Experimental programme

Tools and inquiry · SL

Faster than light?

> A measurement means little until you know its uncertainty.

- The 2011 anomaly prompted timing-chain checks; later neutrino measurements agreed with light speed.
- Offsets can survive repeated readings; uncertainty and calibration matter.
- Uncertainty $\rightarrow$ graphs $\rightarrow$ design $\rightarrow$ evaluation.

Reading instruments

Single reading

Resolution is only one contribution.

Check calibration, alignment and response.

Repeated readings

Mean estimates the stable central value.

Half-range is a simple scatter estimate, not a universal confidence interval.

Timing a pendulum

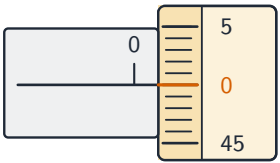
1. **Mean.** Given times for ten cycles: 15.2, 15.5, 15.3, 15.6, 15.4 s. Mean $= 77.0 / 5 = 15.4$ s.
2. **Uncertainty.** half the range $= 0.4 / 2 = 0.2$ s
3. **Period.** 15.4 ± 0.2 s for 10, so $T = 1.54 \pm 0.02$ s

Decision

$T = 1.54 \pm 0.02$ s

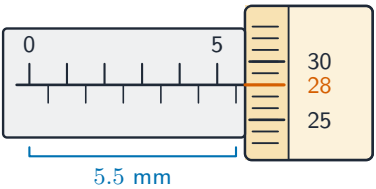
Reading a micrometer

(a) zero check



reads 0.00 mm

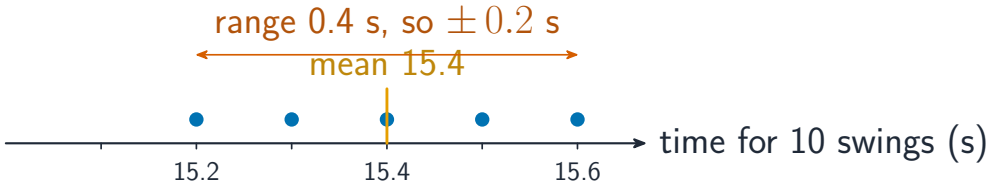
(b) a measurement



$5.5 + 0.28 = 5.78$ mm

Check the zero reading first

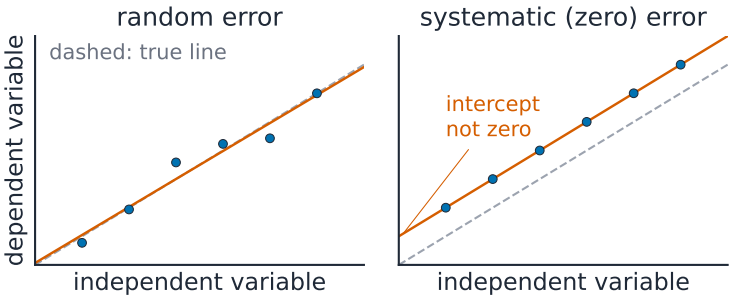
Uncertainty from repeats



15.4 ± 0.2 s for 10 swings, so $T = 1.54 \pm 0.02$ s

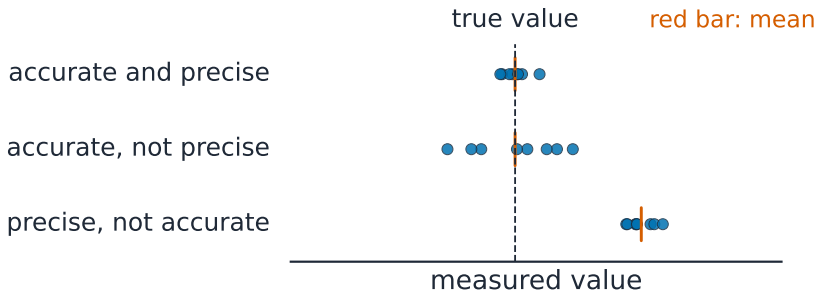
Half the range: ± 0.2 s

Random and systematic errors



- Repeats reduce random uncertainty in the mean, not a shared calibration bias.
- A constant vertical offset changes **intercept**; a scale factor can change **gradient**.

Accuracy and precision



- **Accurate** means close to the true value.
- **Precise** means repeated readings agree with each other.

Three ways to write an uncertainty

> Carry extra digits; round the final value to the uncertainty's decimal place.

- $L = 2.50 \pm 0.05$ m: absolute 0.05 m, fractional 0.02, percentage 2 %.
- Uncertainty to 1 significant figure; value to the same decimal place.

Propagating uncertainties

- Sums/differences: add separate absolute bounds.
- Products/quotients: add fractional bounds; powers: multiply by $|n|$.

$$\frac{\Delta y}{|y|} \approx \frac{\Delta a}{|a|} + \frac{\Delta b}{|b|} + \frac{\Delta c}{|c|}$$

$$\frac{\Delta(a^n)}{|a^n|} \approx |n| \frac{\Delta a}{|a|}$$

First-order maximum estimates for small, separate bounds; shared errors can cancel.

Density of a cube

1. **Volume.** Known: m $= 85.2 \pm 0.1$ g; side a $= 3.20 \pm 0.01$ cm. V $= a^3 = 32.768$ cm^3.
2. **Density.** 85.2 / 32.77 $= 2.60$ g cm^{-3}
3. **Uncertainty.** Fractional bound $= 0.1/85.2 + 3(0.01/3.20) = 1.05487\%$; absolute bound $= 0.02743$ g/cm^3.

