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Education Services

Pre-IB Chemical Research Skills Programme

Chemical Research Skills

A Skills-Building Programme for Independent Chemical Investigation



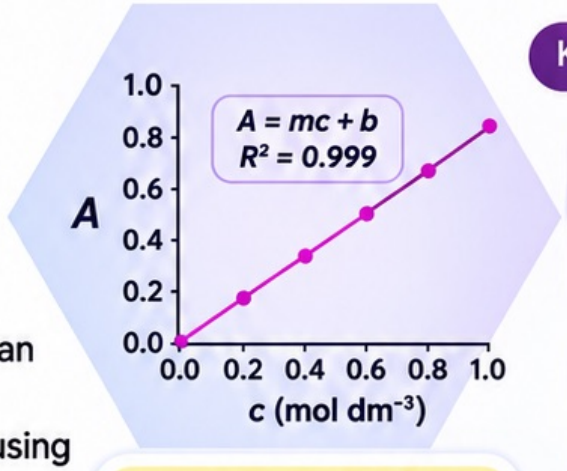
Module 9

Data Analysis and the Calibration Curve

From Raw Data to Reliable Results

In this module, you will:

- Process experimental data systematically
- Construct a calibration curve ($A = mc + b$)
- Determine the concentration of an unknown from the curve
- Evaluate the quality of the data using R^2 and sources of error
- Communicate and justify your conclusions with evidence



$$A = mc + b$$

A = Absorbance (unitless)
m = Gradient (L mol^{-1} dm^{-3})
c = Concentration (mol dm^{-3})
b = y-intercept (≈ 0)

Key Analysis Skills

- Plot & Interpret
- Calculate Unknown
- Evaluate Reliability
- Justify Conclusion

Sunny Chiam

IB Chemistry Specialist & Examiner-Level Educator
Founder, LearningSparks Education Services
Creator of the CHIAM Framework™

PREFACE

Learning to Think Like a Chemical Researcher

Pre-IB Chemical Research Skills Programme | Modules 1–10

Chemistry is more than the study of substances, reactions, and scientific principles. It is also a discipline built upon observation, questioning, experimentation, measurement, and evidence-based reasoning. For many students, learning chemistry begins with understanding concepts, applying equations, and performing laboratory experiments according to established instructions. These are essential foundations. However, there is an important difference between following an experimental procedure and understanding how to design one.

This distinction becomes particularly significant when students progress into the International Baccalaureate Diploma Programme (IBDP), where independent scientific investigation forms an important part of their learning experience. Students are increasingly expected to formulate meaningful research questions, select appropriate analytical techniques, justify experimental decisions, evaluate the quality of their measurements, and draw conclusions supported by scientific evidence. Yet these research skills do not necessarily develop simply through learning more chemistry content or completing more laboratory experiments. They require deliberate preparation.

The **Pre-IB Chemical Research Skills Programme** was developed to address this need.
Drawing upon my experience as an IB Chemistry educator and examiner, I have observed that students may possess a reasonable understanding of chemical concepts yet encounter considerable difficulty when asked to translate those concepts into an independent investigation.

A student may understand concentration but struggle to prepare a suitable series of standard solutions. Another may know the Beer–Lambert law but remain uncertain about constructing and interpreting a calibration curve. Others may be familiar with experimental procedures yet find it challenging to explain why a particular analytical technique is appropriate, how many measurements are necessary, or whether their results are sufficiently reliable to support a conclusion.

These difficulties are not always the result of insufficient chemical knowledge. Often, they reflect a missing connection between conceptual understanding and experimental research design. This programme seeks to build that connection.

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Organised into ten progressive modules, the programme introduces students to the essential thinking processes and practical skills involved in chemical research. Beginning with the formulation of research questions, students gradually develop their understanding of quantitative solution preparation, dilution, calibration, analytical techniques, standardisation, measurement reliability, and experimental planning.

