 kPa).

   ρ = 22.72/(0.2869 × 216.64) ≈ 0.366 kg/m³, about 30% of sea level.

2. Find the temperature at 1,500 m in the NASA model.

   T = 15.04 − 9.74 = 5.3 °C.

3. What is Mach 2 at sea level in m/s?

$2 \times 340 = 680$ m/s.

4. Find the sea-level density from $p = 101.40$ kPa and $T = 15.04$ °C.

   $\rho = 101.40/(0.2869 \times 288.14) \approx 1.227$ kg/m³.

Common misconceptions

Myth: The speed of sound depends on pressure.

Actually: For an ideal gas it depends only on temperature.

Myth: It gets colder all the way up.

Actually: Temperature levels off above 11 km and rises again higher in the stratosphere.

Myth: Thinner air always helps.

Actually: It cuts drag but also lift and engine thrust, so wings must fly faster or at higher lift coefficients.

Flashcards

Standard atmosphere

Average model of T, p, ρ versus altitude.

Troposphere

Ground to ~11 km; temperature falls with height.

Lapse rate

≈ 6.5 °C per km in the troposphere.

Ideal gas law

$p = \rho RT$.

Speed of sound

$a = \sqrt{(\gamma RT)}$.

Mach number

$M = V/a$.

Self-check quiz

1. In the troposphere temperature falls about…

1 °C/km

6.5 °C/km

15 °C/km

0 °C/km

6.5 °C/km. NASA's lapse rate is 0.00649 °C/m.

2. The speed of sound at sea level is about…

100 m/s

340 m/s

1,000 m/s

3,000 m/s

340 m/s. √(1.4 × 287 × 288).

3. Density at 11 km is about what fraction of sea level?

90%

60%

30%

5%

30%. 0.366/1.227.

4. Mach number is…

V × a

V/a

a/V

V^2/a

V/a. Speed divided by the local speed of sound.

Try this quiz again

How this helps save the planet

Aircraft fly where weather and climate happen. NASA studies aircraft emissions through computer modeling, combustion laboratory testing and flight testing, because what engines release at altitude matters for the atmosphere.

The same atmosphere physics underlies how satellites turn the radiation they measure into profiles of the air's temperature.

On Saving Planets: Atmospheric drag

Sources: NASA Glenn: Earth atmosphere model (metric) (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/earth-atmosphere-equation-metric/) · NASA: Sustainable aviation (https://www.nasa.gov/aeronautics/sustainable-aviation/)

Free learning resources

- NASA Glenn: Earth atmosphere model (metric) (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/earth-atmosphere-equation-metric/): The model and equations used in this unit.
- FAA Pilot's Handbook of Aeronautical Knowledge (https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak): Free FAA handbook chapters on the atmosphere and aerodynamics.

☐ **I finished this unit**

Basic Aerodynamics: Lift & Drag

Where lift and drag come from, and the two equations that size every wing: L = ½ρV²SC_L and D = ½ρV²SC_D.

Learning objectives

By the end of this unit you can:

- Explain lift as the result of turning a flow, with pressure differences described by Bernoulli's equation.
- Use the lift and drag equations.
- Compute dynamic pressure, stall speed and Reynolds number.
- Distinguish skin-friction, pressure and induced drag.

Key concepts

- A wing turns the airflow downward; by Newton's third law the air pushes the wing up. Equivalently, faster flow over the top means lower pressure there (Bernoulli). Both describe one flow.
- Dynamic pressure q = ½ρV² sets the scale of every aerodynamic force. Lift and drag coefficients C_L and C_D capture shape and angle of attack.
- Lift grows with V², so halving speed needs four times the lift coefficient or wing area.
- Drag comes from skin friction, pressure (form) drag and induced drag, the cost of making lift with a finite wing.
- Reynolds number Re = ρVc/μ compares inertial and viscous effects; wind-tunnel models must account for it to predict full-size behavior.

Key equations

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

`L=12ρ V^2SC_L`

Lift equation

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

`D=12ρ V^2SC_D`

Drag equation

$$p + \tfrac{1}{2}\rho V^2 = \text{const}$$

`p+12ρ V^2=const`

Bernoulli’s equation (along a streamline)

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

Re=(ρ Vc)/(μ)

Reynolds number

Worked examples, step by step

Example 3.1 A 1,100 kg airplane with a 16.2 m² wing flies level at 55 m/s at sea level (ρ = 1.227 kg/m³). Find C_L.

1. L = W = 10,791 N.
2. q = ½ × 1.227 × 55² = 1,855 Pa.
3. C_L = 10,791/(1,855 × 16.2).

Answer: C_L ≈ 0.36.

Example 3.2 With C_L,max = 1.6, find this airplane’s stall speed at sea level.

1. V_s = √(2W/(ρSC_L,max)).
2. = √(2 × 10,791/(1.227 × 16.2 × 1.6)).

Answer: V_s ≈ 26.1 m/s (about 51 knots).

Example 3.3 Find the Reynolds number of a 1.5 m chord at 55 m/s at sea level (μ = 1.789 × 10⁻⁵ kg/(m·s)).

1. Re = 1.227 × 55 × 1.5/(1.789 × 10⁻⁵).

Answer: Re ≈ 5.7 million.

Practice problems

Work each on paper first, then check.

1. If speed doubles at the same C_L, how does lift change?

   Lift ∝ V², so it quadruples.

2. Find the dynamic pressure at 230 m/s at 11 km ($\rho = 0.366$ kg/m³).

   $q = \frac{1}{2} \times 0.366 \times 230^2 \approx 9{,}680$ Pa.

3. Find the drag of the Example 3.1 airplane if $C_D = 0.032$.

   $D = 1{,}855 \times 16.2 \times 0.032 \approx 962$ N.

4. How much faster is the stall speed at 1,500 m ($\rho = 1.060$ kg/m³) than at sea level?

   $V_s \propto 1/\sqrt{\rho}$: $\sqrt{(1.227/1.060)} = 1.076$, so about 7.6% faster (≈ 28.0 m/s true airspeed).

Common misconceptions

Myth: Air over the top must meet air under the bottom at the trailing edge (equal transit time).

Actually: It does not; the upper flow actually arrives first. NASA Glenn lists equal transit as an incorrect theory of lift.

Myth: Lift is only Bernoulli, or only Newton.

Actually: Both describe the same flow; pressure differences and flow turning go together.

Myth: Drag is just air friction.

Actually: Pressure drag and induced drag are often larger.

Flashcards

Dynamic pressure

$q = \frac{1}{2}\rho V^2$.

Lift equation

$L = qSC_L$.

Drag equation

$D = qSC_D$.

Stall speed

$V_s = \sqrt{(2W/(\rho SC_{L,max}))}$.

Reynolds number

$\rho Vc/\mu$.

Induced drag

Drag due to lift on a finite wing.

Self-check quiz

1. Lift is proportional to...

V

V^2

$\sqrt{V}$

$1/V$

V^2. Through dynamic pressure $\frac{1}{2}\rho V^2$.

2. Doubling wing area at the same speed and C_L…

halves lift

doubles lift

quadruples lift

has no effect

doubles lift. $L \propto S$.

3. Reynolds number compares…

lift and drag

inertial and viscous effects

speed and sound speed

thrust and weight

inertial and viscous effects. $\rho Vc/\mu$.

4. Induced drag is caused by…

paint roughness

making lift with a finite wing

engine exhaust

shock waves only

making lift with a finite wing. Wingtip vortices tilt the lift backward.

