Last updated: November 1, 2026

🗺️ Four-year roadmap · Year 1, Fall

About this course

This free course has 9 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 engineering graphics and design courses such as MIT 2.007 and 2.00b, Purdue's engineering and computer graphics courses, Georgia Tech's ME 1770 and Embry-Riddle's engineering graphics sequence, using free tools: the Onshape Free plan and FreeCAD. We link to free materials throughout. None of these organizations endorse this page.
>
> What we add: every unit connects design choices to material, energy and waste, every number on the page is re-computed by a checking script before it goes live, and four hands-on labs take you from a sketch to a printed, lighter part.
>
> 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

Most of a product's material, energy and waste is locked in at the drawing board. Engineers who model and draw well can remove material that does no work, choose parts that last and can be repaired, and specify tolerances no tighter than needed.

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: 9 units and 4 labs (ENGR 120).
- 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 geometry and trigonometry.
- Comfort with a computer and a mouse; a three-button mouse helps for 3D.
- No drawing talent required: sketching is a skill you will practice.

How to study

- Sketch by hand before you model. Five minutes on paper saves an hour in CAD.
- Rebuild each worked example in CAD yourself.
- Name your sketches and features; future you will thank you.
- Check every drawing as if you had to make the part from it alone.
- Do every practice problem before opening the answer.
- Retake the quizzes a few days later. Spaced practice beats one long session.

What you need

- A computer with a web browser (Onshape runs in the browser; a free account is needed) or FreeCAD installed.
- Grid or isometric paper, a pencil, an eraser and a ruler.
- A caliper (a low-cost digital caliper is fine).
- Optional: access to a 3D printer at a library, school or makerspace.

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	Sketching & Visualization	Sketching, line types, scale	MIT 2.00b

Week	Unit	Topics	Reading
2	Orthographic & Isometric Projection	Orthographic projection; first and third angle	ASME Y14 conventions
3	Orthographic & Isometric Projection	Isometric drawing; true length	Onshape Learning Center
4	Section & Auxiliary Views	Section and auxiliary views	FreeCAD TechDraw
5	Dimensioning & GD&T Basics	Dimensioning rules; datums	ASME Y14.5
6	Dimensioning & GD&T Basics	GD&T: form, orientation, position; MMC	ASME Y14.5
7	Tolerances & Fits	Limits, ISO fits, stack-ups; midterm practice	ISO 286
8	Parametric 3D Modeling	Sketches, constraints, extrude and revolve	Onshape / FreeCAD
9	Parametric 3D Modeling	Features, variables, mass properties; Lab A	Onshape Learning Center
10	Assemblies & Drawings	Assemblies, mates, mechanisms	FreeCAD wiki
11	Assemblies & Drawings	Detail and assembly drawings, BOM; Lab B	FreeCAD TechDraw
12	3D Printing & Design for Manufacture	Manufacturing processes; DFM/DFA	MIT 2.007
13	3D Printing & Design for Manufacture	3D printing design and estimates; Lab C	NIST AM
14	Design for Sustainability & Lightweighting	Lightweighting and design for sustainability; Lab D	DOE; EPA
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

Sketching & Visualization

Freehand sketching as an engineering tool: lines, circles, proportion, and seeing 3D objects in your head.

Learning objectives

By the end of this unit you can:

- Sketch straight lines, circles and arcs freehand with good proportion.
- Use construction boxes to sketch objects in proportion.
- Read and sketch simple objects in oblique and isometric pictorial views.
- Explain the role of sketching in the design process.

Key concepts

- Engineers sketch to think, to explore many ideas fast and to communicate. A quick sketch costs minutes; a wrong CAD model can cost hours.
- Block in the overall size with a light construction box first, then add features, then darken the final lines.
- Proportion matters more than exact size in a sketch: estimate ratios such as width : height.
- Spatial visualization, the ability to rotate and slice objects mentally, is a skill that improves with practice.
- Line weights carry meaning: thick visible lines, thin hidden (dashed) lines, thin center lines (long-short dash).

Key equations

$$\text{scale} = \frac{\text{drawing size}}{\text{real size}}$$

```
scale= sizereal size
```

Drawing scale

$$\frac{w}{h} = \frac{w'}{h'}$$

```
w/h=(w')/(h')
```

Keep proportions when scaling

Worked examples, step by step

Example 1.1 A block is 120 mm wide and 80 mm tall. You sketch its width as 60 mm. How tall should the sketch be?

1. Scale = 60/120 = 0.5.
2. Height = 80 × 0.5.

Answer: 40 mm (a 1:2 sketch).

Example 1.2 A part is 450 mm long. Which standard scale fits it on a 250 mm drawing area: 1:1, 1:2 or 1:5?

1. 1:1 → 450 mm (too big).
2. 1:2 → 225 mm (fits).

Answer: 1:2, the largest scale that fits, so details stay readable.

Example 1.3 At scale 2:1, a 3 mm hole is drawn how large?

1. 3 × 2.

Answer: 6 mm on paper (dimensions still say the real 3 mm).

Practice problems

Work each on paper first, then check.

1. At 1:5, how long is a 1,200 mm beam on paper?

   240 mm.

2. A sketch is drawn at 1:2. A line measures 35 mm. What is the real length?

   70 mm.

3. Which line type shows a hidden edge?

   A thin dashed line.

Common misconceptions

Myth: Sketching is only for artists.

Actually: It is a learnable engineering skill that improves quickly with practice.

Myth: Dimensions on a scaled drawing show the drawn size.

Actually: They always show the real size.

Myth: Start with the details.

Actually: Block in the overall envelope first, then add details.

Flashcards

Construction lines

Light guide lines, erased or left faint.

Visible line

Thick, solid.

Hidden line

Thin, dashed.

Center line

Thin, long-short dash.

Scale

Drawing size ÷ real size.

Spatial visualization

Mentally rotating and slicing 3D objects.

Self-check quiz

1. A center line is drawn as...

thick solid

thin dashed

thin long-short dash

zigzag

thin long-short dash. Standard line convention.

2. At 1:2, a 100 mm part is drawn...

200 mm

50 mm

100 mm

25 mm

50 mm. Half size.

3. The first step in sketching an object is...

darken edges

block in a light construction box

add dimensions

shade it

block in a light construction box. Envelope first.

4. Hidden edges use...

dashed lines

thick lines

no lines

red lines

dashed lines. Thin dashed lines.

Try this quiz again

How this helps save the planet

The cheapest place to save material is in a sketch. Ideas such as fewer parts, standard fasteners and repairable joints are easy to explore on paper and expensive to change after tooling is made.

EPA's sustainable materials management approach looks at materials across their whole life cycle, starting with design.

On Saving Planets: Intro to Aerospace Engineering

Sources: EPA: Sustainable materials management basics (https://www.epa.gov/smm/sustainable-materials-management-basics) · MIT OpenCourseWare 2.00b: Toy Product Design (https://ocw.mit.edu/courses/2-00b-toy-product-design-spring-2008/)

Free learning resources

- MIT OpenCourseWare 2.00b: Toy Product Design (https://ocw.mit.edu/courses/2-00b-toy-product-design-spring-2008/): MIT's sketch-heavy product design course.
- MIT OpenCourseWare 2.007: Design and Manufacturing I (https://ocw.mit.edu/courses/2-007-design-and-manufacturing-i-spring-2009/): Design and manufacturing at MIT.

