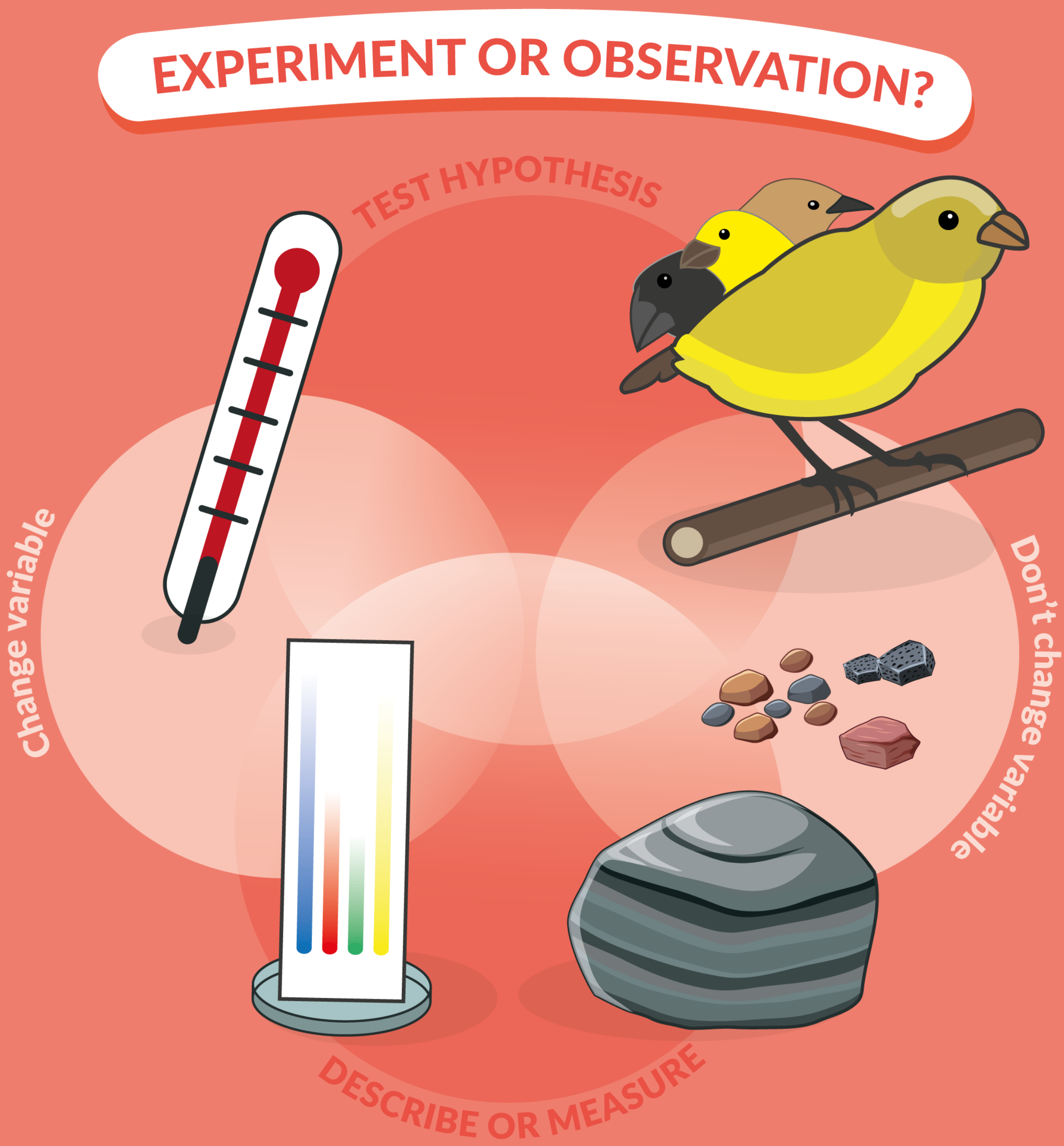
Supporting the teaching of scientific methods in practical science

project calibrate

Supporting the Teaching of Scientific Methods in Practical Science

Stephen Wooding, Alison Cullinane & Sibel Erduran



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PROJECT INFORMATION

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INTRODUCTION

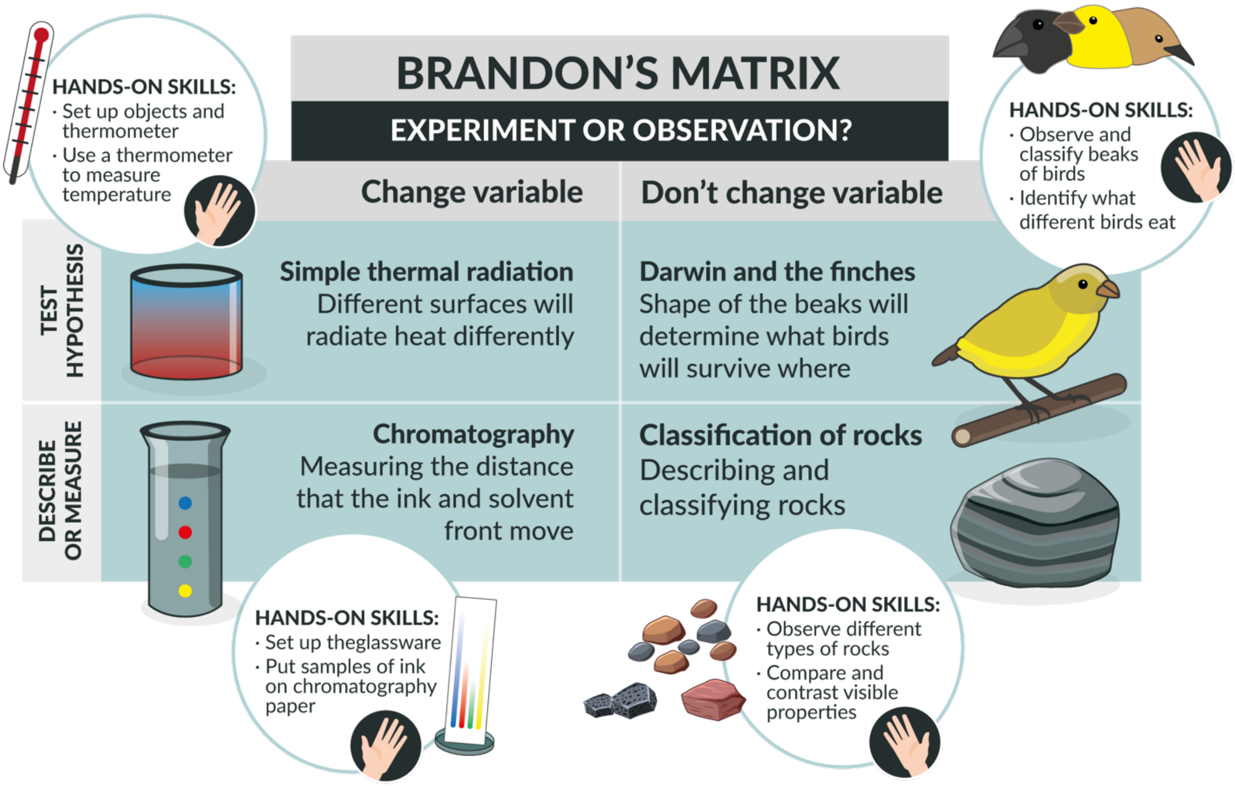
The resources contained in this continuous professional development (CPD) pack have been produced as part of Project Calibrate. The project is a collaboration between the Department of Education at the University of Oxford, and AQA, and aims to foster effective teaching, learning and assessment of practical science.

