# Brandon’s Matrix

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# Brandon's Matrix: A View on Scientific Methods in Biology Classrooms

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## Abstract

Many biology textbooks open with a section on the scientific method, and usually laboratory activities involve a stepwise procedure that is followed in a formulaic fashion Although there are many accounts of the scientific method in biology, they are often problematic as they are not comprehensive in showing the diversity of scientific methods. To solve some tensions regarding the definition of the scientific methods in biology, we introduce Brandon's Matrix as a framework that helps show the complexity of methods as a simple two-by-two matrix. It represents the connections between experiments and observations. Brandon illustrates not all experiments rely on hypothesis testing and not all descriptive work is non-manipulative, as they rely more on a diversity of approaches including parameter measurements. According to Brandon, the nature of the investigation is related to whether or not it involves (i) manipulation and (ii) hypothesis testing or a parameter measurement. In this way, one can think in terms of experiments and non-experiments/observations relative to descriptive versus experimental methods. Hence, Brandon's framework goes beyond the traditional limitations of the scientific method as a linear process of hypothesis testing and provides a more comprehensive, inclusive and realistic account of methods applied by biologists, for both current and historical studies. The chapter will introduce the framework and show its use in a research project with schools in England to produce resources, as well as its utility as an analytical framework for curriculum and assessment documents.

## Introduction

Often textbooks and scientific reports themselves offer a flawed view of how science works by presenting a singular way to do science (Cullinane et al., 2019). For example, current investigations on Covid-19 illustrate quite well how current understanding and knowledge of the virus have been produced through a variety of methods and data collection techniques. Some studies collected data through methods that looked at how the virus might be influencing a patient's breathing over a period of time (Erduran, et al., 2020). Observations such as these are based on the recording of factors where there is no manipulation of variables. By the same token, data might be subjected to hypothesis testing on incubation periods and the extent to which the lung becomes diseased, but without having been part of any experiment. This would result in some non-manipulative hypothesis testing. Scientists will have carried out some 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 these are important approaches and essential to the conduct of science and illustrate that there is no one single method but rather a diversity of scientific methods (Erduran, et al., 2020). The following chapter introduces a framework that offers an alternative to *the scientific method*, called Brandon's Matrix (1994), and will outline findings from a research project that looked at practical science in English schools with Biology teachers and their students.

## Philosophy of Biology and Methods in Biological Sciences.

Biologists should be able to stand over and justify their knowledge claims. It is not enough that they believe in their knowledge claims, they need to demonstrate that the knowledge was produced through reliable methods (de Ridder, 2020). Scientist should be able to understand and explain these methods, as well as provide reasons for their thinking and conclusions that their knowledge claims are true (de Ridder, 2020). One of the issues with biology is that it is often seen as a "soft" science because knowledge in biology is produced through a variety of methods. One issue facing biology students is that knowledge, particularly in issues such as evolution, is produced through complex structures. The whole picture of evolution or the explanation of how the dinosaurs came to be extinct has been produced through evidential consilience (Erduran & Dagher, 2014), and therefore may not fall into linear steps of '*the scientific method'*. This emphasis on diverse ways scientists, particularly biologists, produce knowledge is seldom shown or emphasised in science textbooks and instead tend to emphasise a single scientific method (McComas, 2014, Reiff-Cox, 2020). This approach is posed as a linear set of steps as shown in Figure 1 and starts with 1) a question or recognition of a problem, 2) research to see what you can learn from past experiments, 3) development of a hypothesis, which is usually presented as a guess or prediction, 4) testing the hypothesis through experiments, 5) analysing data and then 6) sharing your results with a wider audience (McComas, 2014). However, science is often not so well-ordered. Therefore, there is a contradiction between the private practice of scientists and those portrayed to the public. When science, particularly the biological science, is not conducted in this way, it can cause public distrust as there is a lack of understanding of the variety of methods that can be used to produce valid and reliable science knowledge. Different philosophers of science education have produced approaches to combat this fallacy, such as the Inquiry Wheel (Reiff-Cox, 2020), the scientists toolbox (Wivagg & Allchin, 2002) and the modes of scientific inquiry flow chart (Sturdivant-West et al., 2020). However, although these approaches have merits, they were not as simplified or as flexible a tool in a two-by-two matrix called Brandon's Matrix (Brandon, 1994). Brandon, a philosopher of biology, acknowledges how philosophical accounts of the nature of science, or of the 'scientific method', are, in part, accounts of the relationship of theory and experiment in science. His ideas are discussed in the next section.