- [ ] **I finished this unit**

Orthographic & Isometric Projection

The language of technical drawing: multiview (orthographic) projection and isometric pictorials.

Learning objectives

By the end of this unit you can:

- Create front, top and right-side views with correct alignment.
- Know first-angle and third-angle projection symbols.
- Draw isometric views of simple parts.
- Find true length and foreshortening.

Key concepts

- Orthographic projection shows an object with parallel projectors perpendicular to each view plane. Three views (front, top, right) usually describe a part fully.
- Third-angle projection (U.S., ASME) places the top view above the front view; first-angle (much of Europe and Asia, ISO) places it below. A symbol in the title block says which.
- Views stay aligned: width is shared by front and top, height by front and side, depth by top and side.
- An isometric view tilts the object so its three axes are 120° apart. Edges along the axes are foreshortened by √(2/3) ≈ 0.816; an isometric drawing ignores that and draws them full length.
- A line shows its true length only in a view parallel to it.

Key equations

$$k = \sqrt{2/3} \approx 0.816$$

`k=2/3≈0.816`

Isometric foreshortening factor

$$L_{true} = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$$

`L_true=Δ x^2+Δ y^2+Δ z^2`

True length of an edge from coordinates

Worked examples, step by step

Example 2.1 A cube edge is 100 mm. How long is it in a true isometric projection, and in an isometric drawing?

1. Projection: 100 × 0.816.
2. Drawing: full size by convention.

Answer: 81.6 mm in projection; 100 mm in an isometric drawing.

Example 2.2 An edge runs from (0, 0, 0) to (30, 40, 0) mm. What is its true length, and in which view does it appear true length?

1. $\sqrt{(30^2 + 40^2)} = 50$.

Answer: 50 mm; true length in the view looking along z (it lies in the x–y plane).

Example 2.3 An edge runs from (0, 0, 0) to (20, 20, 10). Find its true length.

1. $\sqrt{(400 + 400 + 100)} = \sqrt{900}$.

Answer: 30 mm. No principal view shows it true length; you need an auxiliary view (Unit 3).

Practice problems

Work each on paper first, then check.

1. In third-angle projection, where is the right-side view placed?

   To the right of the front view.

2. Which two views share the depth dimension?

   Top and side.

3. Find the true length of an edge from (0, 0, 0) to (12, 16, 0).

   20.

4. In a true isometric projection, how long does a 50 mm edge along an axis appear?

   ≈ 40.8 mm.

Common misconceptions

Myth: Isometric drawings are drawn at 81.6%.

Actually: Isometric drawings use full length; only isometric projection is foreshortened.

Myth: First- and third-angle are just different styles.

Actually: They swap view positions; misreading the symbol mirrors the part.

Myth: More views are always better.

Actually: Use the fewest views that fully describe the part.

Flashcards

Orthographic projection

Parallel, perpendicular projectors; multiple views.

Third-angle

Top above front (U.S.).

First-angle

Top below front (ISO in much of the world).

Isometric

Axes 120° apart.

Foreshortening

Edge appears shorter than true length.

True length

Seen only in a parallel view.

Self-check quiz

1. In third-angle projection the top view is...

below the front view

above the front view

left of the front view

not used

above the front view. ASME convention.

2. Isometric axes are separated by...

90°

120°

45°

60°

120°. Equal angles.

3. Isometric foreshortening factor ≈

0.5

0.707

0.816

1

0.816. √(2/3).

4. Front and top views share…

height

width

depth

nothing

width. They are aligned vertically.

Try this quiz again

How this helps save the planet

Clear drawings prevent scrap. A misread projection symbol can produce a mirror-image part, and every scrapped part wastes the material and energy that went into it.

International standards for projection and tolerancing let one drawing be made correctly anywhere, so parts can be sourced locally and replacement parts can be made to fit.

On Saving Planets: Calculus I

Sources: ASME Y14.5: Dimensioning and Tolerancing (https://www.asme.org/codes-standards/find-codes-standards/y14-5-dimensioning-tolerancing) · EPA: Sustainable materials management basics (https://www.epa.gov/smm/sustainable-materials-management-basics)

Free learning resources

- Onshape Learning Center (https://learn.onshape.com/): Drawing and modeling courses.
- ASME Y14.5: Dimensioning and Tolerancing (https://www.asme.org/codes-standards/find-codes-standards/y14-5-dimensioning-tolerancing): The U.S. drawing standard.

- [ ] **I finished this unit**

Section & Auxiliary Views

Cut parts open to show their insides, and rotate the view to see slanted faces at true size.

Learning objectives

By the end of this unit you can:

- Draw full, half, offset and broken-out sections with hatching.
- Apply section conventions (ribs, shafts and fasteners not hatched lengthwise).
- Construct a primary auxiliary view of an inclined surface.
- Find true size and true length.

Key concepts

- A section view imagines a cutting plane slicing the part; the removed half lets interior features show as visible lines instead of confusing hidden lines.
- Cut material is hatched with thin lines, typically at 45°. Thin ribs, shafts, bolts and pins cut along their length are conventionally not hatched.
- A cutting-plane line with arrows and letters (A–A) shows where the cut is and which way you look.
- An inclined surface is foreshortened in the principal views. An auxiliary view projects onto a plane parallel to it, showing its true size.
- Inclined length = √(horizontal² + vertical²) in the view where it appears as an edge.

Key equations

$$L = \sqrt{a^2 + b^2}$$

L=^2+b^2

True length of an inclined edge

$$A_{true} = \frac{A_{proj}}{\cos\theta}$$

A_true=_projθ

True area of a face tilted θ from the view plane

Worked examples, step by step

Example 3.1 An inclined face appears as an edge in the front view, rising 30 mm over 40 mm. The part is 25 mm deep. Find the face’s true size.

1. Edge length = √(30² + 40²) = 50 mm.

2. True size = 50 × 25.

Answer: 50 mm × 25 mm = 1,250 mm².

Example 3.2 That face is projected in the top view. What area does it appear to have there?

1. Top view sees the 40 mm horizontal run × 25 mm.

Answer: 1,000 mm², which is 1,250 × cos θ with cos θ = 40/50 = 0.8.

Example 3.3 A tube is 40 mm outside diameter with 3 mm walls. In a full section, how wide is each hatched band?

1. Wall thickness = 3 mm on each side.
2. Inner diameter = 40 − 6 = 34 mm.

Answer: Two 3 mm hatched bands, with a 34 mm open bore between them.

Practice problems

Work each on paper first, then check.

1. Why are ribs not hatched when cut lengthwise?

   Hatching would make a thin rib look like a solid mass and misrepresent the part.

2. A face rises 5 mm over 12 mm. True length of its edge?

   13 mm.

3. A 60 mm-long face is tilted so cos θ = 0.6 in the top view. What length does the top view show?

   36 mm.

Common misconceptions

Myth: Sections show hidden lines too.
Actually: Normally hidden lines are omitted in sections.

Myth: Auxiliary views must show the whole part.
Actually: Partial auxiliary views showing just the inclined feature are standard.

Myth: Every cut surface is hatched.

Actually: Ribs, shafts and fasteners cut lengthwise are conventionally left unhatched.

Flashcards

Section view

Imaginary cut to show the interior.

Cutting-plane line

Thick line with arrows and letters.

Hatching

Thin lines on cut material.

Half section

Quarter removed; half shows inside.

