Inquiry-based learning in science and mathematics

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ABSTRACT

This paper sets out strong arguments in favour of inquiry-based education in science and mathematics in terms of benefits to individuals and to society. It draws on research and other sources, such as the publications of the Fibonacci project, to define inquiry and model the development of understanding through inquiry. The rather sparse evidence of the effectiveness of inquiry-based approaches is cited, noting the need for valid means of assessing the outcomes of inquiry. The final section considers the role that student assessment can take both in supporting and in reporting learning through inquiry and changes in current assessment practices that are needed.

KEY WORDS

Inquiry-based learning, model, progression, assessment, tests

RÉSUMÉ

Ce papier présente des arguments forts à faveur de l'enseignement fondé sur l'investigation en sciences et en mathématiques, en termes des bénéfices que celui-ci entraine autant pour les individus que pour la société. Il s'appuie sur la recherche et sur d'autres sources, telles que les publications du projet Fibonacci, pour définir la démarche d'investigation et pour modeler le développement de la compréhension à travers celle-ci. L'évidence plutôt éparse concernant l'effectivité des approches fondées sur l'investigation est citée, tout en constatant la nécessité de développer *de moyens valides pour évaluer ses résultats. Le rôle que peut jouer l'évaluation des apprentissages des élèves pour à la fois soutenir et rapporter l'apprentissage à travers l'investigation, ainsi que les changements requis dans les pratiques actuelles d'évaluation sont considérés dans la section finale.*

Mots-Clés

Apprentissage fondé sur l'investigation, modèle, progression, évaluation, tests

Introduction

The concept of inquiry-based pedagogy is by no means new but it has been promoted actively in science and mathematics education in recent years because of its potential to lead to the understanding, competences and attitudes that are needed by everyone in increasingly technology based societies. In Europe several projects, particularly Pollen, Sinus-Transfer and Fibonacci, have been designed to spread inquiry-based pedagogy in response to the problem identified in the Rocard report of "an alarming decline in young people's interest for key science studies and mathematics" (Rocard et al., 2007, p. 5). This paper looks briefly at the history and rationale of inquiry-based pedagogy, its meaning in general and in science and mathematics specifically, what is involved in its implementation in science and mathematics, and the evidence of its effectiveness. Finally some challenges relating to assessment of inquiry-based learning outcomes are considered.

Why Use Inquiry-Based Pedagogy in Science?

The roots of inquiry-based education can be found in the recognition of importance of children having an active role in their learning in the writings of educators such as Homer Lane (1875-1925), Dewey (1870-1952) and Montessori (1870-1952), drawing on the earlier ideas of Rousseau (1712-1778), Pestalozzi (1746-1827), and Froebel (1782-1852). These educators were concerned with a general approach to education which respected the role of children's curiosity, imagination and urge to interact and inquire. This approach was not specifically related to learning science, which in any case was not regularly included in primary school education until well into the twentieth century. However, its particular relevance for science was noted by those educators advocating the introduction of science into the primary school curriculum in the 1950s and 1960s. For instance, in England, Nathan Isaacs campaigned in favour of introducing 'finding out' activities or 'inquiries' into the primary school curriculum. He wrote that school should use questions to "launch groups of children on their own co-operative quests for answers. They can be guided and steered, helped over difficulties and offered hints in the right directions or suggestive leading questions. In these ways each inquiry that has been set in motion can … become an immensely educative experience for all the children who have shared in it. For not only have they thus built up by their own efforts some fresh scheme of connected knowledge and understanding, but they have experience for themselves some of the typical ways and methods by which such building up can be achieved. A varied series of these co-operative group inquiries … should take children a long way towards a basic understanding of the meaning of scientific inquiry and of scientific knowledge" (Isaacs, 1962, p. 12).

Since that time inquiry has been progressively adopted in science education and more recently in mathematics education. It is seen in the 21st century as being central to providing the skills and understanding that are needed by individuals in a rapidly changing world and also by societies which are increasingly dependent on the applications of these subjects in technology and engineering.

Learning science and mathematics through inquiry can serve the personal interests of individual learners and be of benefit to society. For learners as individuals, it enables them to develop the understanding, powers of reasoning and attitudes that help them to lead physically and emotionally healthy and rewarding lives. Developing understanding about the world around as well as stimulating and satisfying curiosity also informs their personal decisions in life, affecting their wellbeing and choice of career. For society, there are benefits if individuals and groups make more informed choices in relation to avoiding, for instance, waste of energy and other resources, pollution and the consequences of poor diet, lack of exercise and misuse of drugs. As well as impact on their own daily lives, these things have wider implications for their and others' future lives through the longer-term impact of human activity on the environment. Relating science and mathematics to familiar situations and objects used daily stimulates interest in learning these subjects but should also be used to develop the realisation of how wides pread, locally and globally, are the consequences of their applications.

Further, the OECD points out that "Students cannot learn in school everything they will need to know in adult life. What they must acquire is the prerequisites for successful learning in future life. These prerequisites are of both a cognitive and a motivational nature. Students must become able to organise and regulate their own learning, to learn independently and in groups, and to overcome difficulties in the learning process. This requires them to be aware of their own thinking processes and learning strategies and methods" (OECD, 2000, p. 90)

Opportunities to develop these outcomes of education are important for all students not only those who will continue to study science and mathematics and later take up occupations related to STEM (science, technology, engineering and mathematics) subjects. At the same time, the results of effective science and mathematics education may well lead to more students choosing to specialise in science and mathematics and so avoid the threat to Europe's capacity to innovate and the quality of its research identified in the Rocard report.

In summary, there are several reasons why learning through scientific inquiry should be part of the experience of all students. It will not be the only form of pedagogy that they encounter in their science education, for there are some things to be learned such as skills of using equipment, names, conventions and symbols which are best taught directly. Also, in the secondary school, students need to be introduced to complex and abstract ideas that are not accessible to them through inquiry alone. Indeed, at all stages there will be occasions where inquiry contribute to making sense of experience or of scientific or mathematical ideas without being the sole approach used. However, the experience of developing understanding through their own thinking and reasoning has many benefits for students which are not obtained in other ways. These include:

- enjoyment and satisfaction in finding out for themselves something that they want to know;
- seeing for themselves what works rather than just being told;
- satisfying and at the same time stimulating curiosity about the world around them;
- developing progressively more powerful ideas about the world around;
- developing the skills needed in scientific inquiry through participation in it;
- realising that learning science involves discussion and working with and learning from others, directly or through written sources;
- understanding science as the result of human endeavour.

