How Science Works

Background

Science attempts to explain the world in which we live. It provides technologies that have had a great impact on our society and the environment. Scientists try to explain phenomena and solve problems using **evidence**. The data to be used as evidence must be **reliable** and **valid**, as only then can appropriate conclusions be made. A scientifically literate citizen should be equipped to question and engage in debate on the evidence used in decision-making.

The **reliability** of evidence refers to how much we **trust** the data. The **validity** of evidence depends on the reliability of the data as well as whether the research answers the question. If the data is not reliable the research cannot be valid.

To ensure reliability and validity in evidence, scientists consider ideas that relate to:
- How we observe the world
- Designing investigations so that patterns and relationships between variables may be identified
- Making measurements by selecting and using instruments effectively
- Presenting and representing data
- Identifying patterns, relationships and making suitable conclusions.

These ideas inform decisions and are central to science education.
The sections below introduce the key ideas relating to evidence that underpin scientific practice.

Fundamental ideas

Evidence must be approached with a critical eye. It is necessary to look closely at how measurements have been made and what links have been established.
Scientific evidence provides a powerful means of forming opinions. These ideas pervade all of 'How Science Works'.

You should know:
- How to distinguish between opinion based on **valid and reliable evidence**, and opinion based on **non-scientific ideas** (prejudices or hearsay).
- About variables - **continuous** variables (any numerical values, e.g. weight or force) give more information than **ordered** variables (e.g. small, medium or large lumps) which are more informative than **categoric** variables (e.g. names of metals). A variable may also be **discrete**; i.e. restricted to whole numbers (e.g. number of layers of insulation).

Scientific investigations often seek to identify links between two or more variables. These links may be:
- **Causal -** a change in one variable causes a change in another
- **Due to association -** changes in one variable and a second variable are linked by a third variable (e.g. an association noticed between soil acidity and crop growth may be the effect of fertiliser type and quantity on both, rather than acidity affecting crop growth)
- **Due to chance occurrence** (e.g. increase in the early 20th century in radio waves was accompanied by an increase in mental illness).

Evidence must be looked at carefully to make sure that it is:
- Reliable, i.e. it can be reproduced by others.
- Valid, i.e. it is reliable *and* answers the original question.

Observation as a stimulus to investigation

Observation is the link between the real world and scientific ideas. When we observe objects, organisms or events we do so using existing knowledge.
Observations may suggest hypotheses and lead to predictions that can be tested.
You should know that:

- Observing phenomena can lead to the start of an investigation, experiment or survey. Existing theories and models can be used creatively to suggest explanations for phenomena (hypotheses).
- Careful observation is necessary before deciding which the most important variables are. **Hypotheses** can then be used to make **predictions** that can be **tested**. An example is the observation that shrimp only occur in parts of a stream. Knowledge about shrimp and water flow leads to a hypothesis relating the distribution to the stream flow rate. A prediction leads to a survey that looks at both variables.
- Data from testing a prediction can support or refute the hypothesis or lead to a new hypothesis. For example, the data from the shrimp survey could suggest that, at slow flow rates, oxygen availability might determine abundance.
- If the theories and models we have available to us do not completely match our data or observations, we need to check the validity of our observations or data, or amend the theories or models.

Designing an investigation

An investigation is an attempt to determine whether or not there is a relationship between variables. Therefore it is necessary to identify and understand the variables in an investigation. The design of an investigation should be scrutinised when evaluating the validity of the evidence it has produced.

You should know that:

- An independent variable is one that is changed or selected by the investigator.
- The dependent variable is measured for each change in the independent variable.
- Any measurement must be valid in that it measures only the appropriate variable, for instance colour change in a pH indicator to measure respiration in woodlice could be affected by their excretion, so colour change is not valid data.

Fair Test
A fair test is one in which only the independent variable affects the dependent variable, as all other variables are kept the same.
It is important to isolate the effects of the independent variable on the dependent variable. This may be achieved more easily in a laboratory environment than in the field, outside the laboratory, where it is harder to control all variables.

When using large-scale survey results, it is necessary to select data from conditions that are similar (e.g. if a study is to survey the effect of age on blood pressure, a group of people with approximately the same diet or weight could be used).
Control groups are often used in biological and medical research to ensure that observed effects are due to changes in the independent variable alone (e.g. in drug experiments, a placebo drug is used as a control).

Choosing values of a variable
Care is needed in selecting values of variables to be recorded in an investigation. A trial run will help identify appropriate values to be recorded, such as the number of repeated readings needed and their range and interval. For example, in an investigation of the effect of temperature on enzyme activity it is necessary to:

- use a sufficient amount of enzyme so that its activity can be detected
- use a sensible range of temperatures
- have readings ‘closer together’ (at smaller intervals) where a change in pattern is detected.