Auxiliary view

View parallel to an inclined face.

True size

Undistorted shape and area.

Self-check quiz

1. Hatching shows...

hidden edges

cut material

threads

surface finish

cut material. Material the cutting plane passes through.

2. An auxiliary view is parallel to...

the front view

the inclined surface

the floor

the title block

the inclined surface. So it shows true size.

3. A half section shows...

half the part removed

one quarter removed

only the outside

a rotated view

one quarter removed. Inside and outside at once for symmetric parts.

4. True length of an edge rising 9 over 12 is...

21

15

10.5

3

15. √(81 + 144).

Try this quiz again

How this helps save the planet

Sections are how designers check wall thicknesses, and thinner walls where loads allow mean less material. That is lightweighting at the drawing board (Unit 9).

DOE reports that replacing heavy steel parts with lighter materials can cut component weight by 10–60% in the short term.

On Saving Planets: Physics I

Sources: U.S. DOE: Lightweight materials for cars and trucks (https://www.energy.gov/eere/vehicles/lightweight-materials-cars-and-trucks) · ASME Y14.5: Dimensioning and Tolerancing (https://www.asme.org/codes-standards/find-codes-standards/y14-5-dimensioning-tolerancing)

Free learning resources

- FreeCAD wiki: Getting started (https://wiki.freecad.org/Getting_started): FreeCAD TechDraw sections.
- Onshape Learning Center (https://learn.onshape.com/): Onshape drawing courses.

- [ ] **I finished this unit**

Dimensioning & GD&T Basics

Say exactly what size and shape a part must be: dimensioning rules, datums and geometric tolerances.

Learning objectives

By the end of this unit you can:

- Dimension parts clearly following ASME Y14.5 conventions.
- Choose datums based on function.
- Read feature control frames for flatness, perpendicularity, position and profile.
- Compute position error and bonus tolerance at MMC.

Key concepts

- Every feature is dimensioned once, in the view that shows it best, without redundant or chained dimensions that stack up errors.
- Geometric dimensioning and tolerancing (GD&T), standardized in ASME Y14.5 (current edition 2018), controls form, orientation, location and profile relative to datums, the reference surfaces that mate in assembly.
- A feature control frame reads: symbol | tolerance (with Ø for a cylindrical zone) | modifier | datums, e.g. ⌖ Ø0.1 Ⓜ A B C.
- Position error of a hole = 2√(Δx² + Δy²); it must lie within the cylindrical tolerance zone.
- At maximum material condition (MMC), a hole gets a bonus: as it departs from MMC (gets bigger), its allowed position tolerance grows by the same amount.

Key equations

$$\varnothing_{pos} = 2\sqrt{\Delta x^2 + \Delta y^2}$$

```
_pos=2Δ x^2+Δ y^2
```

Measured position error (diameter)

$$t_{allowed} = t_{MMC} + (d_{actual} - d_{MMC})$$

```
t_allowed=t_MMC+(d_actual-d_MMC)
```

Bonus tolerance for a hole at MMC

Worked examples, step by step

Example 4.1 A hole should be at (50, 30). It measures (50.03, 29.98). Position tolerance is Ø0.1. Does it pass?

1. $\Delta x = 0.03$, $\Delta y = 0.02$.
2. $\text{Ø} = 2\sqrt{(0.0009 + 0.0004)} = 0.072$.

Answer: Ø0.072 ≤ Ø0.1: passes.

Example 4.2 The hole is Ø10.0–10.2 with position Ø0.1 at MMC. It measures Ø10.15. What position tolerance is allowed?

1. MMC of a hole = smallest size = 10.0.
2. Bonus = 10.15 − 10.0 = 0.15.
3. Allowed = 0.1 + 0.15.

Answer: Ø0.25.

Example 4.3 Three chained dimensions of 20 ± 0.1 each locate a feature. What is the worst-case variation of the total?

1. Tolerances add: 3 × 0.1.

Answer: ± 0.3 mm. Dimensioning each from one datum would hold it to ± 0.1.

Practice problems

Work each on paper first, then check.

1. A hole measures 0.04 off in x and 0.03 off in y. Position error?

   Ø0.10.

2. With Ø0.1 at MMC, a Ø10.0–10.2 hole measured at Ø10.05 is allowed what position tolerance?

   Ø0.15.

3. What does a datum represent?

   A theoretically exact reference, usually where the part mates or is fixtured.

Common misconceptions

Myth: Position error equals the distance off.

Actually: The tolerance zone is a diameter, so error = 2 × the radial offset.

Myth: Tighter tolerances always make better parts.

Actually: They raise cost and scrap; tolerance only what function needs.

Myth: MMC of a hole is its largest size.

Actually: Maximum material for a hole is the smallest hole.

Flashcards

GD&T

Geometric dimensioning and tolerancing.

Datum

Exact reference feature.

Feature control frame

Symbol | tolerance | modifiers | datums.

Position

Location tolerance, usually a diameter zone.

MMC

Maximum material condition.

Bonus tolerance

Extra tolerance as a feature departs from MMC.

Self-check quiz

1. ASME Y14.5 covers...

welding

dimensioning and tolerancing

electrical symbols

materials

dimensioning and tolerancing. The GD&T standard.

2. A hole 0.03 and 0.04 off has position error...

Ø0.05

Ø0.07

Ø0.10

Ø0.14

Ø0.10. 2 × 0.05.

3. MMC of a shaft is...

smallest size

largest size

nominal

zero

largest size. Most material.

4. Chained dimensions...

reduce error

stack up tolerances

are required

remove datums

stack up tolerances. Errors add along the chain.

Try this quiz again

How this helps save the planet

Tolerancing well is a waste-reduction tool. Functional GD&T and MMC bonus tolerance accept parts that will assemble and work, instead of scrapping them over arbitrary tight numbers.

NIST works on model-based definition, putting tolerances directly in the 3D model so they are read correctly by machines and inspectors, which reduces errors and rework.

On Saving Planets: Intro to Aerospace Engineering

Sources: ASME Y14.5: Dimensioning and Tolerancing (https://www.asme.org/codes-standards/find-codes-standards/y14-5-dimensioning-tolerancing) · NIST: Model-based enterprise and PMI testing (https://www.nist.gov/el/systems-integration-division-73400/mbe-pmi-validation-and-conformance-testing)

Free learning resources

- ASME Y14.5: Dimensioning and Tolerancing (https://www.asme.org/codes-standards/find-codes-standards/y14-5-dimensioning-tolerancing): The standard.
- NIST: Model-based enterprise and PMI testing (https://www.nist.gov/el/systems-integration-division-73400/mbe-pmi-validation-and-conformance-testing): Tolerances in 3D models.

☐ **I finished this unit**

Tolerances & Fits

How much size variation parts can have and still fit together: limits, ISO fits, and tolerance stack-ups.

Learning objectives

By the end of this unit you can:

- Compute limits, clearance and interference.
- Read ISO hole-basis fits such as H7/g6 and H7/p6.
- Do worst-case and root-sum-square (RSS) stack-ups.
- Choose a fit for a function.

Key concepts

- Limits are the largest and smallest allowed sizes. Tolerance = upper limit − lower limit.
- Clearance fits always leave a gap; interference fits always overlap (pressed together); transition fits may do either.
- ISO 286 codes fits as hole letter/number over shaft letter/number. H holes start at the nominal size; the number is the IT grade. For sizes 18–30 mm, IT7 = 21 µm and IT6 = 13 µm.
- Worst-case stack-up adds all tolerances; RSS assumes independent random variation: $\sqrt{(\Sigma t_i^2)}$, smaller and more realistic for many parts.

