Investigating Science Module 5 – Scientific investigations

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## Teaching the Year 12 Modules

The new Stage 6 Investigating Science course was implemented in NSW schools in 2018-2019. This syllabus incorporates new content and learning activities such as Depth Studies. The syllabus is designed around inquiry questions and formal assessment tasks emphasise the skills for working scientifically.

The Year 12 course builds on the skills and concepts learnt in Year 11 with students conducting their own scientific investigations and communicating their findings in scientific reports. Students are provided with the opportunity to examine the interdependent relationship between science and technology and apply their knowledge, understanding and skills to scientifically examine a claim. The course concludes with students exploring the ethical, social, economic and political influences on science and scientific research in the modern world.

Therefore, pedagogies that promote inquiry and deep learning should be employed in the Investigating Science classroom. The challenge presented by the additional content and the change in pedagogical approach were the catalysts for the preparation of these module guides for Stage 6. These guides are intended to assist teachers deliver Investigating Science effectively by outlining overarching concepts (big ideas), core and extended ideas, strategies for teaching the modules, uncovering of alternative conceptions, and strategies to address them. The guides support the teacher in facilitating the development of deep knowledge structures, such as the relationships between concepts. The module guides do not cover all aspects of the syllabus, as that was not within the scope of the project.

It is essential that teachers note that the module guides do not substitute the syllabus, but only support teachers to teach it. The information contained in these documents are correct at the time of publication. While every effort has been made to eliminate errors, any errors or omission that are identified after the release of these documents will be corrected and released as resource updates. It is recommended that teachers access the [Curriculum website](https://education.nsw.gov.au/teaching-and-learning/curriculum/key-learning-areas/science/stage-6/investigating-science) for the latest version of these documents.

## Module summary

This module extends students’ understanding of scientific research. The inquiry questions in Module 5 of the Investigating Science syllabus are numbered as follows:

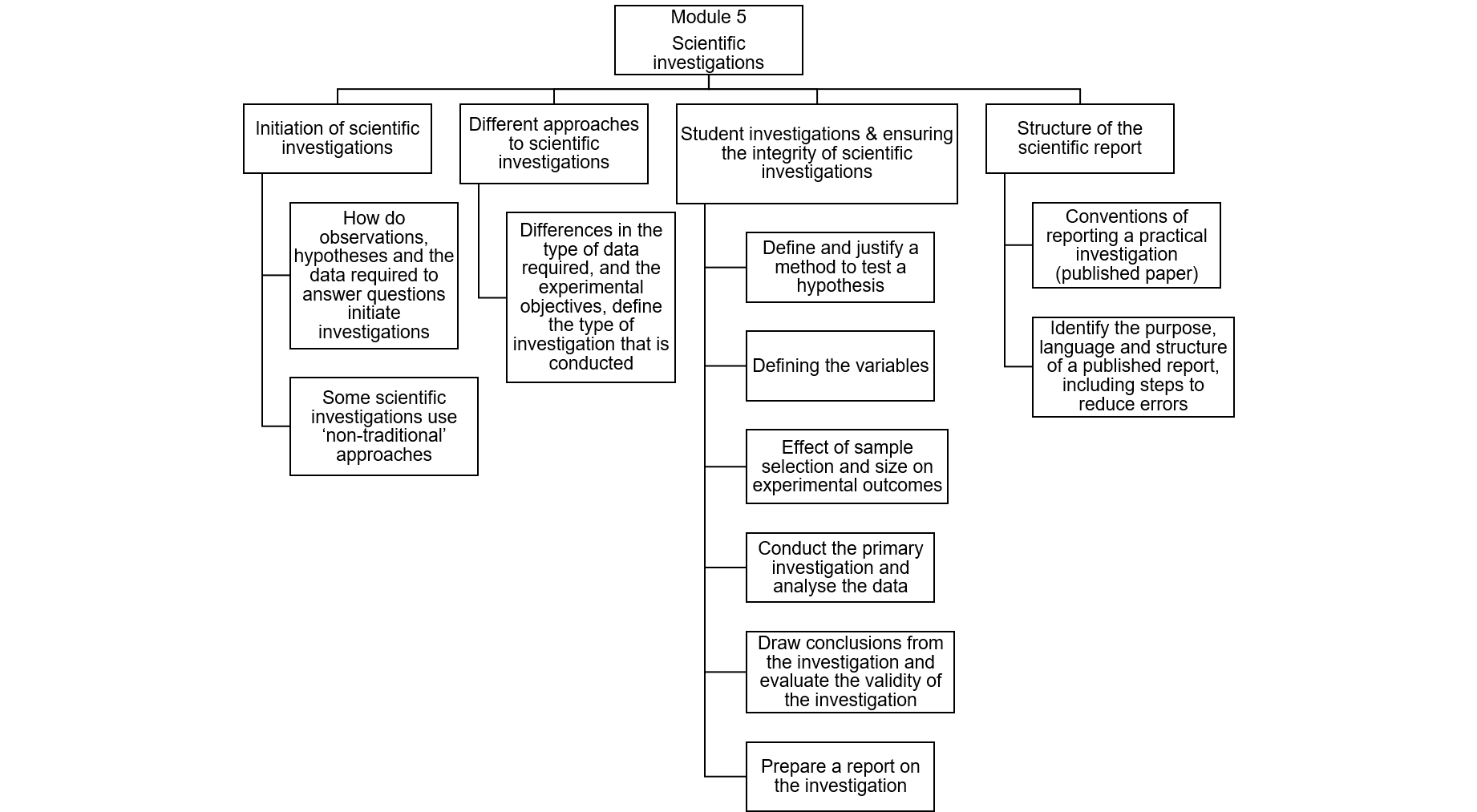
* **IQ5-1**: What initiates an investigation?
* **IQ5-2** What type of methodology best suits a scientific investigation?
* **IQ5-3** How is the integrity of a scientific investigation judged?
* **IQ5-4** What is the structure of an investigative report?

There are many different triggers for scientific investigations. Furthermore, there is not a single ‘scientific method’ that is used by all investigators. The strategies for investigations depend on factors such as the inquiry questions, hypotheses being tested and the types of data that may be collected. However, there are several common attributes to scientific investigations. For example, all scientific investigations must be valid and reliable. Therefore, the experimental designs must ensure that all observations/measurements be repeated and/or replicated to achieve reliability. The design must also include strategies for controlling variables as required so that the tests are fair and valid.

The peer-reviewed scientific publication (for example, research reports, and review articles) is the culmination of scientific investigations. Peer-reviewed publications are highly esteemed in the scientific community. Although there are discipline- and journal-specific differences in the formatting of reports, they are all built around a common structure that helps peer-reviewers and readers assess the validity, reliability and accuracy of the investigation (in addition to the substance of the research).

Most scientific journals will only publish research findings after the manuscripts have been rigorously peer-reviewed. For research to be approved by a panel of peers, investigators need to demonstrate that their research is valid, reliable and accurate. Furthermore, investigators need to apply evidence-based reasoning to show how they arrived at their conclusion, especially in light of related research findings.

Module 5 examines the scientific research process holistically. It explores the common approaches that apply to all scientific investigations, including:

* The varied triggers for scientific investigations.
* The different approaches that constitute scientific investigations.
* The checks and balances in investigations to ensure their integrity, as well as the rigour of the findings.
* The role that the peer-reviewed scientific report plays in scientific communications, education and the development of scientific knowledge.

## Relationship to other modules

Module 5 is closely linked to Module 6. After learning about the processes of scientific investigations in Module 5, students explore how scientific discoveries contribute to the development of technology. Furthermore, students also investigate how scientific research is enhanced by technology. Module 7 investigates how science has penetrated the wider community and how it can be manipulated to serve vested interests. While scientific knowledge has contributed to the development and wellbeing of societies, scientific information has also been misinterpreted or misused by people. Module 8 considers the bigger picture of the relationship between scientific research and society and how they impact each other. While the approaches taken in scientific investigations are guided by ethical principles, societal values also inform acceptable practices and standards (Module 8).

## Big ideas

* Science is both a body of knowledge, as well as an approach to develop explanations of the natural world.
* The approaches used by scientists to investigate natural phenomena have developed over centuries and have been influenced by technological developments, history and philosophy, social and cultural issues, political ideologies and economic factors.
* Students should understand that scientific investigations do not follow a standardised approach. There is not a ‘scientific method’ that all investigators use to conduct their investigations. Instead, scientists incorporate strategies to ensure the integrity of the conduct and analysis of the data generated in scientific investigations. These strategies ensure the accuracy, reliability and validity of the investigations.
* The nature of scientific investigations is not reflected in the structure of the peer-reviewed scientific paper. In other words, the peer-reviewed report is not structured as a series of chronological events that depict the investigation. Instead, the structure of scientific papers facilitates the communication of ideas and processes.
* Science is a social endeavour. Therefore, communication is an important aspect of the scientific process. Of the many ways that scientists communicate their research, the peer-reviewed research paper is the most highly valued. The ideas described in peer-reviewed papers are the ones that form part of the international scientific discourse and contribute to our scientific understanding of the natural world.

