

# Teaching critical thinking? New directions in science education

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**ABSTRACT** Critique and questioning are central to the practice of science; without argument and evaluation, the construction of reliable knowledge would be impossible. The challenge is to incorporate an understanding of the role of critique and, more importantly, the ability to engage in critique, within the teaching of science. The emphasis in both the US 'next generation' science standards and the forthcoming 2015 PISA tests is on using scientific knowledge with the higher order cognitive processes of evaluation, critique and synthesis.

The goal of science is to produce new knowledge about the natural world. In doing so, science attempts to answer three questions (Osborne, 2011):

- 1 What is the natural world like? (the ontological question)
- 2 How can we explain what we observe? (the causal question)
- 3 How do we know or how certain can we be? (the epistemic question)

Contrary to popular belief that science is about 'doing experiments', answers to these questions are *ideas* that scientists have constructed to explain what they observe. Indeed, as a scientist, your name is much more likely to be preserved for posterity if you think of a successful new idea – the names of Darwin, Einstein, Maxwell, Copernicus, Pasteur, Hubble and Wegener being a testament to the fact that it is theories which are the crowning glory of science (Harré, 1984). For teachers of science, the question is how do we ensure that students understand that scientific theories are the apotheosis of science? Data collection may be an essential activity in science but theories are the bedrock on which science is built. Rather, data are the handmaidens to the activity of generating theories about the world.

Not surprisingly, over the years scientists have imagined many ideas to explain the material world. Some have been dead on arrival, such as the suggestion that atoms could be fused at room temperature. Others have had a longer existence, such as the idea that electromagnetic waves were

transmitted through an æther, the idea of a steady-state universe, or the idea that matter could come into being through spontaneous generation. A few erroneous ideas have even survived for centuries, such as Ptolemy's model of the universe as one where the planets orbited the Earth on circular orbits and simultaneously rotated around a point on that orbit in what was called an epicycle.

Ideas in science succeed because scientists are first and foremost a community of sceptics. Nothing is to be believed without careful and rigorous testing. As a consequence, scientists are forced to defend their ideas; a process that happens informally in lab meetings and symposia, and formally in peer review (Latour and Woolgar, 1986; Popper, 1963). Over time, ideas that survive critical examination attain acceptance within the community. Thus, by critically comparing the evidence with the predictions and with what we observe and by argument, science maintains its objectivity (Longino, 1990). Critique and questioning are not, therefore, some peripheral feature of science but rather they are *core* to its practice and, without argument and evaluation, the construction of reliable knowledge would be impossible (Ford, 2008). Not surprisingly, most teachers would argue that their job is to build an understanding of science, not to criticise it. However, in this article, I take the contrary view, arguing that opportunities to engage in critique, argumentation and questioning not only help build students' understanding of science but also develop their ability to reason scientifically. The

article then seeks to show how the developments in the Organisation for Economic Co-operation and Development (OECD) Programme for International Student Assessment (PISA) tests and the US Next Generation Science Standards (NGSS) are also placing more emphasis on argument and critique within science.

### The role of criticism in science education

Contrary to what we might expect, the critical spirit of science is not a strong feature of science education. As Eric Rogers (1948), the founding father of Nuffield Physics, once wrote, '*we should not assume that mere contact with science, which is so critical, will make the students think critically.*' Rather, science is often taught more as dogma – a set of unequivocal, uncontested and unquestioned facts – more akin to the way people are indoctrinated into a faith than into a critical, questioning community. Not surprisingly, research shows that many of our students emerge from school science thinking that the ultimate achievement of science is the establishment of a good fact (Driver *et al.*, 1996).