Accuracy and Precision.
Readings should be repeated to improve the reliability of the data.
An accurate measurement is one which is close to the true value.
The design of an investigation must provide data with sufficient accuracy. For example, measures of blood alcohol levels must be accurate enough to be able to determine whether the person is legally fit to drive.
The design of an investigation must provide data with sufficient precision to form a valid conclusion. For example, in an investigation into the bounce of different balls, less precision is needed to tell if a tennis ball bounces higher than a squash ball than if you wanted to distinguish between the bounce of two very similar tennis balls.

Making measurements

When making measurements we must consider such issues as inherent variation due to variables that have not been controlled, human error and the characteristics of the instruments used. Evidence should be evaluated with the reliability and validity of the measurements that have been made in mind.

A single measurement
There will always be some variation in the actual value of a variable no matter how hard we try to repeat an event. For instance, if a ball is dropped and doesn't land on exactly the same point on its surface there will be a slight difference in the rebound height.
When selecting an instrument, it is necessary to consider the accuracy inherent in the instrument and the way it has to be used.

For example, expensive thermometers are likely to give a reading nearer to the true reading and to be more accurately calibrated.
The **sensitivity** of an instrument refers to the smallest change in a value that can be detected. For example, bathroom scales are not sensitive enough to detect the weekly changes in the mass of a baby, whereas scales used by a midwife are sensitive enough to permit a growth chart to be plotted.
Even when an instrument is used correctly, human error may occur which could produce random differences in repeated readings or a systematic shift from the true value which could, for instance, occur due to incorrect use or poor calibration.
Random error can result from inconsistent application of a technique. Systematic error can result from consistent misapplication of a technique.
Any anomalous values should be examined to try and identify the cause and, if a product of a poor measurement, ignored.

Presenting data

To explain the relationship between two or more variables, data may be presented in such a way as to make the patterns more evident. There is a link between the type of graph used and the type of variable represented. The choice of graphical representation depends upon the type of variable they represent.

You should know that:
Tables are an effective means of displaying data but are limited in how they portray the design of an investigation.
Bar charts can be used to display data in which the independent variable is categoric and the dependent variable continuous (eg the height of bounce of different types of ball).
Line graphs can be used to display data in which both the independent and dependent variables are continuous.
Scattergrams can be used to show an association between two variables (eg water content of soil and height of plants).

Using data to draw conclusions

The patterns and relationships observed in data represent the behaviour of the variables in an investigation. However, it is necessary to look at patterns and relationships between variables with the limitations of the data in mind in order to draw conclusions.

You should know that:

- Patterns in tables and graphs can be used to identify anomalous data that require further consideration.
- A line of best fit can be used to illustrate the underlying relationship between variables.
- The relationships that exist between variables can be linear (positive or negative, eg height of wax remaining in a candle and time it has been burning) or directly proportional (e.g. extension of a spring and applied force). Or the relationship might plot as a curve (e.g. velocity against time for a falling object).
- Conclusions must be limited by the data available and not go beyond them. For example, the beneficial effects of a new drug may be limited to the sample used in the tests (younger men perhaps) and not the entire population.

Evaluation
In evaluating a whole investigation the reliability and validity of the data obtained must be considered. The reliability of an investigation can be increased by looking at data obtained from secondary sources, through using an alternative method as a check and by requiring that the results are reproducible by others.

Societal aspects of scientific evidence

A judgement or decision relating to social-scientific issues may not be based on evidence alone, as other societal factors may be relevant.

Credibility.
The credibility of the evidence is increased if a balanced account of the data is used rather than a selection from it that supports a particular pre-determined stance.
Evidence must be scrutinised for any potential bias of the experimenter, such as funding sources or allegiances.
Evidence can be accorded undue weight, or dismissed too lightly, simply because of its political significance. If the consequences of the evidence might provoke public or political concern, the evidence may not be considered logically.
The status of the experimenter may influence the weight placed on evidence; for instance, academic or professional status, experience and authority. It is more likely that the advice of an eminent scientist will be sought to help provide a solution to a problem than that of a scientist with less experience.

Technology.
Scientific knowledge gained through investigations can be the basis for technological developments.
Scientific and technological developments offer different opportunities for exploitation to different groups of people.
The uses of science and technology developments can raise ethical, social, economic and environmental issues.
Decisions are made by individuals and by society on issues relating to science and technology.