## Core concepts

### How scientific investigations begin

* There are many triggers of scientific investigations, such as:
  + **Challenging prevailing dogmas**: Peptic ulcers were once thought to be caused by lifestyle factors such as stress or diets (e.g. spicy foods). Yet, the data that was available to medical researchers did not support this notion. The Australian physicians, Barry Marshall and Robin Warren, who were studying this condition, observed bacteria in the biopsy sections obtained from their patients. They suspected that those microbes may cause the disease. This led them to undertake their famous experiment, which established that the bacterium Helicobacter pylori was the main cause for the formation of peptic ulcers[[1]](#footnote-1).
  + **Lack of evidence and disagreements with current paradigms**: The Belgian scientist, Jan Baptist von Helmont, was interested in understanding how plants grow. He realised that the contemporary notion that plants ‘ate the soil’ was incorrect and undertook experiments that established that plants only absorbed water from soils and that soils were not consumed by growing plants.
  + **Accidental discoveries**: Percy Spencer was a physicist and engineer who invented the microwave oven. Although he was not the first to notice the ability of microwaves to heat foods, he was the first person to examine this effect closely (this is similar to Alexander Fleming’s discovery of penicillin).

In all cases, the scientists who made these discoveries were well-established in their disciplines. Their discipline knowledge, together with their expertise in conducting scientific inquiries, enabled them to discover new connections that were previously not evident. Their sense of curiosity led them to explore their research interests deeply. As stated by Pasteur, ‘Chance favours the prepared mind’.

* When conducting investigations, scientists seek to collect data that may provide evidence for mechanisms behind the phenomena they are investigating. Not only are the reasons for initiating scientific investigations diverse, but the approaches that scientists take to conduct those investigations also vary considerably. For example:
  + **Marshall and Warren** sought to establish a cause-and-effect relationship between Helicobacter infections and the development of peptic ulcers[[2]](#footnote-2)[[3]](#footnote-3) (Koch’s postulates[[4]](#footnote-4)).
  + **Von Helmont** employed quantitative approaches (measurements) to establish that plants do not consume soils when growing.
  + After discovering that microwaves could melt candy bars, **Spencer** extended his investigations to test if other foods, such as popcorn and eggs, could be cooked with microwaves.
* Although not always true, many scientific investigations are underpinned by hypotheses. Hypotheses are used to verify scientific concepts, generally through controlled experiments.
  + **Marshall and Warren** hypothesised that consuming a solution of Helicobacter bacteria will cause peptic ulcers to develop and that the infection will be cured through antibiotic therapy.
  + **Von Helmont** hypothesised that plant growth will not change the dry mass of soil it grows in.
  + **Spencer** hypothesised that foods would cook when exposed to microwave radiation[[5]](#footnote-5),[[6]](#footnote-6).
* Sometimes, scientists adopt approaches that deviate from the traditional, line methodology that is familiar to science students. For example,
  + In **Marshall and Warren**’s experiments with Helicobacter, their work did not progress via the usual route from animal testing to human testing. Their experiments with laboratory animals (pigs) failed. However, despite this, they tested their hypothesis on humans (themselves)[[7]](#footnote-7).
  + **von Helmont** is considered a pioneer of quantitative biology. He relied on the use of measurements to provide evidence for his hypotheses. This was novel at a time when most biological investigations were qualitative in nature.

### Scientific method vs scientific process

* The notion of a linear, invariant ‘scientific method’ (question → hypothesis → experiment → conclusion) is false. The investigative approach used by scientists depends not only on the type of investigation but also on the preferences of the researchers. However, researches must be able to justify the methods (equipment, reagents and analytical methods) used, and ensure that those methods do not compromise validity (including the minimisation of bias), reliability and accuracy.
* When designing investigations, scientists will use any approach that is fit-for-purpose to obtain evidence in support of scientific ideas. The common goal of all scientific investigations is the collection of observations (data) that are unbiased and robust. Such observations may be qualitative or quantitative data. For example,
  + **Marshall and Warren needed data to establish** Helicobacter’s **role in the formation of gastric ulcers. Thus, their approach employed Koch’s postulates (see above). To achieve this, they had to obtain pure cultures of the bacterium, and use it to infect animals to see if those animals developed gastric ulcers. However, since Helicobacter infected only humans, Marshall and Warren realised that human experimentation was the only option available to them. Marshall conducted the experiment on himself and consequently developed gastric ulcers. He was cured of the disease by treating himself with antibiotics. Thus, the data collected confirmed that** Helicobacter **was the cause of the disease.**
  + **Eratosthenes** (276 – 194 BC) was interested in the [Carl Sagan - Cosmos - Eratosthenes](https://www.youtube.com/watch?v=G8cbIWMv0rI) (duration 6:41). This information was important for travellers, traders and cartographers. Eratosthenes employed measurements of time, distance and angles to calculate the circumference of the Earth. He used these measurements and his understanding of Euclidean geometry (mathematical theorems) to perform his calculations[[8]](#footnote-8). In addition to distance measurements made by surveyors, Eratosthenes made several assumptions[[9]](#footnote-9) (for example, the distance between Alexandria and Syene was 5000 stadia; Alexandria is due north of Syene; the Earth is a sphere (both Pythagoras and Aristotle had established this before Eratosthenes’ time); the light rays emanating from the Sun are parallel). Depending on the conversion of the ancient units of measurement into modern ones, Eratosthenes’ calculation of Earth’s circumference was within 16% of the modern value[[10]](#footnote-10).
  + Christiaan **Doppler** derived his postulate (now called the Doppler Effect) by mathematically deriving the relationship between frequency of an electromagnetic wave and the motion of the observer or source[[11]](#footnote-11). However, the first experimental verification of the Doppler Effect was obtained by another physicist (Buijs-Ballot), using a horn player on a train between Utrecht and Maarsen, and with musicians placed along the railroad tracks. The speed of the train was determined with two chronometers and a marked 100m distance along the track[[12]](#footnote-12).
  + Joseph **Priestly** was interested in the study of gases and in the process of combustion. He developed procedures to collected gases to study their properties. In one experiment, he collected the gas released from burning mercuric oxide. He noticed that this gas was able to increase the brightness of a candle flame and lengthen the life of mice in enclosed containers. Although he called this gas ‘dephlogisticated air’, it was later called oxygen. Priestley’s observations are qualitative in nature[[13]](#footnote-13).
* All of the investigations described above led to significant discoveries about the systems that were studied. All of those discoveries have been verified and corroborated by subsequent studies, sometimes using different approaches to those used in the original investigations. For example,
  + **Marshall and Warren’s** discovery of the microbial cause of gastric ulcers was so significant that they received the Nobel Prize for Physiology or Medicine in 2005[[14]](#footnote-14). Some of their initial research findings on the role of Helicobacter in gastric ulcer disease were published in peer-reviewed journals but did not gain widespread acceptance[[15]](#footnote-15). However, after infecting himself (Marshall) with the bacterial culture and developing the disease, those findings were corroborated by many studies from laboratories around the world. This led to the acceptance of the idea that Helicobacter infections caused gastric ulcers. Their discovery led to the development of new treatment modalities for the disease. It also enhanced our understanding of the gastric environment – for example, prior to this discovery, the stomach was considered a sterile environment, and it was thought that cells could not survive the acidic environment of the organ. It also shed new light into other conditions of the stomach, such as inflammation (gastritis) and malignancies (cancers). After the publication of their seminal work, numerous studies conducted around the world also identified Helicobacter pylori bacteria in gastric biopsy samples.
  + **Eratosthenes’** calculation of the Earth’s circumference was significant even for the people of his time. Many others who came after him applied his strategy to calculate the circumference of the Earth. Even Christopher Columbus read Eratosthenes’ work before embarking on his voyage of discovery of the Americas. However, one source of error was the conversion of the units of measurement employed in different parts of the world. As technology advanced, other methods were used to calculate Earth’s circumference. Today, satellites orbiting the Earth measure Earth’s circumference – modern measurements are very close to the value calculated by Eratosthenes.
  + **Doppler’s** postulate is a fundamental concept of science and is learnt by science students all over the world. Doppler initially presented a paper on the Doppler effect at the Royal Bohemian Society of Science, and later published a detailed paper on the same subject[[16]](#footnote-16). His publication was not peer-reviewed, and his postulate was initially not accepted by the scientific community. It was only after the experimental verification of the postulate did it become an important concept in science. The Doppler effect is the basis of another important concept in science – the red-shifting of galaxies, which was discovered by the astronomer, Edwin Hubble. It also led to the development of technologies such as Radar, Lidar and Sonar. Medically, the Doppler effect is used to measure the flow of blood in people (called the Doppler Ultrasound), as well as the Echocardiogram (an ultrasound of the heart). A search of the scientific publications database, ProQuest, with the keyword ‘Doppler’ returns more than 41,000 scholarly publication since 1959. This indicates the importance of Doppler’s discovery to modern science.
  + **Priestley’s** dephlogisticated air is now known as oxygen (renamed by Lavoisier). This discovery has become very important in the life sciences. Priestley was able to demonstrate that this gas was important to living things, as, in its absence, animals (mice) died. He also showed that plants produced the gas. His findings were the basis of later discoveries of respiration and photosynthesis, including that the equilibrium between these processes was important to the maintenance of stable atmospheric gas compositions. Although many of hisworks were self-published and not peer-reviewed, Priestleypublished his scientific works peer-reviewed journals. He described his discovery of phlogiston in a letter to the Royal Society, which was subsequently published in the Society’s magazine, The Philosophical Transactions of the Royal Society[[17]](#footnote-17). In the times of Priestly, peer review operated differently to today’s peer review methods[[18]](#footnote-18). He also presented his discoveries at various scientific institutions in Europe. He visited several laboratories in Europe and had discussions with other scientists. He had several discussions with Lavoisier, who disagreed with Priestley’s idea of phlogiston in combustion. Indeed, the theory of dephlogisticated air was replaced with Lavoisier’s description of oxygen.

