Experimental programme

Practical skills · SL and HL

An investigation connects a biological explanation to a test

Build a chain from question to qualified conclusion

Shared SL/HL practical skills: design, measurement, techniques, field and digital evidence, processing, uncertainty, statistical decisions and evaluation.

All numerical examples and plotted records are invented teaching data, not published experiments or student submissions.

Practise these skills through the course. Real investigations require teacher supervision and the actual assessment rules.

Turn a broad interest into an observable comparison

1. **Weak question.** Do plants like light? Organism, exposure, timescale and response are undefined.
2. **Operational question.** How does daily light duration affect change in shoot length of a stated seedling species over seven days, with watering and temperature controlled?
3. **Prediction.** Connect light to photosynthetic supply over a specified range, while recognizing other limiting factors and excessive exposure.

Assignment changes the strength of a causal inference

An observed association is not automatically an experiment

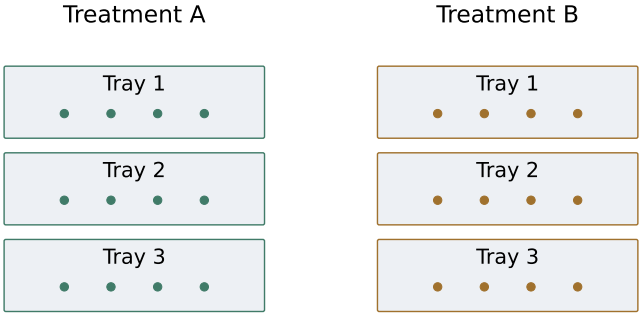
An experiment changes an independent variable and measures a dependent response.

A survey may relate two observed variables without assigning either. Shade and density can also vary with soil moisture or disturbance.

Databases and simulations can support valid questions. Explain data selection, definitions, assumptions and what the model actually tests.

Count the units receiving treatment independently

Independent trays; seedlings within a tray are subsamples



Seedlings within one treated tray do not create independent trays.

Do not multiply treatment replication by repeated readings

1. **Given design.** One tray per light duration; four seedlings per tray, each read on five days.
2. **Unit.** Light duration is assigned to the whole tray. Seedlings are subsamples; dates are repeated observations.
3. **Improvement.** Use several independent trays per duration and randomize assignment within suitable position blocks. Analyse at the level supported by the design.

Use the right protection for the right problem

Design choice	Purpose and limit
Random allocation	Reduces systematic differences in assignment; does not guarantee identical groups
Random sampling	Helps represent the target population; requires a suitable sampling frame
Blocking	Groups similar positions or starting conditions; randomize treatments within blocks
Controlled variable	Keep a relevant factor comparable with a stated method and reason

Controls and a pilot answer different practical questions

Choose comparisons that separate plausible explanations

A solvent-only control can distinguish a delivered substance from its carrier; a positive control checks that a detection method can respond.

A pilot checks a safe relevant treatment range, measurable response and adequate instrument resolution.

More treatment levels describe response shape; more independent repeats estimate variation. Justify the balance using the pilot.

Name the exposure and a concrete control

Context	Risk, responsibility and record
Laboratory	Assess cutting tools, heat, electricity near liquid and chemicals; teacher approval and disposal matter
Human observations	Use approved low-risk procedures, consent, privacy and withdrawal
Fieldwork	Get permission; protect organisms/habitats and avoid releases
Records	Retain dates, assignments, settings, raw values and explained deviations

Preserve the path from observation to conclusion

Honest exceptions are part of a reproducible method

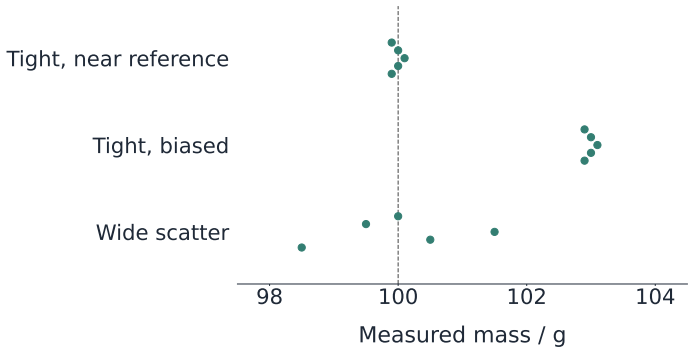
Record failed readings and their cause. Do not erase inconvenient values or invent replacements.