**Figure 1**

*Depiction of Traditional Science Methods as Shown in Classrooms and School Textbooks*

(Image from https://www.weareteachers.com/free-scientific-method-posters/)


**Brandon's Matrix**

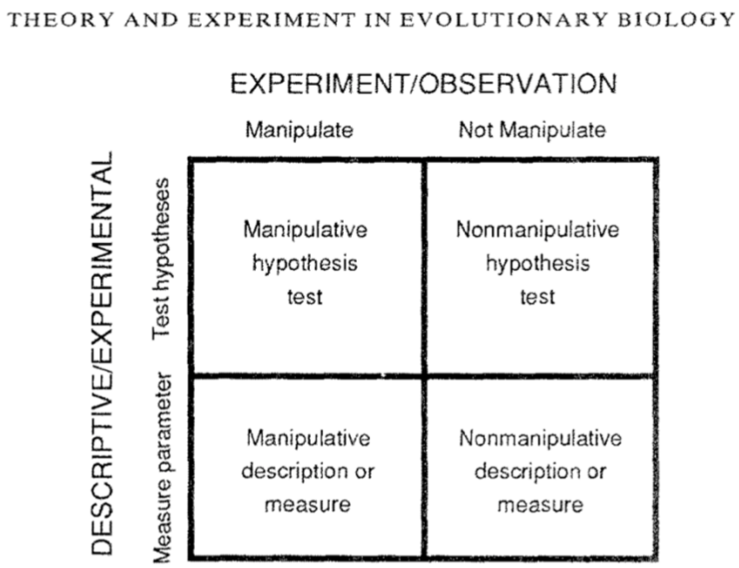
In his 1994 publication, Brandon discusses the need for an expanded view on t*he scientific method* through his explanation:

> …but, if we are interested in a general account of the roles of experiment and theory in science, then we must go beyond the simplistic one-way relation between theory and experiment posited by hypothetico-deductivism. If both inductivism and the [Hypothetico-deductivism]H-D model are one-sided in their portrayal of the relation of experiment and theory, then perhaps some sort of combination of the two would be a step in the right direction (Brandon, 1994, p. 60).

Here he recognises methods in biology on a scale from hypothesis testing to observational and descriptive work. He sees that not all experiments need to involve, nor do they involve, hypothesis testing and not all descriptive work needs to be only non-manipulative. He represents the connections between experiments and observations in which the nature of the investigation is linked to whether it comprises of manipulation or not, and/or involves hypothesis testing or parameter measures. He represents the connections between experiments and observations in terms of a two-by-two table as shown in Figure 2. The nature of the investigation (experiment/observation) is related to whether it involves (a) manipulation and (b) hypothesis testing or parameter measurement. According to his analysis, one can think in terms of experiments and non-experiments/observations relative to descriptive versus experimental methods (Erduran & Dagher, 2014; Cullinane et al., 2019). The matrix was adopted as the theoretical framework for Project Calibrate, a collaborative three-year project between the Department of Education at University of Oxford and the research unit in one of the leading exam boards in the UK; AQA. The next section will elaborate on how the matrix was used within the project to develop professional development sessions, assessments and teaching tools.

**Figure 2**

*Brandon's Matrix from His 1994 Publication, Where Each Cell Represents a Type of Investigation Important in Evolutionary Biology*