Meanings of Inquiry

Inquiry is a term used both within education and in daily life to refer to seeking explanations or information by asking questions. It is sometimes equated with research, investigation, or 'search for truth'. Within education, there is the potential for inquiry to be applied in several subject domains, such as history, geography, the arts, as well as science, mathematics, technology and engineering whenever questions are raised, evidence is gathered and possible explanations are considered. In each area different kinds of knowledge and understanding emerge. What distinguishes *scientific inquiry* is that it leads to knowledge and understanding of the natural and made world through direct interaction with the world and through the generation and collection of data for use as evidence in supporting explanations of phenomena and events.

What is involved in learning science through inquiry has been spelled out in various definitions. A widely quoted description was included in the *National Science Education Standards*, published by the US National Research Council (NRC) in 1996. Referring both to ways in which scientists study the natural world and the activities of students in developing their knowledge and understanding of scientific ideas, inquiry is described as: "a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations" (NRC, 1996, p. 23).

In the more recent *Framework for K-12 Science Education*, however, the NRC makes less use of the term 'inquiry', due to its (mis)interpretation in various ways. Instead, the activity of engaging in scientific investigation is described in terms of 'practices', in order to "stress that engaging in scientific inquiry requires coordination both of knowledge and skills simultaneously" (NRC, 2012, p. 41).

These two aspects are embedded in the definition produced in the course of various pilot projects in many different countries in the past decade initiated by the Science Education Project of the IAP (the Global Network of Science Academies): "IBSE means students progressively developing key scientific ideas through learning how to investigate and build their knowledge and understanding of the world around. They use skills employed by scientists such as raising questions, collecting data, reasoning and reviewing evidence in the light of what is already known, drawing conclusions and discussing results. This learning process is all supported by an inquiry-based pedagogy, where pedagogy is taken to mean not only the act of teaching but also its underpinning justifications" (IAP, 2010).

Some words in this definition deserve emphasis and comment.

- *Progressively developing key ideas* underlines the importance of identifying a few overarching, 'big' ideas that help us to make sense of the phenomena in the world around, and ensuring that through their science learning activities students make progress towards developing these 'bigger' ideas.
- *Learning how to… build their knowledge and understanding* implies the active role of the students in their learning, linking to formative assessment (see later) and to a view of learning as being constructed by students.
- *Using skills employed by scientists* means, in addition to using those skills listed, being rigorous and honest in collecting and using sufficient and relevant data to test hypotheses or answer the questions raised. Scientists check and repeat data collection where possible, and they interpret and attempt to explain their findings. Throughout their investigation they keep careful records, and in drawing conclusions they consult related existing work and present their work to others, in writing or at conferences, and share their ideas. It is obvious in the case of scientists, but worth noting for application of inquiry in school science, that those engaged in inquiry do

not know the answer to the question or problem being studied, find it important to investigate and are excited about trying to find an answer or solution.

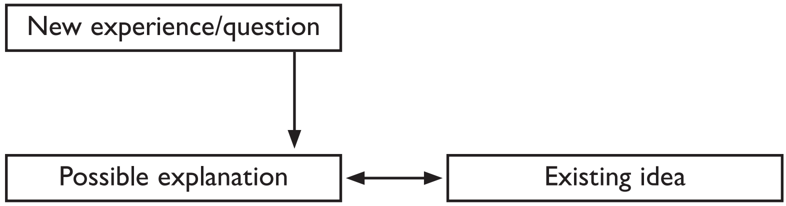
- *Raising questions* underlines the point that students are engaged in answering questions of real interest to them that have stimulated their curiosity. Often these questions will be raised by the teacher, other students or emerge from reading but, whatever the origin of the questions, in inquiry students take them as their own, thus engaging their curiosity and desire to understand. Sometimes raising and answering questions is sometimes equated with problem-solving, where the focus is on finding a solution that 'works'. However, in science the single solution is not enough. Developing theories and models in order to explain phenomena requires that ideas are "evaluated against alternative explanations and compared with evidence…. Thus knowing why the wrong answer is wrong can help secure a deeper and stronger understanding of why the right answer is right" (NRC, 2012, p. 44).

However, there are some different understandings, or even misconceptions, of inquiry-based science education. Since it depends on the use of processes or skills it is sometimes viewed as being concerned exclusively with developing these skills as outcomes in their own right. Related to this view is also the assumption that inquiry is mainly suitable for primary and middle school science; indeed it has proved far more difficult to introduce inquiry-based activities into secondary school science education. A related mistaken view is that inquiry means that students have to 'discover' everything for themselves and should not be given information by the teacher or use other sources. This assumes that students come to new experiences with open minds and develop their ideas by inductive reasoning about what they observe and find through their inquiries. The reality is that students come to new experiences not with empty minds, but with ideas already formed from earlier thinking and experiences, which they use to try to understand the new events or phenomenon. To counter these limited conceptions of inquiry-based science it is necessary to look at how understanding is developed through inquiry and the role of inquiry skills in the process.