Keep raw observations separate from processing. Describe materials, calibration and steps well enough to repeat.

Credit data, images, code and methods. Shared data collection does not authorize copying another student's final reasoning.

A tight cluster can still miss the reference

Invented checks: dashed line = reference mass 100.0 g



Precision describes repeat scatter; accuracy concerns the reference.

Diagnose a persistent offset before collecting more repeats

1. **Observation.** A balance gives tightly grouped readings 0.8 g above an appropriate reference.
2. **Interpretation.** High precision, limited accuracy and positive measurement bias. Repetition alone preserves the offset.
3. **Action.** Check tare and calibration across the relevant range; correct or replace the method as justified. Keep the record of the check.

Do not use one quality word for every limitation

Term	Meaning and implication
Accuracy	Closeness to a suitable reference or true value
Precision	Closeness of repeat readings to each other
Validity	Whether the method supports the question and interpretation
Systematic error	Consistent or predictable measurement bias; averaging does not automatically remove it

An uncertainty needs a stated basis

Display resolution is only one possible contribution

State whether uncertainty comes from resolution, repeat scatter, calibration information or a maximum bound.

Half an analogue division may suit a simple reading exercise; it is not a universal rule for all instruments.

Allow sensors to stabilize, use relevant standards and retain units/settings. A single check does not prove calibration over every value.

Use a scale bar measured on the same image

1. **Teaching example.** A 20 mm image bar represents 50 micrometres. A cell measures 32 mm.
2. **Calculation.** Actual cell length $= 32/20 \times 50 = 80$ micrometres. Magnification $= 20/0.050 = 400$, without units.
3. **Practice.** A 25 mm bar represents 100 micrometres; a 15 mm cell is 60 micrometres. Image magnification is 250.

Microscopy needs preparation, calibration and observation

An image supports only what its resolution and preparation permit

Start at low power with a suitable temporary mount, thin specimen and approved stain if needed. Draw observed features with labels and scale.

Calibrate an eyepiece graticule against a stage micrometer for the objective used.

Resizing an image and scale bar together preserves their ratio. Printed magnification changes; inferred actual size need not.

Measure chromatography movement from a common origin

1. **Setup.** Keep origin above solvent, use a suitable small spot and mark the solvent front promptly.
2. **Ratio.** Pigment 36 mm, solvent front 60 mm: $R_f = 36/60 = 0.60$. Practice 42/70 gives 0.60 too.
3. **Inference.** Different interactions with solvent and stationary material separate components. A reference match under the same conditions supports, but does not uniquely prove, identity.

Invert the calibration before interpreting absorbance

1. **Invented model.** $A = 0.20c + 0.04$, with c in milligrams per litre; absorbance is dimensionless.
2. **Unknowns.** For A = 0.44, c = (0.44 − 0.04)/0.20 = 2.0. For A = 0.64, c = 3.0 milligrams per litre.
3. **Method.** Use a suitable blank, consistent path length and relevant standards. Stay within the validated range; turbidity, saturation or matrix differences can bias results.