Each module builds upon the skills established in the preceding modules, encouraging students to recognise that scientific research is not a collection of isolated laboratory techniques. Rather, it is a connected process in which every experimental decision must serve a clear scientific purpose.

Throughout the programme, particular emphasis is placed on a fundamental principle:
A sophisticated-looking experiment is not necessarily a good experiment. A simple experiment that is thoughtfully designed, carefully measured, and critically evaluated can be an excellent scientific investigation.

Students are therefore encouraged not merely to ask *what should I do?* but also *why should I do it this way?*

Why is a volumetric flask preferable to a measuring cylinder when preparing a standard solution? Why might several smaller extractions be more effective than a single extraction? Why is a calibration curve necessary? Why can repeated measurements still produce inaccurate results? How can we determine whether an experimental method is capable of answering a research question?

These questions represent the foundations of scientific reasoning.
Importantly, this programme is not intended to replace the IB Chemistry syllabus, nor is it a shortcut to completing an Internal Assessment (IA) or Extended Essay (EE). Instead, it provides an early introduction to the research skills that students will eventually need when undertaking more demanding independent investigations.

The intention is to help students enter the IB Diploma Programme with greater confidence, stronger experimental awareness, and a more structured approach to scientific problem-solving. By the end of these ten modules, students should begin to appreciate that successful chemical research does not start with selecting an impressive experiment or sophisticated instrument.

It begins with a meaningful question, followed by careful consideration of the evidence required to answer it.

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Ultimately, the purpose of this programme is not simply to teach students how to conduct experiments. It is to develop their ability to think independently, make scientifically justified decisions, and approach chemical investigations with clarity, confidence, and intellectual curiosity.That is where meaningful scientific research begins.

Sunny Chiam
IB Chemistry Specialist & Examiner-Level Educator
Founder, LearningSparks Education Services
Creator of the CHIAM Framework™
Think Chemistry. Think Structurally.

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Module 9 — Designing the Measurement Strategy
How Do We Plan Measurements That Can Actually Answer Our Research Question?
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Related 1-Minute Chemical Research Skills episodes:

- **Episode 22:** Choosing the Right Measurement Range
- **Episode 23:** Choosing the Right Analytical Technique

Programme phase: Think Like a Researcher
Prerequisite: Module 8 — Reliability, Accuracy & Data Quality
Next module: Module 10 — From Research Question to Experimental Method

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Module Overview

In Modules 1–8, students developed essential chemical research skills:

1. Formulating research questions.
2. Preparing standard solutions.
3. Performing direct and serial dilutions.
4. Constructing calibration curves.
5. Using UV–Vis spectroscopy.
6. Determining unknown concentrations.
7. Performing liquid–liquid extraction.
8. Standardising solutions.
9. Evaluating accuracy, precision, reliability and uncertainty.

Students now understand how to prepare solutions, obtain measurements and evaluate experimental data.

However, an important question remains:

How do we decide what to measure, how to measure it and which measurements are needed before beginning an experiment?

Consider two students investigating how temperature affects the rate of a chemical reaction.

Student A decides to investigate:

$$25, 26, 27, 28, 29^{\circ}\mathrm{C}$$

Student B decides to investigate:

$$20, 30, 40, 50, 60^{\circ}\mathrm{C}$$

Which temperature range is better?

The answer depends on the reaction, the expected effect, the available apparatus, the uncertainty in temperature control and the purpose of the investigation.

A wider range may reveal a clearer trend.

However, it may also introduce complications such as:

- evaporation
- changes in reaction mechanism

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- decomposition
- changes in solubility
- increased experimental hazards

Similarly, a narrow range may provide detailed information about a particular region but fail to reveal a meaningful relationship.

Therefore, choosing measurement conditions requires scientific reasoning.

A good measurement strategy is designed, not guessed.