Yet, school science is replete with ideas that provide opportunities to engage in argumentation, critique and question. For instance, take the Bohr model of the atom – something which is taught universally across the globe. While, as represented

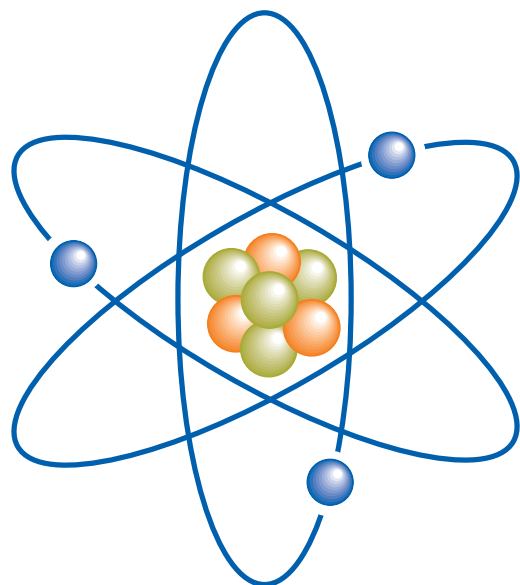


Figure 1 The Bohr model of the atom

in Figure 1, it is a useful iconic picture (and has pedagogic value), it is a gross misrepresentation of what an atom might be like.

It can be criticised, for instance, for the fact that:

- the electrons should be very much smaller than the protons and neutrons;
- the distance between the electrons and the nucleus is not to scale;
- the colour means nothing;
- we do not think we can define the position of the electron accurately in this manner.

The student who can begin to make such criticisms has a much better and deeper understanding of what a more accurate picture of the atom might be. They are, however, not going to develop that understanding unless they are encouraged to:

- a ask the question how the model could be improved;
- b develop an evidence-based argument to justify their claims.

Yes, the sceptics' response will be that you cannot engage in criticism unless you know what you are talking about, that you have to know the rules to break the rules, or that you cannot walk before you can run. However, my point is that those who hold this view miss a valuable learning opportunity. Understanding in science is not the product of fond consensus but of difference, and the absence of critique in science education has several negative consequences:

- an overemphasis on lower level cognitive tasks;
- a less effective process of learning;
- a failure to communicate or represent the nature of the discipline;
- a less engaging experience for students;
- more fundamentally, a reduced likelihood that student will develop the critical capabilities that are increasingly demanded as a required educational outcome (National Research Council, 2012a).

A notable feature of an individual who is critical is that they ask the question 'how do you know?' or 'why should it be believed?' Asking students to engage in questioning and critique matters as it forces the individual to cognitively engage in defending their position. And science has lots of opportunities for generating good questions. After all, common sense tells you that plants get their 'food' from the soil. Why

else do plants have roots and why do we need to water them? Yet, science tells you that most of the matter in the plant comes from the air. Just compare too the difference between the intuitive concepts about our understanding of Earth and space with the scientific concept shown in Table 1. Why should these be believed?

Common sense also tells you that heavier things fall faster and that you have to push an object to keep it in motion, yet science begs to differ. How can these two widely disparate accounts possibly be true? Who, too, would ever have thought that you might look like your parents because every cell in your body carries a chemically coded blueprint of how to reproduce you, that most of the atom consists of empty space, or of the idea that diseases are spread by tiny living microorganisms? Science should, therefore, naturally challenge our students' thinking by inviting critical questions.

Moreover, without questions, there is no need for explanation or argument. Indeed, it is surprising that most textbooks never even tell you what question is being answered! Questioning is a process that supports learning by helping to engender cognitive dissonance (Festinger, 1957) or 'epistemic curiosity' (Berlyne, 1954). Thus, questioning has the potential to promote critical thinking and to foster reflection, deep thinking and the construction of conceptual knowledge.

In science, the search for explanations is driven by the desire to answer the causal question (the second question). For instance, because Eratosthenes asked why the shadow at Alexandria was a different length from that at Aswan on the same day in the year, he was driven to construct an explanation leading him to the argument that the Earth was a sphere. This then enabled him to

calculate the circumference of the Earth. Likewise, Copernicus asked whether placing the Sun at the centre of the solar system would lead to a simpler or better explanation of the retrograde motion of the planets. And because Torricelli asked why it was impossible to siphon water to a height greater than 10 m, his answers led him to building a barometer and a model of the atmosphere.