Try this quiz again

How this helps save the planet

Drag is fuel. In cruise, engine thrust equals drag, so every newton of drag removed is fuel not burned and CO_2 not emitted. Needing less energy to fly is the first of NASA's three paths to sustainable aviation.

The same lift physics drives wind-turbine blades, which turn the wind's aerodynamic force into clean electricity.

On Saving Planets: Physics I

Sources: NASA Glenn: the drag equation (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/drag-equation/) · NASA: Sustainable aviation (https://www.nasa.gov/aeronautics/sustainable-aviation/)

Free learning resources

- NASA Glenn: the lift equation (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/lift-equation/): Lift equation and coefficients.
- NASA Glenn: the drag equation (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/drag-equation/): Drag equation.
- NASA Glenn: Bernoulli's equation (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/bernoullis-equation/): Pressure and velocity.
- NASA Glenn: Bernoulli and Newton (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/bernoulli-and-newton/): Why the equal-transit explanation is wrong.

☐ **I finished this unit**

Airfoils & Wings

Airfoil geometry, the lift curve, stall, and why long, slender wings make less drag.

Learning objectives

By the end of this unit you can:

- Name airfoil geometry: chord, camber, thickness, angle of attack.
- Use thin-airfoil theory: $c_l \approx 2\pi\alpha$.
- Correct the lift slope for a finite wing of aspect ratio AR.
- Use the drag polar $C_D = C_{D0} + C_L^2/(\pi e AR)$ to find the best lift-to-drag ratio.

Key concepts

- An airfoil is a wing's cross-section. Camber lets it lift at zero angle of attack; thickness adds strength and room for fuel.
- Thin-airfoil theory predicts a lift slope of 2π per radian (about 0.11 per degree) until the flow separates and the wing stalls.
- A finite wing loses lift slope to its tip vortices: $a = a_0/(1 + a_0/(\pi e AR))$, with aspect ratio $AR = b^2/S$.
- Total drag $C_D = C_{D0} + KC_L^2$ with $K = 1/(\pi e AR)$. Maximum L/D occurs where induced drag equals parasite drag.
- High aspect ratio (sailplanes, albatrosses, modern airliner wings) means less induced drag and higher L/D.

Key equations

$$c_l = 2\pi\alpha \ (\alpha \text{ in rad})$$

`c_l=2πα\ (α in rad)`

Thin-airfoil lift slope

$$a = \frac{a_0}{1 + a_0/(\pi e AR)}, \quad AR = \frac{b^2}{S}$$

`a=(a_0)/(1+a_0/(π eAR)), AR=^2S`

Finite-wing lift slope

$$C_D = C_{D0} + \frac{C_L^2}{\pi e AR}$$

`C_D=C_D0+(C_L^2)/(π eAR)`

Drag polar

$$\left(\frac{L}{D}\right)_{\max} = \frac{1}{2\sqrt{C_{D0}K}}, \quad C_L^* = \sqrt{\frac{C_{D0}}{K}}$$

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( LD)_=12_D0K,\ \ C_L^*=_D0K
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Best lift-to-drag ratio

Worked examples, step by step

Example 4.1 Thin-airfoil theory: find c_l at α = 5°.

1. α = 5π/180 = 0.0873 rad.
2. c_l = 2π × 0.0873.

Answer: c_l ≈ 0.548.

Example 4.2 Find the lift slope of a wing with AR = 8 and e = 0.9.

1. a = 2π/(1 + 2π/(π × 0.9 × 8)) = 6.283/1.278.

Answer: 4.92 per rad ≈ 0.086 per degree, 22% below the 2D value.

Example 4.3 With C_D0 = 0.025, e = 0.8 and AR = 7.5, find (L/D)max and the C_L where it occurs.

1. K = 1/(π × 0.8 × 7.5) = 0.0531.
2. (L/D)max = 1/(2√(0.025 × 0.0531)).
3. C_L* = √(0.025/0.0531).

Answer: (L/D)max ≈ 13.7 at C_L ≈ 0.69.

Practice problems

Work each on paper first, then check.

1. Find the aspect ratio of a wing with span 11 m and area 16.2 m².

   AR = 121/16.2 ≈ 7.5.

2. Using c_l = 2πα, what angle gives c_l = 0.5?

   α = 0.5/(2π) = 0.0796 rad ≈ 4.6°.

3. For the Example 4.3 airplane, find C_D at $C_L = 0.36$.

   $C_D = 0.025 + 0.0531 \times 0.1296 \approx 0.0319$.

4. If AR rises from 7.5 to 15 (same e and C_{D0}), how does $(L/D)_{max}$ change?

   K halves, so $(L/D)_{max}$ grows by $\sqrt{2}$ to ≈ 19.4.

Common misconceptions

Myth: More angle of attack always means more lift.

Actually: Past the stall angle the flow separates and lift drops.

Myth: Symmetric airfoils cannot lift.

Actually: They lift at a positive angle of attack.

Myth: Wingtip devices make induced drag zero.

Actually: They reduce it; only an infinitely long wing would have none.

Flashcards

Chord

Leading edge to trailing edge.

Camber

Curvature of the mean line.

Angle of attack

Angle between chord and oncoming flow.

Stall

Flow separation; lift drops.

Aspect ratio

b^2/S.

Drag polar

$C_D = C_{D0} + KC_L^2$.

Self-check quiz

1. Thin-airfoil lift slope is...

π per rad

2π per rad

2π per degree

1 per rad

2π per rad. $c_l = 2\pi\alpha$.

2. Aspect ratio is...

b/S

b^2/S

S/b

c/b

b^2/S. Span squared over area.

3. At maximum L/D...

induced drag = parasite drag

drag is zero

$C_L = 0$

the wing is stalled

induced drag = parasite drag. Minimizing C_D/C_L gives $KC_L^2 = C_{D0}$.

4. A higher aspect ratio mainly reduces...

skin friction

induced drag

weight

wave drag

induced drag. $K = 1/(\pi eAR)$.

Try this quiz again

How this helps save the planet

Long, slender wings are one of the most direct ways to cut fuel burn, because induced drag falls as aspect ratio rises. That is exactly the “efficient aircraft technology” path in NASA’s sustainable-aviation work.

The albatross, which glides for hours over the ocean, uses the same physics: a long, thin wing with a high lift-to-drag ratio.

On Saving Planets: Calculus II

Sources: NASA Glenn: induced drag coefficient (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/induced-drag-coefficient/) · NASA: Sustainable aviation (https://www.nasa.gov/aeronautics/sustainable-aviation/)

Free learning resources

- NASA Glenn: FoilSim (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/foilsim/): Explore camber, thickness and angle of attack.
- NASA Glenn: induced drag coefficient (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/induced-drag-coefficient/): Aspect ratio and efficiency factor.
- MIT OpenCourseWare 16.01–16.04: Unified Engineering (https://ocw.mit.edu/courses/16-01-unified-engineering-i-ii-iii-iv-fall-2005-spring-2006/): MIT’s fluids lectures.

☐ **I finished this unit**

Aircraft Performance

How far, how long, how fast and how steep: gliding, climbing, range and endurance.

Learning objectives

By the end of this unit you can:

- Relate glide ratio to L/D.
- Find thrust and power required in level flight.
- Compute climb rate from excess power.
- Use the Breguet range equation.

Key concepts

- A glider with lift-to-drag ratio L/D travels L/D meters forward for every meter of height lost: tan γ = D/L.
- Thrust required in level flight equals drag; power required is drag × speed. Excess power becomes climb: rate of climb = (P_avail − P_req)/W.
- For a jet, range follows the Breguet equation: R = (V/c)(L/D) ln(W_i/W_f). Three levers: engine efficiency (V/c), aerodynamics (L/D) and structures (weight fraction).
- Endurance (time aloft) is maximized at a different speed than range.