Decision

$\rho = 2.60 \pm 0.03$ g cm^{-3}

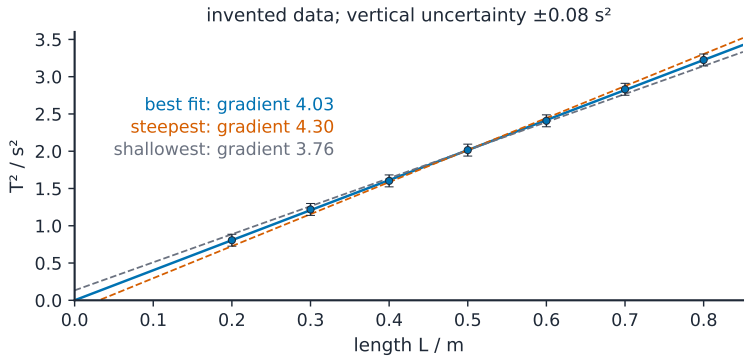
Check: a speed

Your turn

Distance is 1.50 ± 0.01 m and time 0.62 ± 0.02 s. Under separate-bound addition, what is the percentage uncertainty in speed?

A. 2.5 %
B. 3.9 %
C. 4.6 %
D. 7.2 %

Uncertainty in a gradient



- Invented data: vertical bounds $\pm 0.08\ \mathrm{s}^2$; horizontal uncertainty neglected.
- Check every bar: compatible slopes 4.297 and 3.763 s^2/m.

Finding g

- Use **gradient** estimate $4.03 \pm 0.27\ \mathrm{s^2/m}$ before final rounding: about 6.7%.
- The example **intercept** $0.00 \pm 0.13\ \mathrm{s^2}$ includes zero; scale-factor bias can remain.

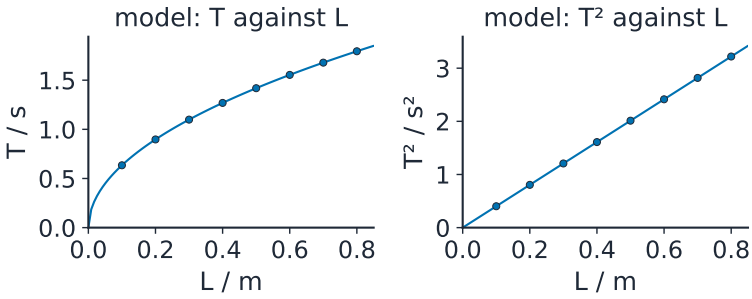
$$T^2 = \frac{4\pi^2}{g} L$$

$$g = \frac{4\pi^2}{4.03} = 9.80\ \mathrm{m\,s^{-2}}$$

$$\Delta g \approx 9.80 \left(\frac{0.27}{4.03} \right) = 0.66\ \mathrm{m\,s^{-2}}$$

Report $g = 9.8 \pm 0.7\ \mathrm{m/s^2}$. Keep unrounded values during processing.

Linearising



- These curves are model-generated, not an independent experimental confirmation.
- Transform uncertainties as well as the variable: $\Delta(T^2) \approx 2T\ \Delta T$.

What to plot

- Log positive dimensionless ratios to fixed reference quantities.
- The slope is the exponent n; changing reference units changes the **intercept**.

$$\ln(y/y_{\mathrm{ref}}) = n\ln(x/x_{\mathrm{ref}}) + \ln(kx_{\mathrm{ref}}^{n}/y_{\mathrm{ref}})$$

For exponential decay, ln(A/Aref) against t has slope $-\lambda$.

Technology

> Sensors remove human start–stop reaction, while timing, response and calibration limits remain.

- Sensors and light gates remove reaction-time error.
- Video analysis, spreadsheets, simulations and databases.

Designing an investigation

Research question

Names both variables and the system.

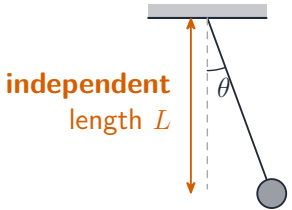
Gives the range studied.

Measurements

Justify settings, repeats and safe range.

Pilot the method and check for drift.

Variables in a pendulum investigation





dependent
period T (time 10 oscillations, $\div 10$)

controlled: bob mass, amplitude (small θ), type of string

Control the bob mass, the amplitude and the string

Comparing with an accepted value

- If reference uncertainty is negligible, 9.81 lies inside $9.8 \pm 0.7\ \mathrm{m/s^2}$.
- Compatibility is not proof: check both uncertainty estimates and model assumptions.

$$\text{percentage error} = \frac{|\text{experimental} - \text{accepted}|}{\text{accepted}} \times 100\,\%$$

Compare the percentage error with the percentage uncertainty.

Evaluating

> "Use a light gate" is an improvement; "be more careful" is not.

- Name each error and say whether it is random or systematic.
- Say how it changed the result, then give a specific improvement.

The internal assessment

Design and analysis

20% of grade; about 10 hours; report at most 3000 words.

Design and analysis: each criterion has 6 marks.

Conclusion and evaluation

Conclusion and evaluation: each has 6 marks.

Individual question, data and authorship; optional groups at most three.

Exam tips

> Name the error, its type, its effect and its fix.

- Report justified uncertainties and matching decimal places.
- Check limiting lines against every bar and include units.
- Name the mechanism, its effect and a targeted improvement.

Check yourself

Try these

Find the volume of a sphere of radius 2.00 ± 0.02 cm with its uncertainty.

State what to plot for exponential decay, and what the gradient gives.

Suggest an improvement for timing one oscillation by hand.