Module Learning Objectives

By the end of Module 9, students should be able to:

1. Explain what a measurement strategy is and why it matters.
2. Identify the quantity that must be measured to answer a research question.
3. Distinguish direct measurements from calculated quantities.
4. Select an appropriate range for the independent variable.
5. Choose suitable intervals and numbers of experimental conditions.
6. Explain why preliminary experiments are valuable.
7. Identify the working range and limitations of analytical instruments.
8. Distinguish interpolation from extrapolation.
9. Select suitable analytical techniques for different chemical investigations.
10. Compare analytical techniques using sensitivity, selectivity, precision, accuracy, cost and practicality.
11. Design calibration and measurement procedures appropriate to expected concentrations.
12. Plan independent repeats and appropriate controls.
13. Consider uncertainty before collecting data.
14. Evaluate whether a proposed measurement strategy can produce a defensible conclusion.
15. Justify experimental decisions using chemical principles rather than convenience alone.

The central progression is:

Research Question → Measurable Quantity → Analytical Technique → Measurement Range → Data Qualit

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Part A — What Is a Measurement Strategy?

1. From Research Question to Measurement

Consider the research question:

How does temperature affect the rate of reaction between sodium thiosulfate and hydrochloric acid?

The independent variable is:

Temperature

The dependent variable is:

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Reaction rate

But how will reaction rate be measured?

The student cannot simply write:

"Measure the reaction rate."

A specific operational method is required.

For example, the reaction produces sulfur, which causes the mixture to become increasingly cloudy.

The student may measure the time taken for a marked cross beneath the reaction vessel to become obscured.

Under carefully controlled conditions, the reciprocal of this time may be used as a relative rate measure:

$$\text{Relative rate} \propto \frac{1}{t}$$

This does not necessarily provide an absolute reaction rate in:

$$\text{mol dm}^{-3}\ \text{s}^{-1}$$

Instead, it provides a comparative rate indicator.

Important distinction

What we want to know ≠ necessarily what we measure directly

A measurement strategy must explain how the measured quantity relates to the chemical property being investigated.

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2. Definition of Measurement Strategy

A measurement strategy is a scientifically justified plan specifying:

- what will be measured
- which analytical method will be used
- the measurement range
- the number and spacing of experimental conditions
- the number and type of repeats
- required calibration and controls
- expected measurement uncertainty
- how raw measurements will be processed
- how the resulting data will answer the research question

It connects the research question to the evidence required.

Example

Research question:

How does dilution affect the absorbance of a coloured solution?

A suitable strategy might involve:

1. Preparing solutions of known concentrations.
2. Measuring absorbance at a suitable wavelength.
3. Selecting concentrations within the instrument's useful range.

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4. Measuring an appropriate blank.
5. Repeating measurements.
6. Plotting absorbance against concentration.
7. Evaluating the relationship and its limitations.

Each decision contributes to the quality of the final conclusion.

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3. Why Measurement Strategy Comes Before Experimental Method

Students often begin by listing apparatus and writing procedural steps.

However, apparatus should be selected only after deciding what evidence is required.

Consider:

How does the concentration of an acid affect the rate of reaction with magnesium?

A student might immediately choose:

- beaker
- measuring cylinder
- stopwatch
- magnesium ribbon

But important questions remain.

What concentration range will be investigated?

How will the rate be measured?

Will hydrogen gas volume be recorded?

Will the initial rate be estimated?

How will temperature be controlled?

Will magnesium surface area be kept constant?

Will the apparatus measure gas production sufficiently accurately?

A complete experimental method cannot be designed until these decisions have been considered.

Measurement Strategy → Experimental Method

This is the bridge between Modules 9 and 10.

Part B — Identifying the Measurable Quantity

4. Direct and Indirect Measurements

A direct measurement is obtained from an instrument or observation.

Examples include:

- mass measured using a balance
- volume measured using a burette
- temperature measured using a thermometer
- time measured using a stopwatch
- absorbance measured using a spectrophotometer

An indirect or calculated quantity is obtained from one or more measurements.

Examples include:

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$$\text{Concentration} = \frac{\text{Amount}}{\text{Volume}}$$

$$c = \frac{n}{V}$$

$$\text{Relative rate} = \frac{1}{t}$$

$$\text{Percentage recovery} = \frac{\text{Amount recovered}}{\text{Initial amount}} \times 100$$

The distinction matters because uncertainty in direct measurements affects calculated results.

