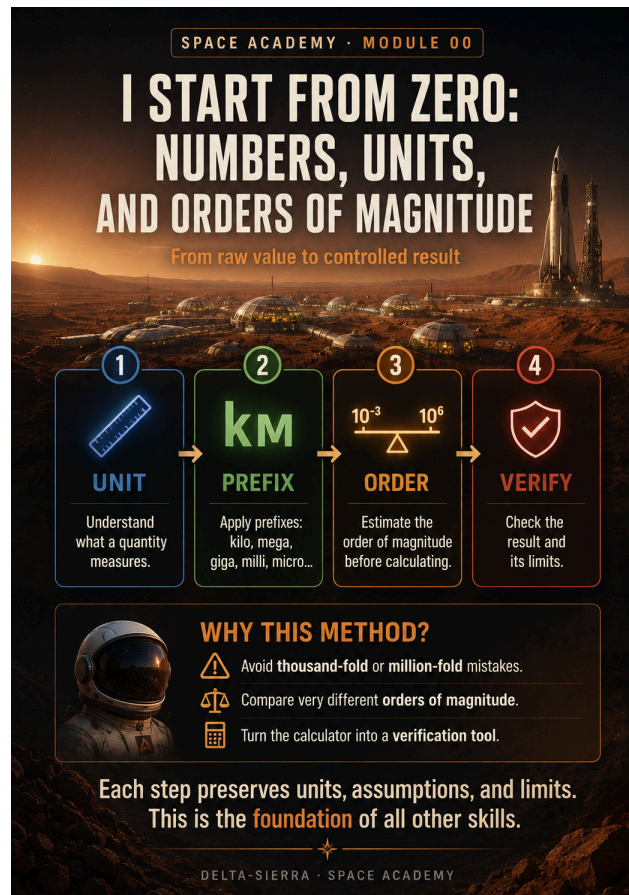


Starting from zero: numbers, units, and orders of magnitude



This module assumes mathematics may be a distant memory. On Mars, a factor-of-one-thousand error can distort inventory, filtration, or power budgets, so the course begins by reading numbers together with their units.

The method is straightforward: identify the quantity, keep the unit, convert explicitly, estimate magnitude, then calculate. It turns the calculator into a checking instrument rather than an oracle.

1. Read the quantity before calculating

A number becomes useful only when you know what it measures. Three kilograms, three metres, and three kilowatts answer different questions. Keep the unit attached to the value. Decimal punctuation and thousands separators must never hide the physical scale.

0.1 is one tenth, 0.01 one hundredth, and 0.001 one thousandth. The gap between 0.003 and 3,000 is a factor of one million. Scale matters more than the number of digits shown.

Exercise 1

Order 0.003, 0.3, 3, 30, and 3,000, then calculate the ratio between the extremes.

Solution: $0.003 < 0.3 < 3 < 30 < 3,000$; $3,000 / 0.003 = 1,000,000$, six orders of magnitude. [Canonical reference.](#)

Why this matters

A numerical value becomes useful only after the physical quantity, unit, and system boundary are known. Pressure, mass, flow, concentration, and energy cannot be added because they do not have the same dimension.

NASA's 2026 limit of 0.1 mg/m³ for Martian particles <10 µm corresponds, in a perfectly mixed 100 m³ cabin, to 10 mg of airborne dust at that average. The calculation below is a consistency test, not a complete truth. [Canonical reference](#).

Mass contained in a volume

$$M = C \times V = 0.1 \text{ mg/m}^3 \times 100 \text{ m}^3 = 10 \text{ mg}$$

1 — Concrete question

What quantity must be determined in “Why this matters”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

A concentration becomes a total mass only after it is applied to the volume actually concerned

3 — Quantities first

M is the contaminant mass, C is the mass concentration, and V is the air volume considered.

4 — Formula

$$M = C \times V = 0.1 \text{ mg/m}^3 \times 100 \text{ m}^3 = 10 \text{ mg}$$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $M = C \times V = 0.1 \text{ mg/m}^3 \times 100 \text{ m}^3 = 10 \text{ mg}$.

6 — Symbols

M is the contaminant mass, C is the mass concentration, and V is the air volume considered.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

M is expressed as a mass (for example mg or kg); C as mass per volume (for example mg/m³ or kg/m³); V as a volume (for example m³). $C \times V$ therefore returns a mass.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

Here the operation expresses the following mechanism: the relationship directly represents the dependency studied in “Why this matters”.

11 — Assumptions

This relation assumes the concentration is representative of the selected volume.

12 — Unit check

M is expressed as a mass (for example mg or kg); C as mass per volume (for example mg/m³ or kg/m³); V as a volume (for example m³). $C \times V$ therefore returns a mass. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

$$M = C \times V = 0.1 \text{ mg/m}^3 \times 100 \text{ m}^3 = 10 \text{ mg}$$

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

An inverse calculation should reconstruct one input within rounding error.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

It turns a local concentration into an inventory useful for filtration, exposure or material balance.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. A concentration is 0.12 mg/m^3 in 120 m^3 of air. Calculate the total dust mass.

Guided solution — open after trying

$M = C \times V = 0.12 \times 120 = 14.4 \text{ mg}$. The m^3 cancels against $/\text{m}^3$, leaving a mass.

Independent exercise. Repeat for 0.08 mg/m^3 in 75 m^3 .

Independent solution — open after trying

$M = 0.08 \times 75 = 6.0 \text{ mg}$. Lower volume and concentration correctly give a smaller total mass.

21 — Mission decision

It turns a local concentration into an inventory useful for filtration, exposure or material balance.

An average concentration does not describe a local airlock peak or the dose actually inhaled by one person.

2. SI units are a grammar

The metre measures length, kilogram mass, second time, ampere current, kelvin thermodynamic temperature, mole amount of substance, and candela luminous intensity. Derived units recombine them: N for force, J for energy, W for power, and Pa for pressure.

Units take part in reasoning. Distance divided by time gives m/s ; force divided by area gives $\text{N/m}^2 = \text{Pa}$. An answer with dimensions that do not match the question is wrong before any decimal places are inspected. [Canonical reference](#).

Quantity	Unit	Meaning
mass	kg	inertia
force	$\text{N} = \text{kg} \cdot \text{m/s}^2$ Canonical reference .	accelerates mass
energy	J	transferable quantity
power	$\text{W} = \text{J/s}$ Canonical reference .	energy rate
pressure	$\text{Pa} = \text{N/m}^2$ Canonical reference .	force per area

Workshop — keep a unit ledger

Imagine receiving three statements: a tank holds 2.4 m^3 of water, a pump transfers 18 L/min , and an emergency plan requires $1,200 \text{ kg}$ of usable water. Comparing 2.4, 18, and 1,200 directly is meaningless. Convert them into a common physical language. Using the teaching approximation $1,000 \text{ kg/m}^3$ for water density, 2.4 m^3 is about $2,400 \text{ kg}$. A flow of 18 L/min is $0.018 \text{ m}^3/\text{min}$, about 18 kg/min . The tank therefore holds roughly twice the required mass, while transferring $1,200 \text{ kg}$ would take about 66.7 minutes at constant flow. Every conclusion can be traced to a visible unit conversion. [Canonical reference](#).

A unit ledger records symbol, physical quantity, input unit, working unit, source, and precision for each value. This feels slow only until a project combines kilograms of water, kilograms per day of loss, electrical kilowatts, and kilowatt-hours of storage. Numbers become comparable after their meaning and units have been made explicit, not because they happen to be printed in the same table.

Chain volume, density and throughput

$2.4 \text{ m}^3 \times 1,000 \text{ kg/m}^3 = 2,400 \text{ kg}$; $1,200 \text{ kg} \div 18 \text{ kg/min} \approx 66.7 \text{ min}$

1 — Concrete question

What quantity must be determined in “2. SI units are a grammar”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

A field problem is often solved by converting volume into mass first, then mass into processing time

3 — Quantities first

This worked chain uses measured quantities directly: volume, density, mass, and mass throughput. No additional symbolic variable is introduced.

4 — Formula

$2.4 \text{ m}^3 \times 1,000 \text{ kg/m}^3 = 2,400 \text{ kg}$; $1,200 \text{ kg} \div 18 \text{ kg/min} \approx 66.7 \text{ min}$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $2.4 \text{ m}^3 \times 1,000 \text{ kg/m}^3 = 2,400 \text{ kg}$; $1,200 \text{ kg} \div 18 \text{ kg/min} \approx 66.7 \text{ min}$.

6 — Symbols

This worked chain uses measured quantities directly: volume, density, mass, and mass throughput. No additional symbolic variable is introduced.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

Use one coherent volume unit for the first product, density as mass/volume, mass as kg, throughput as mass/time, and duration as time. $\text{m}^3 \times \text{kg/m}^3$ reduces to kg; $\text{kg} \div (\text{kg/min})$ reduces to min.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

Here the operation expresses the following mechanism: the relationship directly represents the dependency studied in “2. SI units are a grammar”.

11 — Assumptions

Each step must use compatible units and the throughput must represent the phase being studied.

12 — Unit check

Use one coherent volume unit for the first product, density as mass/volume, mass as kg, throughput as mass/time, and duration as time. $\text{m}^3 \times \text{kg/m}^3$ reduces to kg; $\text{kg} \div (\text{kg/min})$ reduces to min. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

$2.4 \text{ m}^3 \times 1,000 \text{ kg/m}^3 = 2,400 \text{ kg}$; $1,200 \text{ kg} \div 18 \text{ kg/min} \approx 66.7 \text{ min}$

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

An inverse calculation should reconstruct one input within rounding error.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

The chain checks whether a resource-processing task fits inside the available time.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. A tank contains 3.0 m^3 of water at $1,000 \text{ kg/m}^3$. Transfer $1,500 \text{ kg}$ at 25 kg/min . Find contained mass, then transfer time.

Guided solution — open after trying

$M = 3.0 \times 1,000 = 3,000$ kg. For the requested transfer, $t = 1,500/25 = 60$ min. The two relations are chained without mixing units.

Independent exercise. Repeat with 1.8 m^3 of water and transfer 900 kg at 15 kg/min.

Independent solution — open after trying

$M = 1.8 \times 1,000 = 1,800$ kg; $t = 900/15 = 60$ min. Available mass is correctly greater than transferred mass.

21 — Mission decision

The chain checks whether a resource-processing task fits inside the available time.

Physical reading

SI provides a shared grammar: metre for length, kilogram for mass, second for time, ampere for current, kelvin for thermodynamic temperature, mole for amount of substance, and candela for luminous intensity. Derived units keep physical relationships visible.

A pressure difference of 70 kPa is 70,000 Pa, or 70,000 N/m². Across a 1.2 m² hatch, the ideal pressure force is 84 kN. Canonical reference.

Force from a pressure difference

$$F = \Delta P \times A = 70\,000 \text{ Pa} \times 1.2 \text{ m}^2 = 84\,000 \text{ N}$$

1 — Concrete question

What quantity must be determined in “Physical reading”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

Pressure acting over an area creates a total mechanical load that a door, wall or attachment must withstand

3 — Quantities first

F is the force on the surface, ΔP is the pressure difference across it, and A is the loaded area.

4 — Formula

$$F = \Delta P \times A = 70\,000 \text{ Pa} \times 1.2 \text{ m}^2 = 84\,000 \text{ N}$$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $F = \Delta P \times A = 70\,000 \text{ Pa} \times 1.2 \text{ m}^2 = 84\,000 \text{ N}$.