### The integrity of scientific investigations

* The strength of scientific discoveries lies the integrity of the scientific process, particularly in the approach taken by investigators. In practical terms, the integrity of investigations is dependent on the reliability and validity of all aspects of the scientific process. This includes:
  + Identifying and controlling all variables, except for the independent and dependent variables
  + Identifying suitable samples (including sample sizes), equipment, methods for collecting and analysing data, identifying and minimising errors.
  + Ensuring that all ethical regulations are complied with
  + Conclusions are developed through evidence-based argumentation and logical reasoning

#### Designing scientific investigations

* The strength of scientific discoveries lies the integrity of the scientific process, particularly in the approach taken by investigators. In practical terms, the integrity of investigations is dependent on the reliability and validity of all aspects of the scientific process. This includes:
  + Identifying and controlling all variables, except for the independent and dependent variables
  + Identifying suitable samples (including sample sizes), equipment, methods for collecting and analysing data, identifying and minimising errors.
  + Ensuring that all ethical regulations are complied with
  + Conclusions are developed through evidence-based argumentation and logical reasoning
* When designing the investigation described in the syllabus, students should consider the factors shown in Table 1.

Table 1: Factors to consider when designing scientific investigations.

|  |  |
| --- | --- |
| Experimental design criteria | Notes |
| Variables | By varying only the independent variable (and keeping all others constant), any change in the dependent variable can be attributed to the independent variable. This allows for a cause-and-effect variable to be established (assuming the relevant data is obtained). |
| Sample selection | Samples should be sufficiently large so that errors of measurement are minimised. However, large sample sizes will increase the cost of conducting investigations. Therefore, researchers will seek a compromise between these requirements when defining the sample size. When samples are grouped (for example, experimental and control groups), group assignment should be randomised. |
| Materials and methods | The methods employed in an investigation should allow the researcher to obtain relevant data. Therefore, correct equipment and materials must be used (considering the variables of the investigation). The type of instruments used also depends on the accuracy of measurement that is needed (for example, analogue or digital). Finally, the costs of the materials and equipment can also influence experimental design. The investigator should be able to justify the methodology used. |
| Ethics | All investigations must be in accordance with ethical principles of scientific research. Experiments involving vertebrate animals and humans require ethics permits. All data collected in experiments (particularly those involving confidential information, including identifying information) should be kept securely and not shared without prior approval. Note: students will explore the role of ethics in research in Module 8. |
| Timeframes | A well-constructed research plan should contain timelines that indicate when the various parts of the investigation will be conducted, including an expected completion date. |
| Individual/collaborative work | Some investigations may be conducted individually, while others require collaborative efforts. If collaborative work is required, then the roles of the participants should be indicated. |

#### Describing the findings of scientific investigations

* Data should be processed before it is analysed. Irrelevant and inaccurate measurements should be removed, and outliers identified. Consideration should also be given to data presentation (table, graphs) and any statistical analyses that need to be performed. Appropriate analytical tools should be applied to identify pattern and trends in the data. Such patterns and trends may indicate the relationship between the independent and dependent variables. The data should then be interpreted within the context of the inquiry question/hypothesis: does the data provide evidence in support of the hypothesis?
* Students should justify the appropriateness of the methodology that was employed in the investigation. They should reflect on refining the methodology for improved data collection. This could include the use of different types of equipment, measurement intervals or analytical tools.
* Students should investigate the broader implications of their findings (if relevant). This may involve the extrapolation of their experimental findings, or applying their findings to other (but relevant) contexts: for example, the findings from a laboratory investigation on the microplastic levels in water samples may be translated to real-world scenarios that describe plastic pollution in the hydrosphere.
* Students should reflect on their investigative findings and comment on the reliability and validity of their findings:
  + Validity: did the investigation measure what was intended to be measured in a fair test (controlled experiment)?
  + Reliability: were consistent data obtained when the measurements of the dependent variable were repeated (and what measures were taken to reduce the errors of measurement)? Note: further discussion of the errors of measurement occurs in Module 7.

### Scientific reports

* The peer-reviewed publication is the pre-eminent form of scientific communication. Research papers are not chronological summaries of investigations. The structure of the report does not reflect the research process but is designed to make all of the different aspects of a scientific investigation evident.
* Each section of the paper contains specific information about the investigation. This makes it easier for the readers and peer-reviewers to access relevant information as required. For example,
  + Abstract: provides a quick summary of the investigation and its findings
  + Material and Methods: provides information on the equipment, chemicals, specimens, software, as well as experimental and analytical procedures used in the study.

More information on the structure of the scientific paper is provided the section ‘Understanding the peer-reviewed scientific paper’.

* Scientific research is a ‘social activity’, as it seeks to build knowledge about the natural world and thus work for the wellbeing of all. The approaches used by scientists when conducting investigations are limited by numerous factors (for example, economic and political reasons). Scientists are guided by ethical principles, which have developed over time and are based on frameworks that minimise harm. Social expectations also impose standards of ‘acceptable’ research. In many countries, researchers must obtain ethics approvals for several categories of research (for example, human or animal ethics approvals) before commencing scientific investigations.

## Opportunities for extended concepts

* In practice, the process of science is non-linear, iterative and non-determined. A [visual summary](https://undsci.berkeley.edu/article/0_0_0/howscienceworks_02) of the scientific process shows that it is complex, with multiple interconnections between the components of the process.
* Scientific investigations are usually based on inductive or deductive approaches (or a combination of the two).
  + **Inductive approaches** rely on collecting observations before developing theories. For example, scientists may sequence the genome of an organism, before developing conclusions about its evolutionary relationships to other living things. Similarly, astronomers may collect data on specific regions of the universe before making conclusions on the astronomical events that occur there. Therefore, inductive approaches in science imply that observations and data need to be generated before developing scientific theories (observations before theories).
  + **Deductive approaches** are based on existing scientific theories. Deductive investigations are used to verify scientific conclusions or to extend the understanding of those theories. For example, scientific investigations of cells and cellular processes are based on the Cell Theory. It is assumed that the concepts of the Cell Theory are true and therefore certain outcomes may be predicted based on those concepts (that is, if specific conditions are met, then certain outcomes may be predicted, based on the underlying scientific concepts). For example, one approach to treating cancers is chemotherapy, which uses specific drugs that inhibit cell division. Since cancers are cells, then scientists predict that drugs that prevent the replication of DNA in cancer cells will prevent those cells from dividing, resulting in the eradication of the tumour. Deductive approaches often use hypotheses, which are then tested in controlled experiments.
* Ethical, political, social and economic factors influence the decisions made by scientists as to the most appropriate approach for an investigation. Therefore, there are different ways of ‘doing’ and ‘reporting’ Science. This is discussed further in Module 8.

## Alternative conceptions and misconceptions

* Students often assume that there is a ‘scientific method’, which is exemplified by the structure of the scientific research paper. As described above, this is not true. Indeed, rather than the scientific method, explain to students that the scientific process encompasses all the procedures that investigators must follow to ensure the integrity of the procedure, analyses and the conclusions that are arrived at.
* Another misconception/alternative conception is that researchers know the exact method they will use before they begin data collection. Related to this misconception is the idea that there is only one ‘correct’ way to perform an experiment/investigation. Researchers will choose their approaches and methods based on their own contexts and constraints (e.g. cost, resources, time). They may also refine/modify their methods in response to things like the quality of the data being collected (for example, after conducting a preliminary study), or change in the focus of the investigation. No matter what the chosen method may be, researchers must be able to justify and defend their choices based on the validity, reliability and accuracy of their investigations, and any other considerations specific to their situation.
  + Provide students with a research report and ask students to describe what they think happened during the investigation. If the teacher has any published articles from their own research, students will really engage with this.
  + Describe what happened in the study (or show an interview of a scientist discussing their research) and assess students understanding based on the resulting discussion.
  + Provide students with two or three valid methods to investigate the same research question. Ask students to identify which is the correct method. Students without this misconception should understand that each method is a ‘correct’ method and could identify different contexts for which each method is suitable. Here is an exemplar lesson.

Ask students to suggest different ways of measuring the pH of some substance (homemade indicator, laboratory pH indicators, such as litmus paper or universal indicator, and pH probe). Ask students, which method is best suited to measure the pH of a substance (consider factors such as accuracy, ease of use, equipment availability, cost, etc.). Students should be able to indicate and justify the best methods for measuring pH in terms of the purpose of the investigation, cost/access to resources, level of precision required, reliability and validity of the measurements, etc.

## Conceptual difficulties

* Students (and teachers) find peer-reviewed reports to be challenging. Journal articles assume that the reader is an expert in their field, and so use expert language without explanation. Generally, methodologies are reported (summarised) rather than being described as step-by-step procedures (students find it surprising that we teach step-by-step methods at school, whereas peer-reviewed reports present an overall methodology.). While experts can interpret such information, non-experts cannot. Students need to be scaffolded through this process carefully. Some peer-reviewed articles have been written for more general audiences, and these are useful, for example, [Science Journal for Kids](https://www.sciencejournalforkids.org/) and [The National High School Journal of Science](https://nhsjs.com/).
* Students struggle with the difference between validity, reliability and accuracy. A helpful tactic is to scaffold students through a substantial primary investigation (over 2-3 weeks) involving people. This allows the students to focus on validity in terms of potential sources of bias and reliability in terms of how many people are involved. It would also be helpful to introduce precision as a separate concept to accuracy, as is done in Science Extension. An exemplar activity to illustrate the difference between validity and reliability is as follows:

Provide students with blank targets (for example, an A4 sheet of paper with a 5 cm ‘bullseye’ drawn in the centre of the sheet) and coins or plastic counters. Lay the target on the floor and then ask students to flick the coins/counters so that they land as close to the bullseye as possible. Initially, ask the students to stand some distance away from the target (say, 3m) and flick 5-10 coins/counters at the target. Get the students to take a photo of the distribution (or draw the distribution pattern in their books) of the coins/counters. Then, ask the students to move close to the target and repeat the coin/counter flick. Repeat as required but ensure that the students keep a record of the coin/counter falls relative to the bullseye. Students should be able to discern four distinct distributions:

Reliable and valid

Reliable, not valid

Unreliable, valid

Unreliable, invalid

Note that these definitions assume that the goal of the activity is to hit the bullseye as often as possible. The four outcomes indicated above are shown diagrammatically in Figure 1. This activity should illustrate that reliability defines the ‘consistency of measurements’, while validity examines ‘whether the conclusions can be trusted (that is, whether the conclusions are meaningful)’.