The resource pack contains a series of activities for CPD providers to carry out with teachers interested in incorporating new ways of supporting pupils' understanding of and skills in practical science. Although the focus here is primarily GCSE science, the ideas and concepts introduced and discussed during the activities are also applicable at AS and A-level. The activities can be used as part of workshops that could be structured in a standard 4-hour session. They can also be adapted for a shorter meeting lasting for 2 hours, or for an extended full day session that allows for deeper reflection and discussion. Some guidelines are provided to facilitate the choice of activities depending on the goals of the CPD providers. The CPD approaches in the pack are based on research evidence on how best to support science teachers' learning of new approaches to science. For example, there is research evidence that effective CPD approaches provide plenty of opportunities for building on existing expertise, using group discussions among a community of practitioners, and encouraging ownership of the new pedagogical approaches that are covered in CPD sessions.

The CPD is built around addressing a central problem in teaching practical science - that too often students are exposed to only a fairly simplistic account of the scientific method. The mythical 'scientific method' is frequently taught as singular and linear, starting with a hypothesis which is then tested through a recipe-like experiment. The conclusions are drawn in a fairly straightforward fashion. A key contribution of Project Calibrate is to challenge this simplistic account of scientific methods as it is not reflective of the nature of science. At the core of this CPD workshop is a framework called "Brandon's Matrix". Brandon provides an account of diversity in scientific methods (1994).

His framework illustrates that not all experiments rely on hypothesis testing. Instead, scientists use a range of approaches when they engage in scientific investigations. Brandon represents the connections between experiments and observations in terms of a matrix (i.e. two-by-two table) in which an investigation (experiment/observation) is related to whether or not it involves the manipulation of one or more variables, and whether it involves an explicit hypothesis test or is instead concerned with parameter measurement and/or recording observations (see Table 1).

Table 1. Adaptation of Brandon's Matrix.



A contemporary example about Brandon's Matrix involves the Covid-19 pandemic of 2020. Scientists collect data on how the virus might be influencing a patient's breathing over a period of time. Such observation is simply based on the recording of parameters where there is no manipulation of variables in the sense of an experimental design. Sometimes the data might be subjected to hypothesis testing about correlation between incubation period and extent of lung disease, but without an experiment resulting in non-manipulative hypothesis testing. Scientists may also conduct randomised control trials in which a drug could be treated as a variable in interventions that also include control groups to test the placebo effect. All of these different approaches are used in science, and there is no one single method but rather a diversity of scientific methods.

The pack consists of a series of activities that lead to introducing the participants to Brandon's Matrix and then applying it to GCSE science topics. The activities, the suggested length of each activity and the goals for each activity are summarised in Table 2. The key difference between each type of activity is the extent to which the CPD provider can dedicate time to unpack topics and engage in longer discussions with the participants.

Table 2. CPD activities.

Length of Workshop	Key activities	Description
Standard (4 hours)	• Common misconceptions about nature of science	Establishing the rationale for why a new approach is needed for teaching practical science through a diversity of methods
	• Introduction to Brandon's matrix	Introducing a framework on diversity of scientific methods
	• Example lesson topics • Applications in lesson planning	Applying understanding of different methods to school science topics and new lesson plans
Short (2 hours)	The standard framework is covered with fewer examples	The standard activity includes plenty of discussion which is shorter and there is some direct input by the CPD provider in providing examples
Extended (Full day)	The standard framework is extended to include further discussions, for example about different examples of misconceptions and examining the quality of measurements	The extended activity helps participants to consolidate ideas covered in the session by highlighting further points to think about and to discuss

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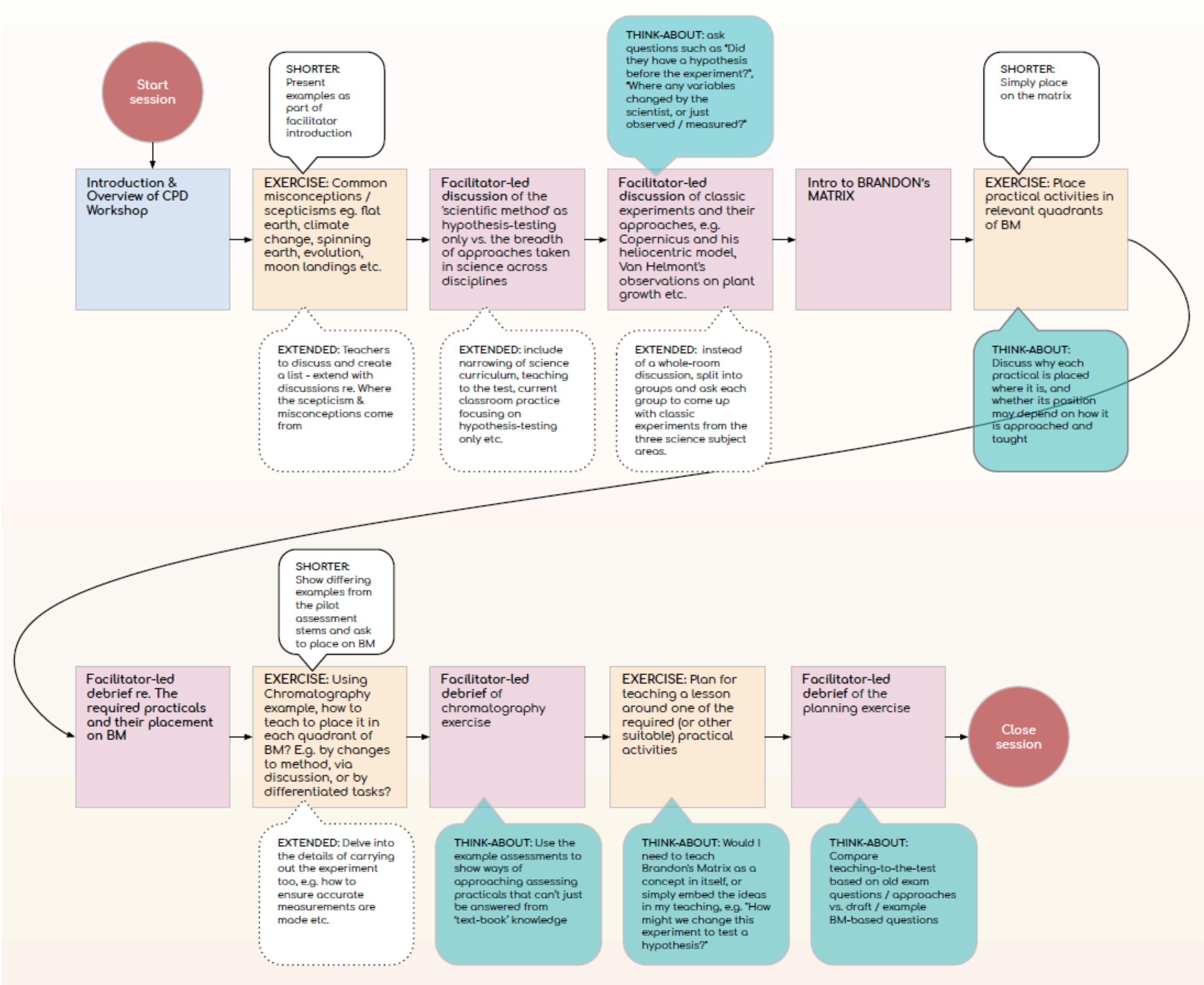
CPD Road Map

The main content of this document will be colour-coordinated to the image below, and further information and a full description will be provided where necessary. The 'road map' provides a schema for delivery of the CPD, with core sections along the central spine of the diagram, and options and other guidance given for some sections.