6 — Symbols

F is the force on the surface, ΔP is the pressure difference across it, and A is the loaded area.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

F is in newtons (N), ΔP in pascals ($\text{Pa} = \text{N/m}^2$), and A in square metres (m²). $\text{Pa} \times \text{m}^2$ reduces to N.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

The mathematical choice is direct: the relationship directly represents the dependency studied in “Physical reading”.

11 — Assumptions

The pressure difference must be the one actually acting across the selected surface.

12 — Unit check

F is in newtons (N), ΔP in pascals ($\text{Pa} = \text{N}/\text{m}^2$), and A in square metres (m^2). $\text{Pa} \times \text{m}^2$ reduces to N. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

$$F = \Delta P \times A = 70\,000 \text{ Pa} \times 1.2 \text{ m}^2 = 84\,000 \text{ N}$$

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

Working backward with the inverse operation provides an independent check.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

The calculation converts an atmospheric condition into a structural or mechanism requirement.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. A 1.5 m^2 hatch sees a 65 kPa pressure difference. Calculate the ideal force.

Guided solution — open after trying

$$65 \text{ kPa} = 65,000 \text{ Pa}. F = \Delta P \times A = 65,000 \times 1.5 = 97,500 \text{ N}, \text{ or } 97.5 \text{ kN}.$$

Independent exercise. Calculate the force for 50 kPa on 0.8 m^2 .

Independent solution — open after trying

$$F = 50,000 \times 0.8 = 40,000 \text{ N} = 40 \text{ kN}. \text{ A smaller area proportionally reduces the force.}$$

21 — Mission decision

The calculation converts an atmospheric condition into a structural or mechanism requirement.

The calculation gives a resultant force, not detailed stress in hinges, seals, or reinforcements.

3. Prefixes and thousand-fold steps

milli means 10^{-3} , kilo 10^3 , mega 10^6 , and giga 10^9 . Case matters: mW and MW differ by a factor of one billion. Convert using factors equal to one: $2.5 \text{ kg} \times (1,000 \text{ g} / 1 \text{ kg}) = 2,500 \text{ g}$. [Canonical reference](#).

Conversion by unit factor

$$2.5 \text{ kg} \times (1,000 \text{ g} / 1 \text{ kg}) = 2,500 \text{ g}$$

1 — Concrete question

What quantity must be determined in “3. Prefixes and thousand-fold steps”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

A reliable conversion changes the unit without changing the physical quantity

3 — Quantities first

This conversion uses a unit factor equal to one: the same mass is written first in kilograms and then in grams.

4 — Formula

$$2.5 \text{ kg} \times (1,000 \text{ g} / 1 \text{ kg}) = 2,500 \text{ g}$$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $2.5 \text{ kg} \times (1,000 \text{ g} / 1 \text{ kg}) = 2,500 \text{ g}$.

6 — Symbols

This conversion uses a unit factor equal to one: the same mass is written first in kilograms and then in grams.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

The starting mass is in kg; the conversion factor is g/kg; the kilograms cancel and the result is in g.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

Here the operation expresses the following mechanism: the relationship directly represents the dependency studied in “3. Prefixes and thousand-fold steps”.

11 — Assumptions

The conversion factor must equal one exactly and the units must cancel explicitly.

12 — Unit check

The starting mass is in kg; the conversion factor is g/kg; the kilograms cancel and the result is in g. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

$$2.5 \text{ kg} \times (1,000 \text{ g} / 1 \text{ kg}) = 2,500 \text{ g}$$

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

An inverse calculation should reconstruct one input within rounding error.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

This discipline prevents a scale error from contaminating a mass, dose or consumption budget.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. Convert 3.2 kg to grams with a unit factor.

Guided solution — open after trying

$3.2 \text{ kg} \times (1,000 \text{ g} / 1 \text{ kg}) = 3,200 \text{ g}$. The factor equals one physically, so the quantity is unchanged.

Independent exercise. Convert 4.6 L to millilitres.

Independent solution — open after trying

$4.6 \text{ L} \times (1,000 \text{ mL} / 1 \text{ L}) = 4,600 \text{ mL}$. L cancels exactly.

21 — Mission decision

This discipline prevents a scale error from contaminating a mass, dose or consumption budget.

The same method handles compound units and prevents memorized shortcuts from silently reversing a conversion.

Move into calculation

Prefixes prevent long strings of zeros but become dangerous when treated as typography. Milli means 10^{-3} , micro 10^{-6} , kilo 10^3 , and mega 10^6 . The multiplier applies to the whole unit. [Canonical reference](#).

0.1 mg/m^3 equals $100 \text{ }\mu\text{g/m}^3$. An 80 kWh battery stores 80,000 Wh; in joules, $80 \times 3.6 \text{ MJ} = 288 \text{ MJ}$. The teaching value is seeing units turn into a decision. [Canonical reference](#).

Prefixes, energy and decimal scales

1 kWh = 3.6 MJ ; 0.1 mg = 100 μg

1 — Concrete question

What quantity must be determined in “Move into calculation”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

Prefixes and derived units let you change scale without losing the physical quantity's order of magnitude

3 — Quantities first

The first equality converts energy between kilowatt-hours and megajoules; the second converts mass between milligrams and micrograms.

4 — Formula

1 kWh = 3.6 MJ ; 0.1 mg = 100 μg

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: 1 kWh = 3.6 MJ ; 0.1 mg = 100 μg .

6 — Symbols

The first equality converts energy between kilowatt-hours and megajoules; the second converts mass between milligrams and micrograms.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

kWh and MJ are both energy units; mg and μg are both mass units. Only the scale changes, not the physical dimension.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

This operation is used because the relationship directly represents the dependency studied in “Move into calculation”.

11 — Assumptions

The conversion must preserve physical dimension and use an exact or explicitly defined factor.

12 — Unit check

kWh and MJ are both energy units; mg and μg are both mass units. Only the scale changes, not the physical dimension. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

1 kWh = 3.6 MJ ; 0.1 mg = 100 μg

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

A second calculation path or inverse operation should recover the original quantity.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

The goal is to compare data from instruments or documents expressed in different units.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. Convert 60 kWh to MJ and 0.25 mg to μg .

Guided solution — open after trying

$60 \times 3.6 = 216$ MJ. For mass, $0.25 \text{ mg} \times 1,000 = 250 \mu\text{g}$. Both conversions use explicit decimal factors.

Independent exercise. Convert 12 kWh to MJ and 0.035 mg to μg .

Independent solution — open after trying

$12 \times 3.6 = 43.2$ MJ; $0.035 \times 1,000 = 35 \mu\text{g}$.

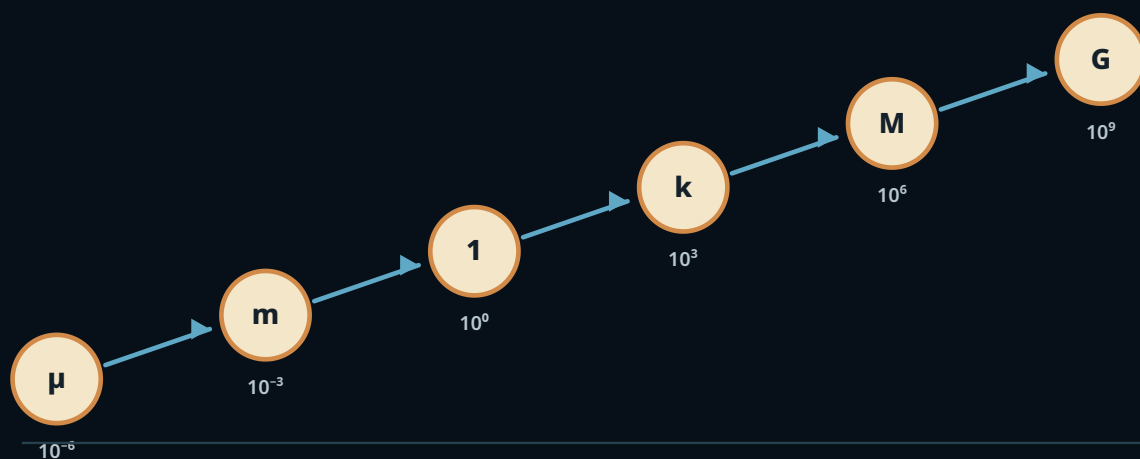
21 — Mission decision

The goal is to compare data from instruments or documents expressed in different units.

Confusing kW and kWh mixes a rate of energy transfer with an amount of energy and can mis-size a battery or power converter.

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Préfixes SI / SI prefixes



Each step = factor 1,000

SI-prefix ladder: moving from micro to mega while preserving the quantity's unit.

4. Powers of ten and orders of magnitude

Scientific notation writes a number as $a \times 10^n$, with $|a|$ between 1 and 10. $45,000 = 4.5 \times 10^4$ and $0.00045 = 4.5 \times 10^{-4}$. Multiplication adds the exponents of powers of ten. [Canonical mini-lesson](#).

Before using a calculator, replace 198×51 with $200 \times 50 \approx 10,000$. A screen result near 100 or ten million should trigger review. [Canonical reference](#).

Exercise 4

Write 6,500,000 and 0.000072 in scientific notation. [Canonical mini-lesson](#).

Solution: 6.5×10^6 and 7.2×10^{-5} . [Canonical reference](#).

Workshop — estimate the scale before the digits

Suppose a construction system must move 287,000 kg of regolith and actually processes 243 kg/h. Before exact division, round to 300,000 kg and 250 kg/h: $300,000 \div 250 \approx 1,200$ h. Exact division gives about 1,181 h. Both answers tell the same engineering story: the job is of order one thousand hours, not ten hours or one hundred thousand hours. An entry such as 118.1 h or 11,810 h should therefore trigger immediate review. [Canonical reference](#).

Order-of-magnitude thinking also decides which uncertainties deserve attention. If uncertainty in bulk density moves the mass estimate by $\pm 20\%$, debating the third decimal place of throughput is wasted precision. Start with the parameters that can materially move the answer. Estimation is not permission to be vague; it is a way to spend measurement effort where it changes decisions.

Order-of-magnitude estimate of duration

$300,000 / 250 \approx 1.2 \times 10^3$ h; exact: $287,000 / 243 \approx 1.18 \times 10^3$ h

1 — Concrete question

What quantity must be determined in “Exercise 4”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

A rough estimate tells you immediately whether a detailed calculation lies in the right decade

3 — Quantities first

The numerator is the total mass to process and the denominator is the processing rate; the quotient is the required duration. The rounded values give an order-of-magnitude check before the precise division.

4 — Formula

$300,000 / 250 \approx 1.2 \times 10^3$ h; exact: $287,000 / 243 \approx 1.18 \times 10^3$ h

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $300,000 / 250 \approx 1.2 \times 10^3$ h; exact: $287,000 / 243 \approx 1.18 \times 10^3$ h.

6 — Symbols

The numerator is the total mass to process and the denominator is the processing rate; the quotient is the required duration. The rounded values give an order-of-magnitude check before the precise division.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

Use mass in kg and throughput in kg/h. $\text{kg} \div (\text{kg/h})$ reduces to h, so the duration is expressed in hours.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

This operation is used because the relationship directly represents the dependency studied in “Exercise 4”.

11 — Assumptions

Rounded values must remain close to the actual inputs and serve only as an independent check.