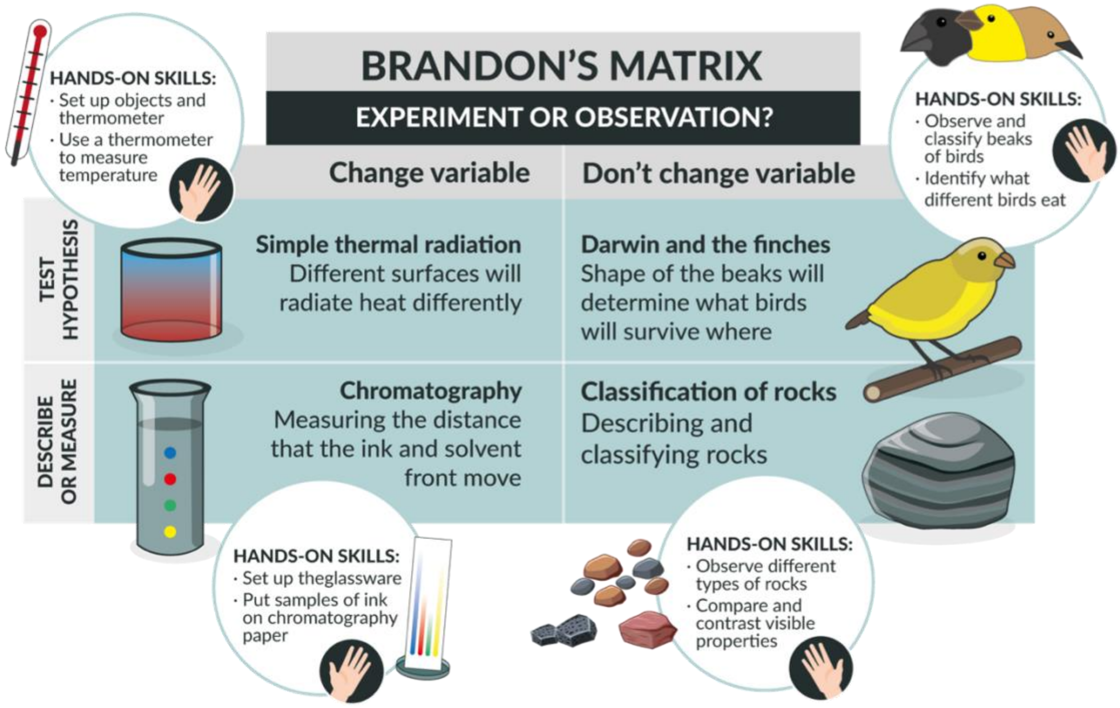


## Project Calibrate

Project Calibrate took place from 2018–2021 and aimed to design, implement and test summative assessments of practical science that looked at methods in science more comprehensively (Cullinane et al., 2019; Erduran et al., 2020; El Masri et al., 2021; Ioannidou & Erduran, 2021; Childs & Baird, 2020). The project was funded by Wellcome Trust, Gatsby Foundation and Royal Society (Grant Number 209659/Z/17/Z) and aimed to address a central problem in teaching practical science about how pupils are often exposed to only a simplistic account of the scientific method. It was a systematic approach that targets assessment where the tagline of the project was "test worth teaching to." Research shows that high-stakes assessment oftentimes drives what is taught and learned in the classroom. The project developed and tested concrete strategies for teaching and assessing a diversity of scientific methods by using Brandon's Matrix, as described above. As his ideas were only theoretical at the onset of the project (Figure 2) and there was no known empirical work using Brandon's framework, the project set to investigate its utility for teaching, learning and the assessment of practical science at GCSE level. Figure 3 shows how the project adapted and transformed Brandon's original matrix for teaching and learning pedagogy. Brandon's Matrix was used as an analytical tool for high-stakes exam papers (Cullinane et al., 2019) and curriculum analysis (Erduran et al., 2020), professional development resources (Wooding et al., 2020) as well as live face-to-face sessions and webinars within the project. All these sessions were delivered with the ethos that if future generations of scientists and citizens are to engage in authentic experiences of science, then practical science in schools needs to be taught and assessed in ways that are consistent with how scientists *do* science.

**Figure 3**

*Project Calibrate's Reconceptualization of Brandon's Matrix with Examples of Science Investigations for Each of the Four Categories of the Matrix*