A Model of Developing Understanding in Science Through Inquiry

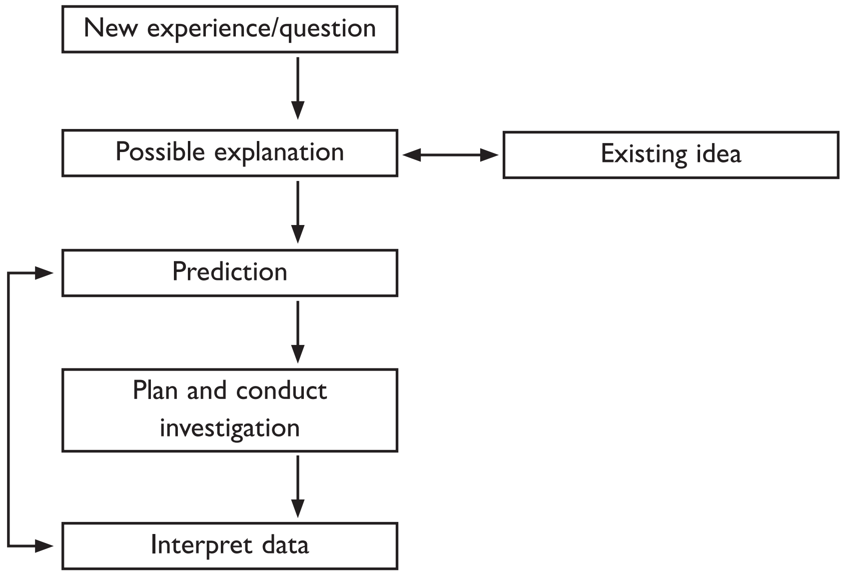
The process begins by trying to make sense of a phenomenon, or answer a question about why something behaves in a certain way or takes the form it does. Initial exploration reveals features that recall previous ideas leading to possible explanations ("*I think it might be…*" "*I've seen something like this when…*" "*It's a bit like…*"). There might be several ideas from previous experience that could be relevant and through discussion one of these is chosen as giving the possible explanation or hypothesis to be tried.

FIGURE 1



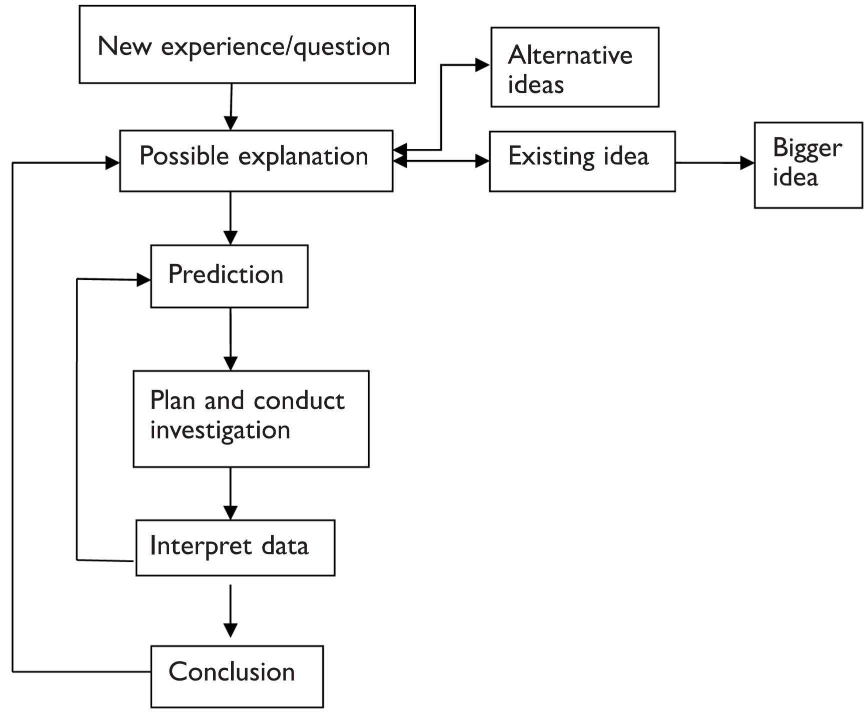
Working scientifically, students then proceed to see how useful the chosen existing idea is by making a prediction based on the hypothesis, because only if ideas have predictive power are they useful. To test the prediction new data about the phenomenon or problem are gathered, then analysed and the outcome used as evidence to compare with the predicted result. This is the 'prediction à plan and conduct investigation à interpret data' sequence in Figure 2. More than one prediction and test is desirable and so this sequence may be repeated several times.

FIGURE 2



From these results a tentative conclusion can be drawn about the initial idea. If it gives a good explanation then the existing idea is not only confirmed, but becomes more powerful –'bigger'– because it then explains a wider range of phenomena (Harlen, 2010). Even if it doesn't 'work' and an alternative idea has to be tried (one of the alternative ideas in Figure 3), the experience has helped to refine the idea, so knowing that the existing idea does not fit is also useful.

FIGURE 3



This is the process of building understanding through collecting evidence to test possible explanations and the ideas behind them in a scientific manner, which we describe as learning through scientific inquiry. Repeating the cycle of processes in Figure 3 when questions are raised by further experience gradually broadens the emerging ideas, leading to ones that apply to a range of different objects and situations. Thus through their inquiry students learn something about particular content, but more importantly they develop understanding of similar events by linking together past and new experiences. For example, the investigation of whether objects sink or float in water leads to information about these particular objects, but to be more widely useful this information needs to be linked to other information and organised to form broader principles and concepts, such as an idea of floating that applies to all objects and fluids and helps understanding of why things do or do not float. However, principles and concepts cannot be directly transmitted to learners, except as meaningless words learned by rote; they must be gradually constructed through the learners' own thinking.

Modelling the building of understanding in this way offers a view of how smaller ideas (ones which apply to particular observations or experiences) are progressively developed into big ideas (ones that apply to a range of related objects or phenomena). In doing so, it is important to acknowledge, and to start from, the ideas the students already have, for if these are just put aside the students will still hold onto their ideas because these are the ones that they worked out for themselves and make sense to them. Students must be given opportunities to see for themselves which ideas are more consistent with evidence. Also, since ability to question, describe, propose, communicate and conclude involve language, it follows that inquiry is closely tied to the development and use of appropriate language.

The role of inquiry skills

The development of understanding in the way depicted in this model depends on the processes involved in making predictions and gathering evidence to test them being carried out in a scientific way. Students, particularly young children, do not instinctively use these processes rigorously. They may not test their initial ideas and when they do so they may not do it scientifically. Their existing ideas may influence what is 'observed' through focusing on certain observations that confirm their ideas, leaving out of account those that might challenge them. Students sometimes make 'predictions' that they already know to be true and so are not a test of an idea. In setting up a test they may not control variables that should be kept constant. When these things happen, the ideas that emerge are not consistent with evidence: hence the importance of helping students to develop the skills needed in scientific investigation.