Yet opportunities for students to ask questions in science are rare (Lemke, 1990; Weiss *et al.*, 2003). Instead, somewhat strangely, it is the teacher, who knows all the answers, who commonly asks all the questions. Asking questions matters because constructing any new understanding is the product of a dialogue between construction *and* critique. Why? Because ideas are never evaluated in isolation but in competition with other ideas, and knowing why your idea is wrong matters as much as knowing why somebody else's idea – in this case the teacher – might be right.

For instance, take something as simple as the explanation for day and night. Observation and common sense would tell you that it is caused by a Sun that rotates around the Earth. After all, it certainly looks like it moves during the day. In addition, the standard scientific account has to answer two good sceptical questions:

- 1 If the Earth is moving as you say, surely when you jump up, you should not land in the same spot?
- 2 If it is moving as you say, its speed at the Equator would be over 1000 m.p.h., which is faster than the speed of sound. How can that be? Surely you would be flung off?

These questions inhibited people from accepting the contemporary scientific explanation for

**Table 1** Differences between the intuitive cosmology and the scientific conception

| Feature               | Intuitive concept  | Scientific concept   |
|-----------------------|--|--|
| Size of solar objects | Earth is larger than the Sun and Moon, which are larger than the stars | Stars are suns that are larger than the Earth, which is larger than the Moon           |
| Shape of the Earth    | Earth is flat  | Earth is spherical   |
| Movement of the Earth | Earth is stationary  | Earth rotates on its axis once every 24 hours and around the Sun once a year           |
| Solar system          | Rotates around the Earth (geocentric)                                  | Rotates around the Sun (heliocentric)  |
| Day and night         | Sun moves, rising and setting  | Earth moves, Sun stays still   |
| Gravity               | There exists an absolute 'down' which is the same everywhere           | 'Down' is towards the centre of the Earth and the direction varies across its surface. |

hundreds of years. Not surprisingly, students might find it difficult to accept the canonical account in a single lesson!

### Why knowing what is wrong matters as much as knowing what is right

Why does giving students the opportunity to ask questions and explore why the wrong answer is wrong matter? The answer is that ideas in general are never evaluated in isolation but by comparing two or more ideas. The mathematician Bayes invented a way of representing this mathematically. As nothing is certain (apart from death and taxes), all ideas have to be evaluated by assessing the probability of how likely they are. This means weighing the evidence for *and* the evidence against, which mathematically is expressed as a likelihood ratio. Weather forecasting now uses such a system for making its predictions where the balance of probability is expressed as a percentage likelihood.

When confronted by a new idea, humans will evaluate a likelihood ratio (how much the evidence supports one hypothesis relative to the other hypothesis). As an example, consider the teaching of the explanation for day and night. For the sake of argument, assume that after some good teaching the probability that an average student will believe what the teacher has just told them being true, compared with their own common sense beliefs, can be expressed mathematically by the ratio of 60% to 40%; that is, a likelihood ratio of 1.5 : 1.

However, imagine if the teacher also spent some time encouraging the students to ask questions and explore why the idea that day and night is caused by a moving Sun might also be wrong, such that the strength of belief for the everyday conception only has a 25% probability. Now the ratio of beliefs becomes 75 : 25, or 3 : 1, and the strength of the teacher's argument is much more convincing. Good teachers know this and spend time exploring the everyday conceptions that students might have and why they might be wrong. For instance, in a research study conducted with 181 middle school science teachers, a Harvard team found that teachers of science who could identify common student misconceptions were significantly more effective teachers (Sadler *et al.*, 2013). Why? Because, as a teacher of science, if you are aware of the common reasoning that your students use, you are likely to explain why it might be wrong.

