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Education Services

Pre-IB Chemical Research Skills Programme

Chemical Research Skills

A Skills-Building Programme for Independent Chemical Investigation



Module 10

Acids, Bases and Buffer Solutions

Principles, Preparation and pH Analysis

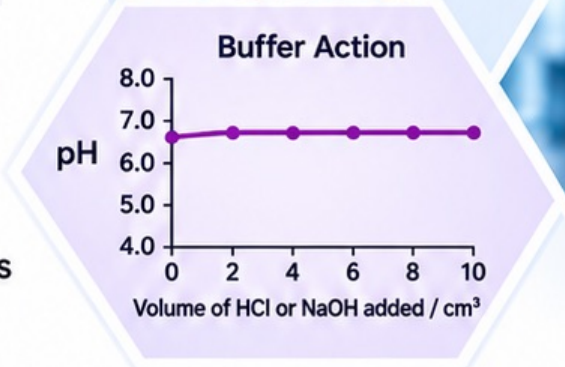
In this module, you will:

- Review key ideas: acid–base equilibria and the pH concept
- Prepare a buffer solution with a specified pH
- Use a pH meter to measure and calibrate pH accurately
- Investigate the buffer action against the addition of small amounts of acid or base
- Analyse results and evaluate the effectiveness and limitations of the buffer



Henderson–Hasselbalch Equation

$$pH = pK_a + \log \frac{[base]}{[acid]}$$





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.

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Creator of the CHIAM Framework™
Think Chemistry. Think Structurally.

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Module 10 — From Research Question to Experimental Method
How Do We Turn a Scientific Idea into a Reliable Chemical Investigation?
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Related 1-Minute Chemical Research Skills episodes:

- **Episode 24:** From Research Question to Experimental Method
- **Episode 25:** What Makes an Experimental Method Scientifically Defensible?

Programme phase: Think Like a Researcher
Prerequisite: Module 9 — Designing the Measurement Strategy
Programme position: Final module — Integrating Chemical Research Skills

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Module Overview

Throughout Modules 1–9, students have learned how to develop a research question, prepare solutions, perform analytical measurements and evaluate experimental evidence. They have studied:

1. Research questions and variables.
2. Standard solutions and volumetric techniques.
3. Direct and serial dilution.
4. Calibration curves and UV–Vis spectroscopy.
5. Determining unknown concentrations.
6. Liquid–liquid extraction.
7. Standardisation and primary standards.
8. Accuracy, precision, reliability and uncertainty.
9. Designing measurement strategies.

However, possessing these individual skills does not automatically mean that a student can design a successful chemical investigation.
A student may understand Beer–Lambert law but prepare unsuitable calibration standards.
Another may understand titration but fail to standardise a solution when necessary.
A third may select an appropriate measurement range but fail to control variables that influence the results.
The final challenge is to integrate these skills into a coherent experimental method.
Consider the research question:
How does the concentration of hydrochloric acid affect the initial rate of reaction with magnesium?

A student proposes:
"***Prepare different concentrations of hydrochloric acid, add magnesium, measure the reaction and repeat.***"
Is this a complete experimental method? No.

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Important information is missing:

- What concentrations will be used?
- How will the solutions be prepared?
- What mass and surface area of magnesium will be used?
- How will reaction rate be determined?
- What apparatus will be used?
- How will temperature be controlled?
- How many independent repeats will be performed?
- How will uncertainty be considered?
- What safety precautions are required?
- How will the data be processed?

A scientifically defensible experimental method must address these questions.

A good experimental method is not simply a list of instructions.

It is a sequence of scientifically justified decisions designed to produce evidence capable of answering the research question.