Key equations

$$\tan\gamma = \frac{D}{L} = \frac{1}{L/D}$$

γ=D/L=1L/D

Glide angle

$$P_R = DV$$

P_R=DV

Power required

$$RC = \frac{P_A - P_R}{W}$$

RC=(P_A-P_R)/(W)

Rate of climb

$$R = \frac{V}{c}\,\frac{L}{D}\,\ln\frac{W_i}{W_f}$$

R= Vc LD (W_i)/(W_f)

Breguet range equation (jet)

Worked examples, step by step

Example 5.1 A sailplane with L/D = 20 is 1,000 m up. How far can it glide in still air, and at what angle?

1. Distance = 1,000 × 20.
2. γ = arctan(1/20).

Answer: 20 km, at a glide angle of about 2.9°.

Example 5.2 A jet cruises at 230 m/s with L/D = 17 and thrust-specific fuel consumption c = 0.6 per hour. Burning fuel lowers its weight from W_i to W_i/1.25. Find its range.

1. c = 0.6/3,600 = 1.667 × 10^{-4} s^{-1}.
2. R = (230/1.667 × 10^{-4}) × 17 × ln 1.25.

Answer: ≈ 5,235 km.

Example 5.3 The Example 3.1 airplane, with the Example 4.3 drag polar, has about 957 N of drag at 55 m/s. What power does level flight require?

1. P = DV = 957 × 55.

Answer: ≈ 52.6 kW (about 71 hp).

Practice problems

Work each on paper first, then check.

1. A paper glider has L/D = 5. Launched level from 2 m, about how far does it glide?

   10 m.

2. An aircraft weighing 10,800 N has 30 kW of excess power. Find its rate of climb.

30,000/10,800 ≈ 2.8 m/s.

3. In Example 5.2, how does range change if L/D rises from 17 to 20?

   Range ∝ L/D: 5,235 × 20/17 ≈ 6,159 km.

4. How far can the Example 4.3 airplane glide from 1,500 m at its best L/D of 13.7?

   1,500 × 13.7 ≈ 20.6 km.

Common misconceptions

Myth: A heavier glider glides farther.

Actually: Glide ratio depends on L/D, not weight; weight changes the best speed.

Myth: Range depends only on the fuel load.

Actually: It depends on engine efficiency, L/D and the weight fraction (Breguet).

Myth: Flying faster always gives more range.

Actually: Best range comes at a moderate speed tied to the best L/D.

Flashcards

Glide ratio

Horizontal distance per unit height = L/D.

Power required

$P_R = DV$.

Rate of climb

$(P_A - P_R)/W$.

Breguet range

$R = (V/c)(L/D)\ln(W_i/W_f)$.

TSFC

Fuel flow per unit thrust.

Endurance

Time aloft.

Self-check quiz

1. Glide ratio equals...

W/D

L/D

T/W

V/a

L/D. Distance over height = L/D.

2. Power required in level flight is...

L × V

D × V

W/V

T/V

D × V. Drag times speed.

3. Breguet range grows with...

c

L/D

structure weight

drag

L/D. R ∝ L/D.

4. Climb comes from...

excess power

extra lift only

lower weight only

lower speed

excess power. RC = excess power/W.

Try this quiz again

How this helps save the planet

The Breguet equation is aviation's climate equation: for a given trip, fuel burned falls when engines get more efficient, wings get higher L/D, or structures get lighter. With the other terms fixed, range is proportional to L/D.

NASA estimates that with today's fleet and operations, worldwide air traffic in 2050 would need more than 620 million tonnes of fuel and emit close to 2,000 million tonnes of CO_2, which is why every term in the equation matters.

On Saving Planets: CO2M: measuring CO_2 from space

Sources: NASA: Sustainable aviation (https://www.nasa.gov/aeronautics/sustainable-aviation/) · FAA Pilot's Handbook of Aeronautical Knowledge (https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak)

Free learning resources

- NASA Glenn: glide angle (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/glide-angle/): Gliding flight.
- FAA Pilot's Handbook of Aeronautical Knowledge (https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak): Aircraft performance chapter.
- NASA Glenn: thrust-to-weight ratio (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/thrust-to-weight-ratio/): Thrust, weight and climb.

Watch the lecture

Lecture 12: Aircraft Performance (https://ocw.mit.edu/courses/16-687-private-pilot-ground-school-january-iap-2019/resources/lecture-12-aircraft-performance/) (in English)

MIT 16.687 Private Pilot Ground School (IAP 2019), MIT OpenCourseWare. License: CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/) · Terms of use (https://ocw.mit.edu/pages/privacy-and-terms-of-use/). Linked for free study only; Saving Planets is not affiliated with or endorsed by this university.

☐ I finished this unit

Stability & Control

Why a well-designed aircraft returns to steady flight by itself, and how pilots and computers control it.

Learning objectives

By the end of this unit you can:

- Name the three axes, pitch, roll and yaw, and their control surfaces.
- Explain static and dynamic stability.
- Locate the center of gravity and the neutral point; compute static margin.
- Explain why a tail stabilizes an aircraft.

Key concepts

- An aircraft rotates about its center of gravity: pitch (elevator), roll (ailerons), yaw (rudder).
- Static stability: after a disturbance, the aircraft initially tends to return. Dynamic stability: the motion actually dies out over time.
- Pitch stability needs the center of gravity ahead of the neutral point. Static margin = (x_np − x_cg)/c̄ must be positive.
- A tail far behind the CG works like the feathers on an arrow: a nose-up disturbance raises the tail's lift and pushes the nose back down.
- Too much stability makes an aircraft sluggish and costs trim drag; some modern fighters are designed unstable and flown by computer.

Key equations

$$\mathrm{SM} = \frac{x_{np} - x_{cg}}{\bar{c}}$$

```
SM=_np-x_cg c
```

Static margin

$$x_{cg} = \frac{\sum m_i x_i}{\sum m_i}$$

```
x_cg=( m_ix_i)/( m_i)
```

Center of gravity

$$\frac{dC_m}{d\alpha} < 0$$

Condition for pitch stability

Worked examples, step by step

Example 6.1 The neutral point is at 40% of the mean chord and the CG at 25%. Find the static margin.

1. SM = 0.40 − 0.25.

Answer: 0.15, or 15%: stable.

Example 6.2 A glider has a 50 g wing at x = 10 cm, a 10 g tail at x = 40 cm and 20 g of nose weight at x = 0. Find the CG.

1. $\Sigma mx = 50(10) + 10(40) + 20(0) = 900$ g·cm.
2. $\Sigma m = 80$ g.

Answer: $x_{cg} = 11.25$ cm from the nose.

Example 6.3 For the Example 6.2 glider (mean chord 8 cm), the neutral point is at 13 cm. Is it stable?

1. SM = (13 − 11.25)/8.

Answer: SM ≈ 0.22: stable. Remove nose weight and the CG moves aft toward instability.

Practice problems

Work each on paper first, then check.

1. Which surface controls pitch?

   The elevator, on the horizontal tail.

2. CG at 30% chord, neutral point at 28%. Stable?

   SM = −0.02 < 0: statically unstable.

3. In Example 6.2, how much nose weight m puts the CG at 12 cm?

   900/(60 + m) = 12 gives m = 15 g.

4. Why does a paper airplane with no nose weight pitch up and stall?

   Its CG is too far aft, near or behind the neutral point.

Common misconceptions

Myth: Statically stable means the oscillation dies out.

Actually: That is dynamic stability; static stability is the initial tendency.

Myth: More stability is always better.