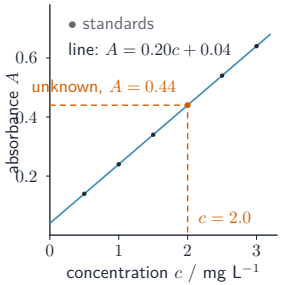
Multiply dilution factors across successive mixed transfers

1. **One step.** Transfer 1.0 mL into 9.0 mL diluent: final volume 10.0 mL; concentration is one-tenth.
2. **Three steps.** A 2.0 milligram-per-millilitre stock becomes 0.0020 after three tenfold steps.
3. **Practice and control.** A 5.0 stock becomes 0.0050. Mix each step and use suitable clean equipment; retain the cumulative factor for back-calculation.

Match each representation to the inference it supports

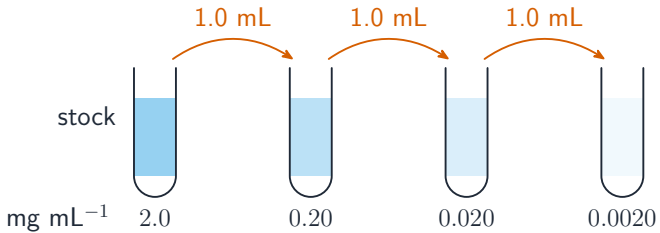
Technique	Reasoning boundary
Identification/key	Use stated characters and contrasting choices; investigate ambiguity
Karyogram	Compare chromosome features; a picture does not measure every genetic difference
Cladogram	Infer relationships from character/sequence evidence and branching order
Molecular model	Shows selected structural features while omitting others

Reading a calibration line



$$c = (0.44 - 0.04)/0.20 = 2.0 \text{ mg dm}^{-3}$$

A serial dilution



each step: 1.0 mL into 9.0 mL diluent, mixed: a tenfold dilution

2.0, 0.20, 0.020, 0.0020 mg/mL

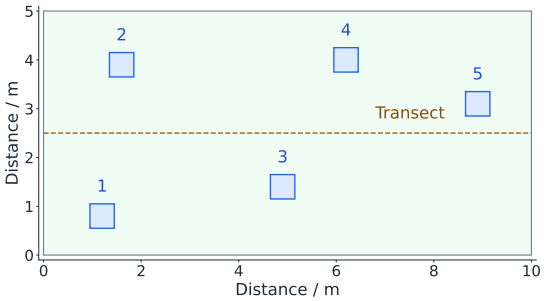
Choose the sample before seeing the desired answer

1. **Field design.** Preselect quadrat locations and record area, identification and boundary-counting rules. A transect describes a measured gradient.
2. **Calculation.** Four plants in 0.25 square metres gives 16 plants per square metre. One quadrat does not establish the whole-site mean.
3. **Representativeness.** Stratify heterogeneous habitats when appropriate and weight strata correctly. Random sampling and systematic gradient sampling have different aims.

Digital tools extend measurement but preserve assumptions

Tool	Check before interpreting
Sensor	Sampling interval, response delay, drift and calibration
Image analysis	Scale, segmentation threshold and overlapping objects
Database	Definitions, units, dates, sampling effort and missing-data rules
Simulation/spreadsheet	Model assumptions, parameter choices and formula cell references

Random quadrats and a transect



A transect samples change across the field

Keep independent records before calculating a summary

An average is not a new observed organism

Label raw-table headings with quantity and unit, retain justified precision and add relevant qualitative observations.

Keep each independent replicate identifiable. Counts are discrete; lengths are continuous even when displayed as rounded values.

Preserve originals and document exclusions. An unusual observation warrants checking, not automatic deletion because it weakens the trend.

Distinguish the centre from scatter and uncertainty of a mean

1. **Invented rates.** 4, 5, 5, 6, 10 mm per day: mean 6.0; median 5; range 6.
2. **Scatter.** Squared deviations sum to 22. Sample SD = square root of $22/4 \approx 2.35$ mm per day.
3. **Mean uncertainty.** SE = SD / square root of $5 \approx 1.05$ mm per day under independence. SD and SE do not describe the same quantity.