Figure 1: A diagrammatic representation of reliability and validity. Image credit: [explorable.com/validity-and-reliability](https://explorable.com/about).

* Investigating Science students may find the concepts about the errors of measurement to be difficult. A laboratory activity that explores such concepts may facilitate learning. Ask students to closely examine the markings on laboratory glassware, such as beakers, graduated cylinders and burettes, especially the notifications of the uncertainties of measurement (for example, ‘±0.5 mL’ on graduated cylinders). They should also read the manufacturer’s digital measuring devices, such as multimeters. Once the teacher has gauged students’ understanding of the significance of such notifications, the lesson may progress to demonstrating the impact that such uncertainties may have on the accuracy of measurement, particularly if the wrong equipment is used. One simple demonstration involves the use of laboratory glassware. Devices such as burettes, graduated cylinders and pipettes are highly calibrated measuring devices, while beakers and conical flasks are not (they only indicate approximate volumes). Students can then perform the following investigation:
  1. Affix a 100 mL burette to a retort stand and fill it with water.
  2. Place a 50 mL graduated cylinder below the burette.
  3. While watching the water in the burette, dispense 40 mL of water into the graduated cylinder.
  4. Measure the volume of water in the graduated cylinder. Repeat this step or collate the class’ results. Then, calculate the average volume of water in the graduated cylinder.
  5. Calculate the error of measurement using the following formula:
  6. Repeat steps a-e, except that the graduated cylinder should be replaced with another glassware, such as a beaker or conical flask.
  7. Students should reflect on the impact that using the wrong equipment (for example, using a beaker to measure a volume of liquid) would have had on the accuracy, reliability and validity of an experiment.

## Suggested teaching strategies

In the Investigating Science Year 12 course, modules 5 and 6 contain related concepts and may be taught together. The same is true for modules 7 and 8.

Before commencing module 5, it may be useful to evaluate whether students understand the role of ‘Peer Review’ in science, which is discussed in Module 2.

As Module 5 focuses on the scientific process, it is central to the ideas discussed in the later modules. Modules 6-8 may be considered to be elaborations of the concept strands in Module 5. It may be beneficial to students to explicitly point out the links between Module 5 and the other modules. For example, in Module 5, students have to consider the ethical implications of their investigation. It may be useful to indicate that the same concept will be discussed again in greater depth in Module 8.

IQ5-1 and IQ5-2 are straight forward and can be done as simple secondary-sourced investigations. They are useful for broadening student understanding of the large range of methodologies available (i.e. activate/build background knowledge for IQ5-3 & IQ5-4). The work of Marshall and Warren (peptic ulcers) provide a great opportunity for discussing ethics around self-experimentation (links to Module 8).

Compared to IQ5-1 and IQ5-2, IQ5-3 and IQ5-4 may require considerably more instructional time. IQ5-4 (the structure of a scientific report) may be better taught before IQ5-3 (reliability and validity) because it helps students to identify the parameters for designing investigations. It also means that students can go through the investigative process and writing a report at the same time to deepen learning.

## Depth studies

The units of work outlined above can all be executed as depth studies with embedded content. The following are other ideas for depth studies.

* Writing an essay that analyses a peer-reviewed article, identifying where it sits within the field of research and potential future development.
* Students use the references in their report to identify what has occurred before this investigation.
* Students can use Google Scholar to identify related investigations and later investigations that have used this article in their research (refer to resources above).
* Students could create an annotated timeline or another visual representation (such as a flow chart) to show how their chosen paper fits within their field of Science, its impact, and potential future developments.
* Through this activity, students are exploring the concepts of the Nature of Science:
  + Building upon what has come before.
  + The importance of secondary-source research to inform investigations (links to Module 2).
  + The importance of the collaboration and the peer-review process (links to Module 2).

Comparing the efficacy of a clinical trial to a survey. Students could develop and conduct a survey investigating what helps people to study/learn. Students could compare their findings to that of the clinical trial and assess the benefits and drawbacks of each method. This would deepen students’ understanding of how the method of data collection affects the outcome (Module 1) and the suitability of different methods to address the same question (Module 5). The students can then draw some conclusions about the relationship between the purpose and constraints of an investigation and the chosen methodology.

## Practical activities

Note that the Investigating Science syllabus requires students to undertake an investigation in this module:

**Practical Investigations to Obtain Primary Data (IQ5-1 and IQ5-2):**

* Students **develop a method most appropriate to test a hypothesis** following observation
* Students**justify the type of methodology** used to test the hypothesis

When conducting practical and secondary-sourced investigations, students use **peer feedback to refine their investigative designs** and report on their findings.

For IQ5-4, Students review a published and peer-reviewed scientific report to **determine the conventions of writing a report** on a practical investigation

When designing and justifying the investigative method, students need to consider the following:

* The independent, dependent and controlled variables.
* The type of data required to answer the research question.
* How the data will be collected and analysed (for primary and secondary data), including processes for ensuring accuracy and reliability, while avoiding bias.

Therefore, the methodology is a critical component for evaluating the investigation’s reliability and validity ([The University of Southern California libraries research guides](https://libguides.usc.edu/writingguide/methodology)).

Here are some suggestions for practical activities:

* Measuring the wavelength of electromagnetic waves in a microwave oven: [How To Calculate The Speed Of Light With Your Microwave](https://www.youtube.com/watch?v=GH5W6xEeY5U) (duration 3:50). This relates to the syllabus example of Spencer’s invention of microwave ovens and is an example of how everyday equipment can be used to explore scientific concepts (links to Module 6).
* [Using shadows to estimate the height of trees and buildings](https://www.wikihow.com/Measure-the-Height-of-a-Tree). This investigation allows students to practically investigate the use of shadows for estimating lengths as was done by Eratosthenes when he estimated the Earth’s circumference (syllabus example). It is also is a great opportunity to discuss estimation/precision and accuracy.
* Practically investigate the [Doppler effect](https://www.stem.org.uk/resources/community/resource/413248/measuring-doppler-effect-classroom) using two different approaches: stationary sound source or moving detector (for example a phone) versus moving source or stationary detector. This links to the development of technology (mobile phones as observational tools) in Module 6.

## Resources

Appendix 4 provides some strategies for teaching experimental design to students. It includes some useful templates that may be used in the classroom. Those templates may be adapted to meet the learning needs of students.

Useful sources of peer-reviewed articles

* [Science in the Classroom (SitC)](https://www.scienceintheclassroom.org/) contains a large collection of annotated, peer-reviewed scientific articles for use in the classroom.
* [Google Scholar](https://scholar.google.com.au/): Google scholar also has very useful tools:
  + It has links to show students how to reference the article for different styles.
  + The ‘**cite**’ tool shows which peer-reviewed articles have referenced the current article (useful for looking at the role of the specific research in its field of science and determining its impact)
  + **‘Related articles’** are a list of articles related to the research.
* [Science Journal for Kids](http://www.sciencejournalforkids.org/)
* [National High School Journal of Science](http://nhsjs.com)
* [Young Scientist journal](https://ysjournal.com/)
* [Frontiers for young minds](https://kids.frontiersin.org/)
* [Journal of Emerging Investigators](https://www.emerginginvestigators.org/)
* [The Student Journal of Science and Technology](http://journal.fsst.ca/jsst/index.php/jsst/pages/view/studentresearch)
* [Science in Schools](https://www.scienceinschool.org/)
* [Elsevier open access journals](http://www.elsevier.com/about/open-science/open-access/open-access-journals)
* [Open access journals](http://www.omicsonline.org/open-access-journals-list.php)
* [Public Library of Science](http://www.plos.org)

[Tuskegee Syphilis](https://allthatsinteresting.com/tuskegee-experiment-syphilis-study) case (useful for discussing ethics as an extension activity when covering methodologies)

A useful video for teaching students how to read/analyse peer-reviewed papers (particularly for more capable students) is [How to Read, Take Notes On and Understand Journal Articles | Essay Tips](https://www.youtube.com/watch?v=hfTpYruV7AE) (duration 5:32). This video is good because it steps the students through a useful, structured process for analysing papers. However, it is important to note that this only one such method. Every scientist develops their own way of analysing journal articles.