Actually: Too much makes control heavy and wastes trim drag.

Myth: The CG can be anywhere as long as the wing lifts.

Actually: An aft CG makes the aircraft unstable.

Flashcards

Pitch / roll / yaw

Elevator / ailerons / rudder.

Static stability

Initial tendency to return.

Dynamic stability

Disturbance dies out over time.

Neutral point

CG location for neutral pitch stability.

Static margin

$(x_{np} - x_{cg})/\bar{c}$.

Trim

Balanced, zero net moment.

Self-check quiz

1. Ailerons control...

pitch

roll

yaw

thrust

roll. They deflect in opposite directions on each wing.

2. For pitch stability the CG must be...

behind the neutral point

ahead of the neutral point

at the tail

at the wingtip

ahead of the neutral point. Positive static margin.

3. A static margin of 0.15 means...

unstable

stable

neutral

stalled

stable. Positive margin.

4. Dynamic stability concerns...

the initial tendency

the motion over time

engine thrust

weight only

the motion over time. Whether oscillations die out.

Try this quiz again

How this helps save the planet

Stability margins cost fuel: a conventional tail usually pushes down to balance the aircraft, and the wing must make extra lift, with extra drag, to carry it. Trimming that penalty is part of the efficient-

aircraft path NASA describes.

The same balance and control ideas keep Earth-observing satellites pointed steadily so their instruments can map the planet.

On Saving Planets: Orbits guide

Sources: NASA Glenn: aircraft rotations (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/aircraft-rotations/) · NASA: Sustainable aviation (https://www.nasa.gov/aeronautics/sustainable-aviation/)

Free learning resources

- NASA Glenn: aircraft rotations (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/aircraft-rotations/): Pitch, roll and yaw.
- FAA Pilot's Handbook of Aeronautical Knowledge (https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak): Stability and flight controls chapters.

- [ ] **I finished this unit**

Propulsion Basics

How propellers, jets and rockets make thrust by throwing mass backward, and why bigger, slower jets are more efficient.

Learning objectives

By the end of this unit you can:

- Use the momentum thrust equation.
- Compute propulsive efficiency.
- Compare turbojets, turbofans and propellers.
- Define specific impulse and thrust-specific fuel consumption.

Key concepts

- Every engine makes thrust by accelerating a mass flow: F = ṁ(v_e − v_0) for an air-breathing engine (ignoring fuel mass and pressure terms).
- Propulsive efficiency η_p = 2/(1 + v_e/v_0): moving a lot of air a little is more efficient than moving a little air a lot. That is why turbofans have huge fans.
- Turbojet: all air passes through the core. Turbofan: most air bypasses the core through the fan. Turboprop: a propeller driven by a gas turbine.
- Specific impulse I_sp = F/(ṁ_fuel g_0) measures thrust per fuel weight flow, in seconds.

Key equations

$$F = \dot{m}(v_e - v_0)$$

`F= m(v_e-v_0)`

Thrust of an air-breathing engine

$$\eta_p = \frac{2}{1 + v_e/v_0}$$

`_p=(2)/(1+v_e/v_0)`

Propulsive efficiency

$$I_{sp} = \frac{F}{\dot{m}_f g_0}$$

`I_sp=(F)/( m_fg_0)`

Specific impulse

Worked examples, step by step

Example 7.1 A turbofan moves 500 kg/s of air from 250 m/s to 320 m/s. Find thrust and propulsive efficiency.

1. F = 500 × 70 = 35,000 N.
2. η_p = 2/(1 + 320/250) = 2/2.28.

Answer: F = 35 kN, η_p ≈ 0.88.

Example 7.2 A turbojet makes the same 35 kN with 100 kg/s of air at v_0 = 250 m/s. What exhaust speed does it need, and what is η_p?

1. v_e = 250 + 35,000/100 = 600 m/s.
2. η_p = 2/(1 + 2.4).

Answer: v_e = 600 m/s, η_p ≈ 0.59: much less efficient.

Example 7.3 An engine makes 100 kN while burning 2.5 kg/s of fuel. Find its I_sp.

1. I_sp = 100,000/(2.5 × 9.80665).

Answer: ≈ 4,079 s. Air-breathers beat rockets on this measure because they do not carry their oxidizer.

Practice problems

Work each on paper first, then check.

1. Find the thrust for $\dot{m}$ = 200 kg/s, v_0 = 200 m/s, v_e = 300 m/s.

   20 kN.

2. Find η_p when v_e = v_0.

   1.0, but the thrust is zero: efficiency and thrust trade off.

3. Why do airliners use high-bypass turbofans?

   They move a large mass of air slowly, which raises propulsive efficiency and cuts fuel burn and noise.

Common misconceptions

Myth: Jets push against the air behind them.

Actually: They accelerate air through the engine; the reaction to that is thrust.

Myth: Faster exhaust always means a better engine.

Actually: For efficiency, exhaust speed should be close to flight speed.

Myth: Specific impulse is a speed.

Actually: It is measured in seconds; $I_{sp} \times g_0$ is an effective exhaust speed.

Flashcards

Momentum thrust

$F = \dot{m}(v_e - v_0)$.

Propulsive efficiency

$2/(1 + v_e/v_0)$.

Turbofan

Fan plus core; most air bypasses.

Bypass ratio

Bypass air ÷ core air.

Specific impulse

$F/(\dot{m}\, g_0)$, in seconds.

TSFC

Fuel flow per unit thrust.

Self-check quiz

1. Thrust of an air-breathing engine ≈

$\dot{m}v_0$

$\dot{m}(v_e - v_0)$

$\dot{m}v_e^2$

ρV^2

$\dot{m}(v_e - v_0)$. Momentum change per second.

2. Propulsive efficiency is highest when v_e/v_0 is...

large

close to 1

zero

negative

close to 1. $\eta_p = 2/(1 + v_e/v_0)$.

3. Most air in a high-bypass turbofan...

goes through the combustor

bypasses the core

is stored

is heated to 2,000 K

bypasses the core. The fan stream.

4. I_{sp} is measured in...

m/s

seconds

newtons

kg

seconds. Thrust per weight flow of propellant.

Try this quiz again

How this helps save the planet

Higher propulsive efficiency is a direct fuel and CO_2 saving. Every kilogram of jet fuel burned produces about 3.16 kg of CO_2 (the fuel's carbon combined with oxygen from the air; see Unit 10), so

efficiency gains add up over an engine's decades of service.

Sustainable aviation fuel, made from wastes and biomass, is blended to match conventional jet fuel's properties for safe operation. NASA notes that SAF does not release new CO_2 into the environment.

On Saving Planets: General Chemistry I

Sources: NASA: Sustainable aviation (https://www.nasa.gov/aeronautics/sustainable-aviation/) · U.S. DOE: Sustainable aviation fuels (https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuels)

Free learning resources

- NASA Glenn: thrust-to-weight ratio (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/thrust-to-weight-ratio/): Engines and thrust.
- NASA Glenn: specific impulse (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/specific-impulse/): Rocket and jet efficiency.
- MIT OpenCourseWare 16.01–16.04: Unified Engineering (https://ocw.mit.edu/courses/16-01-unified-engineering-i-ii-iii-iv-fall-2005-spring-2006/): MIT propulsion lectures.

☐ **I finished this unit**

Rockets & the Rocket Equation

Why reaching orbit is so hard: Tsiolkovsky’s rocket equation, mass ratios and staging.

Learning objectives

By the end of this unit you can:

- Use Δv = I_sp g_0 ln(m_0/m_f).
- Compute required mass ratios.
- Explain why staging works.
- Compute rocket thrust-to-weight ratio.