State the quartile convention and examine unusual values

1. **Excluding the central value.** Lower half 4, 5; upper half 6, 10. Q1 = 4.5; Q3 = 8; IQR = 3.5.
2. **Practice.** 2, 3, 3, 4, 8 gives mean 4 and median 3; the squared-deviation sum is again 22, so SD and SE match the earlier example.
3. **Limit.** Small-sample quartile conventions can differ. Check recording and apparatus before any documented exclusion; preserve the raw value.

For differences, state the absolute-bound convention

1. **Percentage uncertainty.** 50.0 $\pm$1.0 mm gives 2.0%; 40 $\pm$1 cm gives 2.5%.
2. **Difference.** 12.0 $\pm$0.1 minus 10.0 $\pm$0.1 g gives 2.0 $\pm$0.2 g using summed maximum bounds.
3. **Practice.** 15.0 $\pm$0.2 minus 12.0 $\pm$0.2 gives 3.0 $\pm$0.4 g. This bound calculation is not automatically a standard **uncertainty**.

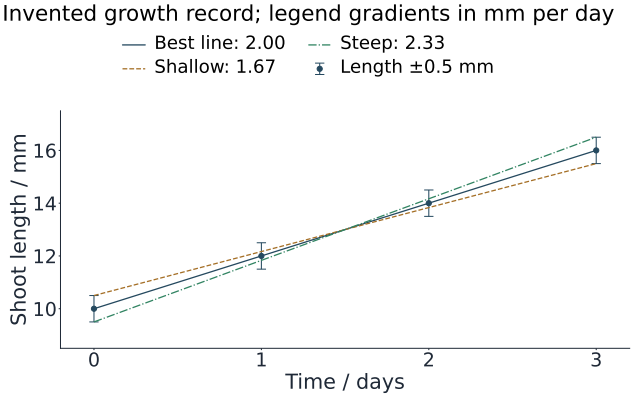
For a rate, propagate the stated fractional bounds

1. **Teaching example.** Change 6.0 $\pm$0.4 mm over 3.0 $\pm$0.1 days: rate 2.0 mm per day; fractional sum $0.4/6 + 0.1/3 = 0.10$.
2. **Practice.** 8.0 $\pm$0.4 over 4.0 $\pm$0.2 gives the same rate and fractional sum. Approximate maximum **uncertainty** is 0.2 mm per day.
3. **Convention.** This first-order maximum-bound approximation differs from quadrature for independent standard uncertainties. Correlated errors need appropriate treatment.

Choose a graph for the variable type and question

Data	Appropriate representation and boundary
Two quantitative variables	Scatter graph; fit and inspect a suitable relationship
Category counts	Bar chart; separate categories
Continuous distribution	Histogram; use frequency density for unequal intervals when area represents frequency
Summary comparison	Box plot or labelled error bars; state convention and sample size

Use every stated bound when evaluating plausible gradients



The endpoint lines also meet all middle bounds in this example.

Separate initial size from growth rate

1. **Invented observations.** Time 0, 1, 2, 3 days; shoot length 10, 12, 14, 16 mm.
2. **Best line.** Gradient $(16 - 10)/(3 - 0) = 2.0$ mm per day. Intercept 10 mm is initial length, not automatically an instrument error.
3. **Model.** A straight line is proportional only if it passes through the origin. A chord estimates interval rate; a tangent estimates instantaneous rate on a curve.

A geometric envelope is not a regression confidence interval

1. **Assumptions.** Each length has a stated ± 0.5 mm bound; time is treated as exact.
2. **Gradients.** Shallow: $(15.5 - 10.5)/3 \approx 1.67$. Steep: $(16.5 - 9.5)/3 \approx 2.33$ mm per day.
3. **Summary.** Midpoint 2.00; half-range about 0.33 mm per day. Check all bars in any new dataset; these are not probabilistic regression limits.

A good fit does not settle every biological explanation

Inspect the model and its residuals before extending it

A curved residual pattern can reveal that a straight line misses a relationship. Scatter can also change with the predictor.