Key equations

$$c_{\max} = H_{\max} - s_{\min}, \quad c_{\min} = H_{\min} - s_{\max}$$

`c_=H_-s_, c_=H_-s_`

Clearance limits

$$T_{wc} = \sum t_i$$

`T_wc= t_i`

Worst-case stack

$$T_{RSS} = \sqrt{\sum t_i^2}$$

`T_RSS= t_i^2`

Root-sum-square stack

Worked examples, step by step

Example 5.1 A Ø25 H7/g6 fit: hole 25.000–25.021, shaft 24.980–24.993. Find the clearance range.

1. c_min = 25.000 − 24.993 = 0.007.
2. c_max = 25.021 − 24.980 = 0.041.

Answer: Clearance 0.007–0.041 mm: a precise sliding fit.

Example 5.2 A Ø25 H7/p6 fit: hole 25.000–25.021, shaft 25.022–25.035. Find the fit.

1. Smallest overlap = 25.022 − 25.021 = 0.001.
2. Largest = 25.035 − 25.000 = 0.035.

Answer: Interference 0.001–0.035 mm: a press fit.

Example 5.3 Parts of 20 ± 0.10, 30 ± 0.05 and 10 ± 0.05 mm stack. Find worst-case and RSS tolerance.

1. Worst case: 0.10 + 0.05 + 0.05 = 0.20.
2. RSS: √(0.01 + 0.0025 + 0.0025) = 0.122.

Answer: 60 ± 0.20 mm worst case; 60 ± 0.12 mm RSS.

Practice problems

Work each on paper first, then check.

1. A hole is 12.000–12.018 and a shaft 11.984–11.995. Clearance range?

   0.005–0.034 mm.

2. What is the tolerance of the H7 hole above?

   0.021 mm = 21 µm.

3. Four parts each ± 0.05: worst-case and RSS?

   ± 0.20 and ± 0.10.

Common misconceptions

Myth: RSS is always safe.

Actually: It assumes independent, centered variation; for safety-critical fits use worst case.

Myth: Interference fits need no calculation.

Actually: Too much interference can crack parts; compute the range.

Myth: The tolerance number is in millimeters.

Actually: IT grades map to micrometer values that depend on size.

Flashcards

Limits

Largest and smallest allowed sizes.

Clearance fit

Always a gap.

Interference fit

Always overlap.

Transition fit

Gap or overlap.

Worst-case stack

Σt_i.

RSS stack

$\sqrt{\Sigma t_i^2}$.

Self-check quiz

1. H7/g6 is a...

press fit

clearance fit

transition fit

thread

clearance fit. g shafts are below the H hole.

2. RSS for ±0.3 and ±0.4 is...

±0.7

±0.5

±0.35

±0.1

±0.5. √(0.09 + 0.16).

3. IT7 for 18–30 mm sizes is…

7 µm

13 µm

21 µm

0.7 mm

21 µm. ISO 286 table.

4. An H hole's lower limit is…

above nominal

exactly nominal

below nominal

random

exactly nominal. Hole-basis system.

Try this quiz again

How this helps save the planet

Good fits make products repairable: standard ISO fits let bearings, pins and bushings be replaced with off-the-shelf parts years later, keeping a machine in service instead of in a landfill.

Choosing RSS where appropriate allows looser individual tolerances, which means cheaper processes and less scrap for the same assembly quality.

On Saving Planets: Calculus II

Sources: ISO 286-1: ISO code system for tolerances and fits (https://www.iso.org/standard/45975.html) · EPA: Sustainable materials management basics (https://www.epa.gov/smm/sustainable-materials-management-basics)

Free learning resources

- ISO 286-1: ISO code system for tolerances and fits (https://www.iso.org/standard/45975.html): The ISO fit system.
- MIT OpenCourseWare 2.007: Design and Manufacturing I (https://ocw.mit.edu/courses/2-007-design-and-manufacturing-i-spring-2009/): Fits in machine design.

- [ ] **I finished this unit**

Parametric 3D Modeling

Build solid models from constrained sketches and features in Onshape or FreeCAD, and make them easy to change.

Learning objectives

By the end of this unit you can:

- Create fully constrained 2D sketches.
- Use extrude, revolve, fillet, chamfer, hole, shell and pattern features.
- Drive models with variables and equations (design intent).
- Compute mass properties and use them in design.

Key concepts

- A parametric model is a recipe: sketches plus features in a history tree. Change a dimension and the model rebuilds.
- A sketch is fully constrained when geometric constraints (parallel, tangent, coincident) and dimensions fix every degree of freedom. Each free 2D point has 2 degrees of freedom.
- Design intent: dimension the way the part functions. If holes must stay centered, constrain them to the midpoint, not to an edge.
- Variables (Onshape) and spreadsheets or expressions (FreeCAD) let one number drive many features.
- CAD computes volume, mass, center of mass and moments of inertia from the material density.

Key equations

$$m = \rho V$$

`m=ρ V`

Mass from volume

$$\mathrm{DOF}_{sketch} = 2n_{pts} - \sum \text{constraints}$$

`DOF_sketch=2n_pts-`

Sketch degrees of freedom (points only)

$$V_{rev} = 2\pi \bar{r} A$$

`V_rev=2π r A`

Pappus: volume of revolution

Worked examples, step by step

Example 6.1 An aluminum plate is 100 × 60 × 5 mm with four Ø6 through holes. Find its mass (ρ = 2.70 g/cm³).

1. V = 100 × 60 × 5 − 4 × π × 3² × 5 = 30,000 − 565.5 = 29,434.5 mm³.
2. m = 29.43 cm³ × 2.70.

Answer: ≈ 79.5 g.

Example 6.2 A rectangle drawn with the rectangle tool has 4 corner points (8 DOF) and comes with 2 horizontal and 2 vertical constraints. How many more dimensions or constraints fully constrain it?

1. 8 − 4 = 4 DOF remain: width, height, and x and y position.
2. Add width and height, then make one corner coincident with the origin (removes 2).

Answer: 4 more: two dimensions plus two for position (e.g. a corner coincident with the origin).

Example 6.3 A ring is made by revolving a 10 × 4 mm rectangle whose centroid is 25 mm from the axis. Find its volume.

1. A = 40 mm².
2. V = 2π × 25 × 40.

Answer: ≈ 6,283 mm³ (6.28 cm³).

Practice problems

Work each on paper first, then check.

1. A steel block 50 × 50 × 20 mm (ρ = 7.85 g/cm³). Mass?

   50 cm³ × 7.85 ≈ 392.5 g.

2. Why fully constrain sketches?

   So changes rebuild predictably; under-constrained sketches shift when edited.

3. A PLA cube 20 mm on a side, solid (ρ = 1.24 g/cm³). Mass?

   8 cm³ × 1.24 ≈ 9.9 g.

Common misconceptions

Myth: A model that looks right is right.

Actually: Check for under-constrained sketches and fragile references; they break on edits.

Myth: Dimension from whatever edge is handy.

Actually: Dimension from functional datums to capture intent.

Myth: Mass properties are exact.

Actually: Only as good as the density and model you enter.

Flashcards

Parametric model

Features driven by editable dimensions.