12 — Unit check

Use mass in kg and throughput in kg/h. $\text{kg} \div (\text{kg/h})$ reduces to h, so the duration is expressed in hours. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

$300,000 / 250 \approx 1.2 \times 10^3 \text{ h}$; exact: $287,000 / 243 \approx 1.18 \times 10^3 \text{ h}$

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

A second calculation path or inverse operation should recover the original quantity.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

A quick estimate catches a factor-of-ten error before it enters a mission decision.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. Estimate, then calculate, 420,000 kg processed at 350 kg/h.

Guided solution — open after trying

Order of magnitude: $4.2 \times 10^5 / 3.5 \times 10^2 \approx 1.2 \times 10^3 \text{ h}$. Exact: $420,000 / 350 = 1,200 \text{ h}$. They agree.

Independent exercise. Estimate 96,000 kg at 480 kg/h.

Independent solution — open after trying

$\approx 10^5 / (5 \times 10^2) \approx 2 \times 10^2 \text{ h}$; exact: $96,000 / 480 = 200 \text{ h}$.

21 — Mission decision

A quick estimate catches a factor-of-ten error before it enters a mission decision.

Control point

Scientific notation separates the significant number from its scale. It makes $3 \times 10^2 \text{ kg}$, $3 \times 10^5 \text{ kg}$, and $3 \times 10^8 \text{ kg}$ easy to compare without losing the three orders of magnitude between each step. [Canonical mini-lesson](#).

Three hundred tonnes of regolith are $3 \times 10^5 \text{ kg}$. At 250 kg/h, an ideal system needs $1.2 \times 10^3 \text{ h}$, or about 50 continuous days. An engineer keeps numerical result, margin, and validity domain separate. [Canonical reference](#).

Duration from mass and throughput

$$t = 3 \times 10^5 \text{ kg} / (2.5 \times 10^2 \text{ kg/h}) = 1.2 \times 10^3 \text{ h}$$

1 — Concrete question

What quantity must be determined in “Control point”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

Dividing the quantity to process by the processing rate gives the ideal required time

3 — Quantities first

t is the processing duration. The numerator is the mass to be processed and the denominator is the mass throughput.

4 — Formula

$$t = 3 \times 10^5 \text{ kg} / (2.5 \times 10^2 \text{ kg/h}) = 1.2 \times 10^3 \text{ h}$$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $t = 3 \times 10^5 \text{ kg} / (2.5 \times 10^2 \text{ kg/h}) = 1.2 \times 10^3 \text{ h}$.

6 — Symbols

t is the processing duration. The numerator is the mass to be processed and the denominator is the mass throughput.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

t is in hours here; mass is in kg; throughput is in kg/h. $\text{kg} \div (\text{kg/h}) = \text{h}$.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

The calculation is structured this way because the relationship directly represents the dependency studied in "Control point".

11 — Assumptions

The throughput must remain applicable over the calculated period and downtime must be handled separately.

12 — Unit check

t is in hours here; mass is in kg; throughput is in kg/h. $\text{kg} \div (\text{kg/h}) = \text{h}$. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

$$t = 3 \times 10^5 \text{ kg} / (2.5 \times 10^2 \text{ kg/h}) = 1.2 \times 10^3 \text{ h}$$

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

An independent check substitutes the result back into the starting relationship.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

This relation checks whether a production or processing campaign closes within the available window.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. Calculate the time to process 240,000 kg at 300 kg/h.

Guided solution — open after trying

$$t = M/q = 240,000/300 = 800 \text{ h. kg cancels, leaving hours.}$$

Independent exercise. Calculate the time for 150,000 kg at 250 kg/h.

Independent solution — open after trying

$$t = 150,000/250 = 600 \text{ h.}$$

21 — Mission decision

This relation checks whether a production or processing campaign closes within the available window.

Order-of-magnitude reasoning does not replace detailed calculation; it catches impossible results before they are trusted.

5. Fractions, ratios, and percentages

A percentage is a fraction per hundred. $98\% = 0.98$, leaving $1 - 0.98 = 0.02$ unrecovered. That small residual often drives makeup logistics. [Canonical reference](#).

Residual fraction after recovery

residual = initial quantity $\times$ (1 – recovery fraction)

1 — Concrete question

What quantity must be determined in “5. Fractions, ratios, and percentages”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

What remains after recovery is the initial amount that was not recovered

3 — Quantities first

Residual is the unrecovered quantity, the initial quantity is the amount before recovery, and the recovery fraction is the dimensionless share recovered between 0 and 1.

4 — Formula

Residual = initial quantity $\times$ (1 – recovery fraction)

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: residual = initial quantity $\times$ (1 – recovery fraction).

6 — Symbols

Residual is the unrecovered quantity, the initial quantity is the amount before recovery, and the recovery fraction is the dimensionless share recovered between 0 and 1.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

Residual and initial quantity use the same physical unit (for example kg or L); the recovery fraction and 1–recovery fraction are dimensionless.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

The calculation is structured this way because the relationship directly represents the dependency studied in “5. Fractions, ratios, and percentages”.

11 — Assumptions

The recovery rate must be expressed as a fraction between zero and one and refer to the same stream.

12 — Unit check

Residual and initial quantity use the same physical unit (for example kg or L); the recovery fraction and 1–recovery fraction are dimensionless. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

With 500 L initially and $R = 0.92$, the residual is $500 \times (1 - 0.92) = 40$ L.

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

An independent check substitutes the result back into the starting relationship.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

The result helps size makeup supply, losses and contingency stocks.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. A loop recovers 92% of 500 L. How much remains to be supplied?

Guided solution — open after trying

$\text{Residual} = 500 \times (1 - 0.92) = 500 \times 0.08 = 40 \text{ L.}$

Independent exercise. Repeat with 320 kg and 87.5% recovery.

Independent solution — open after trying

$320 \times (1 - 0.875) = 320 \times 0.125 = 40 \text{ kg.}$

21 — Mission decision

The result helps size makeup supply, losses and contingency stocks.

Always state what a ratio compares. A language word-count ratio, a mass fraction, and an efficiency are not interchangeable.

Interpretation

A fraction describes part of a whole, a ratio compares quantities, and a percentage expresses a fraction per hundred. Before using a proportion, check that the quantity really scales linearly.

With 20 kg of process water per person per day, 98% overall recovery leaves 0.4 kg/day makeup per person; at 94%, the loss is 1.2 kg/day. For 100 people, the annual difference is 29.2 t in this teaching example. The formula is useful because it makes a system dependency visible.

Makeup demand of a recovery loop

$$M_{\text{makeup}} = q N (1 - R)$$

1 — Concrete question

What quantity must be determined in “Interpretation”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

Makeup demand depends on gross consumption, crew size and especially the fraction that is not recovered

3 — Quantities first

M_{makeup} is the makeup mass required per unit time, q is the gross demand per person and per unit time, N is the number of people served, and R is the dimensionless recovery fraction.

4 — Formula

$$M_{\text{makeup}} = q N (1 - R)$$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $M_{\text{makeup}} = q N (1 - R)$.

6 — Symbols

M_{makeup} is the makeup mass required per unit time, q is the gross demand per person and per unit time, N is the number of people served, and R is the dimensionless recovery fraction.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

If q is in $\text{kg}/(\text{person}\cdot\text{day})$, N is a person count and R is dimensionless, M_{makeup} is in kg/day . The same structure works with $\text{L}/(\text{person}\cdot\text{day})$ to obtain L/day .

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

The mathematical choice is direct: the relationship directly represents the dependency studied in “Interpretation”.

11 — Assumptions

Recovery must be measured over the same time and material boundary as consumption.

12 — Unit check

If q is in $\text{kg}/(\text{person}\cdot\text{day})$, N is a person count and R is dimensionless, M_{makeup} is in kg/day . The same structure works with $\text{L}/(\text{person}\cdot\text{day})$ to obtain L/day . The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

For $q = 3.5 \text{ L}/\text{person}/\text{day}$, $N = 20$ and $R = 0.90$, $M_{\text{makeup}} = 3.5 \times 20 \times 0.10 = 7 \text{ L}/\text{day}$.

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

Working backward with the inverse operation provides an independent check.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

This relation converts recycling performance into the mass that must actually be supplied or produced.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. Gross use is $3.5 \text{ L}/\text{person}/\text{day}$ for 20 people with 90% recovery. Calculate makeup demand.

Guided solution — open after trying

$$M_{\text{makeup}} = qN(1-R) = 3.5 \times 20 \times 0.10 = 7 \text{ L}/\text{day}.$$

Independent exercise. With $q = 4 \text{ L}/\text{person}/\text{day}$, $N = 12$ and $R = 0.85$, calculate makeup.

Independent solution — open after trying

$$4 \times 12 \times 0.15 = 7.2 \text{ L}/\text{day}.$$

21 — Mission decision

This relation converts recycling performance into the mass that must actually be supplied or produced.

The 20 kg/day figure is a teaching assumption, not a NASA requirement; mixing assumptions with institutional data changes the status of the result.

6. Dimensional analysis

A safe conversion is a chain of factors that cancels unwanted units. $72 \text{ km/h} \times 1,000 \text{ m/km} \times 1 \text{ h}/3,600 \text{ s} = 20 \text{ m/s}$. Each removed unit appears once above and once below the fraction line. [Canonical reference](#).

The same discipline converts flow into annual inventory, concentration into total mass, or power into energy.

Exercise 6

Convert 40 kg/day into tonnes over 365 days.

Solution: $40 \times 365 = 14,600 \text{ kg} = 14.6 \text{ t/year}$. [Canonical reference](#).

Field reasoning

Dimensional analysis tests an equation before any numbers are inserted. If the left side is energy, the right side must reduce to joules; if the unknown is mass, the final units must reduce to kilograms.

A flow of 40 kg/day for 365 days gives 14,600 kg because days cancel. Multiplying 40 kg/day by 365 kg is physically meaningless even though a calculator will display a number.

Dimensional check

$(\text{kg/day}) \times \text{day} = \text{kg}$; $\text{W} \times \text{s} = \text{J}$; $\text{Pa} \times \text{m}^2 = \text{N}$

1 — Concrete question

What quantity must be determined in “Field reasoning”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

Units behave like algebraic factors: they reveal immediately whether a relation can produce the intended quantity

3 — Quantities first

This line manipulates units directly: kg is mass, day and s are durations, W is power, J is energy, Pa is pressure, m² is area, and N is force.

4 — Formula

$(\text{kg/day}) \times \text{day} = \text{kg}$; $\text{W} \times \text{s} = \text{J}$; $\text{Pa} \times \text{m}^2 = \text{N}$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $(\text{kg/day}) \times \text{day} = \text{kg}$; $\text{W} \times \text{s} = \text{J}$; $\text{Pa} \times \text{m}^2 = \text{N}$.

6 — Symbols

This line manipulates units directly: kg is mass, day and s are durations, W is power, J is energy, Pa is pressure, m² is area, and N is force.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

$(\text{kg/day}) \times \text{day}$ reduces to kg; $\text{W} \times \text{s}$ reduces to J because $1 \text{ W} = 1 \text{ J/s}$; $\text{Pa} \times \text{m}^2$ reduces to N because $1 \text{ Pa} = 1 \text{ N/m}^2$.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

The calculation is structured this way because the relationship directly represents the dependency studied in “Field reasoning”.

11 — Assumptions

Dimensional analysis checks consistency, not the correctness of the data or the model.

12 — Unit check

$(\text{kg/day}) \times \text{day}$ reduces to kg; $\text{W} \times \text{s}$ reduces to J because $1 \text{ W} = 1 \text{ J/s}$; $\text{Pa} \times \text{m}^2$ reduces to N because $1 \text{ Pa} = 1 \text{ N/m}^2$. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

$45 \text{ kg/day} \times 12 \text{ day} = 540 \text{ kg}$; day cancels. $250 \text{ W} \times 7,200 \text{ s} = 1.8 \times 10^6 \text{ J}$.