Further evidence for the value of critique for learning science comes from the work of Hynd and Alvermann (1986). They found that physics texts that contained text *explaining why* everyday conceptions were wrong resulted in significantly better conceptual gains. Likewise, Ames and Murray (1982) found greater learning gains among discussion groups with differing preconceptions compared with those that held similar beliefs, *even if* those differences were based on incorrect premises. Other research has found that even incorrect information shared with a peer can stimulate student learning (Ames and Murray, 1982; Glachan and Light, 1982; Schwarz, Neuman and Biezuner, 2000). Hence, when it comes to learning science, it is disagreement, questioning and critique that may be the hallmark of a classroom that really supports student learning.

Other authors have made similar observations. For instance, Graff and Birkenstein (2010), in their characterisation of how academic arguments are formulated, state that '*Effective persuasive writers do more than make well-supported claims [...]; they also map those claims relative to the claims of others*'. Indeed, scientific manuscripts often focus as much on criticising alternative theories as they do on the arguments for the new proposed theory. Watson and Crick (1953), in their article outlining their proposed structure for DNA, begin not by making the case for their model but by critiquing two existing alternative models.

Getting students to think why they might be wrong requires them to ask questions about what evidence they have to support their beliefs. Questions raised by students activate their prior knowledge, focus their learning efforts and help them elaborate on their knowledge (Schmidt, 1993). The act of 'composing questions' concentrates the attention of students on content, its main ideas, and checking whether content is understood (Rosenshine, Meister and Chapman, 1996). The ability to ask good thinking questions is also an important component of scientific literacy, where the goal of making individuals critical consumers of scientific knowledge (Millar and Osborne, 1998) requires such a facility. If this is so, why are student questions, argumentation and critique often absent from the science classroom? The answer, in part, is that such competencies are not tested and they are not a feature of what we expect students to learn. There are, however, changes afoot.

## Contemporary developments

The notion of critique as a core feature of science, for instance, is central to the Next Generation Science Standards (NGSS) that are currently being adopted by many US states, including major states such as California. These standards are based on a model of science shown in Figure 2 (Osborne, 2011; National Research Council, 2012b).

What this model attempts to capture is that answering scientific questions depends on engaging in the process of observation and collecting data and the search for commonalities and patterns. Darwin, for instance, engaged in detailed observations on his voyages of the flora and fauna to be found in different locations. As such, Darwin was just trying to answer the first question science addresses – what exists? However, the enormous diversity of species and in particular the variation in species within one geographic context (the Galapagos islands) led him to ask the question of how such variation could have occurred – that is the causal or second question.

Such questions engender the scientists' creative imagination, the construction of models and the production of explanatory hypotheses – the element of activity (*developing explanations and solutions*) that is represented by the right side of Figure 2. This is where the emphasis shifts to addressing the causal question – how could this have happened? The construction of such hypotheses is reliant on a mix of deductive reasoning and abductive reasoning (inference to

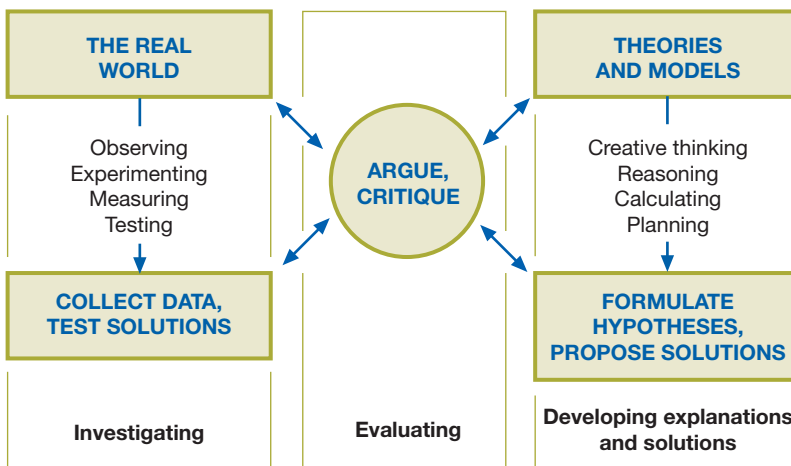
the best possible explanation, for example the theory of evolution or of plate tectonics).