Module Learning Objectives

By the end of Module 10, students should be able to:

1. Translate a research question into a complete experimental plan.
2. Explain the relationship between research questions, measurement strategies and experimental methods.
3. Identify the essential components of a scientifically defensible methodology.
4. Specify independent, dependent and controlled variables.
5. Develop operational definitions for measured quantities.
6. Select suitable reagents, apparatus and analytical techniques.
7. Calculate reagent quantities and prepare solutions appropriately.
8. Write clear, reproducible experimental procedures.
9. Plan calibration, blanks, controls and independent repeats.
10. Incorporate uncertainty considerations into experimental design.
11. Identify hazards and develop appropriate risk-control measures.
12. Construct suitable raw-data tables before collecting measurements.
13. Plan calculations, graphs and data analysis.
14. Identify possible systematic and random errors.
15. Evaluate the feasibility and limitations of a proposed method.
16. Use preliminary experiments to refine the procedure.
17. Justify experimental decisions using chemical principles.
18. Develop a complete research proposal suitable for progression into IB Chemistry IA and EE research.

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The central progression is:

Research Question → Measurement Strategy → Experimental Method → Data Collection → Evaluation → Conclusion

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Part A — Episode 24: From Research Question to Experimental Method

1. Research Question, Measurement Strategy and Experimental Method

These three components serve different purposes.

Research Question

Defines what the investigation aims to determine.

Example:

How does temperature affect the initial rate of hydrogen production when magnesium reacts with hydrochloric acid?

Measurement Strategy

Determines what measurements are required and how they should be obtained.

Example:

- Measure hydrogen gas volume against time.
- Use a gas syringe.
- Investigate five temperatures.
- Perform three independent repeats.
- Determine initial rates from gas-volume–time graphs.

Experimental Method

Specifies the exact sequence of actions required to implement the measurement strategy.

Example:

- Prepare a specified volume and concentration of hydrochloric acid.
- Equilibrate the reaction mixture at a selected temperature.
- Add a specified mass of magnesium.
- Collect hydrogen gas using a gas syringe.
- Record gas volume at specified time intervals.
- Repeat under controlled conditions.

Key distinction

Research Question: What do we want to know?

Measurement Strategy: What evidence do we need?

Experimental Method: How will we obtain that evidence?

Students should not confuse these stages.

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2. What Makes an Experimental Method Complete?

A complete experimental method should specify:

1. Research question.
2. Scientific rationale.
3. Independent variable.
4. Dependent variable.
5. Controlled variables.
6. Apparatus and reagents.
7. Reagent concentrations and quantities.
8. Experimental conditions.
9. Calibration and controls.
10. Step-by-step procedure.
11. Independent repeats.
12. Raw-data collection.
13. Data processing.
14. Measurement uncertainty.
15. Risk assessment.
16. Waste disposal.
17. Expected limitations.
18. Criteria for evaluating the method.

These components must work together.

For example, the apparatus must be suitable for the intended measurement, and the selected measurement range must be compatible with the analytical technique.

Part B — Scientific Rationale: Why Should the Experiment Work?

3. Every Method Needs a Chemical Basis

A scientifically defensible method must explain why the proposed measurements are relevant.

Consider: $$Mg(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$$

The reaction produces hydrogen gas.

Therefore, measuring hydrogen production over time can provide information about reaction rate.

This is the chemical justification for selecting a gas syringe.

Similarly, UV–Vis spectroscopy can be justified through Beer–Lambert law:

$$\boxed{A = \varepsilon lc}$$

Under suitable conditions, absorbance is proportional to concentration.

Titration can be justified through reaction stoichiometry. Liquid–liquid extraction can be justified through the distribution of a solute between two immiscible phases.

Research principle

Every important measurement should have a scientific justification.

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4. Scientific Rationale vs Experimental Procedure

These are not the same.

Scientific rationale

Hydrogen gas is produced during the reaction between magnesium and hydrochloric acid. Measuring gas volume against time therefore allows the rate of hydrogen production to be estimated.

Experimental procedure

Record hydrogen gas volume at suitable time intervals using a gas syringe connected to the reaction vessel.