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

An independent check substitutes the result back into the starting relationship.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

Before trusting a number, this check eliminates many input and formula errors.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. Dimension-check 45 kg/day for 12 days and 250 W for 7,200 s.

Guided solution — open after trying

$45 \times 12 = 540 \text{ kg}$ because day cancels. $250 \times 7,200 = 1,800,000 \text{ J} = 1.8 \text{ MJ}$ because $\text{W} \cdot \text{s} = \text{J}$.

Independent exercise. Check 35 kPa applied over 0.6 m^2 .

Independent solution — open after trying

$35,000 \text{ Pa} \times 0.6 \text{ m}^2 = 21,000 \text{ N} = 21 \text{ kN}$ because $\text{Pa} \cdot \text{m}^2 = \text{N}$.

21 — Mission decision

Before trusting a number, this check eliminates many input and formula errors.

An equation can be dimensionally correct and still be physically wrong; the test eliminates some errors, not all.

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Contrôle dimensionnel / dimensional check

$$\text{flow } 2.5 \text{ L/min} \times 10^{-3} \text{ m}^3 / 60 \text{ s} = 4,17 \times 10^{-5} \text{ m}^3/\text{s}$$

L and min cancel

Units must reduce to the requested quantity

Dimensional check: input, unit, equation, unit cancellation, then result.

7. Calculator discipline

A calculator executes syntax; it does not know whether your model is absurd. Predict sign, scale, and unit before each result. EXP or EE keys commonly enter powers of ten: $6.02 \text{ EE } 23$ represents 6.02×10^{23} . [Canonical reference](#).

Recalculate through a different route when the result matters. Convert back to the starting unit, add recovered plus lost fractions, or divide energy by time to recover the expected power.

Why this matters

Calculator discipline starts with a mental estimate. Write the units, anticipate the scale, then enter the numbers. A calculator checks arithmetic; it does not choose the model or assumptions.

Forty kg/day for a year should be near $40 \times 400 \approx 16,000$ kg. The exact 14,600 kg is plausible. A display of 146 kg or 1.46 million kg would immediately reveal a factor-of-one-hundred error. The calculation below is a consistency test, not a complete truth. [Canonical reference](#).

Calculation checking chain

estimate → calculate → unit-check → order of magnitude → interpret

1 — Concrete question

What quantity must be determined in “Why this matters”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

A trustworthy result is not merely calculated: it is estimated, dimension-checked, compared with an order of magnitude and interpreted

3 — Quantities first

This is a five-step checking sequence rather than an algebraic equation: estimate, calculate, check units, check order of magnitude, then interpret the result.

4 — Formula

Estimate → calculate → unit-check → order of magnitude → interpret

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: estimate → calculate → unit-check → order of magnitude → interpret.

6 — Symbols

This is a five-step checking sequence rather than an algebraic equation: estimate, calculate, check units, check order of magnitude, then interpret the result.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

The sequence itself has no unit. Each numerical result keeps the unit of the physical quantity being checked, and that unit must remain consistent through the chain.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

The calculation is structured this way because the relationship directly represents the dependency studied in “Why this matters”.

11 — Assumptions

Each check should remain as independent as possible from the main calculation.

12 — Unit check

The sequence itself has no unit. Each numerical result keeps the unit of the physical quantity being checked, and that unit must remain consistent through the chain. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

For 48 kg/day over 30 days, estimate $50 \times 30 = 1,500$ kg is close to the exact $48 \times 30 = 1,440$ kg.

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

An independent check substitutes the result back into the starting relationship.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

The chain reduces the risk of using a plausible-looking but wrong number for a decision.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. Check 48 kg/day for 30 days using estimate → calculate → unit-check → order of magnitude.

Guided solution — open after trying

Estimate: $50 \times 30 \approx 1,500$ kg. Exact: $48 \times 30 = 1,440$ kg. Unit is kg and the 4% difference is reasonable.

Independent exercise. Check 2.2 kW for 8 h.

Independent solution — open after trying

Estimate: $2 \times 8 \approx 16$ kWh. Exact: $2.2 \times 8 = 17.6$ kWh. The result has the correct order of magnitude.

21 — Mission decision

The chain reduces the risk of using a plausible-looking but wrong number for a decision.

Copying ten decimal places creates an illusion of precision when the inputs are known only to a few percent.

8. Uncertainty and significant digits

A measurement is not infinitely precise. NIST uncertainty guidance treats uncertainty as information about the dispersion reasonably attributable to a measured quantity. Extra decimal places do not reduce uncertain assumptions.

If a teaching scenario assumes 20 kg/person/day, reporting 14.600000 t/year creates false precision. Use 14.6 t/year and keep the assumption visible.

Workshop — separate precision, uncertainty, and margin

A measurement of 10.0 ± 0.2 kg is different from a requirement of at least 10 kg. The first describes an estimate and uncertainty; the second sets an acceptance threshold. Margin is different again: if calculated need is 10 kg and inventory is 12 kg, nominal margin is 2 kg or 20% of need. Treating uncertainty and margin as interchangeable hides risk.

Consider a 500 L tank with a gauge uncertainty of $\pm 2\%$ and an operational minimum of 430 L. Two percent of 500 L is 10 L. If the display reads 440 L, a simplified 430–450 L interval touches the operational minimum. The displayed ten-litre surplus is therefore not automatically comfortable. This simple example prepares the logic needed for engineering margins, alarm thresholds, redundant sensing, and acceptance testing.

Margin relative to a requirement

margin = (stock – need) / need; $500 \text{ L} \times 2\% = 10 \text{ L}$

1 — Concrete question

What quantity must be determined in “8. Uncertainty and significant digits”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

A margin expresses available reserve relative to the reference need, not merely the raw difference

3 — Quantities first

Margin is the relative reserve above the requirement; stock is the quantity available; need is the required quantity on the same basis. In the example, L denotes litres.

4 — Formula

Margin = (stock – need) / need; $500 \text{ L} \times 2\% = 10 \text{ L}$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: margin = (stock – need) / need; $500 \text{ L} \times 2\% = 10 \text{ L}$.

6 — Symbols

Margin is the relative reserve above the requirement; stock is the quantity available; need is the required quantity on the same basis. In the example, L denotes litres.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

Margin is dimensionless. Stock and need must use the same unit (for example L, kg, doses, or parts). The separate 2% example uses a percentage as a dimensionless fraction and returns litres.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

The calculation is structured this way because the relationship directly represents the dependency studied in “8. Uncertainty and significant digits”.

11 — Assumptions

Stock and need must refer to the same boundary, duration and units.

12 — Unit check

Margin is dimensionless. Stock and need must use the same unit (for example L, kg, doses, or parts). The separate 2% example uses a percentage as a dimensionless fraction and returns litres. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

Margin = (stock – need) / need; $500\text{ L} \times 2\% = 10\text{ L}$

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

An independent check substitutes the result back into the starting relationship.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

A normalized margin lets you compare different-sized scenarios and set a decision threshold.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. A requirement is 600 L and planned stock is 660 L. Calculate relative margin.

Guided solution — open after trying

$(660-600)/600 = 60/600 = 0.10 = 10\%$. Stock exceeds the requirement by 60 L.

Independent exercise. Requirement 700 L, stock 875 L: calculate margin.

Independent solution — open after trying

$(875-700)/700 = 175/700 = 0.25 = 25\%$.

21 — Mission decision

A normalized margin lets you compare different-sized scenarios and set a decision threshold.

Physical reading

A measurement is not just a value; it carries uncertainty from repeatability, calibration, the method, and sometimes the model that turns signal into a physical quantity. NIST distinguishes Type A and Type B evaluations among others.

If a flow is $10.0 \pm 0.2\text{ kg/h}$, the simple relative uncertainty is 2%. Over 24 h the nominal flow is 240 kg, but a systematic 2% uncertainty does not disappear merely because the value is multiplied by 24.

Relative uncertainty

$$u_r = u/x = 0.2/10.0 = 0.02 = 2\%$$

1 — Concrete question

What quantity must be determined in “Physical reading”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

Dividing uncertainty by the measured value shows how large the uncertainty is relative to the signal itself

3 — Quantities first

u_r is relative uncertainty, u is the absolute uncertainty on the measured quantity, and x is the measured value used as the reference scale.

4 — Formula

$$u_r = u/x = 0.2/10.0 = 0.02 = 2 \%$$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $u_r = u/x = 0.2/10.0 = 0.02 = 2 \%$.

6 — Symbols

u_r is relative uncertainty, u is the absolute uncertainty on the measured quantity, and x is the measured value used as the reference scale.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

u and x must use the same physical unit, so $u_r = u/x$ is dimensionless and may be expressed as a fraction or percentage.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

The mathematical choice is direct: the relationship directly represents the dependency studied in “Physical reading”.

11 — Assumptions

The reference value must be non-zero and the uncertainty must follow a documented convention.

12 — Unit check

u and x must use the same physical unit, so $u_r = u/x$ is dimensionless and may be expressed as a fraction or percentage. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

$$u_r = u/x = 0.2/10.0 = 0.02 = 2 \%$$

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

Working backward with the inverse operation provides an independent check.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

This quantity helps decide whether a measurement is precise enough to support an operational threshold.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. A measurement is 25.0 ± 0.5 kg. Calculate relative uncertainty.

Guided solution — open after trying

$$u_r = u/x = 0.5/25.0 = 0.02 = 2\%. \text{ Units cancel.}$$

Independent exercise. Calculate u_r for 80 ± 1.2 L.

Independent solution — open after trying

$$1.2/80 = 0.015 = 1.5\%.$$

21 — Mission decision

This quantity helps decide whether a measurement is precise enough to support an operational threshold.

Random scatter and common bias must be separated: averaging many readings may reduce one without correcting the other.

9. Mars laboratory: dust, water, energy

NASA published a preliminary 2026 requirement for Martian particles under 10 μm : 0.1 mg/m^3 as a 24-hour time-weighted average for specified exposure scenarios up to 30 days. In 100 m^3 of air that concentration corresponds to 10 mg suspended at the average. [Canonical reference](#).

Concentration converted to dust mass

$$0.1 \text{ mg}/\text{m}^3 \times 100 \text{ m}^3 = 10 \text{ mg}$$

1 — Concrete question

What quantity must be determined in “9. Mars laboratory: dust, water, energy”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

An airborne concentration alone does not give the contained mass; it must be applied to the air volume concerned

3 — Quantities first

The first quantity is a dust mass concentration and the second is the sampled air volume; multiplying them gives the total dust mass in that volume.

4 — Formula

$$0.1 \text{ mg}/\text{m}^3 \times 100 \text{ m}^3 = 10 \text{ mg}$$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $0.1 \text{ mg}/\text{m}^3 \times 100 \text{ m}^3 = 10 \text{ mg}$.

6 — Symbols

The first quantity is a dust mass concentration and the second is the sampled air volume; multiplying them gives the total dust mass in that volume.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

Concentration is in mg/m^3 , volume in m^3 , and the m^3 cancels, leaving mass in mg.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

The mathematical choice is direct: the relationship directly represents the dependency studied in “9. Mars laboratory: dust, water, energy”.

11 — Assumptions

The concentration must represent the volume and the air must be sufficiently mixed for the approximation used.