Such ideas must then be tested. The testing of ideas requires the design of investigations and the collection and analysis of data – the left side of Figure 2 (*investigating*). Data is essential to answering the third question – how do we know and how can we be certain? However, achieving consensus and establishing the validity of such claims relies on argument and critique represented by the central portion of Figure 2 (*evaluating*).

All of these activities are dependent on a set of practices in which scientists and engineers engage that are seen as:

- 1 asking questions (for science) and defining problems (for engineering);
- 2 developing and using models;
- 3 planning and carrying out investigations;
- 4 analysing and interpreting data;
- 5 using mathematics and computational thinking;
- 6 constructing explanations (for science) and designing solutions (for engineering);
- 7 engaging in argument from evidence;
- 8 obtaining, evaluating and communicating information.

Only by engaging in these kinds of practice can students begin to understand how scientific knowledge develops – to begin to get a feel for the nature of the discipline. Moreover, engaging in argument from evidence (practice 7) and evaluating information (practice 8) require



**Figure 2** The three spheres of activity for scientist and engineers (Osborne, 2011; National Research Council, 2012b)

students to draw on their knowledge of science and engage in critique, evaluation and synthesis – all higher order cognitive tasks that, although challenging, also stimulate student thinking. It is this kind of activity that enables students to see that, even with their level of knowledge, it is possible to become a critical consumer of scientific knowledge and to see that there is something to be created in science. Indeed, I would argue that one of the reasons for the success of Ben Goldacre's 'Bad Science' blog ([www.badsience.net](http://www.badsience.net)) and *Guardian* newspaper column is that it has enabled non-scientists to appreciate that it is possible to engage critically with science even if you are not an expert.

Similar requirements can be found in the framework that specifies what will be tested in the international OECD PISA tests in 2015. Over 60 countries participate in these tests and politicians take the assessments very seriously, regarding them as a measure of the effectiveness of the country's education system. Every three years, a stratified sample of students is tested in reading, mathematics and science. In 2015, science will be the major emphasis of the assessment. As a result, the framework has been rewritten (OECD, 2013). The focus of this assessment will be on scientific literacy; that is, the ability to:

- explain phenomena scientifically;
- evaluate and design scientific enquiry;
- interpret data and evidence scientifically.

Notably, the model in PISA is based on the notion of competency not 'skill'. Competencies require context-specific knowledge. In the case of science this is not just a knowledge of its content but also a knowledge of the standard procedures that scientists use to obtain reliable and valid data, such as:

- the concept of variables, including dependent, independent and control variables;
- ways of assessing and minimising uncertainty, such as repeating and averaging measurements;
- common ways of abstracting and representing data using tables, graphs and charts and their appropriate use;
- the control of variables strategy and its role in experimental design or the use of randomised controlled trials to avoid confounded findings and to identify possible causal mechanisms;

- the nature of an appropriate design for a given scientific question, for example experimental, field-based or pattern-seeking.

Such knowledge is knowledge of the procedures science uses to obtain reliable knowledge (*procedural* knowledge). PISA goes further, however, in that it argues that the three competencies defining scientific literacy also depend on '*a knowledge of the constructs and defining features essential to the process of knowledge building in science and their role in justifying the knowledge produced by science e.g., a hypothesis, a theory or an observation and its role in contributing to how we know what we know*'. This is called *epistemic* knowledge and consists of elements such as:

- the nature of scientific observations, facts, hypotheses, models and theories;
- the purpose and goals of science (to produce explanations of the natural world) as distinguished from technology (to produce an optimal solution to human need), what constitutes a scientific or technological question and appropriate data;
- the values of science, for example a commitment to publication, objectivity and the elimination of bias;
- the nature of reasoning used in science, for example deductive, inductive, inference to the best explanation (abductive), analogical and model-based;
- the role of collaboration and critique and how peer review helps to establish confidence in scientific claims.