*Summative Assessment of Practical Science in the UK.*

Practical science is a unique term in the UK and Ireland and refers to investigative work that students engage with in school (Osborne, 2015). It is commonly used as an overarching term that refers to any type of science teaching and learning activity involving manipulating and/or observing of objects and materials in order to understand how science works (Osborne, 2015). Similar to many classrooms around the world, practical science in the UK is also often conducted with a focus only on the scientific method, presenting science as a hypothetico-deductive model (Woodcock, 2014. This has led to the cookbook problem in practical science teaching – "laboratory activities have engaged students principally in following ritualistic procedures to verify conclusions previously presented by textbooks and teachers." (Lunetta et al., 2007). Recent work in England has questioned the effectiveness of practical work as a teaching and learning strategy, as well as its ability to motivate students to learn (e.g., Abrahams & Millar, 2008; Abrahams, 2009). As a result of some of these discussions, 2016 saw the introduction of 100% written exams where practical science is now assessed in the high-stake examination at the end of a two-year course where students will be awarded with GCSEs. Science subjects, including biology, no longer include a 'hands-on' assessment of practical science skills. Instead, the final examination papers include items specifically written to assess students' knowledge and understanding of a variety of required practical investigations. Students are now required to conduct a minimum of 10 practical investigations in school that are prescribed by the Department of Education (DfE) and Ofqual. The latter is a non-ministerial government organisation that regulates qualifications, exams and controlled tests in England and, until May 2016, vocational qualifications in Northern Ireland. The high stakes exams are managed by exam boards who design curricula with guidance from the DfE and Ofqual. The exam boards then decide how they will ask the students to undertake and complete practicals that will then be examined in a written exam after two years. Most exam boards have increased the requirement from 10 practical activities and range in scope from 'kitchen science' type undertakings to more laboratory-based procedures (Ofqual, 2015). The Office of Qualifications and Examinations Regulation advocates that at ages 14–16, pupils should 'develop their ability to evaluate claims based on science through critical analysis of the methodology, evidence and conclusions, both qualitatively and quantitatively' (Ofqual, 2015, p. 5). One of the driving forces for Project Calibrate was the change in the examination of practical science in the high-stakes exams, which prompted the research questions presented below.

## Research Questions

Although the project covered a wide range of research activities, this paper will focus on the way in which Brandon's Matrix was used to design and deliver an online lesson on osmosis and the impact of the teaching session on students' learning. The research questions that were addressed in this study are:

1. How can Brandon's Matrix be integrated into online biology lessons to discuss practical work?
2. What impact do resources about osmosis framed using Brandon's Matrix have on students' understanding?

## Methods

Due to Covid-19, the project needed to change from the original plan where teachers would trial these ideas with their students to the team needing to develop videos to support the teaching of the ideas. Given that the study took place during school closures, the online video lessons aimed to be a teaching resource for practical science. Thus, the study followed a combination of voluntary and snowballing sampling methods, as the online lessons were distributed to science teachers in the first instance. Cohen et al. (2007) describe snowballing sampling techniques as when "researchers identify a small number of individuals who have the characteristics in which they are interested. These people are then used as informants to identify, or put the researchers in touch with, others who qualify for inclusion, and these in turn identify yet others" (p. 116). Out of 152 teachers who received and responded to the online resources, 94 indicated they were Biology teachers. After reviewing the resources, the teachers shared the online lessons with their students. Two hundred and eighty-five (N= 285) students completed the designed online Biology lessons. Table 1 provides an overview of the research design implemented in the study.

**Table 1**

*Overview of the Research Design*

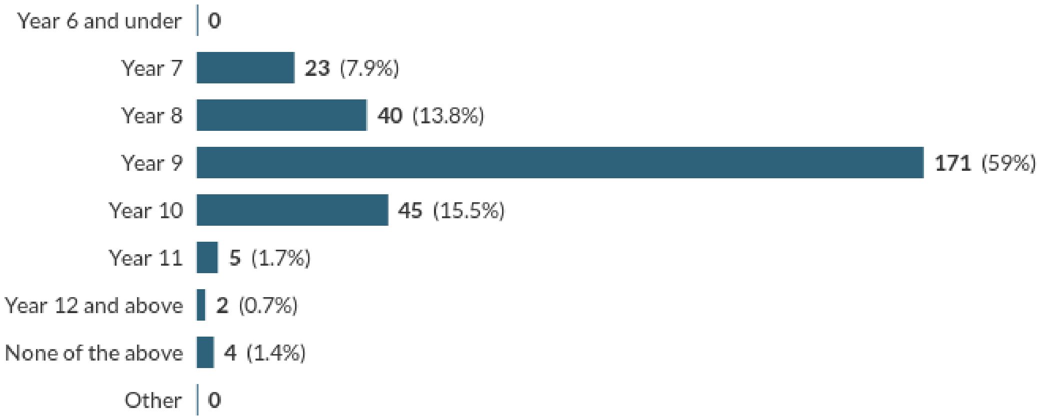
| Pre-test | Intervention | Post-test |
|---|---|---|
| Students' understanding of osmosis. | • Video 1: Introduction to scientific methods<br>• Video 2: Practical investigation on osmosis | Students' understanding of osmosis<br><br>Students' performance on assessment question |

## Sample

Although the study gathered data from students studying all three sciences, the sample reported here were 285 secondary school biology students living in the UK. Out of the 285 students, 141 (49%) were female and 140 (48%) were male. The majority of the students attended academies (52%) and state schools (32%). Figure 4 illustrates the distribution of students according to their year group (grade) which shows that most participants were Year 9 students (N=171).