PART 1

Discussion & Exercise

Misconceptions and Rejections of Science

AIM: The exercise intends to create discussion around the misconceptions in science and other problems with accepted ideas, and the theories and work of scientists. This centres around what constitutes 'proper science' or 'facts' rather than simply opinions or beliefs.

In any science classroom conversation about misconceptions, skepticism, or even conspiracy theories, will often come up as part of the discussion - pupils may know about some of them and some may believe them. These will differ depending on the topic being taught, but might include examples such as:

- The earth is flat
- The earth is stationary and everything goes around it
- Vaccines are dangerous (e.g. cause autism), or aren't needed
- The moon landings were faked and didn't really happen
- Mobile (5G) phone masts cause cancer

Many of these ideas are grounded in a misunderstanding of the nature of science and how science works. For example, the 'theory of evolution' might be treated with skepticism because a) it doesn't follow "the scientific method", or b) it has the word 'theory' in and pupils may assume it means something that can't actually be proved, and is therefore little different to a strong opinion or belief. Or they could see it as just one of several possibilities, all of which are equally valid[1].

[1]Some deeply held religious beliefs may be responsible for pupils or teachers rejecting scientific ideas; these should be shown due respect within the room to allow for well-mannered discussion.

The notion that the earth is stationary may come from the idea that “if it were moving we’d feel it, wouldn’t we?” - a misunderstanding of the nature of motion and our experience of it. Believing that vaccinations are dangerous could have come from negative opinions seen in the media that quote pseudo-science, anecdotal experiences, and poorly conducted studies that rely on misapplied chemistry and biology.

It is assumed that the participants are already seated in groups, e.g. around tables, or will be arranged into groups of 3-4. This is also potentially the first exercise of the day, so can also be used as an ice-breaker by starting the exercise with personal introductions to the rest of the group.

Outline of discussion - 20-30 mins:

1. In groups of 3-4, share and list as many misconceptions / skepticisms you can think of that you have come across in your own experience, preferably when teaching. Within the time allowed, work through each of the misconceptions and discuss how you think they might have come about. For each one, discuss how you might address the misconception / skepticism.
2. Collate any patterns or common sources of misconceptions / skepticisms you spot as the discussion progresses.
3. At the end of the exercise you may be asked to share your main findings with the rest of the participants.

Use slides entitled “Session objectives”, “Introduction”, “Practical Science in School Science” and “National curriculum aims for science” to introduce the ideas (see Appendix).

Note that the discussion may show narrowed teaching practice, e.g. a focus on hypothesis-testing as *the* scientific method, rather than several approaches and methods. If this does occur, hold off any deeper discussion until after the section on historical examples as this contains specific cases where hypothesis-testing was not the approach taken.

It may be useful to have some more prepared examples that can be used in case the teachers are struggling to come up with their own examples.

Use the slide entitled "Claims in science: Misconceptions and rejections of science" (see Appendix).

SHORTER: This exercise could be replaced with a shorter whole-room discussion with the participants based on selected examples from the above list; the more pre-exercise discussion there is, the shorter the exercise itself

EXTENDED: The exercise can be extended by allowing more time for discussion or each example shared in the groups, pattern-spotting and feedback from each group. Some additional prompts for discussion points or questions could be:

- Do you think children are more exposed to misconceptions and conspiracy theories than, say, ten years ago?
- How might you address the issue of religious beliefs 'contradicting' science?
- Can misconceptions be dealt with simply by educating children with the facts, or do they need a broader understanding of how science works in practice?

Discussion

Multiple Scientific Methods

AIM: This section of the workshop flows naturally from the previous exercise and is intended to broaden the discussion around the different approaches and methods scientists use to build theories, knowledge and our understanding of the world around us and how science works.

The current National Curriculum documents explicitly states that there are multiple methods that scientists use and that pupils should be exposed to and learn to use these difference methods, stating:

"They should select the most appropriate ways to answer science questions using different types of scientific enquiry, including observing changes over different periods of time, noticing patterns, grouping and classifying things, carrying out comparative and fair tests and finding things out using a wide range of secondary sources of information. Pupils should draw conclusions based on their data and observations, use evidence to justify their ideas, and use their scientific knowledge and understanding to explain their findings."

(National Curriculum for Primary Science, England[2])

However, classroom practice in teaching practical science tend to fall into a 'cookbook' science[3] approach. This refers to laboratory investigations that begin with teachers explaining in detail what will happen, and then the students will follow a predefined set of steps or a 'recipe' that is usually guaranteed to provide some useful outcome. Often many of these cookbook practicals only require a moderate

[2]Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/425618/PRIMARY_national_curriculum_-_Science.pdf

[3]Leonard, W. H. (1991). A recipe for Uncookbooking laboratory investigations. Journal of College Science Teaching, 21(2), 84–87.

[3]Nott, M. & Smith, R. (1995) "'Talking your way out of it', 'rigging' and 'conjuring': what science teachers do when practicals go wrong.". *International Journal of Science Education*. 17(3). 399-410

level of skill and/or understanding from the pupil to carry out successfully, with teachers or technicians sometimes taking steps to ensure they do work in spite of lower levels of skill.

Often the rationale for this is to keep planning and execution simple, and may be reinforced by a lack of confidence by new or non-specialist teachers, or a school or technician's preference for carrying out experiments in a familiar way. One unfortunate but serious side-effect of this approach, however, is that it creates an increasing emphasis on hypothesis-testing as *the* scientific method, as well as instilling the idea that science somehow 'just works', rather than being unsuccessful at times too. This may also be exacerbated by the coursework elements and grading schemes at GCSE prior to the latest qualification reforms (2013, first teaching in 2015) explicitly requiring a hypothesis-testing approach.

Outline of discussion - 10-20 mins:

1. You should lead a whole-room discussion, building on the previous 'misconceptions' exercise, to explore the participants' ideas and beliefs about this hypothesis-centric view of practical science and the problems that could arise from having such a central focus on this method. This should lead into the next section on classic experiments

Use the slides entitled "Methods in science" and "Discussion: Multiple scientific methods" (see Appendix).

Discussion (& Exercise)

Historical Experiments and Methods

AIM: This section is intended to highlight the variety of methods that scientists have used in the past to generate much of the scientific knowledge we take for granted and teach in our classrooms. There should be a clear emphasis on the multiple methods that create real, trusted science, i.e. not just hypothesis testing.

There are many experiments and explorations from the history of science that fall into the category of hypothesis-testing with independent, dependent and control variables. For example, Louis Pasteur's experiment that disproved the notion of 'spontaneous generation' of living creatures from inanimate materials, e.g. maggots being produced directly from mouldy bread. However, many practical investigations that generated much of today's accepted scientific knowledge do not fit neatly into the framework of hypothesis-testing-with-variables. For example:

- Van Helmont's five-year willow tree experiment to test the theory that plants do not consume / use soil in order to grow (though he did initially conclude that they converted water); no variables were changed and there was no control sample, just the measurement of the weight of the plant and dried soil at the beginning and five years later.
- Rutherford's scattering experiment to explore the 'plum pudding' model of the atom; again, there were no control or independent variables, just the measurement of scattering angles of alpha particles from gold foil, and Thomson's 'plum pudding' atomic model was rejected based on their results.
- Darwin's theory of natural selection developed from multiple observations of similar species on different islands.
- The Copernican helio-centric model of the solar system came from multiple careful astronomical observations; again, there were no variables to change - we cannot reach out and move the planets! Kepler later refined this model based on more measurements and observations.