12 — Unit check

Concentration is in mg/m^3 , volume in m^3 , and the m^3 cancels, leaving mass in mg. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

$$0.1 \text{ mg}/\text{m}^3 \times 100 \text{ m}^3 = 10 \text{ mg}$$

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

Working backward with the inverse operation provides an independent check.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

The calculation links a dust measurement to the load filtration or cleaning must handle.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. A concentration of 0.08 mg/m^3 is measured in 150 m^3 . Calculate total mass.

Guided solution — open after trying

$$M = CV = 0.08 \times 150 = 12 \text{ mg.}$$

Independent exercise. Repeat for 0.12 mg/m^3 in 80 m^3 .

Independent solution — open after trying

$$0.12 \times 80 = 9.6 \text{ mg.}$$

21 — Mission decision

The calculation links a dust measurement to the load filtration or cleaning must handle.

For water, use a teaching assumption of 20 kg/person/day gross flow. At 100 people and 98% total recovery, theoretical makeup is 40 kg/day , or 14.6 t/year . The 20 kg value is not a NASA requirement.

Exercise 9

A 2 kW load operates for 18 h . How much energy is consumed?

Solution: $2 \times 18 = 36 \text{ kWh}$. kW is power; kWh is energy. [Canonical reference](#).

Move into calculation

A good Mars exercise combines several quantities without mixing them. The goal is not to accumulate formulas but to build a dimensionally coherent chain from the observed phenomenon to an operational decision.

A 25 m^3 airlock measured at 0.08 mg/m^3 contains an idealized 2 mg of airborne dust. An airflow of $100 \text{ m}^3/\text{h}$ does not automatically mean 8 mg/h is removed: filter efficiency and actual mixing are still required. The teaching value is seeing units turn into a decision. [Canonical reference](#).

Contained mass and filtered mass

$$M_{\text{air}} = C V ; M_{\text{filtered}} = C Q \eta \Delta t$$

1 — Concrete question

What quantity must be determined in “Move into calculation”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

The balance distinguishes what is present in a volume from what a filtration flow can remove over a given time

3 — Quantities first

M_{air} is contaminant mass present in the air volume, C is mass concentration, V is air volume, M_{filtered} is captured contaminant mass, Q is volumetric airflow, η is filter efficiency, and Δt is filtration time.

4 — Formula

$$M_{\text{air}} = C V ; M_{\text{filtered}} = C Q \eta \Delta t$$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $M_{\text{air}} = C V ; M_{\text{filtered}} = C Q \eta \Delta t$.

6 — Symbols

M_{air} is contaminant mass present in the air volume, C is mass concentration, V is air volume, M_{filtered} is captured contaminant mass, Q is volumetric airflow, η is filter efficiency, and Δt is filtration time.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

M_{air} and M_{filtered} are masses; C is mass/volume; V is volume; Q is volume/time; η is dimensionless; Δt is time. $C \times Q \times \eta \times \Delta t$ therefore returns a mass.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

Here the operation expresses the following mechanism: the relationship directly represents the dependency studied in “Move into calculation”.

11 — Assumptions

Concentration, flow, efficiency and duration must refer to the same stream and remain valid over the interval.

12 — Unit check

M_{air} and M_{filtered} are masses; C is mass/volume; V is volume; Q is volume/time; η is dimensionless; Δt is time. $C \times Q \times \eta \times \Delta t$ therefore returns a mass. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

With $C = 0.06 \text{ mg/m}^3$ and $V = 40 \text{ m}^3$, $M_{\text{air}} = 2.4 \text{ mg}$. For $Q = 120 \text{ m}^3/\text{h}$, $\eta = 0.85$ and $\Delta t = 0.5 \text{ h}$, $M_{\text{filtered}} = 0.06 \times 120 \times 0.85 \times 0.5 = 3.06 \text{ mg}$.

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

An inverse calculation should reconstruct one input within rounding error.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

This balance checks whether the filtration system can actually keep up with the contamination load.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. For $C = 0.06 \text{ mg/m}^3$ and $V = 40 \text{ m}^3$, find contained mass; then with $Q = 120 \text{ m}^3/\text{h}$, $\eta = 0.85$ and $\Delta t = 0.5 \text{ h}$, find filtered mass.

Guided solution — open after trying

$M_{\text{air}} = CV = 0.06 \times 40 = 2.4 \text{ mg}$. $M_{\text{filtered}} = CQ\eta\Delta t = 0.06 \times 120 \times 0.85 \times 0.5 = 3.06 \text{ mg}$. The second term integrates airflow over time, not only the instantaneous inventory.

Independent exercise. With $C = 0.04 \text{ mg/m}^3$, $Q = 90 \text{ m}^3/\text{h}$, $\eta = 0.90$ and $\Delta t = 1 \text{ h}$, calculate M_{filtered} .

Independent solution — open after trying

$$M_{\text{filtered}} = 0.04 \times 90 \times 0.90 \times 1 = 3.24 \text{ mg.}$$

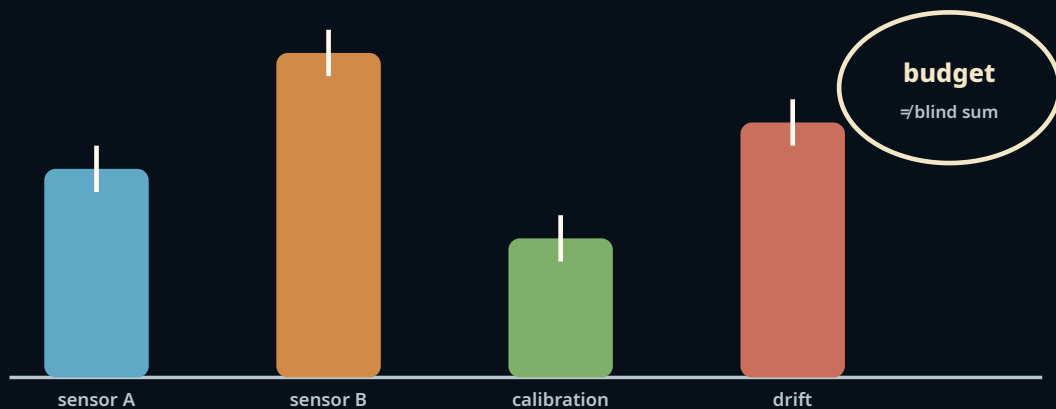
21 — Mission decision

This balance checks whether the filtration system can actually keep up with the contamination load.

A material balance requires a boundary: airlock air, filter capture, surface deposits, and resuspended dust are different inventories.

Space Academy · 00

Budget d'incertitude / uncertainty budget



Separate noise, bias, drift, and assumptions

Uncertainty budget: identify contributions before combining uncertainty and making a decision.

10. Five checks before believing a result

Ask whether the final unit answers the question, the sign is physically possible, the magnitude matches an estimate, the result moves in the right direction when an input changes, and the dominant uncertain assumption is visible.

An engineering calculation is a short argument: data, symbols, units, operation, result, check, and physical meaning. Speed comes later; reliable reasoning is the goal.

Final workshop — audit a complete balance

A small installation draws 4.8 kW for 20 hours of a working sol and 1.2 kW for the remaining 4 hours. Daily energy is $4.8 \times 20 + 1.2 \times 4 = 100.8$ kWh. If usable electrical storage is 320 kWh, that is about 3.17 days at the same average consumption, assuming no generation and deliberately ignoring conversion losses. Naming that simplification is part of the answer, because it separates a teaching model from real system behaviour. [Canonical reference](#).

Now assume an 85% round-trip storage efficiency and interpret 320 kWh as energy stored before those losses. Deliverable energy becomes 272 kWh and autonomy falls to about 2.70 days. The answer changes because one explicit assumption changed. Check the result: the final unit is days, $272/100$ must be a little below three, and lower efficiency should reduce autonomy. This is the complete discipline: data → units → operation → assumptions → scale check → physical meaning. [Canonical reference](#).

Daily energy budget

$$E = \Sigma(P_i \Delta t_i)$$

1 — Concrete question

What quantity must be determined in “10. Five checks before believing a result”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

A daily energy budget is built by adding the energy consumed during each power regime

3 — Quantities first

E is total energy consumed over the accounting period; P_i is the power of operating phase i; Δt_i is that phase duration; Σ means sum over all phases.

4 — Formula

$$E = \Sigma(P_i \Delta t_i)$$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $E = 4.8 \times 20 + 1.2 \times 4 = 100.8 \text{ kWh}$; $320 \times 0.85 / 100.8 \approx 2.70 \text{ days}$.

6 — Symbols

E is total energy consumed over the accounting period; P_i is the power of operating phase i; Δt_i is that phase duration; Σ means sum over all phases.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

E is in J, Wh, or kWh; P_i in W or kW; Δt_i in s or h. Each power×time term is an energy, so the summed terms must use compatible energy units.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

The mathematical choice is direct: the relationship directly represents the dependency studied in “10. Five checks before believing a result”.

11 — Assumptions

Time intervals must not overlap and each power level must represent the actual operating regime.

12 — Unit check

E is in J, Wh, or kWh; P_i in W or kW; Δt_i in s or h. Each power×time term is an energy, so the summed terms must use compatible energy units. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

Course case: 4.8 kW for 20 h followed by 1.2 kW for 4 h gives 100.8 kWh.

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

Working backward with the inverse operation provides an independent check.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

The result sizes generation, storage and endurance during loss of generation.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. Calculate daily energy for 3.5 kW during 18 h, then 1.0 kW during 6 h.

Guided solution — open after trying

$$E = \sum P_i \Delta t_i = 3.5 \times 18 + 1 \times 6 = 63 + 6 = 69 \text{ kWh.}$$

Independent exercise. Calculate 2.4 kW for 10 h, then 0.8 kW for 14 h.

Independent solution — open after trying

$$E = 2.4 \times 10 + 0.8 \times 14 = 24 + 11.2 = 35.2 \text{ kWh.}$$

21 — Mission decision

The result sizes generation, storage and endurance during loss of generation.

Integrated case — the Mars shift-control sheet

You take an operations shift and receive four statements: usable water inventory is shown as 8.4 t, average net loop loss is estimated at 27 kg/day, a 3.2 kW non-critical load can be shed, and the dust sensor reads 0.07 mg/m³ over a monitoring period. The first task is not fast arithmetic but putting each datum into a form that answers a question. The water inventory is 8,400 kg. At 27 kg/day with no other input, 8,400/27 is about 311 days. That is theoretical inventory endurance against this one loss stream, not total base autonomy. [Canonical reference.](#)

Now suppose net loss may vary by $\pm 20\%$. The high case is 32.4 kg/day and endurance falls to about 259 days. The low case, 21.6 kg/day, gives about 389 days. Reporting only 311 days would hide the dominant sensitivity. An operational reserve changes the question again: if sixty days must remain untouched, usable inventory under the conservative high-loss case is 8,400 – 60×32.4 = 6,456 kg. The calculation changes because the decision criterion changed. [Canonical reference.](#)

The 3.2 kW load demonstrates a different trap. Shedding it for ten hours saves 32 kWh, not 32 kW. If a battery has 180 kWh of genuinely usable energy, the saving is about 17.8% of that energy. It still says nothing about whether required peak power can be delivered. A system may have plenty of stored energy yet lack instantaneous current capability, so power and energy remain separate columns in an engineering balance.