Key concepts

- A rocket carries all its propellant, fuel and oxidizer. Its thrust is F = ṁv_e + (p_e − p_a)A_e.
- The ideal rocket equation: Δv = v_e ln(m_0/m_f), with v_e = I_sp g_0. Speed grows only with the logarithm of the mass ratio.
- Reaching low Earth orbit takes roughly 9.4 km/s of Δv once gravity and drag losses are included, so most of a launch vehicle’s mass is propellant.
- Staging drops empty tanks and engines so later stages do not carry dead weight.
- Thrust-to-weight ratio must exceed 1 to lift off.

Key equations

$$\Delta v = I_{sp}\, g_0 \ln \frac{m_0}{m_f}$$

`Δ v=I_sp g_0(m_0)/(m_f)`

Ideal rocket (Tsiolkovsky) equation

$$F = \dot{m} v_e + (p_e - p_a) A_e$$

`F= m v_e+(p_e-p_a)A_e`

Rocket thrust

$$\frac{m_0}{m_f} = e^{\Delta v/(I_{sp} g_0)}$$

`(m_0)/(m_f)=e^Δ v/(I_spg_0)`

Required mass ratio

Worked examples, step by step

Example 8.1 An engine with $I_{sp} = 450$ s fires until $m_0/m_f = 5$. Find Δv.

1. $v_e = 450 \times 9.80665 = 4{,}413$ m/s.
2. $\Delta v = 4{,}413 \times \ln 5$.

Answer: ≈ 7,102 m/s.

Example 8.2 What mass ratio does a single stage need for 9.4 km/s with $I_{sp} = 300$ s? With 450 s?

1. 300 s: e^(9,400/2,942) = e^3.195.
2. 450 s: e^(9,400/4,413) = e^2.130.

Answer: ≈ 24.4 versus ≈ 8.4: about 96% versus 88% of the rocket must be propellant.

Example 8.3 A two-stage rocket: each stage has $I_{sp} = 300$ s and mass ratio 4. Find the total Δv.

1. Each stage: $2{,}942 \times \ln 4 = 4{,}078$ m/s.
2. Add the stages.

Answer: ≈ 8,157 m/s, twice what one stage with mass ratio 4 gives.

Practice problems

Work each on paper first, then check.

1. Find Δv for $I_{sp} = 311$ s and $m_0/m_f = 3$.

   $311 \times 9.80665 \times \ln 3 \approx 3{,}351$ m/s.

2. A 500,000 kg rocket has 7.5 MN of thrust. Find T/W at liftoff.

   $7.5 \times 10^6/(500{,}000 \times 9.81) \approx 1.53$.

3. What I_{sp} gives $\Delta v = 3{,}000$ m/s with mass ratio 2?

   $3{,}000/(9.80665 \times \ln 2) \approx 441$ s.

Common misconceptions

Myth: Rockets push against the air.

Actually: They work best in vacuum; they push on their own exhaust.

Myth: Double the propellant, double the Δv.

Actually: Δv grows with the logarithm of the mass ratio.

Myth: Orbit needs only 7.7 km/s of Δv.

Actually: Gravity and drag losses push the total to roughly 9.4 km/s.

Flashcards

Rocket equation

$\Delta v = I_sp\ g_0 \ln(m_0/m_f)$.

Mass ratio

m_0/m_f.

Staging

Dropping spent stages.

Thrust-to-weight

Must exceed 1 at liftoff.

Δv to LEO

≈ 9.4 km/s including losses.

I_sp

Seconds of thrust per weight of propellant.

Self-check quiz

1. Δv depends on the mass ratio through...

a square

a logarithm

a square root

a straight line

a logarithm. $\ln(m_0/m_f)$.

2. Staging helps because...

it raises I_sp

it drops dead mass

it adds air

it lowers gravity

it drops dead mass. Empty tanks no longer need accelerating.

3. To lift off, thrust-to-weight must be…

< 1

> 1

= 0

exactly 1

> 1. Thrust must exceed weight.

4. The effective exhaust speed for I_sp = 300 s is about…

300 m/s

2,940 m/s

30 km/s

9.8 m/s

2,940 m/s. I_sp × g_0.

Try this quiz again

How this helps save the planet

Every Earth-observing satellite, from Landsat to the missions that track sea level and greenhouse gases, rides a rocket sized with this equation. It is why each kilogram of instrument is precious and why satellites are built to be light.

Our Delta-v calculator lets you run the same numbers for real missions.

On Saving Planets: Delta-v calculator · Landsat 9

Sources: NASA Glenn: ideal rocket equation (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/ideal-rocket-equation/) · NASA Glenn: rocket thrust equation (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/rocket-thrust-equation/)

Free learning resources

- NASA Glenn: ideal rocket equation (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/ideal-rocket-equation/): Derivation and use.
- NASA Glenn: rocket thrust equation (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/rocket-thrust-equation/): Pressure and momentum thrust.
- NASA Glenn: specific impulse (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/specific-impulse/): Comparing propellants.

☐ **I finished this unit**

UNIT 9 · WEEKS 12–13

Orbits & Space Missions

Circular and elliptical orbits, periods, geostationary orbit and the Hohmann transfer, plus how Earth-observing missions choose their orbits.

Learning objectives

By the end of this unit you can:

- Compute circular orbital speed and period.
- Find the geostationary radius.
- Compute a Hohmann transfer Δv and transfer time.
- Describe common Earth orbits and their uses.

Key concepts

- In a circular orbit gravity supplies the centripetal force: v = √(μ/r), with μ = GM.
- Kepler's third law: T = 2π√(a³/μ). Higher orbits are slower and take longer.
- A geostationary orbit has a period of one sidereal day (86,164 s) and sits over the equator at a radius of about 42,164 km.
- A Hohmann transfer uses two burns along an ellipse that touches both circular orbits; it is the most efficient two-burn transfer between coplanar circular orbits.
- Low Earth orbit (about 400 km for the ISS), sun-synchronous polar orbits for imaging, and geostationary orbit for weather each serve different missions.

Key equations

$$v = \sqrt{\mu / r}$$

`v=μ/r`

Circular orbit speed

$$T = 2\pi \sqrt{a^3 / \mu}$$

`T=2π^3/μ`

Orbital period

$$v = \sqrt{\mu \left(\frac{2}{r} - \frac{1}{a} \right)}$$

`v=μ(2r-1a)`

Vis-viva equation

$$\Delta v_1 = \sqrt{\frac{\mu}{r_1}}\left(\sqrt{\frac{2r_2}{r_1+r_2}} - 1\right)$$

`Δ v_1=μr_1(2r_2r_1+r_2-1)`

First Hohmann burn

Worked examples, step by step

Example 9.1 Find the speed and period of a circular orbit 400 km up.

1. r = 6,771 km.
2. v = √(3.986 × 10^{14}/6.771 × 10^{6}) = 7,673 m/s.
3. T = 2π√(r^3/μ) = 5,545 s.

Answer: 7.67 km/s and ≈ 92.4 minutes.

Example 9.2 Find the geostationary radius.

1. r = (μT^2/4π^2)^(1/3) with T = 86,164 s.

Answer: ≈ 42,164 km from Earth's center (about 35,786 km above the equator).

Example 9.3 Find the Hohmann Δv from a 300 km circular orbit to geostationary radius.

1. r_1 = 6,671 km, r_2 = 42,164 km.
2. Δv_1 = 2,428 m/s; Δv_2 = 1,468 m/s.
3. Transfer time = half the transfer ellipse's period.

Answer: Total ≈ 3.90 km/s; transfer ≈ 5.27 hours (ignoring any plane change).