- Eratosthenes' estimation of the circumference of the earth (~200 BC) came from measurements conducted in two separate cities a known distance apart, and subsequent geometric calculations; he measured an important parameter without explicitly testing a hypothesis.
- Mendeleev's construction of the periodic table, based on observations of similarities and differences in the chemical properties of 66 known elements at the time; this enabled the prediction of elements that would fill the gaps in the table, and formed the foundation of the periodic table of elements we are familiar with.
- Foucault's pendulum to show that, through some complex calculations based on the observed motion of the pendulum, the earth rotates on its axis (and is an approximate sphere).

You should lead on from the previous discussion about scientific methods into this section, perhaps asking participants to suggest classic 'experiments' from their specialist field(s) and explore whether those who carried them out originally set out to test a hypothesis (as opposed to a hypothesis or model emerging from their findings) or were simply making measurements or observations, and whether they were actually directly manipulating one (or more) variables as part of the investigation. The thinking that develops during this section helps to build their ideas on how science works in practice and should create a smooth segue into the next section - the introduction to Brandon's Matrix.

Refer to the slides entitled "Historical experiments and methods" (see Appendix).

1 3

EXTENDED: The session could be extended by changing the whole-room discussion into a group exercise with feedback - see below.

Outline of optional exercise - 20-30 mins:

- In groups of 3-4 people, list as many 'classic' experiments from your fields as you can.
- For each one explore whether, *as originally carried out*, the experiment / investigation included each of the following, or not:
  - Testing a hypothesis or answering a specific question that was formulated *before* the experiment? Or were they simply making measurements and/or observations, or generating groups / categories?
  - Directly manipulating or changing one or more variables?

Refer to slide "Optional exercise" (see Appendix).

1 4

Introducing Brandon’s Matrix

AIM: During this section Brandon’s Matrix will be introduced and discussed; this forms the underlying framework for the rest of the workshop. Enough time should be spent in this section and the subsequent exercise to ensure all participants have grasped the core concept.

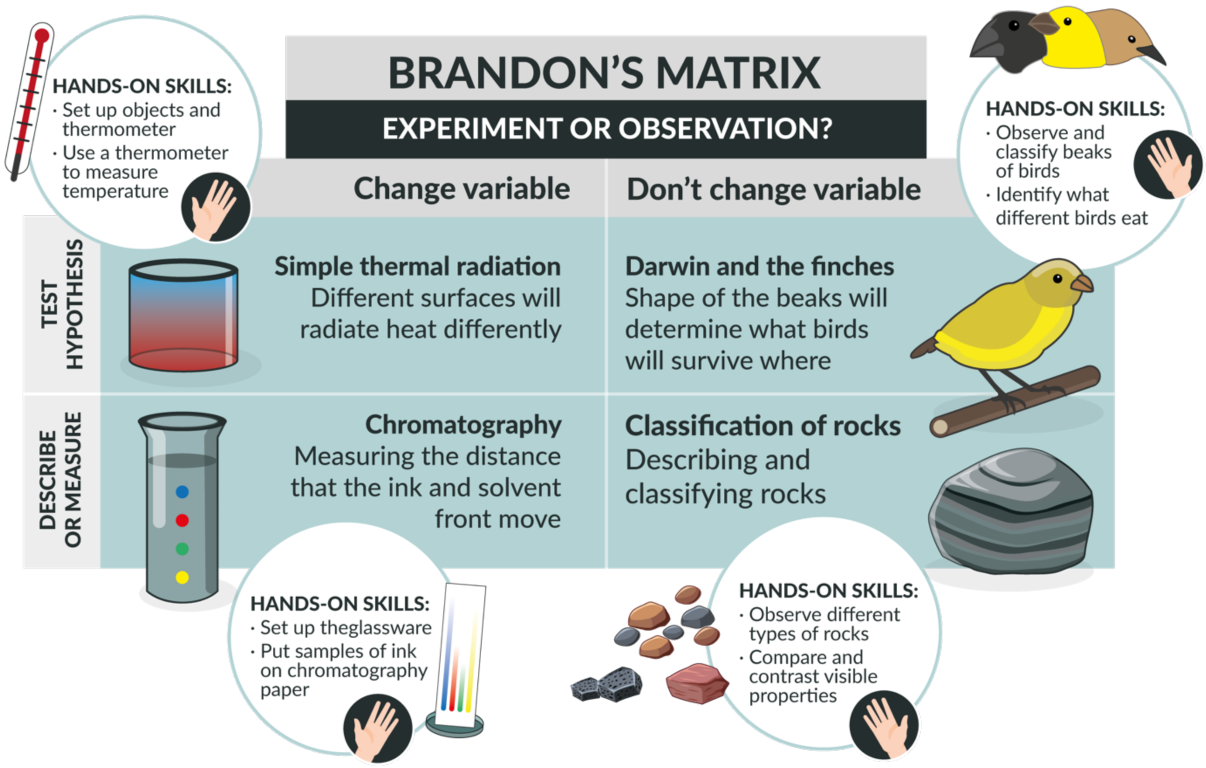
The key ideas from the previous sections of the workshop should build to support the introduction to Brandon’s Matrix (BM). This is a construct from Robert Brandon’s writing about the philosophy of science[4] and is in essence a simple quadrant model that divides practical scientific investigations into four basic categories depending on the answers to the questions asked in the previous section, i.e. did those carrying out the activity:

- Test a hypothesis or answer a specific question that was formulated *before* the experiment? Or did they simply make measurements and/or observations - this could be with the intention of calculating particular parameters, or generating groups / classifications?
- Directly manipulate or change one or more variables? Or did they simply record what resulted from a single set of conditions?

These two dichotomies (points above) can be represented as a matrix, with the first question as the vertical ‘axis’ and the second as the horizontal.

Refer to slides entitled “Introducing Brandon’s matrix”, “Brandon’s matrix” and “Brandon’s matrix and classroom practice” (see Appendix).

Table 3. Brandon's Matrix[4].



The classic experiments referred to in the previous section of the workshop can now be placed on this matrix. Note that the borders to the table aren't 'hard', in that this way of classifying scientific activities can be viewed as more of a continuum, with biological classification exercises definitely at the lower-right corner for example, and the pre-reform AQA ISA[5] activity at the top-left. See the extended section for more information

[4]Brandon, R. (1994). "Theory and experiment in evolutionary biology.", *Synthese*, 99, 59–73
[5]Investigative Skills Assignments were part of the pre-reform GCSE and A-level assessments from AQA and required the pupil to explicitly test a hypothesis as part of their investigation. The controlled assessments, e.g. used by OCR, were broader in scope, requiring a case study and a data analysis task that did not explicitly require a hypothesis test.

Exercise & Discussion

Brandon’s Matrix & Classroom Practicals

AIM: This section is intended to consolidate the participants' understanding of Brandon’s Matrix by considering the differing features of the most frequently used classroom practical activities[1].

Teachers may not have considered the underlying nature of many of the practical activities they use in the classroom with respect to whether a hypothesis is being tested or parameters calculated from measurements taken, etc. This exercise will give them an opportunity to think about this, and should also be guided to uncover how, for some of the practicals, the positioning on Brandon’s Matrix may depend on how the activity is framed and taught rather than being an inherent characteristic of the activity itself. The specialism of the teacher often determines how they will present it to students; when teachers are more confident in a subject area they tend to present practicals as hypothesis testing.