**Figure 4**

*Student Distribution According to Year Group.*




## Instruments

### ***Students' Understanding of Osmosis***

In order to capture student gains relating to their understanding of the phenomenon of osmosis, a set of questions were developed by the research team. Students were asked to answer three multiple choice questions about the process of osmosis before and after the intervention. An example questions is – *Which statement best describes the effect of different concentrations of sugar solutions on plant tissue*?

### ***Students' Performance on Assessment Question***

After watching the online lessons, students were asked to answer a set of assessment questions developed by Project Calibrate (see Appendix A). These questions were conceptualised through the lens of Brandon's Matrix and were developed by professional exam writers. The questions were intended to be equivalent to the high-stakes assessment questions that students sit for GCSE science exams. In this study, one question was based on an example of a manipulative parameter measurement. The scenario presented an investigation on the effect of placing potato chips in different concentrations of sugar solutions. The steps of the method that the student has to follow were described. The assessment questions asked students to calculate the percentage increase in mass of this potato chip and to identify two variables, as well as the independent variable. For the needs of this study, only the question that referred to the independent variable was used.

## Intervention – Designing an Online Biology Lesson

Our first research question aimed to explore the affordances of Brandon's Matrix as a pedagogical tool for teaching and learning. This goal was at the core of Project Calibrate, as it would be one of the few attempts to conceptualise and deliver lessons for practical science based on Brandon's theoretical framework. For this purpose, the research team developed an online teaching session by integrating the theoretical ideas presented in Brandon's Matrix into an online teaching session of practical science. The session was developed by members of the research team who were former teachers and current science education researchers and teacher educators. It was decided to include an introductory lesson that would present the theoretical framing of scientific methods through Brandon's ideas. The second lesson included a practical investigation of osmosis, which was designed and video recorded by the team members. This topic was selected because it was one of the required practicals that students have to undertake in their classrooms (Ofqual, 2015). This lesson was enhanced by reflective questions that aimed to facilitate students' meta-cognitive thinking regarding the performed practical investigation (e.g., "In which quadrant of Brandon's Matrix does this investigation fall?"). The practical investigation examined the effect of a range of sugar solution concentrations on the mass of plant tissue and it was an example of the manipulative parameter measurement category. At the end of the lesson the instructor encouraged students to think of other investigations that would fall into different categories in order to activate students' meta-cognitive thinking regarding scientific methods. These questions were used because the aim of the lesson was not only to present a practical investigation, but to also demonstrate to students that it is possible to perform alternative investigations, for which alternative scientific methods would be applied.