The obvious question is to what extent the new National Curriculum for England and Wales will prepare students to answer the kinds of question that might be used in PISA? The emphasis in both the US NGSS and the PISA tests is on using scientific knowledge with the higher order cognitive processes of evaluation, critique and synthesis, not the lower order cognitive demands of recall and application. Students will only be able to meet such demands if the education they have received to date has prepared them appropriately *and* provided them with experiences that require them to ask questions and think critically.

Both NGSS and PISA are driven by a vision offered by Hill (2008) that the societies that

sustain their competitive edge in the coming decades will be 'post-scientific' societies – post-scientific in that basic research will not be a primary economic imperative as much of it will be outsourced to countries where it can be done more cheaply. In such a society, highly valued competencies will be the ability to draw on a range of disciplines and, notably, to think creatively and to evaluate new ideas in a critical, reflective and rational manner. Yes, employers will require individuals who have a core understanding of scientific and technical principles, but they will be seeking those who have the ability to communicate and synthesise knowledge in an original manner. Gilbert (2005: 197) puts it even more straightforwardly, arguing that *'in a world where there is an oversupply of information, the ability to make sense of information is now the scarce resource'*. More recently, the US National Research Council (2012a) in their report on *Education for Life and Work* argued

that it is important to develop three domains of competence – the cognitive, the intrapersonal, and the interpersonal. Central to the first of these is the development of students' ability to undertake the cognitive process of complex reasoning, which includes critical thinking, non-routine problem solving, and constructing and evaluating evidence-based arguments. However, as Hill (2008) argues, if these are to be a feature of science education then it is important to *'be certain that we emphasize what we want, for we shall surely get what we emphasize'*.

What might this look like in practice? An innovative feature of PISA in 2015 is that all the tests will be computer-based, which means that some of the questions will use simulations that will enable students to manipulate variables, collect data, and analyse and interpret their results. Figure 3 shows a screenshot from one of these assessments used in the US National Assessment of Educational Progress (NAEP) tests in 2009.

NAEP Science 2009: Bottling Honey

nationsreportcard.gov/science2009ict/bottlinghoney/bottlinghoney3a.aspx

DROP RESET

Select Liquid:

Corn Syrup  
Honey  
Water  
Olive Oil

200 mL  
150 mL  
100 mL  
50 mL

Time (s)  
0.0

Temperature (°C)  
30

Next you will use the simulation to investigate how temperature affects the flow rates of the liquids.

You can select which liquid to test. The data from each test you run will be recorded in the table. Time is shown in seconds.

You may clear data from a row by clicking "REMOVE" in that row.

Describe the steps you will take to investigate which liquids flow more quickly at a higher temperature than at a lower temperature.

| Liquid | Temperature (°C) | Time (s) |
|--------|------------------|----------|
|        |                  |          |
|        |                  |          |
|        |                  |          |
|        |                  |          |
|        |                  |          |
|        |                  |          |

Click "NEXT" to start your investigation.

BACK NEXT

**Figure 3** Screenshot from a computer-based simulation used for assessment in the US National Assessment of Educational Progress (NAEP) tests in 2009

This required students to collect a set of data and then analyse and interpret it. Similar items will be in the 2015 PISA test.

Other questions might require students to decide which of four following interpretations of a set of data is better and why (Figure 4).