Even when students are capable of using these processes in some circumstances, they do not necessarily do so in different circumstances. Indeed, there is plenty of evidence that knowledge of the subject matter under study has a strong influence on how these processes are carried out. To some extent this is obvious, since it might be expected that familiarity influences recognition of what variables are likely to be relevant in an investigation. So even a young child might be able to plan a 'fair test' of how well balls bounce on different surfaces but not be able to plan a fair test of something much less familiar to them, such as how the concentration of a liquid affects its osmotic pressure. In other words, the way in which the processes are carried out crucially influences the ideas that emerge. But at the same time the content can influence the use of process. *This complex interaction of process and content means that conceptual understanding and skills of investigation and reasoning need to be developed together.*

Inquiry-Based Mathematics Education

Much of what we have discussed here has concerned inquiry in science education but inquiry is increasingly being applied in mathematics education, for much the same reasons as for science. However, there are both differences and similarities between inquiry in science and mathematics, explored in the Fibonacci project, leading to the following statement: "Inquiry-based practices in mathematics involve diverse forms of activity: articulating or elaborating questions in order to make them accessible to some mathematical work; modelling and mathematising; exploring and experimenting; conjecturing; testing, explaining, reasoning, arguing and proving; defining and structuring; connecting, representing and communicating. Inquiry-based mathematics education engages students in these forms of activity and fosters the development of associated competences. It is expected that the inquiry-based approach will improve students' mathematical understanding, which will result in their mathematical knowledge becoming more robust and functional in a diversity of contexts beyond that of the usual school tasks. It will help students develop mathematical and scientific curiosity and creativity as well as their potential for critical reflection, reasoning and analysis, and their autonomy as learners. It will also help them develop a more accurate vision of mathematics as a human enterprise, consider mathematics as a fundamental component of our cultural heritage, and appreciate the crucial role it plays in the development of our societies" (Fibonacci, 2012a, p. 8).

Here several parallels with the rationale and nature of inquiry in science can be recognised. For example, both are concerned with students developing understanding through processes that start from a question or a problem. Both seek solutions through observation, exploration and through actual or virtual experiments and both involve non-linear processes supporting progressive development of solutions, key ideas and strategies. Some forms of mathematical inquiry are close to actions in science inquiry, particularly in respect of aiming to go beyond answering a particular question or solving a particular problem to reach more general conclusions and understanding of the results and of the processes by which they were achieved.

Despite the similarities with scientific inquiry, there are aspects of mathematical inquiry which are quite distinctly different. These relate in particular to the source of questions or problems, how they are expressed, the nature and function of experimentation and how solutions are validated.

In inquiry-based mathematics the problems can arise in real life situations, as in science, but also in abstract constructions such as numbers, shapes and algebraic structures. An example from real-life would be how to measure an inaccessible or very large object. An inquiry starting from mathematics itself would be: "what is the greatest product which can be obtained by decomposing a positive integer into a sum of positive integers and multiplying the terms of the sum?" (Fibonacci, 2012b, p. 7). In the case of questions arising from real life an important part of the process of inquiry is that these have to be transformed into questions accessible to solution using mathematics. What this transformation involves is described as modeling, but here the word is used in a more restricted sense than in science, where models can be conceptual or physical and used to simulate events or describe relationships and offer explanations.

Thus mathematics inquiry has access to a wide range of problems arising from within mathematics and from the real world and is not restricted to real world questions as is science. Neither are the processes of investigation and experimentation in mathematics limited to observation of or manipulation of the real world. There is also a difference in the way in which solutions are validated. Whereas in science ideas are accepted – even if only provisionally – if predictions based on them are found to be consistent with new evidence, in mathematics inquiry the validity of solutions is demonstrated through logical arguments. This means that when a solution to a mathematical problem has been proved to be true there can be no further evidence to invalidate it. This is quite contrary to scientific explanations, theories and models which are those that fit the facts known at a particular time, are regarded as provisional and can never be proved (Hawking, 1988).

Scientific Inquiry in the Classroom

Two important questions to ask about inquiry-based education are: 'what change does it make in the classroom', and 'does it work?' We deal with the first of these in this section and the second later. This is the logical sequence, since there is no point in trying to evaluate the impact of inquiry-based work unless there is evidence that it is being practised. A good answer to how implementation of inquiry is manifested in observable activities is necessary also in order to develop effective professional development programmes for disseminating relevant practices.

During its work the IAP Science Education Programme identified activities of students and teachers which characterise inquiry-based science education. In the case of students' activities, Harlen (2013) used this to develop the list in Figure 4, which can be contrasted with the list in Figure 5 of students' activities when learning science through transmission rather than inquiry.

An example of inquiry-based learning and teaching is given in some detail by Fitzgerald (2012) in her study of the work of expert teachers of science at the primary school level. Through classroom observations she was able to give an account of how a teacher of grade 3 and 4 students helped the students to develop their ideas about the relationship between the Sun, Earth and Moon.

The teacher used part of a published unit of work on astronomy, called *Spinning in Space* (from the Australian programme *Primary Connections*). Starting from a well structured unit "meant that instead of focusing on preparing the content of the unit [the teacher] could focus her attention on modifying aspects of the unit to better suit her students' learning needs and interests" (Fitzgerald, 2012, p. 47). In brainstorming sessions the teacher explored the students' ideas about the relative position of Sun,

FIGURE 4

- Students pursue questions which they have identified as their own even if introduced by the teacher.
- They do not know the answer to the questions they investigate.
- They know enough about the topic to engage with the question.
- They make predictions based on their emerging ideas about the topic.
- They take part in planning investigations to test their predictions.
- They conduct investigations themselves.
- They use appropriate sources and methods of collecting data relevant to testing their predictions.
- They discuss what they find in relation to their initial expectations or predictions.
- They draw conclusions and try to explain what they find.
- They compare their findings and conclusions with what others have found and concluded.
- They keep notes and records during their work.
- They engage in discussion of the methods used and the results of their investigations.

Student activities: learning through inquiry

FIGURE 5

- Students' activities follow a sequence set out in a text-book or by the teacher with little attention to placing what they do in the context of a question they want to answer
- They may read about how to conduct investigations but have little opportunity to experience the process for themselves.
- They may observe demonstrations by the teachers but may not understand the reasons for what is being done.
- When they do undertake practice activities they follow instructions taking little part in deciding what to do.
- The experiments they observe or conduct are designed to confirm a conclusion already known: 'experiment to show that …'.
- They do not always know why certain steps in an experiment or investigation have to be carried out.
- They write accounts of investigations in a structured form, often copied from a book or dictated by the teacher.
- They record the 'right answer' even if they did not observe what ought to have happened.
- They work independently or in pairs and are discouraged from discussing their work.