You will need a large sheet of flipchart paper per group to draw Brandon’s Matrix on, or pre-printed large sheets (A3 or larger) with the matrix printed on already. Each practical activity should be printed on a separate card or slip of paper, and a set of all activities given to each group[6].

Outline of exercise - 20-30 mins:

Refer to the slide entitled “Group Task” (see Appendix).

1. In groups of 3-4 people, discuss each practical activity in turn and choose where you would place it on Brandon’s Matrix.
2. As you discuss, note the following:
    a. Does everyone in the group suggest the same position on the matrix for an activity?
    b. Do people’s expectation of where some activities should be positioned depend on whether the activity is within their teaching specialism?
    c. Are there any very different approaches to teaching some activities that result in different suggested positions for those activities from person to person?
    d. Are there any activities that are particularly difficult to place?
3. If there are one or more practicals that are not in the pack but are suggested by a group member, feel free to add those to a blank card.

EXTENDED: As mentioned previously, while the methods can be thought of as dichotomies, the matrix can be viewed on a sliding scale as components of two continuous scales that range from extensive hypothesis testing to simple measurement, and from manipulating many variables in a carefully designed experiment to non-manipulation of any variables at all (e.g. simply observing events). A given branch of science can utilize a continuum of methods. The figure below represents this relationship in the way that depicts investigations as more (upper left corner) or less (lower right corner) experimental.

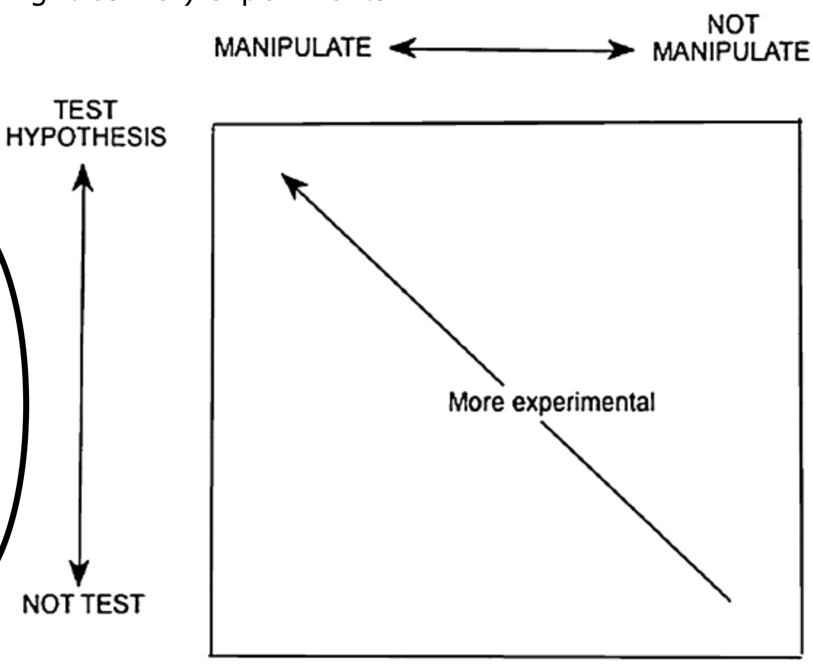


Figure: Brandon's representation of the "space of experimentality" between two continua (Reproduced from Brandon, 1994, p. 66

SHORTER: Simply replace the practical activities with a full-room discussion of some key examples from each science subject.

The proposed exercise for this section can therefore be extended by an additional 5-10 minutes by suggesting that the 'continuum' version of the scales be used rather than the 'either-or', and the practical activities be placed on the continuum.

- Prompts can be given to the groups to think about how the activities could be varied to make them, for example, more and less manipulative. Participants can be encouraged to discuss how activities could also be moved depending on the time available, or the ability (or mixed abilities) of a class.

Exercise & Discussion

The Chromatography Practical

AIM: By discussing or demonstrating how one activity can be reframed to move it around Brandon's Matrix, the participants should become familiar with the concepts of the matrix, and how to vary their approach to cover a variety of scientific methods, rather than just one.

One extremely common classroom chemistry practical is paper chromatography, the technique of separating an ink or dye into its component pigments using a *stationary phase* (or substrate, generally filter paper for school investigations) and a *mobile phase* (or solvent; in school this is usually water). The basic method is fairly simple, and is often carried out by KS3 pupils:

1. Take a standard 200 - 500 ml beaker and place 1-2 cm of water in the bottom.
2. Take a strip of filter paper long enough to reach the bottom of the beaker and tape the top of the paper to something suitable, such as a pencil or wooden dowel, that can rest across the rim of the beaker with the paper suspended so that the bottom of the paper would be in the water.
3. Draw a pencil line across the paper ~ 2 cm from the bottom.
4. Draw a dot on the pencil line with a suitable felt-tip pen.
5. Place the paper into the beaker so that the bottom is in the water but the pencil line with the ink dot is above the water surface, and whatever you taped the paper to is supporting the paper upright.
6. When the water has soaked up the paper almost to the top, take it out and draw a pencil line across the paper where the water has reached, then let the paper dry.

This is the method for generating a chromatogram for one ink, and providing reference lines for the calculation of the R_f values of the pigments the ink is composed of, i.e. this is a non-manipulative parameter-measurement activity in Brandon's Matrix terms. The following exercise is intended to explore how this basic method can be varied, expanded etc. to include variables, test a hypothesis, or both.

Refer to the slide entitled "The chromatography practical" (see Appendix).

Outline of exercise - 15-20 mins:

1. As a group, read through the basic method (reprinted for each group of 3-4 participants or shown on-screen from the PowerPoint) and diagrams (from the e-resources pack).
2. Discuss how to vary the activity, i.e. what to add to or vary within the method, or what questions to ask the pupils before, during or after the practical etc. to move it to each quadrant of Brandon's Matrix.
3. Discuss any issues with using the different variations in a classroom setting, e.g. logistics (would they require too much time?), skill level required, complexity etc. and possible ways around them.

SHORTER: This section can be shortened by directly talking through variations of the chromatography method rather than allowing group discussion, e.g.

- Observing the different pigments that are in M&M or Smarties coloured shells
- Using a single ink in the activity and measuring its R_f value.
- Testing the hypothesis that 'all green inks are made of blue and yellow pigments'

Carrying out a 'crime scene' forensic analysis, comparing the make-up of a pen ink 'found at the scene' with three possible pens.

EXTENDED: Allow another 10-15 minutes or so for an additional step:

Discuss how the knowledge, skills and understanding, including the hands-on skills needed to successfully carry out the practical activity, could be assessed - formatively and summatively. This is especially relevant given the current assessment regime for GCSEs of using written questions rather than some form of non-exam assessment (NEA) to assess practical science knowledge and skills.

Exercise & Discussion

Planning a Classroom Practical Activity

AIM: This section is intended to get the teacher thinking about how they can now plan a lesson which incorporates these new ideas about Brandon's Matrix. The idea is to discuss if the teachers intend to teach Brandon's Matrix as a concept in itself, or simply embed the ideas in their teaching, e.g. "How might we change this experiment to test a hypothesis?".

There are a number of different questions that the teachers can address prior to planning the lesson. Participants could be clustered as mixed subject specialist groups if there are only a few from each specialism. However, if there are at least three or four from each specialism, you can reorganise the table grouping as biology, chemistry and physics groups. They will need to pick a practical investigation to plan and design a lesson around. The lesson should highlight the variety of methods that scientists use to generate scientific knowledge and create real, trusted science, i.e. not just hypothesis testing. Use the reflective questions below to get the teachers thinking about how they will teach:

Before the lesson:

- How will I convey the ideas from Brandon's Matrix to my pupils? (explicit vs. implicit teaching? pre-activity vs. post activity discussion?)
- Which methods from Brandon's Matrix will I focus on in the practical investigation?
- What content/theory do I need to teach prior before the practical activity in order to undertake the practical? Can I teach this in the same lesson or should I do it in a previous lesson?