Practice problems

Work each on paper first, then check.

1. Find v for a circular orbit at r = 7,000 km.

   √(3.986 × 10^{14}/7 × 10^{6}) ≈ 7,546 m/s.

2. If the orbit radius quadruples, how does the period change?

   T ∝ r^(3/2): 8 times longer.

3. Why are many weather satellites geostationary?

   They stay over one spot and can image the same hemisphere continuously.

Common misconceptions

Myth: Astronauts float because there is no gravity in orbit.

Actually: At 400 km gravity is about 89% of its surface value; they are in free fall.

Myth: To catch a spacecraft ahead of you, just speed up.

Actually: Speeding up raises your orbit and lowers your angular rate.

Myth: Higher orbits need more speed.

Actually: Circular speed falls with height, though reaching higher orbits takes more total Δv.

Flashcards

Circular speed

$\sqrt{(\mu/r)}$.

Kepler's third law

$T = 2\pi\sqrt{(a^3/\mu)}$.

Vis-viva

$v^2 = \mu(2/r - 1/a)$.

Hohmann transfer

Two-burn elliptical transfer.

GEO

Period = 1 sidereal day; r ≈ 42,164 km.

Sun-synchronous orbit

Near-polar orbit that passes over each place at about the same local time.

Self-check quiz

1. Circular orbital speed is...

$\sqrt{(\mu r)}$

$\sqrt{(\mu/r)}$

μ/r^2

$2\pi r$

√(μ/r). Gravity supplies the centripetal force.

2. At 400 km a spacecraft orbits Earth about every…

24 h

92 min

10 min

1 week

92 min. ≈ 92.4 minutes.

3. A Hohmann transfer uses…

one burn

two burns

continuous thrust only

aerobraking only

two burns. One at each end of the transfer ellipse.

4. Geostationary radius ≈

6,771 km

42,164 km

384,400 km

20,000 km

42,164 km. Kepler’s third law with one sidereal day.

Try this quiz again

How this helps save the planet

Climate monitoring depends on orbit choice. Sun-synchronous orbits let Landsat image the same place under similar lighting, so changes in forests, crops and ice stand out, while geostationary weather satellites watch storms develop continuously.

Orbits also need care: debris threatens these missions, so spacecraft are increasingly designed to be disposed of at the end of their lives.

On Saving Planets: Orbits guide · Orbital velocity calculator · Orbital period calculator

Sources: NASA JPL: Basics of Space Flight (https://science.nasa.gov/learn/basics-of-space-flight/) · NASA Earth fact sheet (https://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html)

Free learning resources

- NASA JPL: Basics of Space Flight (https://science.nasa.gov/learn/basics-of-space-flight/): NASA JPL's free primer on orbits and missions.
- Physics I, Unit 7: gravitation and orbits: Our orbits unit.

- [ ] **I finished this unit**

Sustainable Aviation & Space

Putting it together: the physics of cutting aviation's climate impact, from efficient aircraft to sustainable fuels and new energy sources, and keeping space usable.

Learning objectives

By the end of this unit you can:

- Compute CO_2 from fuel burned.
- Use the Breguet equation to compare efficiency improvements.
- Explain the roles and limits of sustainable aviation fuel, batteries and hydrogen.
- Describe space sustainability: debris and disposal.

Key concepts

- Burning one kilogram of kerosene-type jet fuel produces about 3.16 kg of CO_2, fixed by chemistry. The only ways to cut it are to burn less fuel or to use fuel whose carbon came recently from the air.
- EPA reports that the aircraft covered by its greenhouse gas rule account for 10% of U.S. transportation greenhouse gas emissions and 3% of the U.S. total.
- NASA's three paths: efficient aircraft technology, sustainable aviation fuel, and better operations and infrastructure.
- Today's batteries store far less energy per kilogram than jet fuel, so electric aircraft suit short, small flights; hydrogen stores a lot of energy per kilogram but needs large tanks.
- Space sustainability means planning disposal so useful orbits stay open for the satellites that monitor Earth.

Key equations

$$m_{\mathrm{CO_2}} \approx 3.16\, m_{\mathrm{fuel}}$$

CO_2 from burning jet fuel

$$\frac{\mathrm{fuel}_2}{\mathrm{fuel}_1} \approx \frac{(L/D)_1}{(L/D)_2}$$

Fuel scales inversely with L/D (same trip, modest changes)

Worked examples, step by step

Example 10.1 Where does 3.16 come from? Model jet fuel as $C_{12}H_{23}$ and find kg of CO_2 per kg of fuel.

1. Molar mass: 12(12.011) + 23(1.008) = 167.3 g/mol.

2. 12 CO_2 per molecule: 12 × 44.01 = 528.1 g.
3. 528.1/167.3.

Answer: ≈ 3.16 kg of CO_2 per kg of fuel.

Example 10.2 NASA estimates 620 million tonnes of fuel in 2050 at today's efficiency. How much CO_2 is that?

1. 620 × 3.16.

Answer: ≈ 1,959 million tonnes, matching NASA's "close to 2,000 megatons."

Example 10.3 A flight burns 20 t of fuel. A new wing raises L/D from 17 to 19. Estimate the fuel and CO_2 saved.

1. Fuel ≈ 20 × 17/19 = 17.9 t.
2. Fuel saved ≈ 2.1 t; × 3.16.

Answer: ≈ 2.1 t of fuel and ≈ 6.7 t of CO_2 per flight (a simplified estimate).

Practice problems

Work each on paper first, then check.

1. A flight burns 5,000 kg of fuel. How much CO_2?

   ≈ 15,800 kg.

2. If engines become 15% more fuel-efficient, by about how much do CO_2 emissions per trip fall?

   About 15%, since CO_2 is proportional to fuel burned.

3. Why can't today's batteries power long-haul airliners?

   Their energy per kilogram is far below jet fuel, and the Breguet trade makes extra weight very costly.

Common misconceptions

Myth: Sustainable aviation fuel emits no CO_2 when burned.

Actually: It emits CO_2 like jet fuel; the benefit is that its carbon came recently from the air, so lifecycle emissions are lower.

Myth: Electric airplanes will soon replace all jets.

Actually: Battery energy density limits them to short, small flights for now.

Myth: Space is too big to pollute.

Actually: Debris in popular orbits is a real hazard.

Flashcards

CO_2 per kg fuel

≈ 3.16 kg.

SAF

Sustainable aviation fuel from wastes and biomass.

Three paths

Efficient aircraft, SAF, operations.

Energy density

Energy per kg; batteries ≪ jet fuel.

Space debris

Defunct objects that threaten useful orbits.

Lifecycle emissions

All emissions from fuel production to use.

Self-check quiz

1. Burning 1 kg of jet fuel makes about…

1 kg CO_2

3.16 kg CO_2

0.3 kg CO_2

10 kg CO_2

3.16 kg CO_2. The fuel's carbon combines with oxygen from the air.

2. NASA's three paths to sustainable aviation are…

bigger fuel tanks

efficient aircraft, SAF, operations and infrastructure

flying lower only

slower climbs only

efficient aircraft, SAF, operations and infrastructure. As listed by NASA.

3. If L/D rises 10%, fuel for the same trip falls roughly…

1%

9–10%

50%

0%

9–10%. Fuel ∝ 1/(L/D).

4. U.S. aircraft covered by EPA's rule emit what share of total U.S. greenhouse gases?

0.3%

3%

30%

50%

3%. EPA: 3% of the national total.

Try this quiz again

How this helps save the planet

This unit is the course's planet tie-in in full: each equation from Units 3–7 is a lever on fuel burn, and fuel burn is CO_2. Engineers who can run these numbers design the cleaner aircraft that NASA and industry are working toward.