However, there is a more fundamental reason why the teaching of school science has to shift gear and provide opportunities for students to ask questions and engage in critical evaluation of evidence and ideas. This is a need captured by the disenchanted student who commented that *'the problem with school science is that it gives us answers to questions we have never asked'*. This criticism of the teaching of science can only be remedied by encouraging students to ask *their* questions and to think critically. This means that as teachers of science we must do one or more of the following:

- a model question-asking;
- b provide question prompts or stems;

- c ask students to pose questions via a learning journal, weekly report, question board, question box, or online computer systems;
- d establish a question corner in the classroom to supply 'questions of the week';
- e include a 'free question time' and 'brainstorm' sessions during lessons;
- f set 'question-making' homework;
- g include question-asking in evaluation;
- h use interactive instructional approaches where students work in collaborative groups to generate questions;
- i last, but by no means least, create a non-threatening classroom atmosphere where students feel free to ask questions.

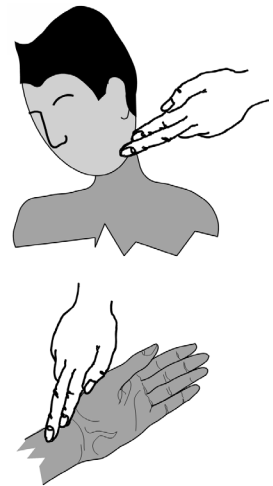
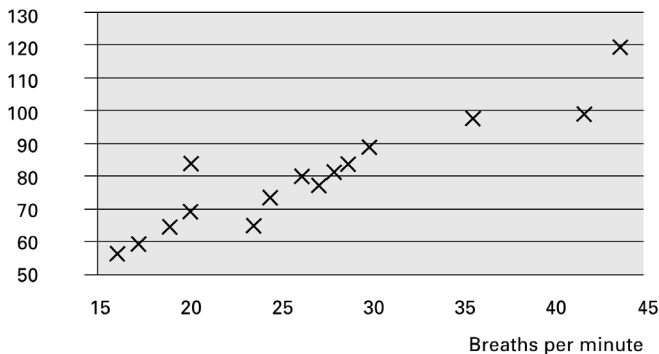
After all, just take a couple of 'facts' that are really unbelievable but which are elegantly expressed by popular science writers:

*But if all these examples of our cosmic connectedness fail to impress you, hold up your hand. You are looking at stardust made flesh. The iron in your blood, the calcium in your bones, the*

### Is there a pattern between people's pulse rate and the number of breaths they take each minute?

Some pupils investigated this. Their scatter graph is shown below.

Pulse beats per minute



1. They tried to describe the pattern in the graph. Which one do you think is the best?
  - A. Jenny had the most breaths and she also had the highest pulse rate
  - B. All the people with a high breath rate had a high pulse rate
  - C. The higher your breathing rate, the higher your pulse rate
  - D. On the whole, those people with a higher breath rate had a higher pulse rate
2. How would you justify your choice of answer in Q1?

**Figure 4** A question testing students' ability to evaluate competing interpretations of data; adapted from Goldsworthy, Watson and Wood-Robinson (2000)



oxygen that fills your lungs each time you take a breath – all were baked in the fiery ovens deep within stars and blown into space when those stars grew old and perished. Every one of us was, quite literally, made in heaven. (Chown, 1998)

The fact that we live at the bottom of a deep gravity well, on the surface of a gas-covered planet going around a nuclear fireball 90 million miles away and think this to be normal is

obviously some indication of how skewed our perspective tends to be. (Adams, 2002)

Such ‘facts’ are really ideas – ideas that are worthy of discussion and some searching questions. How do we know? Why doesn’t the nuclear fireball explode? How do stars age? How long has the Earth been in existence? Only by asking such questions can we really begin to show students the awe, the wonder and the intellectual challenge and achievement that science represents.

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#### Websites

OECD PISA tests: [www.oecd.org/pisa](http://www.oecd.org/pisa).

Next Generation Science Standards (NGSS) (USA): [www.nextgenscience.org](http://www.nextgenscience.org).

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