Finally, 0.07 mg/m³ does not mean '70 percent safe.' The preliminary Mars dust criterion discussed earlier is a 24-hour time-weighted average for a particle class and defined exposure scenarios. You need the sensor averaging window, method, uncertainty, and knowledge of post-EVA peaks. The correct check is whether quantity, unit, integration period, and criterion describe the same physical object. A correct unit attached to the wrong definition still produces a bad decision. [Canonical reference.](#)

A useful shift sheet therefore ends each line with four fields: measured datum or assumption, conversion, result with unit, and validity limit. This discipline becomes the bridge to every later module. Mathematics and physics will become more sophisticated, but the rule remains: never let a number travel without its meaning.

Question	Minimum calculation	What it does not prove
Water	8,400/27 $\approx$ 311 d Canonical reference.	total base autonomy
Sensitivity	8,400/32.4 $\approx$ 259 d Canonical reference.	probability of high loss
Energy	3.2×10 = 32 kWh Canonical reference.	available peak power
Dust	0.07 mg/m ³ Canonical reference.	compliance without time window

Integrated mini-budget for mass, consumption and energy

$$8.4 \text{ t} = 8,400 \text{ kg}; 27 \times 1.20 = 32.4 \text{ kg/day}; 3.2 \text{ kW} \times 10 \text{ h} = 32 \text{ kWh}$$

1 — Concrete question

What quantity must be determined in "Daily energy budget", and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

A simple scenario forces several conversions to be chained without mixing mass, daily consumption and energy

3 — Quantities first

This mini-budget combines three direct calculations: converting tonnes to kilograms, scaling per-person demand to a daily total, and converting power sustained over time into energy.

4 — Formula

$8.4 \text{ t} = 8,400 \text{ kg}$; $27 \times 1.20 = 32.4 \text{ kg/day}$; $3.2 \text{ kW} \times 10 \text{ h} = 32 \text{ kWh}$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $8.4 \text{ t} = 8,400 \text{ kg}$; $27 \times 1.20 = 32.4 \text{ kg/day}$; $3.2 \text{ kW} \times 10 \text{ h} = 32 \text{ kWh}$.

6 — Symbols

This mini-budget combines three direct calculations: converting tonnes to kilograms, scaling per-person demand to a daily total, and converting power sustained over time into energy.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

8.4 t converts to kg; $\text{person count} \times \text{kg}/(\text{person} \cdot \text{day})$ gives kg/day; $\text{kW} \times \text{h}$ gives kWh. Each line keeps its own physical dimension.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

Here the operation expresses the following mechanism: the relationship directly represents the dependency studied in “Daily energy budget”.

11 — Assumptions

Each sub-calculation keeps its own units and the final result must be interpreted separately for each resource.

12 — Unit check

8.4 t converts to kg; $\text{person count} \times \text{kg}/(\text{person} \cdot \text{day})$ gives kg/day; $\text{kW} \times \text{h}$ gives kWh. Each line keeps its own physical dimension. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

$8.4 \text{ t} = 8,400 \text{ kg}$; $27 \times 1.20 = 32.4 \text{ kg/day}$; $3.2 \text{ kW} \times 10 \text{ h} = 32 \text{ kWh}$

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

An inverse calculation should reconstruct one input within rounding error.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

This type of budget quickly reveals which resource becomes limiting before a mission or campaign.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. A stock is 6.5 t; 22 kg/day gets a 15% allowance; a 2.8 kW load runs 12 h. Find kg stock, adjusted demand, endurance and energy.

Guided solution — open after trying

6,500 kg; $q = 22 \times 1.15 = 25.3 \text{ kg/day}$; $t = 6,500/25.3 \approx 257 \text{ days}$; $E = 2.8 \times 12 = 33.6 \text{ kWh}$.

Independent exercise. Repeat with 5.4 t, 18 kg/day plus 20%, and 2.5 kW for 10 h.

Independent solution — open after trying

5,400 kg; $q = 18 \times 1.20 = 21.6$ kg/day; endurance = $5,400/21.6 = 250$ days; $E = 25$ kWh.

21 — Mission decision

This type of budget quickly reveals which resource becomes limiting before a mission or campaign.

11. End-of-module check

- I distinguish mass, force, energy, power, and pressure.
- I convert prefixes safely.
- I read scientific notation. [Canonical mini-lesson](#).
- I turn percentages into decimal factors.
- I check dimensions and magnitude.

Final exercise

A habitat processes 1,200 kg water per day at 98% recovery. Find daily and yearly makeup and its order of magnitude.

Solution: $1,200 \times 0.02 = 24$ kg/day; $\times 365 = 8,760$ kg = 8.76 t/year, roughly 10 t/year. [Canonical reference](#).

Corrected drill set — independent check

1. Convert 0.35 t to kilograms and then grams.

$0.35 \text{ t} \times 1,000 = 350 \text{ kg}$; $350 \text{ kg} \times 1,000 = 350,000 \text{ g}$. Moving tonne $\rightarrow$ kilogram $\rightarrow$ gram multiplies by one thousand twice, which supplies an immediate scale check. [Canonical reference](#).

2. A loop loses 1.5% of 800 kg each day. What makeup is required?

$1.5\% = 0.015$; $800 \times 0.015 = 12$ kg/day. Across thirty unchanged days, makeup associated with this one loss stream is 360 kg. [Canonical reference](#).

3. A 750 W device runs for 16 h. Give energy in kWh.

$750 \text{ W} = 0.75 \text{ kW}$, so energy is $0.75 \times 16 = 12$ kWh. Multiplying 750×16 gives 12,000 Wh, the same energy expressed in a different unit. [Canonical reference](#).

4. A measurement is 4.0 ± 0.3 . Is reporting 4.0000 justified?

A calculator can print the digits but the measurement does not support them. Uncertainty of 0.3 overwhelms ten-thousandth precision. Report a precision consistent with uncertainty and state what that uncertainty represents.

5. Why is $5 \text{ kg} + 3 \text{ kW}$ invalid?

Kilograms and kilowatts have different physical dimensions: mass and power. Only compatible quantities can be added. Dimensional analysis rejects the operation before arithmetic begins.

Deep practice workshop

Before calculating, name the quantity you are trying to find and convert the data into a coherent set of units. In this module, a trustworthy answer depends less on calculator speed than on catching a missing prefix, an impossible power of ten, or false precision. Estimate the order of magnitude first, then compare your reasoning with the solution.

1. Cross conversion

A pump is rated at 2.5 L/min. Convert to m^3/s and estimate water mass moved in 8 h with $\rho = 1,000 \text{ kg}/\text{m}^3$. [Canonical reference](#).

Reasoned solution: $2.5 \text{ L}/\text{min} = 2.5 \times 10^{-3} \text{ m}^3/\text{min} = 4.167 \times 10^{-5} \text{ m}^3/\text{s}$. Over 8 h the volume is $2.5 \times 60 \times 8 = 1,200 \text{ L} = 1.2 \text{ m}^3$, about 1,200 kg. A few litres per minute for several hundred minutes should indeed yield roughly a thousand litres. [Canonical reference](#).

The two conversion routes are the check: volumetric flow and integrated mass should tell the same story. If density differed substantially from $1,000 \text{ kg}/\text{m}^3$, the final mass step would have to be recomputed rather than copied. [Canonical reference](#).

2. Prefix error

A sensor reads $250 \mu\text{g}/\text{m}^3$. Express it in mg/m^3 and compare with $0.1 \text{ mg}/\text{m}^3$. [Canonical reference](#).

Reasoned solution: $250 \mu\text{g}/\text{m}^3 = 0.250 \text{ mg}/\text{m}^3$, or 2.5 times $0.1 \text{ mg}/\text{m}^3$. This alone does not determine acceptability because the cited 2026 NASA requirement is a 24-hour time-weighted average for particles $<10 \mu\text{m}$; duration and size distribution still matter. [Canonical reference](#).

Comparison with a limit is meaningful only after the units match. The factor 2.5 is arithmetic; an exposure decision still depends on duration, particle size, sensor location, and measurement uncertainty.

3. Power versus energy

A load draws 3 kW for 20 min. Find energy in kWh and MJ.

Reasoned solution: $20 \text{ min} = 1/3 \text{ h}$. $E = 3 \times 1/3 = 1 \text{ kWh} = 3.6 \text{ MJ}$. Power is the rate; energy is what is transferred over the stated duration. [Canonical reference](#).

Converting minutes to hours is essential because kilowatts multiplied directly by minutes would not give the requested energy unit. The megajoule conversion provides an independent route and catches a missing factor of 3.6.

4. Loss percentage

A loop processes 5,000 kg/day and recovers 97.5%. What ideal makeup is required?

Reasoned solution: Loss is 2.5%, so $5,000 \times 0.025 = 125 \text{ kg/day}$, or 3,750 kg in 30 days. Percentages should be translated into absolute mass before logistics are judged. [Canonical reference](#).

A percentage becomes an operational mass when applied to throughput. That translation matters for storage and makeup: a small relative loss can become tonnes over a long campaign.

5. Relative uncertainty

A scale reports $42.0 \pm 0.6 \text{ kg}$. What is relative uncertainty?

Reasoned solution: $0.6/42.0 \approx 0.0143$, or 1.43%. Stating $\pm 0.6 \text{ kg}$ alone makes comparisons across very different measurement scales difficult. [Canonical reference](#).

Relative uncertainty lets measurements at very different scales be compared. The percentage expresses spread relative to the reading, but it does not prove absence of bias or a valid calibration.

6. Dimensional check

Why does $P \times t/m$ have units of J/kg?

Reasoned solution: P is $W = \text{J/s}$. Multiplying by time in seconds gives joules and dividing by kilograms gives J/kg. The check confirms specific-energy dimensions but does not by itself establish the correct physical model. [Canonical mini-lesson](#).

7. Order of magnitude

An architecture processes $4 \times 10^6 \text{ kg}$ of local material in 200 days. What average t/day is required? [Canonical reference](#).

Reasoned solution: $4 \times 10^6 \text{ kg} = 4,000 \text{ t}$. Dividing by 200 days gives 20 t/day. A machine processing 0.25 t/h for 16 h/day supplies only 4 t/day, so throughput, operating hours, or machine count must increase. [Canonical reference](#).

The average throughput does not describe machine availability. Comparing the required daily tonnage with one machine's realistic output immediately shows whether more units, more operating hours, or a longer campaign are needed.

8. Capstone

Build a check sheet for a 30 m^3 airlock at $0.06 \text{ mg}/\text{m}^3$ dust, 95% filter efficiency, $180 \text{ m}^3/\text{h}$ recirculation for 15 min. Find initial airborne mass and discuss an ideal removal estimate. [Canonical reference](#).

Reasoned solution: $M_0 = 0.06 \times 30 = 1.8 \text{ mg}$. In 15 min the filter sees a nominal 45 m^3 , more than the airlock volume because air is recirculated. Therefore $C \times 45 \times 0.95$ is not a valid one-pass mass removal without a dynamic mixing model; the same air can cross the filter repeatedly. The correct lesson is to recognize when a static balance must become a decay model. [Canonical reference](#).

The capstone separates airlock volume from recirculated air volume: a filter can process the same air more than once. Captured mass therefore depends on mixing, real efficiency, and repeated passes, not flow multiplied by time alone.

Additional advanced problems

1. Unit chain

A 1.8 kW pump runs 45 min. Energy in kWh and MJ?

Reasoned solution: 45 min=0.75 h. $E=1.8 \times 0.75=1.35$ kWh=4.86 MJ. The same result is $1,800 \text{ J/s} \times 2,700 \text{ s}=4.86 \text{ MJ}$.