Refer to slides entitled "Planning the classroom practical activity" (see Appendix).

During the lesson:

- Which aspects of the lesson do I think the pupils will struggle with most? What can I do to minimise the likelihood of any struggles?
- What questions can I ask my pupils during and after the activity to identify whether they understood the learning material?

After the lesson reflection:

- Which aspects of the lesson went well?
- Did the pupils grasp the idea of there being more than one method that scientists use?
- Did the pupils understand how the practical activity could be changed to use a different approach from Brandon's Matrix?
- Which aspects of the lesson could be improved upon?

Outline of exercise - 20- 30 mins:

1. As a group, read through the reflective questions (reprinted for each group of 3-4 participants or shown on-screen from the PowerPoint) and lesson plan template (from the e-resources pack).
2. Discuss how you will each address these aspects prior to teaching the practical, i.e. what to add to or vary within the method, or what questions to ask the pupils before, during or after the practical etc. to move it to each quadrant of Brandon's Matrix.
3. Discuss any issues with using the different variations in a classroom setting, e.g. logistics (would they require too much time?), skill level required, complexity etc. and possible ways around them.

EXTENDED: Allow another 10 - 20 minutes or so for an additional step:

Allow the teachers to view and discuss the sample assessment questions. Discussions can centre around their views on:

- How the sample assessment questions compare to the current exam questions / approaches.
- Would you need to vary the way you approach teaching overall, and approach revision etc. if exam questions looked more like the sample assessment questions?

How do you think these questions could enhance the integration of hands-on with minds-on knowledge and understanding and, if not, why?

KEY TEACHING POINTS

At the end of the CPD session, you should summarise and ensure that all the participants have grasped the core ideas of the workshop from the discussions and exercises:

- **There is no single 'scientific method'.**

  Instead there are many approaches to science and the generation of scientific knowledge, not just hypothesis testing. What is common to all the approaches, however, is the 'scientific mindset' - understanding what each method can and can't reveal, what 'good' and 'bad' evidence is, and being able to vary approach depending on the question being asked and/or the measurements and classifications being made. Scientific knowledge is being refined all the time by new investigations and explorations, all based on many methods and approach.

- **Brandon's Matrix is a useful framework for understanding the ways in which science is carried out in practice.**

  This can be taught directly to more able pupils, or for taught implicitly via guided questions and activities, along with pre- and post-practical discussion. The core science curriculum in schools already includes examples of the wide range of methods but they are rarely labelled and discussed as such. For example, the periodic table is at the heart of chemistry teaching but is based on observation and measurement, i.e. non-manipulative activities. Our knowledge of the stars and planets is also based on careful, repeated observations and measurements.

- **Almost all school practical activities can be varied to illustrate the different approaches to science.**

  By considering the purpose of each activity, they can be planned and carried out in a variety of ways to reinforce the different methods in science. While some experiments are easier to carry out in one way, consideration should be given by teachers to varying the methods used. This is especially important across the practical science curriculum, e.g. the required practicals for GCSE, so pupils are aware of the range of ways practical activities can be done.

- **Assessment questions, e.g. in exams, can ask pupils to think about an activity in a way that may be different to the method they were taught**.

  Note that this doesn't mean that the subject content or material will vary in the exams, just that an exam question might ask pupils to consider how a particular practical could be used to test a hypothesis even if they carried it out as a simple observation in their particular classroom version. By learning to recognise the different methods that can be used for a single activity, pupils will be more prepared to recognise what's being asked of them when it comes to assessments and exams too.

Refer to slides entitled "Key points from the session" (see Appendix).

SUMMARY

The overarching aim of using Brandon’s Matrix as an explicit or implicit part of classroom teaching is to broaden pupils’understanding of what ‘is’ and ‘isn’t’ scientific knowledge, moving them on from any narrow view that science is only about testing hypotheses in controlled experiments. Pupils should also be taught to recognise ‘poor science’, i.e. claims that are based on assumptions, poorly made or recorded observations, badly constructed experiments, or simply strong opinions or beliefs. More able or more mature pupils could also be led in discussion about the differences between anecdotal experience and useful evidence, and how the selective use of poor or piecemeal observations along with misconceptions can give rise to conspiracy theories.

The overarching aim of using Brandon’s Matrix as an explicit or implicit part of classroom teaching is to broaden pupils’ understanding of what ‘is’ and ‘isn’t’ scientific knowledge, moving them on from any narrow view that science is only about testing hypotheses in controlled experiments. Pupils should also be taught to recognise ‘poor science’, i.e. claims that are based on assumptions, poorly made or recorded observations, badly constructed experiments, or simply strong opinions or beliefs. More able or more mature pupils could also be led in discussion about the differences between anecdotal experience and useful evidence, and how the selective use of poor or piecemeal observations along with misconceptions can give rise to conspiracy theories.

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RESOURCES

If you want to continue exploring the idea of methods in science, below are some resources that may be of interest.

Websites

- Project Calibrate website: https://projectcalibrate.web.ox.ac.uk/
- What's Wrong with the Scientific Method?: https://www.wired.com/2013/04/whats-wrong-with-the-scientific-method

Literature

1. Brandon, R. (1994). Theory and experiment in evolutionary biology. *Synthese*, 99, 59–73.
2. Childs, A., & Baird, J. (2020). General Certificate of Secondary Education (GCSE) and the assessment of science practical work: an historical review of assessment policy. *The Curriculum Journal*, Vol. 31, No. 3, pp. 357–378.
3. Cullinane, A., Erduran, S. & Wooding S. J. (2019): Investigating the diversity of scientific methods in high-stakes chemistry examinations in England, *International Journal of Science Education*, DOI: 10.1080/09500693.2019.1666216
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13. Woodcock, B. A. (2014). "The Scientific Method" as myth and ideal. *Science & Education*, 23: 2069-2093.

2 5

PROJECT CALIBRATE ASSESSMENTS

Project Calibrate wanted to design "*tests worth teaching to*" from the perspective of assessing methods in science. The link below takes you to the assessments produced as part of Project Calibrate on various topics. These can be used in the CPD sessions to orientate teachers to how methods in science could be presented in teaching and assessed in their classroom.

- Examiners working on Project Calibrate produced written summative assessments using Brandon's Matrix as a framework. The content is aligned with the Assessment Objectives and *Working Scientifically* learning outcomes for Key Stage 4.
- The assessments are based on six practical science topics: Ecology and Osmosis in Biology; Chromatography and Mixtures in Chemistry; and Electrical Circuits and Light in Physics.
- Each topic contains five sets of assessment questions: one set for each category of Brandon's Matrix separately and one set targeting all categories together.

  https://ora.ox.ac.uk/objects/uuid:36e3eeec-dc36-490a-9b36-43db0b09c8eb

2 6

APPENDIX

PowerPoint slides

Teachers' Workshop

project calibrate

For more information and teaching resources please visit our website:
https://projectcalibrate.web.ox.ac.uk/

University of Oxford AQA

1

Session objectives

- Introduction
- Misconceptions and Rejections of Science
- Multiple Scientific Methods
- Historical Experiments and Methods
- Introducing Brandon's Matrix
- The Chromatography Practical
- Planning a Classroom Practical Activity

2

Introduction

- The CPD is built around addressing a central problem in teaching practical science –
  - often students are exposed to only fairly simplistic account of the scientific method.
  - The mythical 'scientific method' is frequently taught as singular and linear, starting with a hypothesis which is then tested through a recipe-like experiment.
  - The conclusions are drawn in a fairly straightforward fashion.
  - A key contribution of Project Calibrate is to challenge this simplistic account of scientific methods as it is not reflective of the nature of science.
- At the core of this CPD workshop is a framework called "Brandon's Matrix".
  - Brandon provides an account of diversity in scientific methods.
- The Session will introduce you to this concept and then facilitated your own planning of practical activities related to Brandon.