The rationale explains **why**.

The procedure explains **how**.

A strong research proposal contains both.

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5. Hypotheses and Predictions

A hypothesis is a scientifically reasoned statement that can be tested.

For example:

Increasing hydrochloric acid concentration is expected to increase the initial rate of reaction with magnesium, provided other relevant conditions remain constant.

The reasoning may involve collision theory and the availability of reacting particles at the metal surface.

However, the precise relationship should not be assumed without evidence.

For example, students should not automatically claim:

$$\text{Rate} \propto [HCl]$$

unless the relevant kinetic relationship has been established.

Important distinction

$$\boxed{\text{Expected trend} \neq \text{proven mathematical relationship}}$$

A hypothesis should guide the investigation without predetermining its conclusion.

Part C — Translating Variables into Experimental Controls

6. Identifying Variables Is Only the Beginning

Consider the research question:

How does hydrochloric acid concentration affect the initial rate of hydrogen production from magnesium?

Independent variable

Hydrochloric acid concentration.

Dependent variable

Initial rate of hydrogen production.

Controlled variables

- temperature
- magnesium mass

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- magnesium surface area
- total solution volume
- reaction vessel
- mixing procedure
- gas-collection apparatus

Simply listing controlled variables is insufficient.

Students must explain **how** each variable will be controlled.

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7. The Control-Variable Table

A useful research-planning tool is:

Controlled variable	Why it matters	How it will be controlled
Temperature	Affects reaction rate	Use a thermostatically controlled water bath
Magnesium mass	Affects total amount of reactant	Use equal measured masses
Magnesium surface area	Affects reaction rate	Use magnesium pieces of comparable dimensions and preparation
Total solution volume	Affects reaction conditions	Maintain the same total liquid volume
Apparatus	May influence gas collection	Use the same apparatus arrangement
Mixing	Affects contact between reactants	Use a consistent mixing procedure

Key principle

Identifying a controlled variable ≠ explaining how it will be controlled

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8. Why Surface Area Is Particularly Important

Magnesium reacts at its exposed surface.

Two samples may have the same mass but different surface areas.

For example:

- A compact piece of magnesium.
- A long, thin strip of magnesium.

Even if both have the same mass, their reaction rates may differ.

Therefore, controlling mass alone does not necessarily control surface area.

A suitable method should specify the physical form and preparation of magnesium.

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Part D — Selecting Apparatus and Reagents

9. Apparatus Should Be Selected for a Reason

Students sometimes select equipment based on familiarity rather than suitability.

For example:

"Use a measuring cylinder because it is available."

This is not a sufficient scientific justification.

A stronger explanation is:

"Use a volumetric pipette to transfer a fixed aliquot because its specified tolerance is suitable for the required measurement."

The selected apparatus should provide acceptable measurement performance.

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10. Apparatus Selection Table

Experimental requirement	Possible apparatus	Reason
Measure mass	Analytical balance	Provides quantitative mass measurements
Transfer a fixed aliquot	Volumetric pipette	Suitable for accurate fixed-volume transfer
Deliver variable liquid volume	Burette	Allows controlled delivery and volume measurement
Prepare a standard solution	Volumetric flask	Provides a defined final volume
Measure absorbance	UV–Vis spectrophotometer	Measures optical absorbance
Measure pH	pH meter	Provides quantitative pH values
Measure gas volume	Gas syringe	Collects and measures gas
Control temperature	Water bath	Helps maintain selected temperatures
Record temperature	Temperature probe	Monitors actual temperature

Teacher note: Apparatus choice depends on the required precision, range, chemical compatibility and practical constraints.

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11. Reagents Must Be Specified

An incomplete procedure might state: "Add hydrochloric acid to magnesium."

A reproducible method should specify:

- hydrochloric acid concentration
- hydrochloric acid volume
- magnesium mass or dimensions
- reagent purity or grade where relevant

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