[Canonical reference.](#)

2. Concentration margin

A limit is 0.1 mg/m^3 and measurement is $0.072 \pm 0.010 \text{ mg/m}^3$. Is the limit exceeded under a simple worst-case reading?

[Canonical reference.](#)

Reasoned solution: Upper reading= 0.082 mg/m^3 , still below 0.1. This does not replace duration, particle-size, or sensor-bias analysis, but immediate numerical margin is 0.018 mg/m^3 . [Canonical reference.](#)

3. Thousand factor

Why does 3 MW for 2 h not equal “6 MWh of power”?

Reasoned solution: MW is power and MWh is energy. Integration over two hours gives 6 MWh. Calling that “power” mixes dimensions.

4. Mini-project

Build a unit sheet for habitat water, air, energy, and dust.

Reasoned solution: A strong sheet lists variable name, symbol, SI unit, operational unit, expected range, precision, and sampling frequency. It prevents kg/day, L/min, kW, kWh, and mg/m^3 from being mixed. [Canonical reference.](#)

Operational numeracy laboratory — make every quantity auditable

This R54 parity extension deepens the operational reasoning of the English curriculum without replacing the existing lesson. It is designed to make the learner explain assumptions, verify a calculation or chain, and convert the result into a decision.

Keep quantity, value and unit together

A number is not yet engineering information. The useful object is a quantity with a meaning, a value, a unit, a source and a time stamp when the value can change. A crew member reading 45 on a display must know whether the display represents kilopascals, litres per minute, percent state of charge or degrees Celsius before any decision is made. In a Mars settlement, this discipline prevents values from different subsystems from being copied into the same worksheet merely because they look numerically similar. The habit to build is simple: write the quantity name first, then the symbol if one is used, then the value and unit. If a value is estimated rather than measured, mark it as an estimate. If it is a limit, mark the authority or procedure that defines the limit.

Convert explicitly and preserve the chain

Unit conversion should be visible enough that another person can reconstruct it. Convert with factors equal to one, keep prefixes attached to the correct term and do not round in the middle of a chain unless the procedure explicitly requires it. For example, converting a daily water demand into an hourly average is not the same as claiming the real demand is constant every hour. The conversion changes the time basis; it does not erase peaks. This distinction matters whenever a tank, pump, battery or thermal store must absorb short-duration demand. A good calculation sheet therefore separates average rate, peak rate, stored quantity and reserve margin rather than collapsing them into a single number.

Estimate before using the calculator

Before pressing keys, predict the sign and order of magnitude. If a habitat contains tens of cubic metres of air, a result claiming billions of kilograms of gas is not a small arithmetic error; it is evidence that a prefix, exponent or unit has been mishandled. Estimation is particularly useful with scientific notation because it exposes factors of one thousand or one million immediately. The calculator should confirm a physical expectation, not create the expectation. When the exact result disagrees with the rough estimate, stop and inspect the chain before carrying the value into a downstream budget.

[Canonical mini-lesson.](#)

Separate precision from accuracy

A display with six digits can still be based on a poor measurement or a crude model. Report only the precision supported by the inputs and by the purpose of the decision. In a training calculation, extra digits may be kept internally to avoid cumulative rounding, but the final statement should explain the uncertainty or the practical resolution. The central question is not 'how many digits can the calculator show?' but 'how many digits can the evidence defend?' This is also why two independently measured quantities should not be forced to agree by silently adjusting one of them.

Use dimensional checks as an error detector

Dimensional analysis is a fast independent check. A duration divided by a duration must be dimensionless; a mass flow multiplied by a duration must produce a mass; power multiplied by time must produce energy. A dimensionally correct equation can still be physically wrong, but a dimensionally wrong equation cannot be rescued by a plausible numerical answer. In operational work, write at least one line that shows the unit cancellation for any calculation that will be reused by another module or inserted into a mission budget.

Turn arithmetic into a decision record

The end product of a calculation is not the number alone. Record the inputs, assumptions, method, result, margin and decision. If the answer depends on a parameter that is poorly known, identify that parameter as a measurement priority. If a decision changes when one input moves by ten percent, the system is sensitive to that input and should not be treated as robust. This final step turns elementary numeracy into engineering traceability and prepares the learner for every later Space Academy module.

Progressive mastery drills — eight linked checks

▼ Drill 1 — Reading a quantity

A console shows 0.0065 with no unit in the exported log. Explain why the value cannot be used yet and list the metadata needed before it enters a budget.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

▼ Drill 2 — SI-unit chain

Convert a mixed statement of litres, cubic metres and kilograms into a single consistent ledger while preserving density assumptions explicitly.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

▼ Drill 3 — Prefixes

Audit a table containing mW, W, kW and MW and identify the type of error that could create a factor-of-one-thousand discrepancy.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

▼ Drill 4 — Scientific notation

Estimate the result of multiplying 3.2×10^4 by 6×10^{-3} before calculating the exact product. [Canonical reference.](#)

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

▼ Drill 5 — Ratios and percentages

Explain the difference between a 98% recovery fraction and a 2% daily loss when the system boundary or time basis changes.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

▼ Drill 6 — Dimensional analysis

Check whether a proposed calculation of energy from power divided by time can be dimensionally correct.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

▼ Drill 7 — Uncertainty

Two sensors report values that differ by 4%, while each has stated uncertainty. Describe how to decide whether the disagreement is significant.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

▼ Drill 8 — Inventory decision

Turn a tank volume and daily demand into a days-of-supply statement that includes protected reserve and limitations.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

▼ Integrated exercise — Audit a mixed-unit consumables statement

A training log states that a reserve tank contains 0.42 m³ of water, the planned essential demand is 38 L per person per day for four people, and the procedure requires a 20% protected reserve. Re-express all quantities on a common basis, calculate the nominal days of supply, then calculate the usable days after protecting the reserve. State every assumption and explain why the answer is only an operational estimate. [Canonical reference](#).

Reasoned solution. Convert 0.42 m³ to 420 L. Nominal daily demand is $4 \times 38 = 152$ L/day, so the nominal duration is about 2.76 days. Protecting 20% leaves 336 L usable, or about 2.21 days at the assumed constant essential demand. The result does not predict real consumption peaks, leaks, inaccessible volume or water quality. Those limitations belong in the decision record. [Canonical reference](#).

Primary-source bridge for this extension. [Official source 1](#) [Official source 2](#) [Official source 3](#). These links are evidence anchors already present in the French reference module; values and limits must still be checked against the source version applicable to the mission.

Sources and references

These references anchor SI units, uncertainty, and the two Mars examples used in the exercises. Teaching flow assumptions are identified as such when they do not come directly from a source.

- [NIST — Definitions of SI Base Units](#) — SI base units and exact defining constants.
- [NIST Technical Note 1297 — Measurement Uncertainty](#) — Framework for expressing measurement uncertainty.
- [NASA — ISS 98% water recovery milestone](#) — Demonstrated total water recovery milestone and prior 93–94% level.
- [NASA — Martian dust exposure limits](#) — 2026 preliminary exposure requirement for Martian particles under 10 µm.

First Man foundation dossier — numbers that can survive a review board

A calculation is not trustworthy because a calculator produced digits. It becomes trustworthy when another person can identify the quantity, the unit, the source, the conversion chain, the uncertainty and the decision that depends on it. This closure dossier turns the first module into a miniature engineering review. The learner moves from reading a value to defending why a value is usable.

A quantity is more than a number

Engineers separate the physical quantity from the numerical value written beside it. '3.2' is not yet useful information: it could be kilograms, kilowatts, milligrams per cubic metre, metres per second or a dimensionless ratio. The unit gives the quantity a grammar, and the context gives the unit a purpose. A reviewable record therefore keeps four items together: name of quantity, numerical value, unit and status. Status matters because a measured value, a design requirement, a forecast and a teaching assumption do not carry the same authority.

The SI system is the common language used to prevent silent conversion errors. The [NIST — Definitions of SI Base Units](#) is a primary reference for base-unit definitions. In this course, SI is not treated as a vocabulary test. It is treated as error control: if a pressure is entered in kilopascals while a program expects pascals, or a length in kilometres while a formula expects metres, the arithmetic may remain perfectly legal while the engineering conclusion becomes wrong by factors of one thousand or one million.

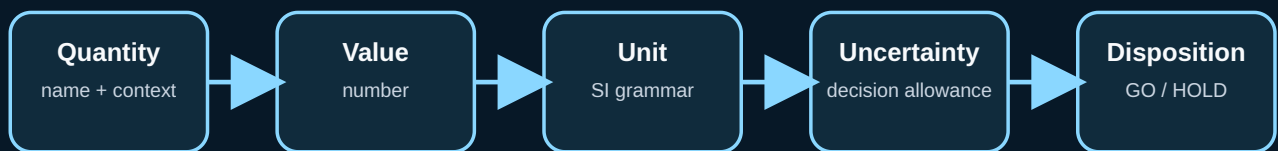
Conversions must leave a visible trail

A defensible conversion shows the cancellation. Converting 2.4 kilometres to metres is not a magic decimal move: $2.4 \text{ km} \times 1,000 \text{ m/km} = 2,400 \text{ m}$. Writing the conversion factor makes the kilometre unit cancel visibly. The same discipline scales to density, flow, energy and dose. When several conversions are chained, each factor becomes an audit point. The chain may look slower than mental arithmetic, but it is faster than finding an error after a test, EVA or cargo manifest has already been approved. [Canonical reference](#).

A useful habit is to estimate first, convert second, calculate third and compare the result with the estimate. If a habitat requires a few cubic metres of water, an answer of a few litres or a few million litres should trigger immediate suspicion. Orders of magnitude are therefore not an academic side topic; they are the fastest gross-error detector available to a beginner.

Measurement evidence chain

From physical quantity to released engineering decision.



Evidence is traceable only when every link remains attached

Delta-Sierra pedagogical synthesis · schematic, not to scale

From physical quantity to released engineering decision. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

Precision, accuracy and uncertainty are different questions

A display can show six decimal places and still be wrong. Precision describes repeatability or numerical resolution; accuracy describes closeness to the relevant value; uncertainty describes the range within which the result is expected to lie under stated conditions. [NIST Technical Note 1297 — Measurement Uncertainty](#) provides formal guidance on expressing measurement uncertainty. The operational lesson is simpler: never let extra digits disguise weak evidence.

If a dust sensor reports 0.843 mg/m^3 with an uncertainty of $\pm 0.12 \text{ mg/m}^3$, the decision maker should not reason from 0.843 alone. The upper plausible value is 0.963 mg/m^3 under that uncertainty model. If the applicable design or exposure threshold is 0.90 mg/m^3 , the nominal reading looks acceptable but the uncertainty envelope crosses the limit. That is a HOLD for investigation, not a confident GO based on the central value. [Canonical reference](#).

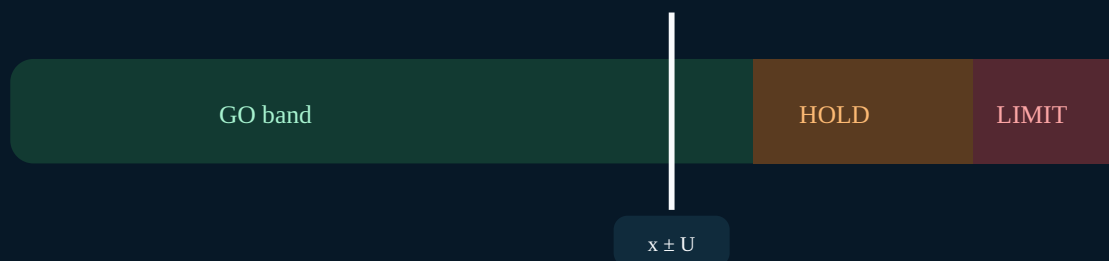
Percentages must declare their reference

A percentage is always a ratio to a reference. 'Recovery improved by 5%' is ambiguous unless the baseline is stated. A system moving from 80% to 85% recovery gains five percentage points but improves by 6.25% relative to the original 80%. Those are not interchangeable statements. The same distinction appears in battery state of charge, filtration efficiency, spare-stock reductions and schedule growth.