Interpolation remains within observed values; extrapolation requires extra assumptions.

A high R-squared describes fitted variation under that model and dataset. It does not state what percentage of the response the predictor biologically caused.

Select a test for the data and design

Question	Method and assumptions to check
Linear association	Pearson correlation; near zero can hide a curved relationship
Difference in means	Suitable independent or paired t-test; variance assumptions depend on version
Category counts	Chi-squared with appropriate independence and adequate expected counts
All designs	Repeated readings are not independent organisms; report effect, variation and sample size

Interpret a p-value relative to a specified null model

1. **Preselected threshold 0.05.** A valid test giving $p = 0.03$ supplies evidence against the stated null model.
2. **Non-significant example.** $p = 0.12$ does not meet that threshold. It does not establish zero effect.
3. **Meaning.** Neither value is the probability that the hypothesis is true or that chance caused the outcome. Include assumptions, effect size and biological importance.

Ecological estimates require formulas and assumptions

1. **Lincoln estimate.** Initial marks 40, later catch 50, recaptures 10: $40 \times 50 / 10 = 200$. Practice $30 \times 40 / 8 = 150$.
2. **Assumptions.** Suitable mixing, retained marks, comparable capture and a sufficiently closed population.
3. **Simpson reciprocal.** Using $N(N-1)$ divided by sum of $n(n-1)$, counts 4 and 6 give $90/42 \approx 2.14$. Counts 5 and 5 give $90/40 = 2.25$; estimates are not counts of observed species.

Answer the actual question within the method's limits

Connect a pattern to mechanism and uncertainty

Give direction, size, range and uncertainty of the observed effect, then relate it to biological knowledge.

Recognize alternatives. Controlled assignment can support causal inference more strongly than a survey, within its sampled conditions.

The individual investigation requires independent reasoning; the collaborative sciences project develops joint inquiry. Neither a template nor a practice answer guarantees a mark.

Turn a specific limitation into a useful improvement

1. **Resolution.** A ± 0.5 mm method poorly resolves a 0.4 mm change. Use a suitable calibrated higher-resolution method.
2. **Evaporation.** Water loss can alter concentration. Use compatible covers and check mass loss.
3. **Replication.** Roots share one treated tray. Add independent trays rather than repeatedly reading the same roots. Prioritize limitations that affect the conclusion.

Attempt all 14 handout questions before checking the answers

Keep the units, assumptions and experimental unit visible

Re-design the light comparison, diagnose the balance bias, and calculate image size, chromatography movement, dilution and calibrated concentration.

Calculate sample SD/SE, percentage uncertainty, difference/rate bounds and gradient envelopes. Select graphs and interpret a statistical decision.

Estimate ecological quantities and build a limitation $\rightarrow$ consequence $\rightarrow$ improvement chain with authentic records and appropriate ethics.

Check the main practice calculations independently

1. **Optical and dilution.** Cell 60 micrometres; magnification 250; Rf 0.60; final concentration 0.0050 milligrams per millilitre; calibration unknown 3.0 milligrams per litre.
2. **Statistics and uncertainty.** Mean 4, median 3, SD about 2.35, SE about 1.05 mm per day. Percentage **uncertainty** 2.5%; mass difference 3.0 $\pm$0.4 g; rate 2.0 $\pm$0.2 mm per day under stated bounds.
3. **Graph and ecology.** Gradient envelope 2.00 $\pm$0.33 mm per day; abundance estimate 150; Simpson reciprocal 2.25 with the stated finite-sample formula.

Check yourself

Make the inference traceable rather than merely confident

Name the quantity, unit, independent experimental unit and uncertainty convention.

Separate repeat readings from independent replication, SD from SE, an envelope from a confidence interval, and association from causation.

Evaluate the effect's size and biological meaning alongside the test decision. Link each limitation to a result and feasible improvement.