For high ability students, teaching students how to synthesise different papers on the same topic may be appropriate. In this case, students will need to be explicitly taught how to extract and compare themes and ideas from different papers, rather than simply summarising the information. Visual tools such as concept matrices and concept maps (mind maps) are helpful for this process. Students will most likely take a ‘source focused’ approach in which they create a mind map to summarise the content in a few papers and draw links between similar ideas. High ability students may be able to create a ‘concept focus’ map, which identifies major themes and shows how each source addresses that theme. Some useful resources for doing this are:

* Creating a [concept matrix](https://familyneuroscience.wordpress.com/2015/11/13/literature-reviews-concept-matrices-and-concept-maps/): This has a useful image but doesn’t describe how to do this process.
* How to [use mind mapping to analyse information](https://www.adelaide.edu.au/writingcentre/sites/default/files/docs/learningguide-mindmapping.pdf) and plan for writing. The reference list provides links to various examples.
* Example of [concept map](https://www.fpce.up.pt/contextualizar/designs/Mapeamento_IN.jpg) showing how different papers are related according to themes.
* Example of a [concept focused mind map](https://www.mindmeister.com/54803492/academic-integrity-paper) (that is interactive):
* Tools for creating the maps:
  + Static mind map in OneNote (just move text boxes around and use the drawing tools
  + For larger mind maps, dynamic mapping software is very useful, as you can hide/show elements as you need them. An example of a free mind mapping software is [Mindmeister](https://www.mindmeister.com) (three free mind maps with a basic account). [Bubbl.us](https://app.education.nsw.gov.au/digital-learning-selector/LearningTool/Browser) is a free mind mapping software that may be accessed via a DET email account. The website, [Makeuseof](https://www.makeuseof.com/tag/8-free-mind-map-tools-best-use/), lists other free and paid mind mapping software.

## Appendices

## Appendix 1: Evaluating scientific investigations

### Scope

This document describes the following aspects of data analysis:

* evaluating data using accuracy, precision, reliability, and validity
* errors and uncertainty of measurements

### The limitations of generating scientific data

Scientific advances rely on a solid foundation of evidence. The strength of any scientific concept is only as strong as the quality of the evidence that supports it. Thus, scientists place great emphasis on gathering, manipulating, and analysing evidence.

Data are measurements and observations that scientists use to develop scientific conclusions. The term measurement refers to the amount or quantity of some particular property that a system possesses (e.g. the mass of an object). Often, scientists manipulate raw measurements before using them as the data. Scientific investigations do not produce single measurements. Rather, the data are the averages of multiple, independent measurements. Most measurements contain errors (note that scientific errors are not mistakes – this is discussed in a later section). It is important to anticipate, identify and minimise (or even eliminate) sources of error in measurements. Indeed, proper data analysis requires an understanding of measurement errors. Every aspect of a scientific investigation must be scrutinised for errors, as they may affect the investigator’s conclusions. When experiments are repeated, the errors of measurement may compound. Therefore, scientists use several criteria to decide if an experiment, and the conclusions derived from it, are acceptable.

Table 2 below defines criteria that are used to evaluate scientific investigations[[19]](#footnote-19).

Table 2: Definitions of the quality of scientific investigations. These definitions are used in NESA syllabuses.

|  |  |  |  |
| --- | --- | --- | --- |
| Term | Definition | Synonym(s) | Notes |
| Accuracy | The extent to which a measured value agrees with its true value (i.e. reference value). | Exact | Requires prior knowledge about the measured variable (i.e. reference values) |
| Reliability | The extent to which the findings of repeated experiments, conducted under identical or similar conditions, agree with each other. | Consistency Repeatability Reproducibility Stability |  |
| Validity | The extent to which an experiment addresses the question under investigation. | - | The criterion examines how well the design, conduct and analyses of an investigation address the inquiry question/hypothesis being investigated. |

After learning about the meaning and use of these terms, students should explore the relationship between them. For example, measurements may be accurate but not reliable. Validity is a holistic evaluation of scientific investigations and relies on all aspects of investigations to be accurate/precise and reliable. An unreliable investigation cannot be valid, but a reliable investigation may be invalid if it does not address the question under investigation. Note that NESA does not use the term ‘precision’ in the Investigating Science syllabus: accuracy encompasses precision.

## Appendix 2: Errors and uncertainties of measurement

### Errors of measurement

In science, measurement errors refer to the difference between the measured and true values of a quantity. It is important to note that a scientific error is not a mistake in making the measurements.

Generally, there are two classes of errors of measurement. [Note that errors of measurement should not be confused with statistical errors].

* **Systematic errors**: Systematic errors are deviations from the true value by a constant amount. They are also called ‘biases’. Systematic errors affect the accuracy, but not the reliability of measurements. Repeating the measurements will not improve the accuracy of the data. If a piece of equipment does not read zero when it should, it is not calibrated correctly. If a bathroom scale reads 2 kg when no one is standing on it, it will measure a person’s mass as being 2 kg heavier than it actually is. Calibration error can be minimised by zeroing the equipment before it is used or by subtracting the false reading (what it reads when it should read zero) from each measurement.
* **Random errors**: These are the ‘component of measurement error that in replicate measurements varies unpredictably’. Random errors cause deviations from true values by varying amounts. An example of a random error is the effect of environmental factors on measurement (e.g. temperature or humidity). Random errors affect the precision and reliability of measurements. Repeating the measurements can reduce random errors of measurement.
  + Parallax error. This is an example of a random error. When the object being measured is viewed at an angle, the scale being used to measure the object may not line up exactly with the object. This will lead to the measured value being higher or lower than the actual value. For example, when a car speedometer is viewed from the passenger’s seat, it will appear to show a higher speed than when viewed from the driver’s seat. Parallax error can be minimised. When reading from a scale, the scale needs to be viewed from directly in front. Some electrical meters have a mirror behind the needle; if the reflection of the needle can be seen, the observer is not viewing the scale from directly in front.

Predictably, the closer the measured value is to its real value, the lower the error of measurement. Conversely, the lower the error, the greater the accuracy of the measurement. Therefore, we must be aware of the errors of measurements when conducting and analysing experiments.

### Uncertainty

Uncertainty refers to the spread or dispersion of measurements. It implies that the true value of a measurement is not known accurately, but that it lies within a range of values. When reporting measurements, the uncertainty is shown with a ± symbol. Therefore, the measurement is reported as

Measurement ± uncertainty (for example, 0.86 ± 0.05 s)

There are two ways of determining the uncertainty associated with measurements:

* **Analogue instruments** (e.g. ruler): the uncertainty is half of smallest division. For example, standard laboratory thermometers show gradations of 1oC. Therefore, the uncertainty of measurements associated with this device is 0.5oC (i.e. temperature ± 0.5oC).
* **Digital instruments** (e.g. voltmeter): the uncertainty is half of the highest significant figure. Consider a digital voltmeter that provides measurements to two decimal places. For example, if a voltmeter provides a reading of 1.55V, then the error of measurement is associated with the value of the number in the second decimal place (in this case, 0.05V). Since this number varies by 0.01V (the reading lies between 1.55V and 1.56V), the uncertainty of measurement is half of this value, or 0.005V. Therefore, this measurement is reported as 1.55 ± 0.005V.

## Appendix 3: Understanding the peer-reviewed scientific paper

There are different types of peer-reviewed scientific papers. The most common ones are[[20]](#footnote-20):

* **Original research**: This is the most common type of journal manuscript used to publish full reports of data from research. It includes the full Introduction, Methods, Results, and Discussion sections.
* **Short reports or Letters (sometimes called brief communications)**: These papers communicate brief reports of data from original research that will likely stimulate further research in the field. This format may not contain all the sections found in original research papers. They are shorter in length, and some experimental details may not be included. These papers are also sometimes called.
* **Review Articles**: Review Articles provide a comprehensive summary of research on a certain topic, and a perspective on the state of the field and where it is heading. They do not contain the sections found in research articles. Reviews are often widely read (for example, by researchers looking for a full introduction to a field) and highly cited.
* **Case Studies**: These articles report specific instances of interesting phenomena (to make other researchers aware of the possibility that a specific phenomenon might occur). These do not contain the sections found in research articles
* **Methodologies or Methods**: These articles present a new experimental method, test or procedure. They do not contain the sections found in research articles but have detailed procedures and expected results.

Therefore, scientific findings are communicated in different ways in the different types of peer-reviewed publications. As suggested above, ask students to analyse peer-review scientific papers (original research articles). The focus should be on the information that is conveyed in each section of the paper. Then, ask students to read scientific articles from journals that are targeted for high school students (for example, [Science Journal for Kids](https://www.sciencejournalforkids.org/) and [The National High School Journal of Science](https://nhsjs.com/)) and answer the following questions[[21]](#footnote-21):

1. What are the research questions the authors trying to answer?
2. What makes that research question significant? (That is, why try to answer that question? Why does it matter?)
3. What data did the authors collect?
4. What is the authors' interpretation of their data?
5. Do you think that the data they collected supports their conclusions? Why or why not?

### Teaching sequence

IQ5-4 (the structure of a scientific report) may be the most challenging section to teach as this is new territory for the students. It may be helpful to teach the content for IQ5-4 in a different sequence to that in the syllabus, that is, start broad and then flush out the different sections. Suggested sequence:

* Present a peer-reviewed report and the modified version through [Science Journal for kids](http://www.sciencejournalforkids.org/). Discuss the similarities and differences, audience, language, purpose and so on.
* Collect a range of peer-reviewed reports from different sources, such as [Science Journal for Kids](http://www.sciencejournalforkids.org/) (SJfK), [National High School Journal of Science](http://nhsjs.com/) (NHSJ), journal papers from at least two different fields, and a paper authored by someone familiar to the students. If you have access to a published researcher who is willing to talk to the students, invite them into class to discuss their research during IQ5-1 & IQ5-2, and then use one of their papers in this lesson).
* A multi-lesson sequence comparing the different publications (each student could be responsible for one publication with low achieving students using SJfK):
  + Presentation and structure, including where to find a summary of what the investigation is about and its findings (abstract), how is the abstract different from the introduction.
  + Language style, the purpose of the report (big picture, but also start looking at the specific purpose of the author), measures taken to reduce error (location in report and type of wording),
  + Highlight parts the report where validity, reliability and accuracy are addressed and how they are reported.
  + Formative assessment: students create a block planner for their publication and compare that to a typical high school experimental report planner (refer to the previous section).
  + Students can then attempt IQ3 through a long investigation with the final product being a peer-reviewed style report (which is broken down for them in IQ4).
* Extension: Analysing multiple peer-reviewed papers on one topic.
* For high ability students, ask them to find 2-3 papers on an area that interests them and ask them to analyse them as they would if they were to write a literature review. They do not need to write the literature review or an annotated bibliography, just scientific the papers and create a concept matrix and/or mind map to show the analysis. The resources listed previously will help in this process. The following process is a useful and effective method for analysing peer-reviewed papers.
* For each paper:
  + Highlight main points -it makes it quicker to read later, but DO NOT highlight everything!
  + Write notes on the things that you could directly use in your analysis.
  + Students synthesise their analysis using one of the following methods.
  + Source focused mind map (easier).
  + Make sure students draw links (connecting lines) between the information in different sources to show how they are connected/related.
  + Idea focused mind map (harder).
  + Identify common themes amongst the sources and have these as the major elements. Students then list the key points from each paper that relate to the common themes.
  + Dot-point summary of each source WITH a concept matrix or simple concept map showing the connections between sources.
  + Students could then present their findings to the class informally.