Water-loop reporting is a good example. NASA has reported very high water-recovery performance on the International Space Station; the [NASA — ISS water recovery milestone](#) provides mission context. A Mars design still has to separate gross water demand, recovered water, unrecovered losses, verified potable inventory and emergency reserve. A single percentage cannot replace that inventory logic.

Decision band with uncertainty

Measured value, uncertainty envelope, HOLD band and release threshold.



A central value can be inside the limit while its uncertainty envelope reaches HOLD

Delta-Sierra pedagogical synthesis · schematic, not to scale

Measured value, uncertainty envelope, HOLD band and release threshold. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

Numbers become mission evidence only after a decision rule

A measurement without a threshold is information, not yet a decision. An engineering record should state what happens if the value is comfortably inside the acceptable band, close to the boundary, or outside it. The rule should also identify who may release the system, what independent evidence is required and whether the decision can be reversed. This prevents teams from inventing criteria after seeing an inconvenient result.

Martian dust illustrates why the rule must be tied to evidence rather than visual intuition. Dust affects health, mechanisms, optics and seals, and relevant exposure work is documented by [NASA — Martian dust exposure limits](#). 'The air looks clear' is not a measurement. The beginner should learn to ask: what was measured, with what unit, over what time, with what uncertainty, against which threshold and with which response if the threshold is approached?

Worked review packet — from raw measurement to released value

A habitat maintenance team replaces a flow sensor on a water-processing branch. The new instrument reports 82.4 L/h while the old branch model predicted 80 L/h. The correct response is not to average the two numbers and move on. The team first records instrument identity, calibration status, location, timestamp, fluid state and the conversion path used by the display. It then compares the reading with an independent timed-volume check. The point of the exercise is to make the evidence chain visible before any conclusion is attached to the number.

Suppose the timed-volume check produces 81.0 L/h with an estimated uncertainty of ± 2.0 L/h. The sensor result and the independent check overlap within the uncertainty band, so the difference is not automatically a fault. The next question is operational: does the allowed process window tolerate either value? If the branch must remain between 76 and 86 L/h, both measurements support continued operation, but the work order should still record that a new sensor was installed and that the cross-check agreed within the stated uncertainty. If the allowed upper limit were 82 L/h, the same evidence would justify a HOLD until the calibration or process state was clarified.

This example illustrates why a beginner needs more than arithmetic. The final review packet should contain the original reading, independent check, units, uncertainty, acceptance band, decision, person responsible for release and the next verification date. A future operator should not have to infer why the value was accepted. That is the difference between a number in a notebook and engineering evidence.

Record item	Example	Why it matters
Quantity	Water branch flow	Prevents a number being detached from its meaning
Primary reading	82.4 L/h	Instrument output
Independent check	81.0 ± 2.0 L/h	Challenges sensor bias
Acceptance band	76–86 L/h	Connects evidence to decision
Disposition	GO with documented replacement	Makes ownership explicit

Integrated zero-prerequisite challenge — one page of quantities, five traps

Review a fictional maintenance sheet containing: battery energy 48 kWh, heater power 6 kW, water stock 1.8 m³, dust concentration 0.62 mg/m³ and a recovery ratio of 94%. For each entry, write the physical meaning, convert it into a second useful unit where appropriate, state one plausible uncertainty source and name one mistake that could arise from reading the value without context. For the battery, convert 48 kWh into an ideal endurance only after a load is defined. For the water, convert 1.8 m³ to 1,800 L before comparing it with daily demand. For the recovery ratio, identify the reference stream before multiplying it by any inventory. [Canonical reference](#).

The point is not to produce one master number. It is to practice resisting premature calculation. Some values are stocks, some are rates, some are concentrations and some are dimensionless ratios. Putting them in the same spreadsheet column because they are all 'numbers' destroys the physical structure. The learner should be able to look at the five entries and immediately ask which can be added, which can be multiplied, which require time integration and which need a threshold before they support action.

Review drills — move from explanation to operational judgement

- Unit trap.** A cargo list says 2.8 t while a spreadsheet column is labelled kg. Write the conversion chain and identify the error if 2.8 is entered directly.
- Reference trap.** A recovery rate rises from 90% to 93%. State both the change in percentage points and the relative percentage increase.
- Uncertainty trap.** Two instruments disagree by less than their displayed resolution but more than their stated uncertainty. Explain which quantity governs the engineering concern.
- Decision trap.** A value is below a limit but the uncertainty band crosses it. Write a HOLD rule that specifies the next evidence required.

Decision margin with uncertainty allowance

$$M = L - (x + U)$$

1 — Concrete question

What quantity must be determined in “Review drills — move from explanation to operational judgement”, and how does this relationship calculate it without losing the physical meaning?

2 — Intuition without symbols

A limit is not truly protected if measurement uncertainty can still push a plausible value beyond the threshold

3 — Quantities first

M is the remaining decision margin, L is the limiting allowance or available capacity, x is the nominal demand or estimate, and U is the uncertainty allowance added conservatively to that demand.

4 — Formula

$$M = L - (x + U)$$

5 — Read aloud

Read the relationship from left to right, naming each quantity and operation: $M = L - (x + U)$.

6 — Symbols

M is the remaining decision margin, L is the limiting allowance or available capacity, x is the nominal demand or estimate, and U is the uncertainty allowance added conservatively to that demand.

7 — Pronunciation

Say the operations, subscripts and exponents explicitly so another person can reconstruct the relationship without seeing the page.

8 — Units

M, L, x, and U must all use the same unit (for example kg, kWh, L, or another mission resource unit), because they are subtracted directly.

9 — Convention

Keep the sign, time-base and system boundary defined in the section; do not change reference halfway through the calculation.

10 — Why this operation

This operation is used because the relationship directly represents the dependency studied in “Review drills — move from explanation to operational judgement”.

11 — Assumptions

Limit, measurement and uncertainty must use the same basis and a declared uncertainty convention.

12 — Unit check

M, L, x, and U must all use the same unit (for example kg, kWh, L, or another mission resource unit), because they are subtracted directly. The unit check must recover the physical dimension expected for the requested result.

13 — Numerical case

If limit $L = 50$, measured value $x = 42$ and conservative uncertainty $U = 3$, then $M_{\text{decision}} = 50 - (42 + 3) = 5$.

14 — Why each operation

Each operation corresponds to one reasoning step: it combines, compares or scales quantities exactly as required by the model.

15 — Algebra check

A second calculation path or inverse operation should recover the original quantity.

16 — Mental estimate

Round the inputs to one useful digit and check that the detailed result remains in the same order of magnitude.

17 — Interpretation

This margin separates a measured result from a decision robust enough for operations.

18 — What it does not prove

This calculation proves neither universal model validity nor input-data quality; it answers only the declared scenario and assumptions.

19 — Sensitivity or limit case

Vary one input at a time to identify which assumption drives the result most strongly.

20 — Guided and autonomous practice

Guided exercise. A limit is 50 units, the measured value is 42 and conservative uncertainty is 3. Calculate decision margin.

Guided solution — open after trying

$M_{\text{decision}} = L - (x + U) = 50 - (42 + 3) = 5$ units. Margin remains positive.

Independent exercise. With $L = 80$, $x = 74$ and $U = 4$, calculate margin.

Independent solution — open after trying

$80 - (74 + 4) = 2$ units: still admissible, but with little margin.

21 — Mission decision

This margin separates a measured result from a decision robust enough for operations.

Normalized scientific notation

$x = a \times 10^n$, with $1 \leq |a| < 10$

1 — Concrete question

How should “normalized scientific notation” be used without losing order of magnitude or the meaning of the calculated quantity?

2 — Intuition without symbols

Separate the useful digits from decimal scale so it is immediately clear whether a value is near one, one thousand or one million.

3 — Quantities first

x is the written quantity, a the normalized mantissa and n the integer exponent.

4 — Formula

$x = a \times 10^n$, with $1 \leq |a| < 10$

5 — Read aloud

Read the relationship by naming every operation: $x = a \times 10^n$, with $1 \leq |a| < 10$.

6 — Symbols

x is the written quantity, a the normalized mantissa and n the integer exponent.

7 — Pronunciation

Name subscripts, exponents, angles and functions explicitly before entering numbers.

8 — Units

x and a carry the same unit; the power of ten is dimensionless.

9 — Convention

Keep the sign, angle and significant-figure convention stated in the course.

10 — Why this operation

The relationship isolates the useful mathematical structure so scale or direction is handled without ambiguity.

11 — Assumptions

The mantissa stays between one inclusive and ten exclusive in absolute value, and significant figures must not exceed input precision.

12 — Unit check

x and a carry the same unit; the power of ten is dimensionless. The left and right sides must describe the same physical dimension.

13 — Numerical case

$6,771,000 \text{ m} = 6.771 \times 10^6 \text{ m}$.

14 — Why each operation

Each operation corresponds to an explicit mathematical property; it must not be replaced by an unexplained decimal shift or calculator keystroke.

15 — Algebra check

Work backward from the calculated form to the starting form to check the algebra independently of numerical entry.

16 — Mental estimate

Before calculating, bound the answer with an order of magnitude or simple geometry to catch a gross error.

17 — Interpretation

Use this notation to check the order of magnitude of every very large or very small mission input before using it in a calculation.

18 — What it does not prove

The calculation validates neither the input data nor the physical model that led to this relationship.

19 — Sensitivity or limit case

Change one input at a time to see whether the result responds linearly, quadratically or through a change of direction.

20 — Guided and autonomous practice

Guided exercise. Write 4,520,000 in normalized scientific notation.

Guided solution — open after trying

Move the decimal six places: $4,520,000 = 4.52 \times 10^6$, with $1 \leq 4.52 < 10$.

Independent exercise. Write 0.00073 in scientific notation.

Independent solution — open after trying

$0.00073 = 7.3 \times 10^{-4}$; the exponent is negative because the value is below 1.

21 — Mission decision

Use this notation to check the order of magnitude of every very large or very small mission input before using it in a calculation.

Final numeracy review — would another operator trust the number?

- Can the quantity be named without looking at the column heading?
- Is the unit explicit and compatible with every operation?
- Can every conversion be reconstructed from written factors?
- Is uncertainty separated from display precision?
- Does the decision threshold use the same basis and averaging period?
- Is the GO/HOLD disposition recorded with its evidence source?

A beginner passes this module when arithmetic becomes auditable. Before accepting a result, deliberately try to break it with a unit check, an order-of-magnitude estimate and an uncertainty question. If the answer survives all three, then connect it to the operational rule rather than stopping at the digits.

Primary-source bridges used in this closure dossier

- [NIST — Definitions of SI Base Units](#)
- [NIST Technical Note 1297 — Measurement Uncertainty](#)
- [NASA — ISS water recovery milestone](#)
- [NASA — Martian dust exposure limits](#)

Closure rule. A numeracy review is closed only when value, unit, uncertainty, source and disposition remain traceable together.