Student activities: learning through transmission methods

Earth and Moon. In groups, the students used spherical objects of very different sizes to explore why the Sun and Moon appear to be the same size from Earth. The students' ideas were also captured in the questions they asked, such as: What is the Moon made of? How does the Sun disappear at night? How does the Earth spin?

The ideas in the unit were found to be quite challenging for grade 3 and 4 students and the teacher reduced the demand by focusing on the question of what causes day and night, a question that the students clearly wanted to explore. She gathered their initial ideas and found a persistent belief that it is the Moon that is the cause of day and night. Consequently the teachers modified the unit to enable the students to consider other ideas. She used a variety of activities involving group work on models, PowerPoint presentations to the whole class and use of other communication technologies (such as You Tube clips). The students were involved in most of the activities listed in Figure 4 in addressing questions that appear at first to be difficult to address through inquiry.

The Fibonacci project has developed tools for observing teachers and their classes at work and for teachers themselves to use in reflecting on their own practices (Fibonacci, 2012c). In the case of teachers' activities, the aspects included relate to 'building on students' ideas', 'supporting students' own investigations' and 'guiding analysis and conclusions'. The items included under these headings help to specify more precisely what inquiry-based pedagogy means in science. For example, under 'guiding analysis and conclusions', the items are:

- Teacher asks students to state their conclusions
- Teacher asks students to check that their conclusions fit with their results
- Teacher asks students to compare their conclusions with their predictions
- Teachers asks students to give reasons or explanations for what they found
- Teacher helps students identify possible sources of error
- Teacher helps students identify new or remaining questions
- Teacher encourages students to reflect on what they have done or found.

Does Inquiry-Based Science Education Work?

The rationale for inquiry-based science and mathematics education, outlined earlier, sets up expectations that it will result in changes in students' understanding, skills, attitudes and interests that are of benefit to individuals and to society. So it is understandable that the question should be asked as to whether these change in students' learning do take place, particularly if the considerable changes that implementation of inquiry-based pedagogy requires in teacher education, curriculum aims and assessment are to be justified. However, there are two massive obstacles to having a clear cut answer to this question. First, is the obvious point that before attempts are made to assess learning outcomes from inquiry-based education it is important to ensure that the students being studied have indeed been experiencing inquiry-based pedagogy. Despite the activity in various projects to disseminate inquiry-based learning and teaching, it remains the case that these practices are only beginning to be embedded in many countries. Attempt too early to measure outcomes may well generate misleading data about the impact of inquiry. The second problem is the lack of instruments for measuring the kinds of outcomes envisaged, which is discussed later.

However, it is possible to glean some relevant evidence from research that has been conducted on programmes that have some of the elements of inquiry. For instance in the USA a meta-analysis of studies of the early elementary school projects showed that these had an impact on students' use of scientific processes rather than on their knowledge (Bredderman, 1983). Another synthesis of comparative studies of activity-based methods reported mixed results (Atash & Dawson, 1986).

The most recent research synthesis, by Minner, Levy and Century (2009), reviewed 138 studies of inquiry-based science education (30 experimental; 35 quasi-experimental; 73 non-experimental) mostly carried out in the USA. It was found that just over half of the studies showed positive impacts of some level of inquiry science instruction on student content learning and retention. Overall there was a positive trend favouring inquiry-based practices, particularly those emphasising student active thinking and drawing conclusions from data. Studies of the effect of hands-on activities on student learning showed a statistically significant difference, as did those where students were given greater responsibility. Although the authors were highly critical of the quality of many of the studies, they concluded that 'teaching strategies that actively engage students in the learning process through scientific investigations are more likely to increase conceptual understanding than are strategies that rely on more passive techniques, which are often necessary in the current standardized-assessment laden educational environment" (Minner, Levy & Century, 2009, p. 474).

Despite the strong arguments in favour of inquiry-based science education it appears that clear and convincing quantitative evidence of the promised impact on students' measured learning is sparse, even though there is anecdotal evidence that students enjoy and are engaged by inquiry-based activities. Assessment, both for formative and summative purposes, that is consistent with the conception of learning underpinning inquiry-based education is woefully underdeveloped. Given the strong influence of what is assessed on what is taught, assessment is an areas requiring urgent attention if we are to avoid the use of traditional assessment procedures restraining the spread of inquiry-based practices. The next section explores the roles that assessment can take in inquiry-based pedagogy.

Assessment and Inquiry-Based Education

All assessment involves the generation, collection, interpretation and communication of data. The process is the same whether purpose is to help learning (formative assessment) or to summarise and report it (summative assessment). Whether a particular assessment practice is formative assessment or summative assessment is essentially determined by the *use* made of the data. So, for instance, a classroom test may be used to help students and teacher to identify what students already know about a new topic – a formative use – or to judge and report on what they have learned at the end – a summative use.

Formative assessment and inquiry-based science education

Formative assessment, also known as assessment *for* learning, is best thought of as a repeated cycle of events. It is not something that happens only occasionally but is an on-going and integral part of the process of making decisions that is happening all the time in teaching. It involves the collection of evidence about learning as it takes place, the interpretation of that evidence in terms of progress towards the goals of the work, the identification of appropriate next steps and decisions about how to take them.

Students are at the centre process, of course, since it is they who do the learning. They are both the source of information that teachers can use to ensure that there is progression and the recipients of feedback from the teacher and from other students. Feedback from students to teachers is needed so that teachers can consider what are the appropriate next steps and the actions to help students take them. If it is evident that students are experiencing difficulty this feedback helps teachers to decide what, if any, adjustments are needed to the pace of the work or amount of help given to students. In this way the feedback helps to regulate teaching, enabling teachers to adjust the challenges they provide for students to be neither too demanding, making success out of reach, nor too simple to be engaging. The feedback might indicate a misconception held by many that must be addressed, as was the case in the example of the unit on astronomy given earlier. In response to the students' misconceptions about the cause of day and night, the teacher reduced the level of conceptual demand to focus on just this idea and how day and night can be explained without reference to the Moon.