EPA reports that the aircraft covered by its rule produce 10% of U.S. transportation greenhouse gas emissions, and NASA notes the U.S. committed in 2021 to net-zero aviation greenhouse gas emissions by 2050.

On Saving Planets: CO2M: measuring CO_2 from space · Delta-v calculator

Sources: NASA: Sustainable aviation (https://www.nasa.gov/aeronautics/sustainable-aviation/) · EPA: greenhouse gas emissions from aircraft (https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-greenhouse-gas-emissions-aircraft)

Free learning resources

- NASA: Sustainable aviation (https://www.nasa.gov/aeronautics/sustainable-aviation/): NASA's overview and goals.
- EPA: greenhouse gas emissions from aircraft (https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-greenhouse-gas-emissions-aircraft): U.S. emissions standards and data.
- U.S. DOE: Sustainable aviation fuels (https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuels): How SAF is made.

☐ **I finished this unit**

Problem Sets

These practice problems live inside each unit. Work on paper first, then open the answer.

1. History of Flight & the Design Process
   3 problems
2. The Atmosphere
   4 problems
3. Basic Aerodynamics: Lift & Drag
   4 problems
4. Airfoils & Wings
   4 problems
5. Aircraft Performance
   4 problems
6. Stability & Control
   4 problems
7. Propulsion Basics
   3 problems
8. Rockets & the Rocket Equation
   3 problems
9. Orbits & Space Missions
   3 problems
10. Sustainable Aviation & Space
    3 problems

Labs

Four labs put the course to work: a virtual wind tunnel with NASA's FoilSim, a rocket-equation calculator, a glider you design and fly, and an atmosphere and stall-speed spreadsheet.

Sample data is labeled as such. Your own measurements will differ, and explaining why is part of the lab.

Safety reference: FAA Pilot's Handbook of Aeronautical Knowledge (https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak)

Lab A: Virtual wind tunnel with NASA FoilSim

WEEK 5

Goal: Measure an airfoil's lift curve in FoilSim and compare it with thin-airfoil theory.

$$c_l \approx 2\pi\alpha$$

Thin-airfoil theory (α in radians)

Procedure

1. Open FoilSim and choose a symmetric airfoil (zero camber) about 12% thick.
2. Record the lift coefficient at α = 0°, 2°, 4°, 6° and 8°.
3. Add a column with 2πα and compare. Then add camber and repeat.
4. Increase α until FoilSim warns of stall; note the angle.

Data table

α (deg)	Theory c_l = 2πα
0	0.000
2	0.219
4	0.439
6	0.658
8	0.877

Computed theory values. Your FoilSim readings will differ somewhat; explain why (thickness, model assumptions).

Sample calculation

1. 2π × (4π/180) = 0.439.
2. Theory slope: 0.110 per degree. A finite wing with AR = 8 and e = 0.9 would show only about 0.086 per degree (Unit 4).

> **Safety**
>
> - None beyond normal computer use.

Home or virtual alternative

- Runs in a web browser.

NASA Glenn: FoilSim (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/foilsim/)

Planet link: Wind-tunnel testing, real and virtual, is how designers find low-drag wings that burn less fuel. NASA: Sustainable aviation (https://www.nasa.gov/aeronautics/sustainable-aviation/)

- [ ] **I completed this lab (wet or virtual)**

Lab B: Rocket-equation calculator

WEEK 11

Goal: Build a spreadsheet that gives Δv from I_sp and mass ratio, and use it to size a two-stage rocket.

$$\Delta v = I_{sp}\, g_0 \ln(m_0/m_f)$$

```
Δ v=I_sp g_0(m_0/m_f)
```

Ideal rocket equation

Procedure

1. Columns: I_sp, m_0, m_f, mass ratio, Δv.
2. Fill rows for I_sp = 300 s and 450 s at mass ratios 2, 4 and 8.
3. Add a two-stage sheet: total Δv = sum of the stages. Find stage mass ratios that reach 9.4 km/s.
4. Check one result against our Delta-v calculator.

Data table

I_sp (s)	Mass ratio	Δv (m/s)
300	2	2,039
300	4	4,078
300	8	6,118
450	4	6,118
450	8	9,177

Computed values (ideal: no gravity or drag losses).

Sample calculation

1. 300 × 9.80665 × ln 2 = 2,039 m/s.
2. Each doubling of the mass ratio adds the same 2,039 m/s at 300 s: the logarithm at work.
3. Two stages at 300 s, each with mass ratio 5, give 2 × 4,735 = 9,470 m/s, just above 9.4 km/s.

> **Safety**
>
> - None beyond normal computer use. Do not build or fly rocket motors without trained supervision and local permission.

Home or virtual alternative

- A spreadsheet is enough.

Saving Planets Delta-v calculator · NASA Glenn: ideal rocket equation (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/ideal-rocket-equation/)

Planet link: Every kilogram saved on a climate satellite shrinks the rocket needed to launch it.
NASA Glenn: ideal rocket equation (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/ideal-rocket-equation/)

☐ **I completed this lab (wet or virtual)**

Lab C: Design, build and fly a glider

WEEK 8

Goal: Design a card-stock or foam glider, set its CG for a positive static margin, then measure its glide ratio.

$$L/D \approx \frac{\text{glide distance}}{\text{launch height}}$$

Glide ratio from a steady glide

Procedure

1. Sketch a design: pick a wing span and chord for an aspect ratio between 5 and 8, a tail about 20% of the wing area, and a fuselage stick.
2. Build it. Find the CG by balancing it on a finger; add nose weight until the CG is about 25% of the wing chord behind the wing's leading edge.
3. Launch gently and level from a measured height in still air, at least five times; record each distance.
4. Compute L/D. Then move the CG aft in small steps and record what happens.

Data table

Trial	Height (m)	Distance (m)
1	2.0	9.6
2	2.0	10.4
3	2.0	10.0
Mean	2.0	10.0

Sample data for practice, not a measured result.

Sample calculation

1. Mean L/D ≈ 10.0/2.0 = 5.0.
2. Glide angle = arctan(1/5) ≈ 11.3°.
3. Typical finding: with the CG too far aft the glider pitches up and stalls (negative static margin); too far forward, it dives.

> **Safety**
>
> - Cut away from your body; an adult should handle any craft knife.
> - Fly away from people's faces, in an open space.

Home or virtual alternative

- Card stock, tape and a coin for nose weight work well.

NASA Glenn: glide angle (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/glide-angle/)

Planet link: Gliders show how far good aerodynamics alone can take you, with no fuel at all.

☐ **I completed this lab (wet or virtual)**

Lab D: Atmosphere and stall-speed spreadsheet

WEEK 4

Goal: Implement NASA's atmosphere model and see how altitude changes density, the speed of sound and stall speed.

$$V_s = \sqrt{\frac{2W}{\rho S C_{L,\max}}}$$

V_s=2Wρ SC_L,

Stall speed (true airspeed)

Procedure

1. Implement NASA's troposphere and lower-stratosphere fits from 0 to 12 km in 1 km steps.
2. Compute ρ, a and V_s for W = 10,791 N, S = 16.2 m², C_L,max = 1.6.
3. Plot ρ/ρ_0 and V_s against altitude.

Data table

Altitude (m)	ρ (kg/m³)	V_s (m/s)
0	1.227	26.1
5,000	0.738	33.6
10,000	0.414	44.8

Computed from NASA's model.