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5. Operational Definitions

An operational definition specifies exactly how a quantity will be measured or determined.

Consider:

How does temperature affect reaction rate?

The dependent variable, reaction rate, is not sufficiently defined.

A better operational definition might be:

The initial reaction rate will be estimated from the initial gradient of a graph of hydrogen gas volume against time.

Alternatively:

The relative reaction rate will be represented by the reciprocal of the time required for a fixed observable change.

These approaches do not necessarily measure the same quantity.

Therefore, the operational definition must be appropriate to the research question.

Key principle

A measurable dependent variable must have a clear operational definition.

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6. Does the Measurement Actually Represent the Intended Quantity?

Suppose a student investigates:

How does extraction-solvent volume affect extraction efficiency?

The student measures the volume of the organic layer.

Is that sufficient?

No.

The volume of the organic layer does not directly establish the amount of analyte extracted.

The student must measure or determine the amount of analyte recovered.

For example:

$$n_{\text{recovered}} = c_{\text{organic}} V_{\text{organic}}$$

Then:

$$\boxed{\%\text{ recovery} = \frac{n_{\text{recovered}}}{n_{\text{initial}}} \times 100}$$

This requires a suitable method for determining the analyte concentration.

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Research lesson

Before selecting an instrument, ask:

Does the measured signal actually provide the chemical information required?

Part C — Episode 22: Choosing the Right Measurement Range

7. What Is a Measurement Range?

A measurement range defines the minimum and maximum values investigated.

For example:

$$20^\circ\text{C} \leq T \leq 60^\circ\text{C}$$

The selected range should be:

- scientifically relevant
- experimentally achievable
- sufficiently broad to reveal meaningful changes
- within safe operating conditions
- compatible with the chosen analytical method

The largest possible range is not automatically the best range.

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8. Why a Range Can Be Too Narrow

Suppose a reaction rate changes noticeably between:

$$20^\circ\text{C}$$

and:

$$60^\circ\text{C}$$

A student investigates only:

$$20, 21, 22, 23, 24^\circ\text{C}$$

The effect may be too small relative to measurement uncertainty.

For example:

Temperature / °C	Relative rate / s^{-1}
20	0.0200
21	0.0204
22	0.0207
23	0.0211
24	0.0215

If the relative-rate uncertainty is approximately:

$$\pm 0.0020\ \text{s}^{-1}$$

the differences between neighbouring temperatures may be difficult to distinguish confidently.

Key principle

The expected effect should be considered relative to measurement uncertainty.

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9. Why a Range Can Be Too Wide

A very wide range may introduce additional chemical effects.

For example, investigating reaction rate from:

$$20°C$$

to:

$$95°C$$

may introduce:

- significant evaporation
- changes in dissolved gas concentration
- decomposition of reactants
- changes in reaction mechanism
- apparatus limitations

The observed trend may no longer be explained by temperature alone.

Therefore:

Wider range ≠ automatically better experimental design

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10. Choosing a Range Based on Expected Behaviour

Different chemical relationships require different measurement ranges.

Relationship A — Approximately Linear

Example:

Absorbance against concentration within the validated Beer–Lambert range.

A suitable range should contain enough points to establish the linear relationship.

Relationship B — Curved

Example:

Reaction rate against temperature.

The range should be sufficiently broad to reveal curvature where relevant.

Relationship C — Plateau

Example:

Extraction recovery against number of extraction steps.

The range should extend far enough to determine whether further changes produce diminishing improvement.

Relationship D — Maximum or Minimum

Example:

Reaction rate against pH for an enzyme-catalysed process.

The range should include values on both sides of the expected optimum.

Research lesson

Choose the range to reveal the expected chemical relationship.

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11. Number of Experimental Conditions

Suppose a student investigates the effect of temperature on reaction rate.

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