Constraint

Geometric relationship, e.g. tangent.

Design intent

Model behaves as the function requires.

Feature

Extrude, revolve, fillet, hole, pattern...

History tree

Ordered list of features.

Mass properties

Volume, mass, center of mass, inertia.

Self-check quiz

1. A fully constrained sketch has...

no dimensions

zero remaining DOF

only constraints

only dimensions

zero remaining DOF. Every DOF fixed.

2. The history tree records…

emails

the sequence of features

materials only

render settings

the sequence of features. The parametric recipe.

3. Revolving area A at centroid radius r̄ gives volume…

$\pi \bar{r} A$

$2\pi \bar{r} A$

$\bar{r} A$

$2\pi A$

$2\pi \bar{r} A$. Pappus's theorem.

4. Onshape runs…

only on Linux

in a web browser

only offline

on phones only

in a web browser. Cloud-native CAD.

Try this quiz again

How this helps save the planet

Parametric models make it cheap to try lighter versions: change a wall thickness variable and the whole part updates, with its new mass. That turns lightweighting from guesswork into a quick

study (Lab D).

Onshape's Free plan and FreeCAD put professional modeling in anyone's hands, so open-source designs for repair parts and appropriate technology can be shared and improved.

On Saving Planets: Intro to Aerospace Engineering

Sources: Onshape Free plan (https://www.onshape.com/en/products/free) · FreeCAD (free, open source) (https://www.freecad.org/)

Free learning resources

- Onshape Learning Center (https://learn.onshape.com/): Free self-paced modeling courses.
- FreeCAD wiki: Getting started (https://wiki.freecad.org/Getting_started): FreeCAD Part Design basics.
- Onshape Free plan (https://www.onshape.com/en/products/free): Sign up for the Free plan.

- [ ] **I finished this unit**

Assemblies & Drawings

Put parts together with mates, check motion and interference, and produce drawings someone can build from.

Learning objectives

By the end of this unit you can:

- Assemble parts with mates (fastened, revolute, slider) and count degrees of freedom.
- Check interference and clearance.
- Produce detail and assembly drawings with a title block, bill of materials and balloons.
- Use Gruebler’s equation for planar mechanisms.

Key concepts

- A free rigid body has 6 degrees of freedom (3 translations, 3 rotations). A revolute mate leaves 1; a slider leaves 1; a fastened mate leaves 0.
- Bottom-up assembly inserts finished parts; top-down designs parts in context of the assembly.
- A planar mechanism’s mobility is M = 3(n − 1) − 2j_1 − j_2 (Gruebler), with n links including ground, j_1 full joints and j_2 half joints.
- Drawings come from the model: views, sections, dimensions and notes, a title block (part, material, scale, projection symbol, units, tolerances) and, for assemblies, a bill of materials (BOM) with balloons.
- Interference checks catch parts that overlap before anything is made.

Key equations

$$M = 3(n-1) - 2j_1 - j_2$$

`M=3(n-1)-2j_1-j_2`

Gruebler’s equation (planar)

$$\text{DOF}_{3D} = 6 - \text{removed}$$

`DOF_3D=6-removed`

Remaining DOF of a mated part

Worked examples, step by step

Example 7.1 Find the mobility of a four-bar linkage (4 links including ground, 4 pin joints).

1. $M = 3(4 - 1) - 2(4) = 9 - 8$.

Answer: M = 1: one input drives it.

Example 7.2 A slider-crank: ground, crank, connecting rod, slider; 3 pins and 1 slider joint.

1. $n = 4$, $j_1 = 4$ (pins and slider are full joints).
2. $M = 9 - 8$.

Answer: M = 1, as in an engine.

Example 7.3 A BOM lists 4 × M5 screws at 1.2 g, 1 plate at 79.5 g and 2 brackets at 15.0 g. Total assembly mass?

1. 4.8 + 79.5 + 30.0.

Answer: 114.3 g.

Practice problems

Work each on paper first, then check.

1. Mobility of 5 links, 5 pins?

   $M = 12 - 10 = 2$.

2. Mobility of 3 links, 3 pins?

   $M = 6 - 6 = 0$: a rigid structure (a triangle).

3. What must every title block state?

   Part name/number, material, scale, units, projection method, general tolerances, author and revision.

Common misconceptions

Myth: More mates are safer.

Actually: Redundant mates over-constrain and can fail to solve or hide errors.

Myth: Assembly drawings need every dimension.

Actually: Detail drawings carry part dimensions; assembly drawings show how parts go together.

Myth: If the model fits, the real parts will.

Actually: Only if tolerances are checked (Unit 5).

Flashcards

Mate

Relationship that positions parts.

Revolute

Pin joint; 1 rotational DOF.

Gruebler

$M = 3(n - 1) - 2j_1 - j_2$.

BOM

Bill of materials.

Balloon

Numbered callout linking a part to the BOM.

Title block

Drawing's identity, scale, units and tolerances.

Self-check quiz

1. A free rigid body in 3D has...

3 DOF

6 DOF

1 DOF

12 DOF

6 DOF. 3 translations, 3 rotations.

2. A four-bar linkage has mobility...

0

1

2

3

1. Gruebler.

3. A BOM lists...

tolerances

parts and quantities

colors only

mates

parts and quantities. Bill of materials.

4. A revolute mate leaves...

0 DOF

1 DOF

2 DOF

6 DOF

1 DOF. One rotation.

Try this quiz again

How this helps save the planet

A clear assembly drawing and BOM are a repair manual. Designs that use standard fasteners and can be taken apart are easier to fix, refurbish and recycle, which is a core idea of sustainable materials management.

Counting parts in the BOM is also a design-for-assembly check: fewer parts usually means less material, less energy and fewer failures.

On Saving Planets: Physics I

Sources: EPA: Sustainable materials management basics (https://www.epa.gov/smm/sustainable-materials-management-basics) · FreeCAD wiki: Getting started (https://wiki.freecad.org/Getting_started)

Free learning resources

- FreeCAD wiki: Getting started (https://wiki.freecad.org/Getting_started): FreeCAD assemblies and TechDraw.
- Onshape Learning Center (https://learn.onshape.com/): Onshape assemblies and drawings.
- MIT OpenCourseWare 2.007: Design and Manufacturing I (https://ocw.mit.edu/courses/2-007-design-and-manufacturing-i-spring-2009/): Mechanisms in MIT 2.007.

- [ ] **I finished this unit**

3D Printing & Design for Manufacture

How parts are actually made, and how to design them so they are easy, cheap and low-waste to make, including 3D printing.

Learning objectives

By the end of this unit you can:

- Describe additive (3D printing), subtractive (machining) and forming processes.
- Design for FDM printing: overhangs, supports, wall thickness, orientation.
- Estimate print mass, filament length and time.
- Apply design-for-manufacture and assembly (DFM/DFA) rules.

Key concepts

- Additive manufacturing builds parts layer by layer; NIST works on measurement science and standards to make AM parts reliable. Machining removes material; molding and casting shape it.
- Fused-filament (FDM) printing: overhangs steeper than about 45° from vertical usually need supports; orient parts so loads do not pull layers apart, because layer bonds are the weak direction.
- Infill (often 10–20%) and a few perimeter walls make prints light; solid prints waste material and time.
- Filament length per gram = 1/(ρπr²). For 1.75 mm PLA (ρ = 1.24 g/cm³) that is about 33.5 cm per gram.
- DFM/DFA: fewer parts, standard features and fasteners, generous radii, self-locating features, and avoiding needlessly tight tolerances.

