

Significant Figures and Measurement

How do you count significant figures and use them in calculations?

●○○ Beginner

Foundations

Last reviewed 4 October 2026

What is it?

Every measurement has some **uncertainty**. A balance that reads 12.47 g is certain about 12.4 and estimates the last digit, 7. The **significant figures** (sig figs) in a number are all the digits known with certainty **plus one estimated digit**.

A measurement therefore has three parts: a **number**, a **unit**, and an implied **uncertainty**. 12.47 g and 12.5 g describe the same object, but the first was measured more precisely.

KEY IDEA

The number of significant figures shows how precisely something was measured. A calculated answer can never be more precise than the measurements it came from.

Why does it matter?

- **Honest results.** Writing 2.8409090 g/mL when your data supports only 2.84 g/mL claims a precision you don't have.
- **Comparing data.** Significant figures tell another scientist how far to trust your numbers.
- **Exams and lab reports.** Answers are expected to the correct number of significant figures, with units.

How does it work?

1. Counting significant figures

Rule	Example	Sig figs
Non-zero digits are always significant	4.56 g	3
Zeros between non-zero digits are significant	1.05 m	3
Leading zeros (before the first non-zero digit) are not	0.0042 L	2
Trailing zeros after a decimal point are significant	2.500 mL	4
Trailing zeros in a whole number with no decimal point are ambiguous	1200 m	2, 3 or 4

Exact numbers have unlimited significant figures: counted numbers (3 beakers) and defined relationships (1 km = 1000 m; 1 in = 2.54 cm exactly). They never limit an answer.

2. Scientific notation

Scientific notation removes the ambiguity: every digit written in the first part is significant.

- $0.000\ 520\ \text{m} = 5.20 \times 10^{-4}\ \text{m}$ (3 sig figs)
- $1200\ \text{m}$ to 3 sig figs = $1.20 \times 10^3\ \text{m}$

3. Calculations

Operation	Rule	Example
$\times$ and $\div$	answer has the fewest significant figures of the inputs	$4.56\ \text{cm} \times 1.4\ \text{cm} = 6.384\ \text{cm}^2 \rightarrow \mathbf{6.4\ \text{cm}^2}$ (2 s.f.)
$+$ and $-$	answer has the fewest decimal places of the inputs	$25.12\ \text{g} + 3.4\ \text{g} = 28.52\ \text{g} \rightarrow \mathbf{28.5\ \text{g}}$ (1 d.p.)

In a calculation with several steps, **keep extra digits** in the intermediate results and round only the final answer.

4. Rounding

Look at the digits you are dropping:

Dropped part	Rule	Example (to 3 s.f.)
less than half (starts with 0–4)	keep the last digit	$0.0012349\ \text{m} \rightarrow 0.00123\ \text{m}$
more than half (5 followed by any non-zero digit, or 6–9)	round up	$2.4562\ \text{g} \rightarrow 2.46\ \text{g}$
exactly half (5, 50, 500...)	round to the even digit	$2.345\ \text{g} \rightarrow 2.34\ \text{g}$; $2.355\ \text{g} \rightarrow 2.36\ \text{g}$

The “round half to even” rule means that, over many results, exact halves are rounded up and down equally often, so averages are not pushed upward. Note that most calculators and spreadsheet ROUND functions always round an exact 5 up, so apply this rule yourself.

5. Accuracy, precision and replicate measurements

- **Accuracy:** how close a result is to the **true (accepted) value**.
- **Precision:** how close **repeated measurements** are to **each other**.

A single measurement cannot show its own precision. That’s why careful work uses **replicate measurements**: the same measurement repeated, usually in **triplicate** (3 times) or **quintuplicate** (5 times), or more. From the replicates:

$$\bar{x} = \frac{\sum x_i}{n}$$

$$s = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}}$$

$$\text{RSD} = \frac{s}{\bar{x}} \times 100\%$$

- The **mean**, $\bar{x}$, is the best estimate of the value. Comparing it with the accepted value, x_{true} , measures **accuracy**: $\text{error} = \bar{x} - x_{\text{true}}$, and percent error = $\frac{\bar{x} - x_{\text{true}}}{x_{\text{true}}} \times 100\%$.
- The **standard deviation**, s , measures **precision**: a small s means the replicates agree closely. The **relative standard deviation** (RSD) lets you compare the precision of results of different sizes.

Two kinds of error affect results. **Random errors** scatter replicates on both sides of the mean and lower **precision**. **Systematic errors** (for example a badly calibrated balance) shift every result the same way and lower **accuracy**, even when the precision is excellent.

THINK OF IT LIKE THIS

Measuring with a ruler marked only in centimetres is like reading a clock with only an hour hand: you can estimate “about half past”, but not the exact minute. A ruler marked in millimetres lets you estimate one more digit, so your measurement has one more significant figure.

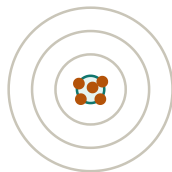
MORE PRECISELY

Significant figures are a simple way to show uncertainty. In research, uncertainty is stated explicitly, usually as the mean $\pm$ the standard deviation (for example 10.04 ± 0.02 mL, $n = 5$), and is combined through calculations using statistics. The standard deviation uses $n - 1$ (the “sample” standard deviation) because the mean was calculated from the same data. With only two measurements it means little, which is why at least three replicates are recommended.