The [University of Guelph library](https://www.lib.uoguelph.ca/) has a [template](https://www.lib.uoguelph.ca/sites/default/files/student_worksheet.pdf) that may be used in the classroom to guide students’ analysis of scientific papers.

The website [Science in the Classroom (SitC)](https://www.scienceintheclassroom.org/) contains a large collection of annotated scientific papers which may be used by teachers to illustrate the finer aspects of peer-reviewed publications in science.

## Appendix 4: Teaching experimental design[[22]](#footnote-22)

### Introduction

The following teaching activity may be used to explain to students the essential elements of experimental design. The activities may be adjusted to meeting the learning needs of the students (and some parts may be skipped altogether). Some activities may be used in flipped classroom settings or assigned as homework. Approximately five 60-minute lessons may be required to complete all of the activities.

### Lesson 1: How do scientists conduct scientific investigations?

This is an introductory activity to elicit students’ ideas of scientific investigations. It may be performed as a general classroom discussion to engage students with the topic. Some prompts for discussion include:

* What kinds of experiments have you done on your own (outside of the classroom)? (this does not have to be scientific experiments, but general inquiries that they have conducted to explore something in their lives – for example cooking (testing ingredients/recipes), developing sports techniques (analysing swimming strokes, cricket bowling techniques) or fixing things around the house).
* Are all scientific experiments designed and conducted in the same way?
* Are there “rules” for designing an experiment?
* How do scientists communicate their research findings? Or, how did you hear about a recent scientific discovery?

At this stage, teachers should determine if students hold misconceptions/alternative conceptions about the scientific process, such as[[23]](#footnote-23):

* There is a single Scientific Method that all scientists follow.
* Experiments are a necessary part of the scientific process. Without an experiment, a study is not rigorous or scientific.
* Scientific ideas are absolute and unchanging.
* Scientists' observations directly tell them how things work (i.e., knowledge is "read off" nature, not built).
* Scientific ideas are judged democratically based on popularity.
* The job of a scientist is to find support for his or her hypotheses.
* Scientists are judged on how many correct hypotheses they propose (i.e., good scientists are the ones who are "right" most often).
* Science is pure. Scientists work without considering the applications of their ideas.

Teachers should address any misconceptions/alternative conceptions held by students in the subsequent lesson activities.

### Lesson 2: Understanding the vocabulary of scientific experiments

The following activity examines students’ understanding of key terms used in scientific investigations. It is an important aspect of scientific literacy, and a good grasp of these terms can facilitate the development of skills such as experimental design and reading scientific publications. This activity may be done individually, or as small group work (for example, think-pair-share). It may also be set as a flipped classroom activity. Table 3 is the student worksheet, while Table 4 is the teacher guide which contains NESA-approved definitions.

Table 3: Student worksheet: understanding the vocabulary of scientific experiments

|  |  |  |  |
| --- | --- | --- | --- |
| Vocabulary | What it means to me | What it means in science | Hint(s) to remember this term or phrase |
| Inference |  |  |  |
| Variable |  |  |  |
| Independent Variable |  |  |  |
| Dependent Variable |  |  |  |
| Controlled Variable |  |  |  |
| Experimental Control |  |  |  |
| Hypothesis |  |  |  |
| Observation |  |  |  |
| Qualitative Observation |  |  |  |
| Quantitative Observation |  |  |  |
| Inquiry Question |  |  |  |
| Scientific inquiry |  |  |  |
| Primary data (sources) |  |  |  |
| Secondary data (sources) |  |  |  |

Table 4: Understanding the vocabulary of scientific experiments\_teacher guide

|  |  |  |  |
| --- | --- | --- | --- |
| Vocabulary | What it means to me | What it means in science | Hint(s) to remember this term or phrase |
| Inference |  | An attempt to explain or interpret observations or to identify the cause of what was observed. |  |
| Variable |  | In an investigation, a factor that can be changed, maintained (kept the same) or measured – for example, time, distance, light, temperature. |  |
| Independent Variable |  | A variable that is changed in an investigation to see what effect it has on the dependent variable. |  |
| Dependent Variable |  | A variable that changes in response to changes to the independent variable in an investigation. |  |
| Controlled Variable |  | A variable that is kept constant (or changed in constant ways) during an investigation. |  |
| Experimental Control |  | The sample in an experiment to which all the other samples are compared |  |
| Hypothesis |  | A tentative explanation for an observed phenomenon expressed as a precise and unambiguous statement that can be supported or refuted by an investigation. |  |
| Observation |  | That which can be sensed either directly by an individual or indirectly by measuring devices. |  |
| Qualitative Observation |  | To use descriptive explanations involving features, characteristics or properties to identify important components. Data and information that is not numerical in nature (such as colour or texture) |  |
| Quantitative Observation |  | Data or components that can be expressed or measured numerically, including chemical formulae or numbers. Use numbers to describe information about an object such as mass, length, or volume. |  |
| Inquiry Question |  | The question that is being investigated in |  |
| Scientific inquiry |  | A scientific process of answering a question, exploring an idea or solving a problem, which requires activities such as planning a course of action, collecting data, interpreting data, reaching a conclusion and communicating these activities. Investigations can include practical and/or secondary-sourced data or information. |  |
| Primary data (sources) |  | Information created by a person or persons directly involved in a study or observing an event. |  |
| Secondary data (sources) |  | An investigation that involves systematic scientific inquiry by planning a course of action and sourcing data and/or information from other people, including written information, reports, graphs, tables, diagrams and images. |  |

### Lesson 3: Exploring experimental design

In this lesson, students will analyse a stimulus text about a student’s inquiry. The investigation described in the stimulus is similar to inquiries conducted in Stage 4 and 5 Science Student Research Projects. After students have answered the questions, teachers should unpack their responses to explain all relevant scientific processes described in the stimulus text and emphasise how they relate to the vocabulary of scientific experiments (lesson 2).

Tom noticed that there were times of the day when he found it difficult to focus on his lessons. AT those times, his attention would drift, and he found it hard to remember things his teachers taught. Often, the period before lunch was difficult. Things got better after lunch. Tom suspected that hunger was the reason for his inability to focus. He researched online and discovered that one of the effects of lowered blood sugar levels was decreased attention to tasks that require focus.

Tom thought that he might test this idea with a simple experiment. He asked his classmates and other friends to join him in the experiment which involved the [Stroop test](https://faculty.washington.edu/chudler/java/ready.html). The Stroop test is an indicator of the participants’ ability to focus on the activities and provides their reaction times in the test. He divided his participants into two groups. One group ate five lollies (jelly babies) before completing the Stroop test 15 minutes later. The other group completed the test without eating the lollies (in the spirit of fairness, Tom gave the participants in the second group lollies after they had finished the experiment).

Answer the following questions (sample answers are provided for teachers)

1. **What question is Tom trying to answer?**

Tom is examining whether increased glucose levels improves concentration.

1. **What made him want to answer this question?**

He noticed that his ability to focus on his lessons was rather low before lunch but improved after lunch. After conducting some research, he predicted that this was due to low blood sugar before lunch, which was restored by the meal he has at lunch.

1. **What is being measured or observed in this experiment?**

The reaction time of the participants conducting the Stroop test.

1. **Are the observations recorded in words or numbers?**

The observations are recorded in numbers (reaction time in seconds).

1. **What factor does Tom think might cause the measurement to change?**

The sugars in the lollies will increase the blood sugar levels, which in turn, improves concentration and lowers reaction time.

1. **What parts of the experiment were kept the same throughout?**

Participants in the ‘lolly’ group all were given five lollies each. All participants completed the same Stroop test.

1. **Is there a standard of comparison in this experiment (something he compared** **everyone to)?**

No, Tom compared one group of participants (‘lolly group’) with another (‘no lolly group’).

1. **How many times was the experiment completed?**

Once.

### Lesson 4 and 5: The Pepsi versus Coke challenge

In this lesson, students will conduct an investigation called the Pepsi versus Coke challenge. The inquiry question is: Can girls taste the difference between Pepsi and Coke better than the boys?