Feedback from teacher to students gives students information to help them take the necessary steps to improve their understanding or skills. The form and focus of the feedback has to be carefully judged by the teacher. The focus of the feedback influences what students pay attention to and the form it takes determines whether it can be used to advance learning.

The involvement of students in the assessment of their work is a significant part of formative assessment, having a key role in helping students begin to take responsibility for their learning. In order to take part in assessing their work students need to know what to aim for - the learning goals of their activities. Students, like all learners, direct their effort more effectively if they know what they are trying to achieve, rather than just knowing what they have to do. Teachers are good at telling students what to do ('wrap the ice cubes in different materials and see which takes the longest to melt') but not so good at providing a purpose and a goal ('to see if the different materials you use for wrapping round the ice makes a difference and try to explain what you find'). A prerequisite for being able to judge their work is that students understand what they are trying to do, not in terms of what is to be found, but in terms of the question to be addressed or problem to be solved. They also need to have some idea of what it means to produce work of good quality. Some of this is conveyed implicitly through the feedback that teachers give to students. Teachers can also discuss more explicitly what makes one piece of work or investigation better than another, using examples where some show the features of good work and others do not.

The importance of formative assessment lies in the evidence of its effectiveness in improving learning. Empirical studies of classroom assessment have been the subject of several research reviews. The review by Black and Wiliam (1998) attracted attention world-wide partly because of the attempt to quantify the impact of using formative assessment. Since then there have been a number of other reviews and investigations which have justified the considerable claims made by Leahy and Wiliam (2012, p. 52): "The general finding is that across a range of different school subjects, in different countries, and for learners of different ages, the use of formative assessment appears to be associated with considerable improvements in the rate of learning. Estimating how big these gains might be is difficult… but it seems reasonable to conclude that use of formative assessment can increase the rate of student learning by some 50 to 100%".

It is easy to see that formative assessment is essential to the implementation of IBSE. Learning through inquiry is a process of developing understanding which takes account of the way in which students learn best, that is, through their own physical and mental activity. It is based on recognition that ideas, knowledge and understanding are constructed by students through their own thinking about their experiences. What is known about learning tells us that this happens when students' activities enable them to develop their understanding, that is, when they are working in the area between existing and more advanced ideas and competence, or the zone of potential (proximal) development (Vygotsky, 1978). Formative assessment is the strategy by which these activities and the whole learning environment are designed to ensure that this progress in learning is possible.

Summative assessment and inquiry-based science education

Summative assessment, or assessment *of* learning serves a different purpose in education than formative assessment (assessment *for* learning). It is not intended to help learning directly as does formative assessment, although it can and should be of value in a less direct way (Harlen, 2010). Its main purpose is to find out and report what students have achieved at a particular time. It enables teachers, parents, schools and students themselves to keep track of students' learning, both as individuals and as members of certain groups (such as those who are high achievers and those who need special help). It provides data which, together with contextual factors, can be used for school evaluation and improvement. Unfortunately summative assessment data can be used inappropriately, in ways which distort teaching and learning and the consequences of this are particularly serious when the data do not fully reflect the goals of learning. The danger is acute in the case of IBSE on account of its range of different goals, which are not easily assessed by conventional methods. This makes it even more important to consider the ways in which dependable information can be gathered for summative assessment.

As noted earlier, assessment is a process of generating and interpreting evidence of students' learning, involving decisions about what evidence to use, the generation and collection of that evidence in a systematic and planned way, interpretation of the evidence to produce a judgment and the communication and use of the judgement. The evidence for summative assessment can be derived from tests, special tasks or regular activities and can be collected by a range of means from different sources: written answers, artefacts constructed by students, portfolios, observation of actions, discussion or presentations of work. Clearly the collection of evidence about performance in relation to all relevant understanding and competences is the most important part of the process, for without it the final report on achievement is unlikely to provide dependable information about students' achievement of the goals of learning. So here we focus on the source of data whilst noting that other aspects concerned with interpreting and communicating have important roles in determining the validity and reliability of the reported outcome.

The potential and limitations of tests for assessing inquiry-based science education

Assessment for summative purposes should provide data that are as reliable (free from error and bias) as possible. There is an attraction in using special tasks or tests because they can be controlled and presented to all students in the same way, thus appearing to give the same opportunities for students to show what they can do. Testing is a method of assessment in which procedures, such as the task to be undertaken and often the conditions and timing for answering are specified. Tests are usually marked (scored) using a prescribed scheme (rubric), either by the students' teacher or external markers, who are often teachers from other schools, or by machines. The reason for the uniform procedures is to allow comparability between the results of students, who may take the tests in different places. There are different forms of test according to the nature of the task and the form in which a response is given, for example:

- performance tests (sometimes called 'practical')
- embedded tests (set in the context of regular work)

- multiple choice tests (where alternative answers are provided)
- open-ended, or open-response tests (where student write short or long answers in their own words)
- open-book tests (where students have access to a controlled number of sources)

… and many more. Most involve some writing, except in some performance tests and tests of reading for young children. The more formal tests, leading to a certificate or qualification, are often described as examinations.

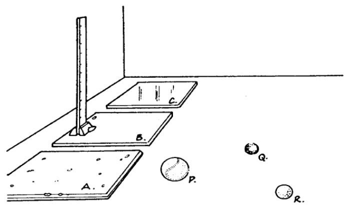
The potential of tests for assessing the understanding and skills that inquiry-based learning in science aims for is best seen by looking at three examples of test items designed for this purpose.

FIGURE 6

Emma and Anita were finding out if the surface on which a ball is bounced makes a difference to how high it bounces.

They found three different kinds of surface, which they called A, B and C.

They also had three different balls P, Q and R.



For a fair test what should they change in their trials and what should they keep the same?