Key equations

$$\ell = \frac{m}{\rho \, \pi r^2}$$

```
=(m)/(ρ π r^2)
```

Filament length for a print of mass m

$$t \approx \frac{V}{w \, h \, v}$$

Print time from volume, line width w, layer height h and speed v

Worked examples, step by step

Example 8.1 How much 1.75 mm PLA filament does a 10 g print use?

1. Cross-section $\pi(0.0875\ \text{cm})^2 = 0.02405\ \text{cm}^2$.
2. Length per gram = $1/(1.24 \times 0.02405) = 33.5$ cm.
3. × 10.

Answer: ≈ 3.35 m.

Example 8.2 Estimate print time for 10 g of PLA with a 0.4 mm line, 0.2 mm layers at 50 mm/s.

1. $V = 10/1.24 = 8.065\ \text{cm}^3 = 8{,}065\ \text{mm}^3$.
2. Rate = $0.4 \times 0.2 \times 50 = 4\ \text{mm}^3/\text{s}$.
3. t = 8,065/4 = 2,016 s.

Answer: ≈ 34 minutes of extrusion (real prints take longer due to travel moves).

Example 8.3 A 20 mm solid PLA cube weighs 9.9 g. At about 15% infill with walls, it weighs about 3.5 g. What fraction of material is saved?

1. (9.9 − 3.5)/9.9.

Answer: ≈ 65% less plastic (sample estimate; your slicer reports the real figure).

Practice problems

Work each on paper first, then check.

1. How many grams is 1 m of 1.75 mm PLA?

   100/33.5 ≈ 2.98 g.

2. Why print a bracket so layers run along the load path?

   Layer bonds are weaker than the extruded lines.

3. Name two DFA rules.

   Reduce part count; use self-locating features and standard fasteners.

Common misconceptions

Myth: 3D printing is always greener.

Actually: It can save material, but energy, failed prints and non-recycled waste matter; compare per part.

Myth: Prints are as strong in every direction.

Actually: FDM parts are weakest between layers.

Myth: 100% infill is strongest so always best.

Actually: Walls carry most bending load; extra infill adds mass and time with little benefit.

Flashcards

Additive manufacturing

Layer-by-layer building.

FDM

Fused-filament 3D printing.

Infill

Internal lattice percentage.

Support

Temporary structure under overhangs.

DFM

Design for manufacture.

DFA

Design for assembly.

Self-check quiz

1. FDM parts are weakest...

along the filament

between layers

at the surface

nowhere

between layers. Layer adhesion.

2. Overhangs beyond about 45° usually need...

supports

more infill

faster speed

paint

supports. Nothing to print onto.

3. Filament per gram for 1.75 mm PLA ≈

3.4 cm

33.5 cm

3.35 m

335 m

33.5 cm. $1/(\rho\pi r^2)$.

4. A key DFA rule is…

add parts

reduce part count

tighten all tolerances

use custom screws

reduce part count. Fewer parts, fewer steps.

Try this quiz again

How this helps save the planet

Plastics are a large waste stream: EPA reports that U.S. plastics generation was 35.7 million tons in 2018, 12.2% of municipal solid waste, and only 8.7% was recycled. Designing prints with low infill, few supports and fewer failed attempts directly cuts that waste.

Additive manufacturing can place material only where loads need it, enabling lighter parts; NIST's work aims to make those parts reliable enough for demanding uses.

On Saving Planets: Intro to Aerospace Engineering

Sources: EPA: Plastics, material-specific data (https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data) · NIST: Additive manufacturing (https://www.nist.gov/additive-manufacturing)

Free learning resources

- NIST: Additive manufacturing (https://www.nist.gov/additive-manufacturing): Standards and measurement for 3D printing.
- MIT OpenCourseWare 2.007: Design and Manufacturing I (https://ocw.mit.edu/courses/2-007-design-and-manufacturing-i-spring-2009/): Manufacturing processes.
- EPA: Plastics, material-specific data (https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data): Plastics data.

☐ **I finished this unit**

Design for Sustainability & Lightweighting

Use your CAD skills to make parts lighter, longer-lasting and easier to repair and recycle, and estimate the payoff.

Learning objectives

By the end of this unit you can:

- Compare sections by mass and stiffness (second moment of area).
- Estimate fuel and CO_2 savings from vehicle lightweighting.
- Apply design-for-repair, disassembly and recycling principles.
- Choose materials with their whole life cycle in mind.

Key concepts

- Bending stiffness depends on EI. Moving material away from the neutral axis (tubes, I-beams) raises I with less mass.
- DOE reports that a 10% reduction in vehicle weight can improve fuel economy by 6–8%, and that lightweight materials can reduce component weight by 10–60% in the short term.
- EPA reports that every gallon of gasoline burned creates about 8,887 g of CO_2 (about 2.35 kg per liter).
- Design for disassembly: screws over glue, single materials where possible, and labeled plastics.
- Lightest is not always greenest: compare materials over the life cycle, including production energy and recyclability.

Key equations

$$I_{rect} = \frac{bh^3}{12}, \quad I_{tube} = \frac{B^4 - b^4}{12}$$

```
I_rect=(bh^3)/(12), I_tube=(B^4-b^4)/(12)
```

Second moment of area: solid and square tube

$$\Delta \mathrm{CO_2} = \Delta \mathrm{fuel} \times 2.35\ \mathrm{kg/L}$$

```
ΔCO_2=Δfuel×2.35\ kg/L
```

CO_2 from gasoline saved

Worked examples, step by step

Example 9.1 Compare a solid 20 × 20 mm square bar with a 25 × 25 mm square tube with 2 mm walls: area (mass) and I.

1. Bar: $A = 400\ mm^2$, $I = 20^4/12 = 13{,}333\ mm^4$.
2. Tube: $A = 625 - 441 = 184\ mm^2$, $I = (25^4 - 21^4)/12 = 16{,}345\ mm^4$.

Answer: The tube uses 54% less material and is 23% stiffer in bending.

Example 9.2 A 1,500 kg car is lightened by 10% (150 kg). It uses 8 L/100 km and drives 15,000 km a year. Using DOE's 6–8%, estimate the fuel saved per year.

1. Yearly fuel = 15,000/100 × 8 = 1,200 L.
2. 6%: 72 L; 8%: 96 L.

Answer: About 72–96 L per year.

Example 9.3 Convert that to CO_2 with EPA's 8,887 g per gallon.

1. 8.887 kg / 3.785 L = 2.35 kg/L.
2. 72 × 2.35 = 169; 96 × 2.35 = 225.

Answer: ≈ 170–225 kg of CO_2 per car per year (a simplified estimate).

Practice problems

Work each on paper first, then check.

1. I of a solid 10 × 30 mm bar bending about its 10 mm-wide axis (h = 30)?

   $10 \times 30^3/12 = 22{,}500\ mm^4$.

2. Same bar turned flat (h = 10, b = 30)?

   $30 \times 10^3/12 = 2{,}500\ mm^4$: 9 times less stiff.

3. How many liters of gasoline make 1 tonne of CO_2?

   1,000/2.35 ≈ 426 L.

Common misconceptions

Myth: Lighter always means greener.

Actually: Some light materials need much more energy to produce; judge over the life cycle.