**Note: This lesson assumes that the school is co-educational. In single-sex schools, teachers may alter the variables to be tested (for example, time of day or age). As this lesson involves food consumption, appropriate measures need to be taken to ensure that adverse outcomes (for example, allergic reactions) are avoided. Some students may have medical conditions that may prevent them from participating in this experiment (for example, diabetes, food intolerance and dietary preferences). Teachers may modify this activity so that students explore other inquiry questions.**

As a class, plan the Pepsi versus Coke experiment (use the **planner (Table 5)** provided to guide students in experimental design. Some other factors to consider:

* This experiment may be conducted as a blind or double-blind study. Although these concepts are discussed in Module 7, it may be relevant to introduce those aspects of experimental design for the current investigation.
* Although the investigation directly tests the dependent variable against the independent variable, the investigator can collect additional information to determine other correlations (which may form the bases of other studies). It is pertinent to discuss the complex data collection system in experimental design. In this investigation, additional data on age, frequency of drinking soda (daily, weekly, monthly, rarely), ability to roll tongue will be collected.

Suggestions for setting up the experiment:

* Remove the labels from the drink bottles. Styrofoam cups may be labelled underneath to identify the type of cola in them. A coding system may be useful: numbered cups are Pepsi; lettered cups are Coke). Therefore, each student gets two cups of cola, labelled A and B. However, the label at the bottoms of the cups indicate the type of cola present in them.
* In double-blind studies, the students who set up the experiments will not record the results. In this way, the students setting up the experiment will not be able to influence the participants about their selections. Furthermore, the students recording the results will not the type of cola in each of the cups.
* The data recorders can use the **data collection template (Table 6)** to record the results, as well as to obtain the additional data for further analyses.
* Collate the data when all participants have completed the taste-testing.

Table 5: Experiment planning template

|  |
| --- |
| **What is the inquiry question?** |
| **What prompted this inquiry (background)?** |
| **What is the Dependent Variable (DV)?** |
| **Hypothesis:** |
| **Independent Variable (IV): How will you vary the IV in the experiment?** |
| **Data to be collect (what will I be measuring or observing for each variable?)**  DV:  IV: |
| **Describe what could affect the DV and how they may be controlled.** |
| **Grouping:**   * Does the experiment involve 2 or more groups? Y/N (if N, move to the next row). * Is this experiment control VS experimental? \_\_\_\_\_\_\_ Or, group VS group? \_\_\_\_\_\_\_\_\_\_\_ * What is the first group (or control)? \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ What is the second group (or experimental)? \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ |
| **Risk assessment** (What could go wrong in this experiment and how can they be managed or prevented? |

|  |
| --- |
| **Other things to do:**   * Make a timeline showing the events in your experiment and the times you will measure or observe. * Write a clear procedure that others can follow step by step. * Create an organised data table (Table 6 shows an example of a suitable data table). * Complete the experiment. * Make adjustments to the written procedure if necessary and explain changes. * Display the data in an organised chart or graph (if possible). |

Table 6: Data collection template

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Gender | Age | Frequency of drinking carbonated drinks  (daily, weekly, monthly, rarely) | Ability to roll tongue  (Yes/No) | Cup A | Cup B |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
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### Lesson 6: Analysing the results of the experiment

After all of the results have been collected and collated, students should embark on analysing the data. Since data for multiple variables have been collected, students should analyse the results methodically:

* To determine if the inquiry question can be answered with the data collected
* To determine if other associations are revealed from the additional data collected (and which can be used for further investigations.

Table 7: Summary of the effects of different independent variables on the ability to correctly guess the type of cola.

|  |  |  |  |
| --- | --- | --- | --- |
| Type of comparison | Categories | Number of correct guesses | Percentage of correct guesses |
| Girls versus boys | Girls |  |  |
| Girls versus boys | Boys |  |  |
| Frequency of drinking carbonated drinks | Daily |  |  |
| Frequency of drinking carbonated drinks | Weekly |  |  |
| Frequency of drinking carbonated drinks | Monthly |  |  |
| Frequency of drinking carbonated drinks | Rarely |  |  |
| Age | 16 year |  |  |
| Age | 17 years |  |  |
| Ability to roll tongue | Yes |  |  |
| Ability to roll tongue | No |  |  |

Table 7 represents the processed data from this experiment. Generally, tables of processed data are shown in the results sections of published scientific papers. Raw, unprocessed data should be provided in the appendices of the publications.

**Graph:**

For each comparison, answer the following question:

1. What type of graph should be plotted? Why?
2. Which axis should the I.V. be on?
3. Which axis should the D.V. be on?

**Analysis:**

Answer the following questions. Use evidence-based reasoning (that is, data from the analysis done above) to support your answers.

1. How did gender affect the ability to identify Pepsi and Coke?
2. How did age affect the ability to identify Pepsi and Coke?
3. How did the frequency of drinking soda affect the ability to identify Pepsi and Coke?
4. How did the ability to roll your tongue affect the ability to identify Pepsi and Coke?
5. Do you think these results are accurate? Why or why not?
6. How could this experiment be improved? Give at least two ideas and describe how they would help achieve this.

**Note to teachers**: the purpose of this activity is to explain how scientific experiments are designed. All investigations begin with an inquiry question, and a well-designed investigation is necessary for the experiment to be a fair test. Students often assume that conducting the investigation, together with the analysis of the data, is the most important part of an investigation. However, all steps taken are designed to ensure that the dependent variable is measured

* as accurately as possible, with the most appropriate devices available.
* repeatedly.
* with all other variables (except for the independent variable) controlled.
* in a safe environment.

The experiment should allow the investigator to confidently conclude that any effect observed on the dependent variable is solely due to the manipulation of the independent variable. Finally, the investigator should be aware of any limitations that apply to the conclusions and seek to improve on the investigation itself.

## Appendix 5: Measuring the period of oscillation of a pendulum

**Preamble**: the following practical activity introduces Investigating Science students to the concepts of errors, accuracy, and reliability of measurement.

**Introduction**: the period of oscillation of a pendulum is proportional to its length (the distance of the weight from the fulcrum). Therefore, the shorter the length of the pendulum, the shorter its period of oscillation. In this investigation, we will measure the period of oscillation of pendula that you will construct in class.

**Materials**: Retort stand, string, weights (50-100 g), timer, computer with Microsoft Excel installed.

**Method**:

1. Measure 3 identical lengths of string (20 cm).
2. Tie each of the strings to identical weights (for example, 50 g).
3. Mount one of the pendula to a retort stand clamp (Experiment 1).
4. Determine the time taken to complete 10 oscillations of the pendulum, and record the measurement in Table 3 below (note that the data can be directly entered into a Microsoft Excel spreadsheet).
5. Repeat step 3 four times (total of 5 measurements).
6. Repeat steps 3-5 for the remaining pendula (Experiments 2 and 3).

Table 8: Table to record measurement obtained in the experiment

|  |  |  |  |
| --- | --- | --- | --- |
| Trial | Experiment 1  Time for 10 oscillations/s | Experiment 2  Time for 10 oscillation/s | Experiment 3  Time for 10 oscillation/s |
| 1 |  |  |  |
| 2 |  |  |  |
| 3 |  |  |  |
| 4 |  |  |  |
| 5 |  |  |  |
| Average |  |  |  |
| Standard deviation |  |  |  |

**Sample results:**

Table 9: Sample data that may be used for discussion in the classroom. The means and standard deviations were calculated in Microsoft Excel using the ‘=average’ and ‘=stdev’ function, respectively.

|  |  |  |  |
| --- | --- | --- | --- |
| Trial | Experiment 1  Time for 10 oscillations/s | Experiment 2  Time for 10 oscillation/s | Experiment 3  Time for 10 oscillation/s |
| 1 | 15.3 | 14.8 | 15.0 |
| 2 | 15.1 | 14.9 | 15.0 |
| 3 | 15.2 | 14.7 | 15.2 |
| 4 | 15.2 | 14.3 | 14.9 |
| 5 | 15.3 | 15.0 | 15.0 |
| Mean | 15.2 | 14.7 | 15.0 |
| Standard deviation | 0.1 | 0.2 | 0.1 |

The average periods of oscillations shown in Table 9 are plotted in the graph shown in Figure 2.