Practical Science in School Science

- Beyond the cookbook problem
- Doing and **reflecting on the doing**
- Minds-on as well as hands-on
- Promoting pupils' understanding of
  - What practical science is
  - Why practical science is important
  - How practical science works

National curriculum aims for science

"…develop understanding of the nature, processes and methods of science through **different types of science enquiries** that help them to answer scientific questions about the world around them…"

National curriculum in England: science programmes of study (2015)

Misconceptions and Rejections of Science

"Day and night are caused by a spinning earth."

How do we know?

Misconceptions and Rejections of Science

- The earth is flat
- The earth is stationary and everything goes around it
- Vaccines are dangerous (e.g. cause autism), or aren't needed
- The moon landings were faked and didn't really happen
- Mobile (5G) phone masts cause cancer

How do we know?

Claims in Science: Misconceptions and Rejections of Science

Outline of discussion - 20-30 mins:

1. In groups of 3-4, share and list as many misconceptions / scepticisms you can think of that you have come across in your own experience, preferably when teaching.

Within the time allowed, work through each of the misconceptions and discuss how

1. you think they might have come about. For each one, discuss how you might address the misconception / scepticism
2. Collate any patterns or common sources of misconceptions / scepticism you spot as the discussion progresses
3. At the end of the exercise you may be asked to share your main findings with the rest of the participants

How do we know?

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Science
Notes & Theories

The universe is an egg and the moon isn't real: notes from a Flat Earth conference

Michael Marshall

Wed 2 May 2018 14.33 BST

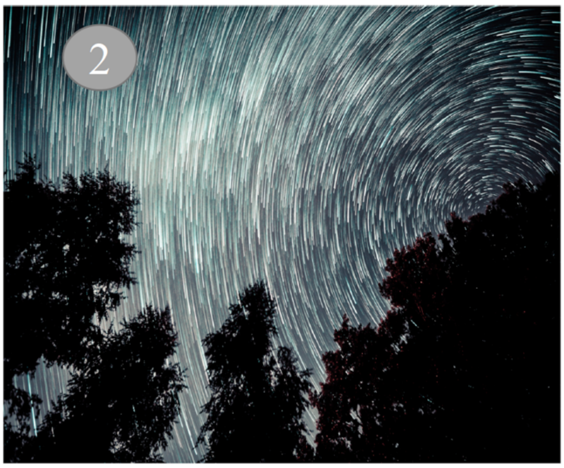
Michael Marshall attended the UK's annual gathering of people who share the unshakeable belief that the Earth is flat

Flat Earthers believe this photo of the Earthrise taken in 1968 from Apollo 8, is a fake. Photograph: -/AFP/Getty Images

There was the three-hour presentation which contended that the universe is a giant egg. There was the Manchester musician who posited that the Earth is the shape of a diamond. And another who believes that the moon is a projection.

Welcome to the Flat Earth UK Convention, a raucous departure from scientific norms where people are free to believe literally anything.

Methods in Science



- **Non-manipulative observation** and description and/or measurement (e.g. angle, time)
- **Hypothesis testing**
  - If the earth spins, then…
  - If the earth doesn't spin, then…

Discussion: Multiple Scientific Methods

The current National Curriculum documents explicitly states that there are multiple methods that scientists use and that pupils should be exposed to and learn to use these difference methods, stating:

"They should select the most appropriate ways to answer science questions using different types of scientific enquiry, including observing changes over different periods of time, noticing patterns, grouping and classifying things, carrying out comparative and fair tests and finding things out using a wide range of secondary sources of information. Pupils should draw conclusions based on their data and observations, use evidence to justify their ideas, and use their scientific knowledge and understanding to explain their findings."

Discussion: Multiple Scientific Methods

Outline of discussion - 10-20 mins:

- Building on the previous 'misconceptions' exercise, explore ideas and beliefs about this hypothesis-centric view of practical science and the problems that could arise from having such a central focus on this method.

Historical Experiments and Methods

Look at the following historical science investigations. Suggest if the classic 'experiments' originally set out to test a hypothesis (as opposed to a hypothesis or model emerging from their findings) or were simply making measurements or observations, and whether they were actually directly manipulating one (or more) variables as part of the investigation.

1. Van Helmont's five-year willow tree experiment to test the theory that plants do not consume / use soil in order to grow (though he did initially conclude that they converted water); no variables were changed and there was no control sample, just the measurement of the weight of the plant and dried soil at the beginning and five years later.
2. Rutherford's scattering experiment to explore the 'plum pudding' model of the atom; again, there were no control or independent variables, just the measurement of scattering angles of alpha particles from gold foil, and Thomson's 'plum pudding' atomic model was rejected based on their results.
3. Darwin's theory of natural selection developed from multiple observations of similar species on different islands.

(More examples on the next slide)

Historical Experiments

4. The Copernican helio-centric model of the solar system came from multiple careful astronomical observations; again, there were no variables to change - we cannot reach out and move the planets! Kepler later refined this model based on more measurements and observations.
5. Eratosthenes' estimation of the circumference of the earth (~200 BC) came from measurements conducted in two separate cities a known distance apart, and subsequent geometric calculations; he measured an important parameter without explicitly testing a hypothesis.
6. Mendeleev's construction of the periodic table, based on observations of similarities and differences in the chemical properties of 66 known elements at the time; this enabled the prediction of elements that would fill the gaps in the table, and formed the foundation of the periodic table of elements we are familiar with.
7. Foucault's pendulum to show that, through some complex calculations based on the observed motion of the pendulum, the earth rotates on its axis (<u>and</u> is an approximate sphere).

Optional exercise

Outline of optional exercise - 20-30 mins:

- In groups of 3-4 people, list as many 'classic' experiments from your fields as you can.
- For each one explore whether, *as originally carried out*, the experiment / investigation included each of the following, or not:
  - Testing a hypothesis or answering a specific question that was formulated *before* the experiment? Or were they simply making measurements and/or observations, or generating groups / categories?
  - Directly manipulating or changing one or more variables?

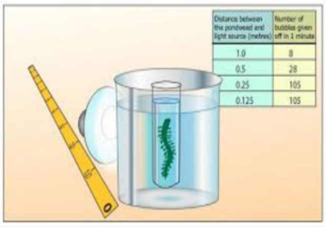
Introducing Brandon's Matrix

This is a construct from Robert Brandon's writing about the philosophy of science and is in essence a simple quadrant model that divides scientific investigations into four basic categories depending on the answers to the questions asked in the previous section, i.e. did those carrying out the activity:

- Test a hypothesis or answer a specific question that was formulated *before* the experiment? Or did they simply make measurements and/or observations - this could be with the intention of calculating particular parameters, or generating groups / classifications?
- Directly manipulate or change one or more variables? Or did they simply record what resulted from a single set of conditions?