Tick Change or Not change for each thing below:

	Change	Not change
The ball	☐	☐
The surface	☐	☐
The height it is dropped from	☐	☐

Assessing planning skills of students at the end of primary school (aged 11)

The example in Figure 6 is an item from a large bank of items used in national surveys of performance in science in the UK in the 1980s (DES, DENI & WO, 1981). It requires students to identify with the situation described and the question being addressed. The subject matter is likely to be familiar to all students, thus the level of knowledge required is low and the burden of the task is about conducting a fair test. The format for answering, and the requirement of the scoring scheme for the answer in each box to be correct, makes the chance of succeeding by guessing very low. This is a way of making a multiple choice question into one that reduces the chance of success by

FIGURE 7

Read the following information and answer the questions which follow.

WHAT HUMAN ACTIVITIES CONTRIBUTE TO CLIMATE CHANGE?

The burning of coal, oil and natural gas, as well as deforestation and various agricultural and industrial practices, are altering the composition of the atmosphere and contributing to climate change. These human activities have led to increased concentrations of particles and greenhouse gases in the atmosphere. The relative importance of the main contributors to temperature change is shown in Fig. 1.

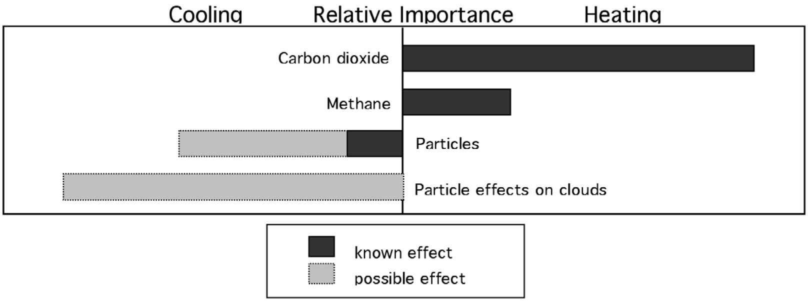


Fig. 1: Relative importance of the main contributors to change in temperature of the atmosphere. Source: adapted from http://www.gcrio.org/ipcc/qa/04.html

Bars extending to the right of the centre line indicate a heating effect. Bars extending to the left of the centre line indicate a cooling effect. The relative effect of 'Particles' and 'Particle effects on clouds' are quite uncertain: in each case the possible effect is somewhere in the range shown by the light grey bar.

Fig. 1 shows that increased concentrations of carbon dioxide and methane have a heating effect. Increased concentrations of particles have a cooling effect in two ways, labelled 'Particles' and 'Particle effects on clouds'.

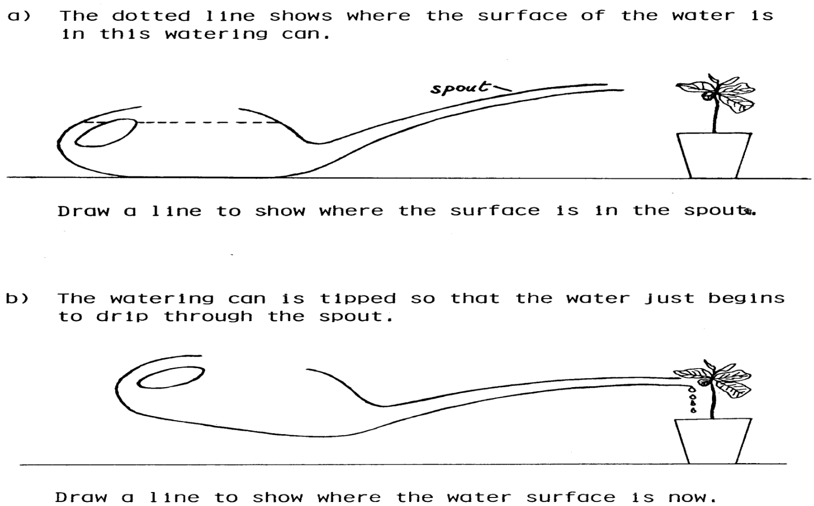
Question 1:
Use the information in Fig. 1 to support the view that priority should be given to reducing the emission of carbon dioxide from the human activities mentioned.

Question 2:
Use the information in Fig. 1 to support the view that the effects of human activity do not constitute a real problem.

Assessing ability to draw conclusions from data of students aged 15 guessing. It also means that students have to read and understand the instructions for recording their answer, otherwise there is a risk of failure for reasons other than not having the skill needed to the answer the question.

Figure 7 shows one of the released items used in OECD PISA surveys (OECD, 2000, p. 88). Information is given and students are asked to use it, in this case to support alternative conclusions about action that the data suggest could be taken. The information is authentic and presents the sort of problem that the scientifically literate should be able to engage with. The two parts to the task illustrate the uncertainty of interpreting scientific information in certain cases. In theory all the information is provided and the students are told how to interpret the graph. They do not need to know how carbon dioxide, methane, particles and their effects on clouds cause heating and cooling. However, without any knowledge of these things the question is likely to be meaningless and they are unlikely to engage with the problem posed.

FIGURE 8



Item assessing understanding suitable for primary and middle school students

The item in Figure 8 (DES, DENI & WO, 1981) requires application of knowledge about water flowing until reaching a common level. The context is assumed to be familiar and the response is by drawing, thus being less dependent on writing and vocabulary than other examples. However, although a scoring scheme can allow for inaccuracy in drawing, the correct completion of the task still requires students to read how they are intended to respond.

Problems in using tests for inquiry-based learning

The examples in Figures 6, 7 and 8 all attempt to place the tasks in contexts that can seem real to the student, consistent with what is needed for assessing understanding, avoiding questions where the answers could be supplied from memory without understanding the ideas involved or using the skills intended. But this means that students have to read and engage with the context in order to respond to the question. This raises the questions of whether the nature of this context makes a difference to how the student responds. For instance, would the identification of variables in the example in Figure 6 be more difficult for some students if the context were about comparing the effect of changing the ingredients in making a cake, or the speed of toy cars down a slope? The answer from research is that familiarity with the context does indeed affect performance and when this familiarity is unequally spread among the population it gives rise to inequality of opportunity to show what they know or can do. Girls and those from economically poor backgrounds, or who struggle with the language of the test, are likely to be at a disadvantage.

This is just the beginning of a long list of difficulties arising in using tests to assess the outcomes of inquiry-based science education. Underlying many of the problems is that assessing students in isolation from each other in an examination room does not reflect the view of learning that underpins inquiry. What is required instead is evidence of performance when students:

- are actually involved in undertaking inquiry
- are engaged with a question that is novel to them
- have the knowledge and experience which is inevitably required, but is not being assessed (such as the vocabulary to understand and communicate).