## Results

### *Students' Understanding of Osmosis*

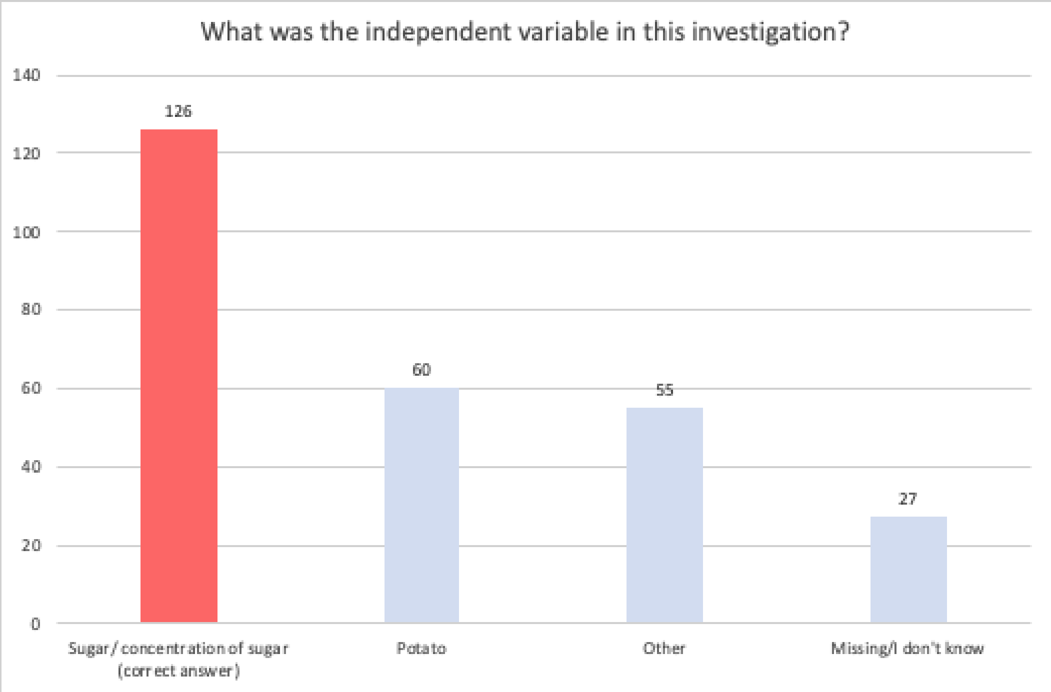
The results of the study showed that students demonstrated an improvement in their understanding of osmosis, since more students answered the questions correctly in the post-test. More explicitly, 54% of the students answered correctly in the pre-test compared to 60% in the post-test. Many of the students indicated they had encountered this practical already and therefore were familiar with it. To have evidence of gains in understanding is a positive indicator of the capacity of resources to improve the learning of practical work.

### *Students' Performance on Assessment Question*

The majority of the students were able to identify the independent variable in the investigation, which was the concentration of sugar solution. Figure 5 illustrates the distribution of student answers concerning the assessment question designed by Project Calibrate. Although most of the students included both the keywords 'sugar' or 'concentration of sugar', a number of students (n=60) falsely identified the independent variable as the 'potato' or 'chip'. Other incorrect answers included 'time' and 'water'.

**Figure 5**

*Distribution of Student Answers for the Assessment Question on Osmosis.*




## Conclusion

The ethos of Project Calibrate worked on the assumption that high stakes examinations are the driver of what is taught and what is learned in the classroom (Hargreaves, 1989; Erduran et al., 2020). Capitalising on a model of diversity of scientific methods, online resources for teaching, learning and summative assessment were produced and tested with a national sample of pupils and teachers. The findings show how the assessments can improve their understanding of the theory of the practical and shift the balance between the assessment of practical skills and the cognitive reasoning skills necessary for the study of biology (Ioannidou & Erduran, 2021). The videos presented to the students illustrated how a balanced approach to the representation of methods can influence their understanding as shown in the results in assessment items. Studies conducted within Project Calibrate demonstrated a significant effect of the intervention on students' understanding of scientific methods. Similar interventions as those presented above for biology were developed for practical investigations for physics and chemistry, illustrating comparable significant effects on students' understanding of scientific methods (Project Calibrate, 2020). This indicates that presenting a diverse range of methods in teaching and assessments can improve students' understanding of how different methods work in biology practical activities. Considering that the breadth and scope of practical work undertaken by students is limited in England (SCORE, 2008), it is vital that future efforts to ensure that national examinations can be put to effective use by promoting meaningful teaching and learning of practical science in biology. The project engaged a variety of key stakeholders in England's education system – from science education researchers, assessment experts and examiners to teachers and their pupils. Reforming summative assessments about practical science to design "tests worth teaching to" needs this systemic approach if change is to occur in how practical activities can benefit students' understanding of how science works (Abrahams & Millar, 2008). For more information about Project Calibrate please visit https://projectcalibrate.web.ox.ac.uk.

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Appendix A. Assessment questions

18. A student investigated the effect of placing potato chips in different concentrations of sugar solutions. This is the method he used:

1. Prepare six different concentrations of sugar solution in separate boiling tubes.
2. Cut six equal sized pieces of potato.
3. Dry each potato chip and record its mass.
4. Place one potato chip in each boiling tube and leave for 2 hours.
5. Remove the potato chips and dry them before recording the final mass.

Give **two** variables the student should control in this investigation.

19. What was the independent variable in this investigation?

20. The mass of one of the potato chips was 4.1g at the start and 4.5g after being in the sugar solution. Calculate the percentage increase in mass of this potato chip.

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