Introducing Brandon’s Matrix

Scientific Methods (Brandon, 1994, p. 63)

	Change one or more variables	No variables changed
Test a hypothesis		
Measure parameters / make observations only		

Brandon’s Matrix

	Experiment /Observation	
	Change one or more variables	No variables changed
Test Hypothesis	This scientific approach tests a hypothesis by changing dependent and independent variables.	This scientific approach tests a hypothesis without changing dependent and independent variables.
Measure Parameter	This scientific approach does not test a hypothesis, but conducts an investigation by changing dependent and independent variables to measure the outcome.	This scientific approach has no hypothesis; it is an exploratory approach to measure or observe an outcome.

Brandon's Matrix

This scientific approach **tests a hypothesis by changing** dependent and independent variables.	This scientific approach **tests a hypothesis without changing** dependent and independent variables.
This scientific approach **does not test a hypothesis**, but conducts an investigation **by changing** dependent and independent variables to measure the outcome.	This scientific approach has **no hypothesis**; it is an exploratory approach to measure or observe an outcome **without changing** variables.

Brandon's Matrix & Classroom Practicals

Outline of exercise - 20-30 mins:

- In groups of 3-4 people, discuss each practical activity in turn and choose where you would place it on Brandon's Matrix.
- As you discuss, note the following:
  - Does everyone in the group suggest the same position on the matrix for an activity?
  - Do people's expectation of where some activities should be positioned depend on whether the activity is within their teaching specialism?
  - Are there any very different approaches to teaching some activities that result in different suggested positions for those activities from person to person?
  - Are there any activities that are particularly difficult to place?
- If there are one or more practicals that are not in the pack but are suggested by a group member, feel free to add those to a blank card.

Group task

Questions to think about

- Did all the statements 'fit'?
- Were there any that did not?
- What are the trends in the coverage for each subject and across subjects?

Manipulative hypothesis test	Non-manipulative Hypothesis test
Manipulative description or measure	Non-manipulative description or measure

Brandon's Matrix (extended)

As mentioned previously, while the methods can be thought of as dichotomies, The matrix can be viewed on a sliding scale as components of two continuous scales that range from extensive hypothesis testing to simple measurement, and from manipulating many variables in a carefully designed experiment to non-manipulation of any variables at all (e.g. simply observing events). A given branch of science can utilize a continuum of methods.

In this exercise suggest what activities fit on the 'continuum' version of the scales rather than the 'either-or', and place the practical activities on the continuum.

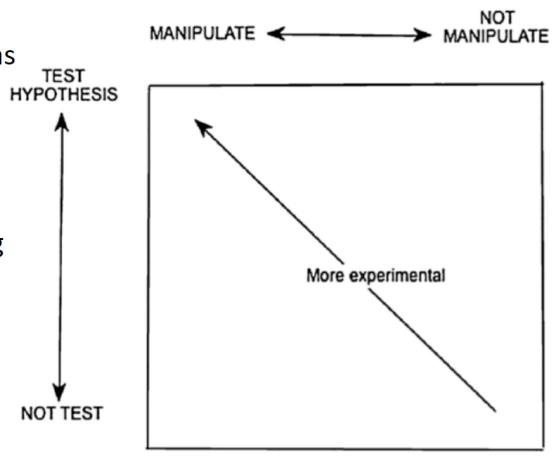


Figure: Brandon's representation of the "space of experimentality" between two continua (Reproduced from Brandon, 1994, p. 66)

The Chromatography Practical

Outline of exercise - 15-20 mins:

- As a group, read through the basic method (reprinted for each group of 3-4 participants or shown on-screen from the PowerPoint) and diagrams (from the e-resources pack).
- Discuss how to vary the activity, i.e. what to add to or vary within the method, or what questions to ask the pupils before, during or after the practical etc. to move it to each quadrant of Brandon's Matrix.
- Discuss any issues with using the different variations in a classroom setting, e.g. logistics (would they require too much time?), skill level required, complexity etc. and possible ways around them

The Chromatography Practical (extended)

Outline of exercise – 10-15 mins:

Allow another 10-15 minutes or so for an additional step:

- Discuss how the knowledge, skills and understanding, including the hands-on skills needed to successfully carry out the practical activity, could be assessed - formatively and summatively. This is especially relevant given the current assessment regime for GCSEs of using written questions rather than some form of non-exam assessment (NEA) to assess practical science knowledge and skills.

Planning a Classroom Practical Activity

- Plan a lesson which incorporates these new ideas about Brandon's Matrix. Discuss how you intend to teach Brandon's Matrix as a concept in itself, or simply embed the ideas in their teaching, e.g. "How might we change this experiment to test a hypothesis?".
- Use the lesson plan templates if desired.

Planning a Classroom Practical Activity

Outline of exercise - 20- 30 mins:

- As a group, read through the reflective questions (reprinted for each group of 3-4 participants or shown on-screen from the PowerPoint) and lesson plan template (from the e-resources pack).
- Discuss how you will each address these aspects prior to teaching the practical , i.e. what to add to or vary within the method, or what questions to ask the pupils before, during or after the practical etc. to move it to each quadrant of Brandon's Matrix.
- Discuss any issues with using the different variations in a classroom setting, e.g. logistics (would they require too much time?), skill level required, complexity etc. and possible ways around them

Planning a Classroom Practical Activity

Before the lesson think about:
- How will I convey the ideas from Brandon's Matrix to my pupils? (explicit vs. implicit teaching? pre-activity vs. post activity discussion?)
- Which methods from Brandon's Matrix will I focus on in the practical investigation?
- What content/theory do I need to teach prior before the practical activity in order to undertake the practical? Can I teach this in the same lesson or should I do it in a previous lesson?

During the lesson think about:
- Which aspects of the lesson do I think the pupils will struggle with most? What can I do to minimise the likelihood of any struggles?
- What questions can I ask my pupils during and after the activity to identify whether they understood the learning material?

After the lesson reflection think about:
- Which aspects of the lesson went well?
- Did the pupils grasp the idea of there being more than one method that scientists use?
- Did the pupils understand how the practical activity could be changed to use a different approach from Brandon's Matrix?
- Which aspects of the lesson could be improved upon?

Planning a Classroom Practical Activity (extended)

Outline of exercise - 10- 20 mins:
Allow another 10 - 20 minutes or so for an additional step:
- Allow the teachers to view and discuss the sample assessment questions. Discussions can centre around their views on:
- How the sample assessment questions compare to the current exam questions / approaches.
- Would you need to vary the way you approach teaching overall, and approach revision etc. if exam questions looked more like the sample assessment questions?
- How do you think these questions could enhance the integration of hands-on with minds-on knowledge and understanding and, if not, why?

Key points from the session

1. **There is no single 'scientific method'.**
2. **Brandon's Matrix is a useful framework for understanding the ways in which science is carried out in practice.**
3. **Almost all school practical activities can be varied to illustrate the different approaches to science.**
4. **Assessment questions, e.g. in exams, can ask pupils to think about an activity in a way that may be different to the method they were taught.**

Resources

Websites

- **Project Calibrate website: https://projectcalibrate.web.ox.ac.uk/**
- What's Wrong with the Scientific Method?: https://www.wired.com/2013/04/whats-wrong-with-the-scientific-method

Literature

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Resources

Literature (continued)

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Project Calibrate Assessments

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- https://ora.ox.ac.uk/objects/uuid:36e3eeec-dc36-490a-9b36-43db0b09c8eb

Physics
- *Circuits*
- *Electricity*

Biology
- *Osmosis*
- *Ecology*

Chemistry
- *Chromatography*
- *Separating & making salts*

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