Myth: Stiffness depends only on the amount of material.

Actually: Where the material sits (I) matters more.

Myth: Glue makes products better.

Actually: It often blocks repair and recycling.

Flashcards

Second moment of area

I; geometric bending stiffness.

Lightweighting

Removing mass without losing function.

DOE rule

10% lighter → 6–8% better fuel economy.

Gasoline CO_2

≈ 8,887 g/gal ≈ 2.35 kg/L.

Design for disassembly

Easy to take apart for repair and recycling.

Life cycle

Materials, making, use and end of life.

Self-check quiz

1. Bending stiffness depends on...

E only

EI

mass only

color

EI. Modulus × second moment of area.

2. DOE: 10% lighter vehicle → fuel economy improves...

1–2%

6–8%

20–30%

50%

6–8%. DOE figure.

3. A gallon of gasoline burned makes about…

889 g CO_2

8,887 g CO_2

88 kg CO_2

2 g CO_2

8,887 g CO_2. EPA figure.

4. A design-for-disassembly choice is…

adhesive everywhere

screws and single materials

mixed laminated plastics

welded covers

screws and single materials. Easier repair and recycling.

Try this quiz again

How this helps save the planet

Lightweighting is one of the most direct climate tools a CAD user has. DOE reports that a 10% lighter vehicle can get 6–8% better fuel economy, and EPA puts every gallon of gasoline at about 8,887 g of CO_2.

Designing for repair and recycling keeps materials in use; EPA describes sustainable materials management as a systematic approach to using and reusing materials more productively over their entire life cycles.

On Saving Planets: Physics I

Sources: U.S. DOE: Lightweight materials for cars and trucks (https://www.energy.gov/eere/vehicles/lightweight-materials-cars-and-trucks) · EPA: Greenhouse gas emissions from a typical passenger vehicle (https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle)

Free learning resources

- U.S. DOE: Lightweight materials for cars and trucks (https://www.energy.gov/eere/vehicles/lightweight-materials-cars-and-trucks): Lightweight materials data.
- EPA: Greenhouse gas emissions from a typical passenger vehicle (https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle): Vehicle CO_2 figures.
- EPA: Sustainable materials management basics (https://www.epa.gov/smm/sustainable-materials-management-basics): Life-cycle thinking.

☐ **I finished this unit**

Problem Sets

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

1. Sketching & Visualization
   3 problems
2. Orthographic & Isometric Projection
   4 problems
3. Section & Auxiliary Views
   3 problems
4. Dimensioning & GD&T Basics
   3 problems
5. Tolerances & Fits
   3 problems
6. Parametric 3D Modeling
   3 problems
7. Assemblies & Drawings
   3 problems
8. 3D Printing & Design for Manufacture
   3 problems
9. Design for Sustainability & Lightweighting
   3 problems

Labs

Four labs take a part from paper to plastic: a parametric bracket in Onshape, an assembly and drawing in FreeCAD, a 3D-printing estimate and print, and a lightweighting study.

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

Safety reference: NIST: Additive manufacturing (https://www.nist.gov/additive-manufacturing)

Lab A: A parametric bracket in Onshape

WEEK 9

Goal: Model an L-bracket driven by variables, then change one variable and watch the model and its mass update.

$$m = \rho V$$

`m=ρ V`

Mass from volume

Procedure

1. Create a free Onshape account (Free plan) or use FreeCAD.
2. Define variables: plate 100 × 60 mm, thickness t = 5 mm, hole Ø6, hole inset 10 mm.
3. Sketch, extrude, add four holes with a pattern, and set the material to aluminum (2.70 g/cm³).
4. Record the mass. Change t to 4 mm and record again.

Data table

Thickness t (mm)	Volume (mm³)	Mass (g)
5	29,434	79.5
4	23,548	63.6
3	17,661	47.7

Computed values for the flat plate with four Ø6 holes; your full bracket will differ.

Sample calculation

1. V = (100 × 60 − 4π × 3²) × t = 5,886.9 × t mm³.
2. Mass = V × 2.70 g/cm³: 79.5 g at 5 mm. Each millimeter of thickness costs 15.9 g.

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

Home or virtual alternative

- Runs in a browser.

Onshape Free plan (https://www.onshape.com/en/products/free) · Onshape Learning Center (https://learn.onshape.com/)

Planet link: Parametric thickness studies are the quickest way to find the lightest part that still works. U.S. DOE: Lightweight materials for cars and trucks (https://www.energy.gov/eere/vehicles/lightweight-materials-cars-and-trucks)

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

Lab B: Assembly and drawing in FreeCAD

WEEK 11

Goal: Assemble a four-bar linkage, check its motion and mobility, and produce a drawing with a title block and BOM.

$$M = 3(n-1) - 2j_1$$

`M=3(n-1)-2j_1`

Gruebler's equation

Procedure

1. Model a ground link (100 mm), crank (40 mm), coupler (120 mm) and rocker (80 mm), each 10 mm wide with Ø6 holes at the ends.
2. Assemble with pin (revolute) joints and drive the crank.
3. Check whether the crank turns fully (Grashof: shortest + longest ≤ sum of the other two).
4. Make a drawing: views, dimensions, title block, BOM and balloons.

Data table

Check	Value
Mobility M	1
Shortest + longest (mm)	160
Other two (mm)	180
Crank can rotate fully?	Yes

Computed values for the given link lengths.

Sample calculation

1. M = 3(4 − 1) − 2 × 4 = 1.
2. Grashof: 40 + 120 = 160 ≤ 100 + 80 = 180, and the shortest link is the crank, so it can rotate fully.

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

Home or virtual alternative

- FreeCAD is free for Windows, Mac and Linux.

FreeCAD (free, open source) (https://www.freecad.org/) · FreeCAD wiki: Getting started (https://wiki.freecad.org/Getting_started)

Planet link: Drawings with clear BOMs make products easier to repair and maintain. EPA: Sustainable materials management basics (https://www.epa.gov/smm/sustainable-materials-management-basics)

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

Lab C: Print it (or estimate it)

WEEK 13

Goal: Slice a 20 mm calibration cube at different infill settings, compare mass and time, print one if you can, and measure it.

$$\ell = \frac{m}{\rho \pi r^2}$$

`=(m)/(ρπ r^2)`

Filament length

Procedure

1. Export your cube as STL and open it in a free slicer.
2. Record the slicer's mass and time at 100%, 20% and 10% infill.
3. Print one cube if you have access; measure it with a caliper in x, y and z.
4. Compute the dimensional error and filament length.

Data table

Measured axis	Nominal (mm)	Measured (mm)
x	20.00	20.12
y	20.00	20.08
z	20.00	19.90

Sample measurements for practice, not a real print.

Sample calculation

1. Errors: +0.12, +0.08 and −0.10 mm, i.e. +0.6%, +0.4% and −0.5%.
2. A solid cube is 9.9 g ≈ 3.32 m of 1.75 mm filament; slicer values at low infill will be much lower.

> **Safety**
>
> - Printer nozzles and beds are hot (often 200 °C+ and 60 °C): do not touch during or just after printing.
> - Print in a ventilated room and follow the printer's and makerspace's rules.

Home or virtual alternative

- A library or makerspace printer works; or complete the slicer part only.