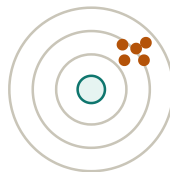
Visualise it

Accuracy and precision

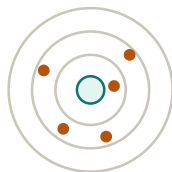
Centre = true value; dots = repeated measurements.



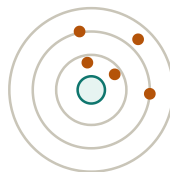
Accurate and precise
close together, on target



Precise, not accurate
close together, off target



Accurate, not precise
spread out, average on target



Neither
spread out and off target

Accuracy is about hitting the true value; precision is about agreeing with each other.

Worked example

WORKED EXAMPLE: Counting significant figures

Question: How many significant figures are in (a) 0.00420 g (b) 105.0 mL (c) 3.010×10^5 J?

Step 1 0.00420 g: leading zeros don't count; the trailing zero after the decimal point does: **3**.

Step 2 105.0 mL: the zero between 1 and 5 counts, and so does the trailing zero after the decimal point: **4**.

Step 3 3.010×10^5 J: every digit in 3.010 counts: **4**.

WORKED EXAMPLE: Multiplying and dividing

Question: A sample has a mass of 10.0 g and a volume of 3.52 mL. What is its density?

Step 1 $\rho = \frac{m}{V} = \frac{10.0 \text{ g}}{3.52 \text{ mL}} = 2.8409 \dots \text{ g/mL}$

Step 2 Both inputs have 3 sig figs, so the answer has 3: **2.84 g/mL**.

 WORKED EXAMPLE: Adding

Question: Masses of 12.0 g, 0.335 g and 4.5 g are added to a beaker. What is the total mass?

Step 1 $12.0 \text{ g} + 0.335 \text{ g} + 4.5 \text{ g} = 16.835 \text{ g}$

Step 2 The fewest decimal places is one (12.0 g and 4.5 g), so the answer is **16.8 g**.

 WORKED EXAMPLE: Assessing accuracy and precision from replicates

Question: A student checks a 10.00 mL pipette by delivering water five times (quintuplicate) and finds the volumes 10.05 mL, 10.02 mL, 10.06 mL, 10.03 mL and 10.04 mL. Assess the accuracy and precision.

Step 1 Mean: the sum is 10.05 mL + 10.02 mL + 10.06 mL + 10.03 mL + 10.04 mL = 50.20 mL, so

$$\begin{aligned}\bar{x} &= \frac{50.20 \text{ mL}}{5} \\ &= 10.04 \text{ mL}\end{aligned}$$

Step 2 Deviations from the mean: +0.01 mL, -0.02 mL, +0.02 mL, -0.01 mL and 0.00 mL. Their squares are 0.0001 mL², 0.0004 mL², 0.0004 mL², 0.0001 mL² and 0.0000 mL², which add up to 0.0010 mL².

Step 3 Standard deviation:

$$\begin{aligned}s &= \sqrt{\frac{0.0010 \text{ mL}^2}{5 - 1}} \\ &= 0.016 \text{ mL}\end{aligned}$$

Step 4 $\text{RSD} = \frac{0.016 \text{ mL}}{10.04 \text{ mL}} \times 100\% = 0.16\%$ (the units of mL cancel): **very precise**.

Step 5 Error = 10.04 mL - 10.00 mL = +0.04 mL, a percent error of $\frac{+0.04 \text{ mL}}{10.00 \text{ mL}} \times 100\% = +0.4\%$. The error is more than twice the standard deviation, so the pipette has a small **systematic error**: it delivers slightly too much.

Answer: 10.04 ± 0.02 mL (n = 5): precise, but slightly inaccurate.

Common mistake

 **COMMON MISTAKE:** Copying every digit from the calculator

$100.0\text{ g} \div 3.0\text{ mL} = 33.333 \dots\text{ g/mL}$, but 3.0 mL has only 2 sig figs, so the answer is **33 g/mL**.

 **COMMON MISTAKE:** Using the sig-fig rule for addition

For addition and subtraction, count **decimal places**, not significant figures: $6.38\text{ cm} - 2.1\text{ cm} = 4.28\text{ cm} \rightarrow \mathbf{4.3\text{ cm}}$.

 **COMMON MISTAKE:** Dropping significant zeros

A volume of a cube with side 2.00 cm is $(2.00\text{ cm})^3 = 8.00\text{ cm}^3$, not 8 cm^3 . The zeros show the precision.

NOTATION NOTE

- “s.f.” or “sig figs” = significant figures; “d.p.” = decimal places.
- A decimal point after a whole number, as in “100.” or “500. nm”, shows that the trailing zeros are significant (3 sig figs).

Remember this

REMEMBER THIS

- Sig figs = certain digits + one estimated digit. Leading zeros never count; trailing zeros after a decimal point always do.
- $\times$ and $\div$: fewest significant figures. $+$ and $-$: fewest decimal places.
- Exact numbers (counts, definitions) don't limit precision. Round only the final answer; round an exact 5 to the even digit.
- Accuracy: mean close to the true value (error). Precision: replicates close to each other (standard deviation).
- Measure in replicate (at least triplicate) and report mean $\pm$ standard deviation with the number of measurements.

References

1. Brown, T. L.; LeMay, H. E., Jr.; Bursten, B. E.; Murphy, C. J.; Woodward, P. M.; Stoltzfus, M. W. Chemistry: The Central Science, 15th ed.; Pearson, 2022.

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