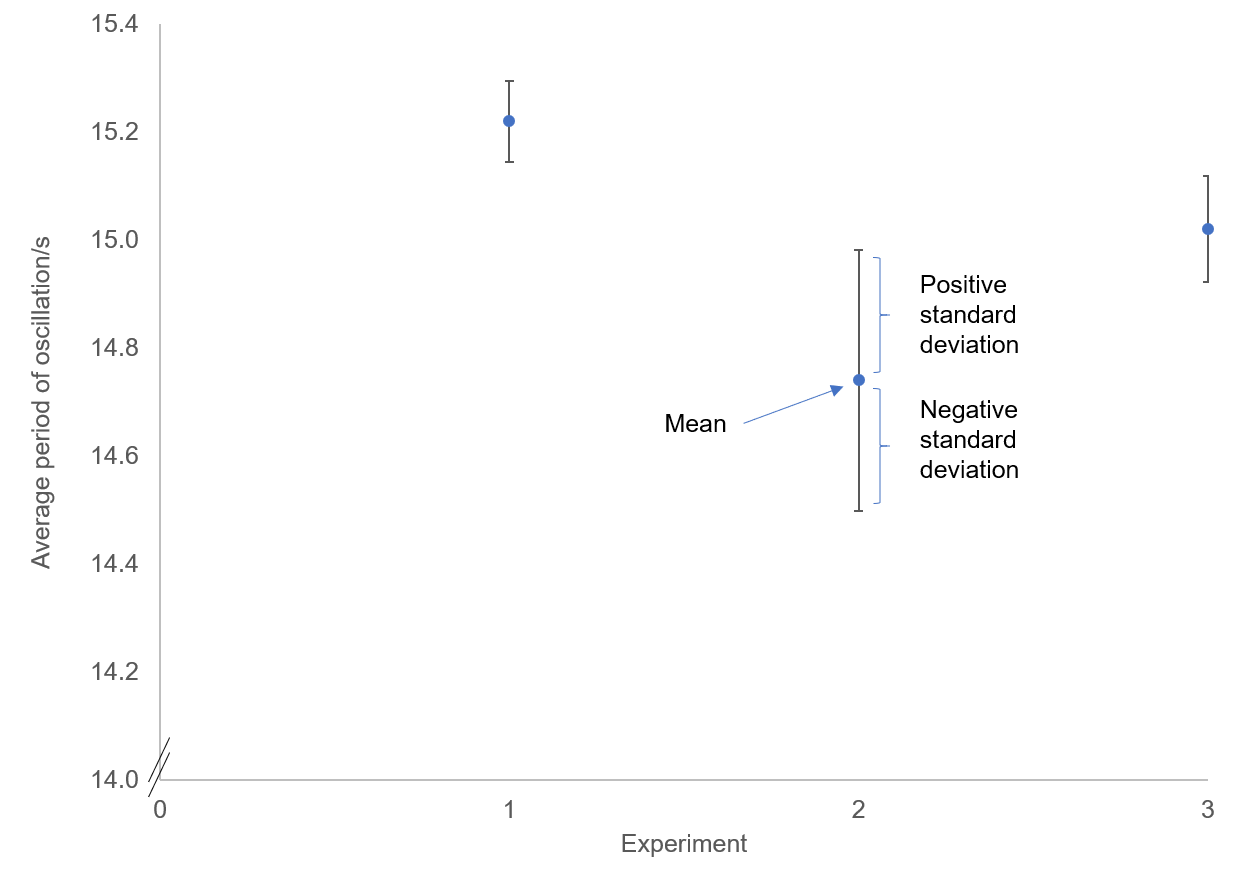


Figure 2. Scatter plot of the data from Table 9. For each data point, the mean and standard deviation are shown. The standard deviations were plotted in Microsoft Excel, with the standard deviations used to plot the error bars (positive and negative standard deviations). A YouTube video that describes how this is done may be viewed [here](https://www.youtube.com/watch?v=JeqCl_aD_8Y).

As shown in Figure 2, the measurements conducted experiment 2 had the largest standard deviation (0.2 s), compared to the other experiments (0.1 s). The standard deviation is a measure of the accuracy[[24]](#footnote-24) of the measurements and indicates the spread of measurements around the mean. In the example above, the results can be represented, as shown in Table 10.

Table 10: The periods of oscillations for the 3 experiments are shows as mean±standard deviation.

|  |  |
| --- | --- |
| Experiment | Period of oscillation (for 10 oscillations)/s |
| 1 | 15.2±0.1 |
| 2 | 14.7±0.2 |
| 3 | 15.0±0.1 |

This means that the data in experiment 1 spans from 15.1s to 15.3s, with an average of 15.2s. Since experiment 2 has the largest standard deviation, it is the least accurate.

Reliability refers to inter-experimental consistency. In this investigation, the original experiment was repeated twice (total of 3 experiments). The consistency of data between the replicated experiments (Table 5) indicates that the investigation is reliable. Scientists employ a statistical tool, called Cronbach alpha, to calculate reliability between experiments[[25]](#footnote-25). The Cronbach alpha value is analogous to the Correlation Coefficient. Statistical software packages, such as SPSS, SAS, Matlab and R, can calculate the Cronbach alpha value for a dataset. Excel requires multiple steps to do the same. Alternatively, [online calculators](https://www.easycalculation.com/statistics/reliability-coefficient.php) can perform Cronbach alpha calculations. For the dataset shown above, the Cronbach alpha value is 0.83. The closer this value is to 1, the more reliable the measurements.

Therefore, in summary, measures of accuracy and reliability of measurements require:

* Replication **within** experiments: to achieve consistency of measurements (smallest possible standard deviation).
* Replication **across** experiments: this is used to determine reliability (largest possible Cronbach alpha value).

1. [Press release](https://www.nobelprize.org/prizes/medicine/2005/press-release/). NobelPrize.org. Nobel Media AB 2020. Sat. 8 Feb 2020. [↑](#footnote-ref-1)
2. Ahmed N. 23 years of the discovery of Helicobacter pylori: Is the debate over? Annals of Clinical Microbiology and Antimicrobiology. 2005; 4: 17. [↑](#footnote-ref-2)
3. Pincock S. Nobel Prize Winners Robin Warren and Barry Marshall. The Lancet. 2005. 366:1429. [↑](#footnote-ref-3)
4. Non-biology students may not know about Koch’s postulates and this may be an extended concept to be discussed in the class. However, it may be sufficient to say that Marshall and Warren used establish scientific procedures to demonstrate the microbial cause of peptic ulcers. [↑](#footnote-ref-4)
5. Spencer did not employ hypothesis testing in the manner that most scientists do these days. Spencer knew that scientists before him had proposed that electromagnetic radiation may be used to cook or warm food. However, Spencer’s approach of testing whether microwaves will cook other food items (in addition to the candy bar in his pocket) illustrates the predictive nature of scientific hypotheses. Thus, Spencer’s research did not explain how microwaves warmed food. [↑](#footnote-ref-5)
6. Blitz, M. (2014). The Amazing True Story of How the Microwave Was Invented by Accident. [Popular Mechanics](https://www.popularmechanics.com/technology/gadgets/a19567/how-the-microwave-was-invented-by-accident/). [↑](#footnote-ref-6)
7. Allen P. What's the story H pylori? The Lancet. 2001 Mar 3;357(9257):694. [↑](#footnote-ref-7)
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10. Russell, R. (2007). [Eratosthenes' Calculation of Earth's Circumference](https://www.windows2universe.org/?page=/citizen_science/myw/w2u_eratosthenes_calc_earth_size.html). [↑](#footnote-ref-10)
11. Isoardi, G. (2012). [Explainer: the Doppler effect](https://theconversation.com/explainer-the-doppler-effect-7475). [↑](#footnote-ref-11)
12. Becker, B. (n.d.). [Redshift, Blueshift](https://faculty.humanities.uci.edu/bjbecker/ExploringtheCosmos/lecture15.html). (note: refer to the section that describes the work of Doppler and Buijs-Ballot) [↑](#footnote-ref-12)
13. American Chemical Society [International Historic Chemical Landmarks. Discovery of Oxygen by Joseph Priestley](http://www.acs.org/content/acs/en/education/whatischemistry/landmarks/josephpriestleyoxygen.html). [↑](#footnote-ref-13)
14. [Press release](https://www.nobelprize.org/prizes/medicine/2005/press-release/). NobelPrize.org. Nobel Media AB 2020. [↑](#footnote-ref-14)
15. Marshall B, Warren JR. Unidentified curved bacilli in the stomach of patients with gastritis and peptic ulceration. The Lancet. 1984; 323:1311-5. [↑](#footnote-ref-15)
16. Toman K. Christian Doppler and the Doppler effect. Eos, Transactions American Geophysical Union. 1984. 27;65(48):1193-4. [↑](#footnote-ref-16)
17. Priestley, J. (1775). [An Account of Further Discoveries in Air](http://www.jstor.org/stable/106209). By the Rev. Joseph Priestley, LL.D. F. R. S. in Letters to Sir John Pringle, Bart. P. R. S. and the Rev. Dr. Price, F. R. S. Philosophical Transactions (1683-1775), 65, 384-394. [↑](#footnote-ref-17)
18. In its early days, the Royal Society council determined which manuscripts were worthy of publication in the Philosophical Transactions. Later, manuscripts were sent out to “members who are most versed in these matters”, rather than subject matter experts (as it is done today). The emphasis was on the novelty of the discovery, rather than the scientific rigour of the investigation. Reference: Dinerstein, C. (2017). [The Surprising History of Peer Review](https://www.acsh.org/news/2017/10/02/surprising-history-peer-review-11888). [↑](#footnote-ref-18)
19. This table references the Stage 4 and 5 Science syllabuses, as well as the Stage 6 Biology, Chemistry, Physics, Investigating Science, Earth and Environmental Science, as well as the Science Extension Syllabus © 2017 [NESA](http://syllabus.nesa.nsw.edu.au/copyright/) for and on behalf of the Crown in right of the State of New South Wales. [↑](#footnote-ref-19)
20. Adapted from [Springer Nature](https://www.springer.com/gp/authors-editors/authorandreviewertutorials/writing-a-journal-manuscript/types-of-journal-articles/10285504). [↑](#footnote-ref-20)
21. Adapted from [Ormand, Carol, Guided reading of scientific articles](https://serc.carleton.edu/NAGTWorkshops/structure/activities/47021.html). [↑](#footnote-ref-21)
22. This lesson was adapted from DiFrancesca, D. (n.d.). [Critical Thinking in Science](https://kenanfellows.org/kfp-cp-sites/cp08/cp08/part-1-introduction-experimental-design/index.html). [↑](#footnote-ref-22)
23. "[Misconceptions about science](https://undsci.berkeley.edu/teaching/misconceptions.php)." Understanding Science. University of California Museum of Paleontology. 3 January 2020. [↑](#footnote-ref-23)
24. Note that the Investigating Science syllabus uses the term ‘accuracy’ to describe data quality. Instead, the term precision is a better descriptor of the spread of measurements. Accuracy refers to how well measurement correspond to the true or expected value. If the true/expected value is not known (as in this investigation), then precision is used to describe the spread of the data. However, for the purpose of this course, accuracy and precision may be used interchangeably. [↑](#footnote-ref-24)
25. Note the Investigating Science students do not need to learn about statistical measures of reliability. This information is provided for teachers. [↑](#footnote-ref-25)