NIST: Additive manufacturing (https://www.nist.gov/additive-manufacturing)

Planet link: Low infill and good orientation cut plastic use and failed prints. EPA: Plastics, material-specific data (https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data)

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

Lab D: Lightweighting study

WEEK 14

Goal: Compare beam sections for mass and stiffness in CAD and by hand, then estimate what lightweighting is worth for a car.

$$I_{tube} = \frac{B^4 - b^4}{12}$$

```
I_tube=(B^4-b^4)/(12)
```

Square tube second moment of area

Procedure

1. Model 500 mm beams: a solid 20 × 20 mm bar and 25 × 25 mm tubes with 2 mm and 1.5 mm walls.
2. Read each beam's mass (steel, 7.85 g/cm³) and section properties from CAD.
3. Compute I by hand and compare.
4. Use DOE's 6–8% rule and EPA's CO_2 figure to estimate the yearly savings for the Unit 9 car.

Data table

Section	Area (mm²)	I (mm⁴)	Mass, 500 mm steel (g)
Solid 20 × 20	400	13,333	1,570
Tube 25 × 25 × 2	184	16,345	722
Tube 25 × 25 × 1.5	141	13,031	553

Computed values.

Sample calculation

1. The 1.5 mm tube is within about 2% of the solid bar's stiffness (13,031 vs 13,333 mm⁴) at 35% of the mass.
2. Mass = area × 500 mm × 7.85 g/cm³: 400 mm² → 1,570 g.

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

Home or virtual alternative

- A spreadsheet and CAD are enough.

U.S. DOE: Lightweight materials for cars and trucks (https://www.energy.gov/eere/vehicles/lightweight-materials-cars-and-trucks)

Planet link: DOE: a 10% lighter vehicle can get 6–8% better fuel economy. U.S. DOE: Lightweight materials for cars and trucks (https://www.energy.gov/eere/vehicles/lightweight-materials-cars-and-trucks) · EPA: Greenhouse gas emissions from a typical passenger vehicle (https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle)

- [ ] **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. At 1:5, how long is a 1,200 mm beam on paper?

    1. 1,200/5.

    Answer: 240 mm.

2. Find the true length of an edge from (0, 0, 0) to (20, 20, 10).

    1. √(400 + 400 + 100).

    Answer: 30 mm.

3. A hole is 0.04 off in x and 0.03 in y. Position error?

    1. 2√(0.0016 + 0.0009).

    Answer: Ø0.10.

4. Hole 25.000–25.021, shaft 24.980–24.993. Clearance range?

    1. 25.000 − 24.993; 25.021 − 24.980.

    Answer: 0.007–0.041 mm.

5. Stack 20 ± 0.10, 30 ± 0.05, 10 ± 0.05: worst case and RSS?

    1. 0.20; √0.015.

    Answer: ± 0.20 and ± 0.12 mm.

Final practice set (all units)

1. Mass of a 100 × 60 × 5 mm aluminum plate with four Ø6 holes?

    1. V = 29,434.5 mm³; × 2.70 g/cm³.

    Answer: ≈ 79.5 g.

2. Mobility of a planar linkage with 5 links and 5 pins?

    1. 3(4) − 10.

    Answer: 2.

3. Filament length for a 10 g PLA print (1.75 mm)?

    1. 10 × 33.5 cm.

    Answer: ≈ 3.35 m.

4. Compare I of a solid 20 × 20 bar and a 25 × 25 × 2 tube.

    1. 13,333 vs 16,345 mm⁴.

    Answer: The tube is 23% stiffer with 54% less material.

5. A car saves 72 L of gasoline a year. CO_2 saved?

    1. 72 × 2.35.

    Answer: ≈ 169 kg.

Formula sheet

$$\text{scale} = \text{drawing}/\text{real}$$

$$k_{iso} = \sqrt{2/3} \approx 0.816$$

$$L = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$$

$$A_{true} = A_{proj} / \cos\theta$$

$$\varnothing_{pos} = 2\sqrt{\Delta x^2 + \Delta y^2}$$

$$t_{allowed} = t_{MMC} + |d - d_{MMC}|$$

$$c_{\min} = H_{\min} - s_{\max},\ c_{\max} = H_{\max} - s_{\min}$$

$$T_{wc} = \sum t_i,\ T_{RSS} = \sqrt{\sum t_i^2}$$

$$m = \rho V$$

$$V = 2\pi \bar{r} A$$

$$M = 3(n-1) - 2j_1 - j_2$$

$$\ell = m/(\rho \pi r^2)$$

$$t \approx V/(whv)$$

$$I = bh^3/12$$

$$I_{tube} = (B^4 - b^4)/12$$

$$\mathrm{CO_2} \approx 2.35\ \mathrm{kg\ per\ L\ gasoline}$$

Constants

Constant	Value
Isometric foreshortening	√(2/3) ≈ 0.816
Isometric axis angles	120° apart (30° from horizontal)
ISO A-series sheet ratio	√2 ≈ 1.414
A4 sheet	210 × 297 mm
PLA density (typical)	1.24 g/cm³
Common filament diameter	1.75 mm
IT7 tolerance, 18–30 mm sizes	21 µm
IT6 tolerance, 18–30 mm sizes	13 µm

Source: ISO 286-1: ISO code system for tolerances and fits (https://www.iso.org/standard/45975.html)

Free tools and references

Use these free tools alongside the course.

- Onshape Free plan (https://www.onshape.com/en/products/free): Browser-based professional CAD, free for non-commercial, public projects.
- Onshape Learning Center (https://learn.onshape.com/): Free self-paced Onshape courses.
- FreeCAD (free, open source) (https://www.freecad.org/): Free, open-source parametric CAD for Windows, Mac and Linux.
- FreeCAD wiki: Getting started (https://wiki.freecad.org/Getting_started): FreeCAD's official beginner guide.
- MIT OpenCourseWare 2.007: Design and Manufacturing I (https://ocw.mit.edu/courses/2-007-design-and-manufacturing-i-spring-2009/): MIT's design and manufacturing course.

Glossary

Auxiliary view
View projected parallel to an inclined surface.

Bill of materials
List of parts and quantities in an assembly.

Clearance fit
Fit that always leaves a gap.

Datum
Exact reference feature for measurement.

Design for assembly
Designing parts to be easy to put together.

Design intent
How a model should behave when changed.

Feature control frame
GD&T callout box.

GD&T
Geometric dimensioning and tolerancing.

Infill
Internal fill percentage of a 3D print.

Interference fit
Fit with guaranteed overlap.

Isometric
Pictorial view with axes 120° apart.

Lightweighting
Reducing mass while keeping function.

MMC
Maximum material condition.

Orthographic projection
Multiview drawing with perpendicular projectors.

Parametric model
CAD model driven by editable dimensions and features.

RSS stack-up
Statistical tolerance sum $\sqrt{\Sigma t^2}$.

Second moment of area
Geometric property I that sets bending stiffness.

Section view
View of an imaginary cut.

Third-angle projection
U.S. convention: top view above front.

Title block
Drawing information area.

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	Drawings and models are complete, unambiguous and capture design intent; choices are justified with numbers.
3 · Proficient	Correct work with occasional omissions.
2 · Developing	Follows tutorials but drawings are incomplete or models break when edited.
1 · Beginning	Views misaligned or dimensions missing; revisit the unit.

Suggested weighting if you want a score

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

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

Related courses

- Intro to Aerospace Engineering AERO 101
- Intro Programming ENGR 130
- General Chemistry I + Lab CHEM 110 + CHEM 110L
- All courses