Limitations of scientific evidence

Science can help us in many ways but it cannot supply all the answers. We are still finding out about things and developing our scientific knowledge. There are some questions that we cannot answer, maybe because we do not have enough reliable and valid evidence. For example, it is generally accepted that the extra carbon dioxide in the air (from burning fossil fuels) is linked to global warming, but some scientists think there is not sufficient evidence and that there are other factors involved. And there are some questions that science cannot answer at all. These tend to be questions where beliefs and opinions are important or where we cannot collect reliable and valid scientific evidence. For example, science may be able to answer questions that start ‘How can we ...’ such as ‘How can we clone babies?’ but questions starting ‘Should we ..’ such as ‘Should we clone babies?’ are for society to answer.

Glossary of Terms

Accuracy
An accurate measurement is one which is close to the true value.

Calibration
This involves fixing known points and then marking a scale on a measuring instrument, between these fixed points.

Data
This refers to a collection of measurements. e.*g. Data can be collected for the volume of a gas or the type of rubber.*

Datum The singular of data.

Errors:
- random These cause readings to be different from the true value. Random errors may be detected and compensated for by taking a large number of readings e.*g. Random errors may be caused by human error, a faulty technique in taking the measurements, or by faulty equipment.*

- systematic These cause readings to be spread about some value other than the true value; in other words, all the readings are shifted one way or the other way from the true value.
E.g. A systematic error occurs when using a wrongly calibrated instrument.

- zero These are a type of systematic error. They are caused by measuring instruments that have a false zero e.*g. A zero error occurs when the needle on an ammeter fails to return to zero when no current flows, or when a top-pan balance shows a reading when there is nothing placed on the pan.*

Evidence This comprises data which have been subjected to some form of validation. It is possible to give a measure of importance to data which has been validated when coming to an overall judgement.

Fair test A fair test is one in which only the independent variable has been allowed to affect the dependent variable *e.g. A fair test can usually be achieved by keeping all other variables constant.*

Precision The precision of a measurement is determined by the limits of the scale on the instrument being used. Precision is related to the smallest scale division on the measuring instrument that you are using. It may be the case that a set of precise measurements has very little spread about the mean value *e.g. using a ruler with a mm scale on it to measure the thickness of a book will give greater precision than using a ruler that is only marked in cm..*

Reliability The results of an investigation may be considered reliable if the results can be repeated. If someone else can carry out your investigation and get the same results, then your results are more likely to be reliable. One way of checking reliability is to compare your results with those of others. The reliability of data can be improved by carrying out repeat measurements and calculating a mean.

True Value This is the accurate value which would be found if the quantity could be measured without any errors at all.

Validity
Data is only valid for use in coming to a conclusion if the measurements taken are affected by a single independent variable only. Data is not valid if for example a fair test is not carried out or there is observer bias *e.g. In an investigation to find the effect on the rate of a reaction when the concentration of the acid is changed, it is important that concentration is the only independent variable. If, during the investigation, the temperature also increased as you increased the concentration, this would also have an effect on your results and the data would no longer be valid.*

Variables:

- categoric
A categoric variable has values which are described by labels.
When you present the result of an investigation like this, you should not plot the results on a line graph; you must use a bar chart or pie chart *e.g. If you investigate the effect of acid on different metals, e.g. copper, zinc and iron, the type of metal you are using is a categoric variable.*

- continuous
A continuous variable is one which can have any numerical value.
When you present the result of an investigation like this you should use a line graph e.g. *If you investigate the effect on the resistance of changing the length of a wire, the length of a wire you are using is a continuous variable since it could have any length you choose.*

- control
A control variable is one which may, in addition to the independent variable, affect the outcome of the investigation. This means that you should keep these variables constant; otherwise it may not be a fair test. If it is impossible to keep it constant, you should at least monitor it; in this way you will be able to see if it changes and you may be able to decide whether it has affected the outcome of the experiment.

- dependent and independent variables
Often in science we are looking at 'cause' and 'effect'. You can think of the independent variable as being the 'cause' and the dependent variable as being the 'effect'. In other words, the dependent variable is the thing that changes *as a result* of you changing something else.

- dependent The dependent variable is the variable the value of which you measure for each and every change in the independent variable.

- independent The independent variable is the variable for which values are changed or selected by the investigator. In other word, this is the thing that *you deliberately change* to see what effect it has.

- discrete A type of categoric variable whose values are restricted to whole numbers e.g. *the number of carbon atoms in a chain.*

- ordered A type of categoric variable that can be ranked, e.g. *the size of marble chips could be described as large, medium or small.*