Sample calculation

1. At 5,000 m: √(2 × 10,791/(0.738 × 16.2 × 1.6)) = 33.6 m/s.
2. V_s grows as 1/√ρ: at 10 km it is 1.72 times its sea-level value.

> **Safety**
>
> - None beyond normal computer use.

Home or virtual alternative

- A spreadsheet is enough.

NASA Glenn: Earth atmosphere model (metric) (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/earth-atmosphere-equation-metric/)

Planet link: Standard-atmosphere physics also underlies how satellites measure the air.

- [ ] **I completed this lab (wet or virtual)**

Exam prep practice sets

Time yourself: about 10 minutes per problem. Then compare with the full solutions.

Midterm practice set (Units 1–5)

1. Find ρ at 5,000 m with NASA's model.
    1. T = −17.41 °C; p = 54.11 kPa.
    2. ρ = 54.11/(0.2869 × 255.69).

    Answer: ≈ 0.738 kg/m³.

2. A 1,100 kg airplane (S = 16.2 m², $C_{L,max}$ = 1.6): find its stall speed at 5,000 m.
    1. $V_s = \sqrt{(2 \times 10{,}791/(0.738 \times 16.2 \times 1.6))}$.

    Answer: ≈ 33.6 m/s.

3. Find $(L/D)_{max}$ for C_{D0} = 0.025, e = 0.8, AR = 7.5.
    1. K = 0.0531; $(L/D)_{max} = 1/(2\sqrt{(C_{D0} K)})$.

    Answer: ≈ 13.7.

4. A glider with L/D = 13.7 starts 1,500 m up. How far can it glide?
    1. 1,500 × 13.7.

    Answer: ≈ 20.6 km.

Final practice set (all units)

1. Find the static margin for $x_{np} = 0.40\bar{c}$ and $x_{cg} = 0.25\bar{c}$.
    1. 0.40 − 0.25.

    Answer: 0.15 (stable).

2. An engine moves 500 kg/s of air from 250 to 320 m/s. Find thrust and η_p.
    1. F = 500 × 70; $\eta_p = 2/(1 + 1.28)$.

    Answer: 35 kN; ≈ 0.88.

3. Find Δv for I_sp = 450 s and mass ratio 5.

    1. 4,413 × ln 5.

    Answer: ≈ 7,102 m/s.

4. Find the period of a circular orbit 400 km up.

    1. T = 2π√(r³/μ) with r = 6.771 × 10⁶ m.

    Answer: ≈ 92.4 min.

5. Find the Hohmann Δv from a 300 km orbit to geostationary radius.

    1. Δv_1 = 2,428 m/s; Δv_2 = 1,468 m/s.

    Answer: ≈ 3.90 km/s.

6. A flight burns 20 t of fuel. How much CO_2?

    1. 20 × 3.16.

    Answer: ≈ 63 t.

Formula sheet

$$L = W,\ T = D$$

$$T = 15.04 - 0.00649h,\ p = 101.29\left(\tfrac{T+273.1}{288.08}\right)^{5.256}$$

$$\rho = p/(RT),\ a = \sqrt{\gamma RT},\ M = V/a$$

$$L = \tfrac{1}{2}\rho V^2 S C_L,\ D = \tfrac{1}{2}\rho V^2 S C_D$$

$$V_s = \sqrt{2W/(\rho S C_{L,\max})}$$

$$Re = \rho V c/\mu$$

$$c_l = 2\pi\alpha$$

$$a = a_0/(1 + a_0/(\pi e AR))$$

$$C_D = C_{D0} + C_L^2/(\pi e AR)$$

$$(L/D)_{\max} = 1/(2\sqrt{C_{D0}K})$$

$$\tan\gamma = 1/(L/D)$$

$$R = (V/c)(L/D)\ln(W_i/W_f)$$

$$\mathrm{SM} = (x_{np} - x_{cg})/\bar{c}$$

$$F = \dot{m}(v_e - v_0),\ \eta_p = 2/(1 + v_e/v_0)$$

$$\Delta v = I_{sp} g_0 \ln(m_0/m_f)$$

$$v = \sqrt{\mu/r},\ T = 2\pi\sqrt{a^3/\mu}$$

$$v^2 = \mu(2/r - 1/a)$$

$$m_{CO_2} \approx 3.16\, m_{fuel}$$

Constants

Constant	Value
Standard gravity g_0	9.80665 m/s²
Sea-level air density (NASA model)	1.23 kg/m³
Sea-level pressure (NASA model)	101.3 kPa
Speed of sound, sea level (15 °C)	340 m/s
Gas constant of air R	287 J/(kg·K)
Ratio of specific heats γ (air)	1.4
Earth's GM	3.986 × 10¹⁴ m³/s²
Earth's mean radius	6,371 km

Source: NASA Glenn: Earth atmosphere model (metric) (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/earth-atmosphere-equation-metric/)

Simulators and references

Free tools and references to use alongside the course.

- NASA Glenn: Beginner's Guide to Aeronautics (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/): NASA's free reference for every equation in this course, with simulators.
- NASA Glenn: FoilSim (https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/foilsim/): Virtual wind tunnel for airfoils (Lab A).
- MIT OpenCourseWare 16.00: Introduction to Aerospace Engineering and Design (https://ocw.mit.edu/courses/16-00-introduction-to-aerospace-engineering-and-design-spring-2003/): MIT's first-year design course.
- FAA Pilot's Handbook of Aeronautical Knowledge (https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak): Free FAA handbook on aerodynamics, performance and stability.
- NASA JPL: Basics of Space Flight (https://science.nasa.gov/learn/basics-of-space-flight/): Free primer on orbits and missions.

Glossary

Angle of attack
Angle between the chord line and the oncoming air.

Aspect ratio
Span squared divided by wing area.

Breguet range equation
Range of a jet from speed, fuel use, L/D and weight fraction.

Camber
Curvature of an airfoil's mean line.

Center of gravity
Point where the weight acts.

Drag polar
C_D as a function of C_L.

Dynamic pressure
$\frac{1}{2}\rho V^2$.

Geostationary orbit
Equatorial orbit with a one-sidereal-day period.

Hohmann transfer
Two-burn elliptical transfer between circular orbits.

Induced drag
Drag caused by producing lift with a finite wing.

Mach number
Speed divided by the local speed of sound.

Neutral point
CG position giving neutral pitch stability.

Propulsive efficiency
Fraction of jet power that becomes useful thrust power.

Reynolds number
Ratio of inertial to viscous effects, $\rho V c/\mu$.

Rocket equation
$\Delta v = I_sp\ g_0 \ln(m_0/m_f)$.

Specific impulse
Thrust per weight flow of propellant, in seconds.

Stall
Loss of lift when flow separates from the wing.

Standard atmosphere
Average model of air properties versus altitude.

Static margin
Distance from CG to neutral point in mean chords.

Sustainable aviation fuel
Jet fuel made from wastes or biomass.

Self-assessment rubric

No grade or credit is given. Use this to judge honestly where you are in each unit.

Level	What it looks like
4 · Mastery	Sets up problems from forces and requirements, checks units and orders of magnitude, and explains trade-offs.
3 · Proficient	Solves the practice problems with occasional slips.
2 · Developing	Follows worked examples but struggles to choose the right equation.
1 · Beginning	Plugs in numbers without checking units or assumptions; revisit the unit.

Suggested weighting if you want a score

Part	Weight
Practice problems	25%
Labs	20%
Midterm practice set	25%
Final practice set	30%

Aim for level 3 or better in every unit before moving to the next course.

Related courses

- Calculus II MATH 111
- Engineering Graphics / CAD ENGR 120
- General Chemistry I + Lab CHEM 110 + CHEM 110L
- All courses