The difference that this can make has been demonstrated by research in Denmark using items from the PISA tests. The research involved students in answering some PISA questions orally in an interview and conducting, in pairs, an investigation described in a PISA item. The conclusion reached was that 'when compared directly and following the scoring criteria of PISA, pupils' performance increased by 25% when they were allowed to exercise their knowledge in a socio-culturally oriented test format' (Dolin & Krogh, 2010).

Alternatives to tests

These inherent defects of tests make it necessary to ask if there are alternatives that can be used for summative assessment. Fortunately there are; all of them depending on the fact that the experiences that students need in order to develop desired skills, understanding and attitudes also provide opportunities for their progress to be assessed. The key factor is judgement by the teacher. Assessment by teachers can use evidence from regular activities supplemented, if necessary, by evidence from specially devised tasks introduced to provide opportunities for students to use the skills and understanding to be assessed.

Over the period of time – such as a semester or half year – for which achievement is being reported, students have opportunity to engage in a number of activities in which a range of competences can be developed. These same activities provide opportunities for this development to be assessed by the teacher. In other words, the limitation on the range of evidence that can be obtained through a test does not apply when assessment is teacher-based.

There are other advantages that go beyond more valid assessment of understanding and inquiry skills, since a greater range of competences can be included. Observation during regular work enables information to be gathered about processes of learning rather than only about products. Even performance or practical tests are not capable of assessing qualities such as reflection on the process of learning. Evidence can be collected by teachers through:

- observing students involved in scientific investigation
- a portfolio of work collected over a period of time including account, reflections, photographs and other products of inquiry
- students' note-books and /or electronic postings
- presentations made by students individually or in groups.

Interpreting evidence is not just a matter of teachers using their individual judgments, but the application of criteria and the use of moderation procedures to enhance the reliability of teacher-based assessment (for further discussion of procedures and examples see Harlen, 2004).

There are of course problems in teacher-based assessment just as there are in using tests. Some of the relative advantages and disadvantages are summarised by Harlen (2013) as follows:

- Tests provide teachers with clear examples of the meaning of learning goals, but they direct teaching in specific directions which are the same for all students. Assessment by teachers allows teachers greater freedom to pursue learning goals in ways that suit their students.
- Tests that are provided externally to the school enable teachers to distinguish their role as teacher from that as assessor. Responsibility for assessment unites the role of teacher and assessor and may seem to increase teachers' workload.
- In some circumstances the results of tests can be used to provide feedback that helps learning, but generally these opportunities for formative use are limited. When teachers gather evidence from students' on-going work, it can be used formatively, to help learning, as well as for summative purposes.

- It is well known that tests induce anxiety in many students. Not all are affected equally and the impact is often exacerbated by frequent test-taking practice. Assessment by teachers reduced this source of error and inequality.
- Time spent by teachers in preparing students for tests can be more effectively used for learning when assessment is on-going. Financial resources are also released when fewer commercial tests are purchased.
- Users of assessment data often have more confidence in tests than in teachers' assessment, especially for older students. Any change requires greater openness about both test accuracy and procedures that can enhance assessment by teachers.

Conclusion

Inquiry-based-teaching and learning has the potential to counter the lack of interest in science and mathematics which is found particularly as students move into high school. It is known that attitudes towards science develop during the pre-secondary years, earlier than attitudes to some other school subjects. Research evidence reported by The Royal Society (2006, 2012) and by the French Académie des Sciences (Charpak, Léna & Quéré, 2005) shows that most children develop interests and attitudes towards science well before the age of 14 and many before the age of 11. This adds importance to developing inquiry-based pedagogy in science in the primary school and to helping primary school teachers to develop their confidence in teaching science. Nevertheless, inquiry-based science education should not be confined to the primary school. It has a key role in developing secondary school students' conceptual understanding in science and understanding of the nature of scientific knowledge and of how it is created, at a time when they are making decisions about their future studies.

The model of how understanding is developed has been used to show how, through inquiry, ideas become more powerful in their ability to explain the world. That is, how 'big' ideas of science can be progressively developed from the 'small' ideas that students use in answering questions about particular objects, events or phenomena. The model also shows that it is important to help students to develop conceptual understanding and the skills of inquiry and investigation *at the same time*.

The popularity of inquiry brings with it some risks that it is used as a label for practices that, either because they are too limited or are too vaguely defined, do not match the intentions of inquiry-based teaching and learning. It is important to counter these misconceptions in order to avoid inquiry becoming a slippery concept that anyone can apply to any practice. A common limited view of inquiry is that it is just about 'hands-on' activities. This misses the point that inquiry is essentially about the use of evidence which may be found in a range of ways beyond direct action on objects; it may be found from secondary sources, the media and the internet. A related mistaken view is that inquiry means that students have to 'discover' everything for themselves and should not be given information by the teacher or use other sources. This assumes that students come to new experiences with open minds and develop their ideas by inductive reasoning about what they observe and find through their inquiries. In contrast, the model embodies a constructivist view of learning, acknowledging that students come to new experiences not with empty minds but with ideas formed from earlier experience.

So far attempts to find out whether students achieve the learning and better attitudes and interests in science though inquiry have produced only sparse evidence of convincing results. This is partly because the practice of inquiry, although the subject of pilot projects in countries across the world, is not embedded to the extent needed to show large change in students. After all, the pedagogical approach is only one of many factors both within and outside school that impact on students' interests and dispositions. Since is it one that we can change, it is well worth the effort of doing so, particularly as it has other benefits in relation to students' understanding of science, but it needs to be sustained to have a measurable impact. Another reason is the need to develop better measures of the outcomes of learning through inquiry.

Consideration of some examples of test items has shown that it is difficult to provide valid measures of the outcomes of inquiry using conventional tests, even with good test items. We know that what is assessed influences what is taught. Consequently the continuation of the use of assessment designed for learning through conventional transmission (Figure 5), can restrain effort to change to learning through inquiry (Figure 4). Thus attention to alternative approaches to student assessment is urgent. Moreover, it is important to develop the formative role of assessment in helping learning and developing deeper understanding relating to the goals of science education.

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