Having the ball in my office also led to its use earlier in the course. Just as centripetal acceleration is a tricky concept, Newton's second law itself, and the distinction between acceleration and velocity--even in one dimension--can be subtle. I let the ball roll to the right, and I hit it with the plank toward the left. The ball does not turn around and go left, but continues to the right at a slightly slower speed. Similarly, a single sideways impact can be used to demonstrate the law of compound motion. According to this venerable theorem, in two-dimensional motion, say, the component of velocity in a particular direction will be affected only by the component of a force in this same direction; it will not be affected by a force acting in a perpendicular direction. Students can hit a moving bowling ball side-on as hard as they want, but they cannot give it a final velocity in the direction of the strike, because the force being applied has no component in the original direction of motion and hence cannot change that component of velocity. These simpler observations precede, and lead up to, the demonstration of centripetal force and the polygon-circle. In all these cases, the large inertia of the bowling ball makes it an effective demonstration tool, and this property directs attention to the inertial character of Newton's first law.

Readers may not be aware that Newton, giving credit to Huygens, uses the kind of polygonal motion described here to derive the equation for the magnitude of centripetal acceleration. This argument, based on elastic collisions with the interior of a cylindrical wall, is given in modern terminology by Arons (1990).

Reference

Arons, A. B. (1990). *A guide to introductory physics teaching*. New York: Wiley.

Imaginative Thinking and the Learning of Science

Yannis Hadzigeorgiou and Nick Fotinos
University of the Aegean, Greece
hadzigeo@rhodes.aegean.gr

Abstract

This article discusses the role of imagination in science education. It provides a justification for imaginative thinking in the context of school science, as well as some strategies that can be implemented by science teachers in their classrooms.

No doubt one would feel more comfortable about discussing the role of imagination in subjects such as literature and the fine arts, rather than science education. And it would not be an exaggeration to say that, for some, imagination should be considered a blasphemy in science education. But before making such a judgement, they should seriously ask the question: Is imagination important in science? Certainly the answer to this question cannot be found in journals where scientists report their research (i.e., their methods and results). It can be found, though, in books, where scientists, in speaking "autobiographically," make an explicit or implicit reference to the role of imagination in their own work or in the work of others. Van't Hoff, for example, in a letter to his father, wrote: "The fact is the basis, the foundation. Imagination the building material, the hypothesis the ground to be tested, and reality is the building" (Van't Hoff, 1967, p. 2). Maxwell, in admiring Faraday's exceptional imaginative thought, said: "Faraday, in his mind's eye, saw lines of force, traversing all space, where the mathematicians saw centres of force attracting at a distance. Faraday saw a medium where mathematicians saw nothing but distance" (cited in McAllister, 1996, p. 54). And Planck (1933) remarked: "Imaginative vision and faith in the ultimate success are indispensable. The pure rationalist has no place here [in modern physics]" (p. 215). The history of science, of course, provides many examples that testify to the importance of imagination (Di Trocchio, 1997).

It appears that if the true image of science is to be presented to pupils, then imagination should become the ubiquitous element in the teaching-learning process. However, research based on the life stories of scientists (e.g., Einstein, Maxwell, Faraday, Watts, and Feynman) provides evidence that imaginative skills are not developed by formal schooling. Shepard (1988) has pointed out that "their development occurs before, outside of or perhaps in spite of such schooling - apparently through active but largely solitary interaction with physical objects of one's world" (p. 181). So it appears that the development of imagination in the context of formal education is a real challenge. Fortunately, though, science is a subject that can provide opportunities for free exploration, for self-directed inquiry, and for taking science outside the classroom and the school. And, even more fortunately, science is a subject that can inspire pupils by making them feel the mystery and wonder inherent in its very ideas (Hadzigeorgiou, 1999, 2005). However, more than being just a challenge, imaginative thinking is crucial in the wider context of science education, and there are a number of reasons to justify this.

A Justification for Imaginative Thinking

If we realize that imagination is not simply a capacity to form mental images, but a capacity to think in a particular way--that is, a way that involves our capacity to think of the possible rather than just the actual (Egan, 1990)--then its significant role in science education can be easily comprehended. It must have been in the aforementioned sense that Einstein considered imagination more important than knowledge. For he is reputed to have said that, while knowledge points to what there is, imagination points to what there can be. And he also urged people who want to become scientists to take 30 minutes a day and think like non-scientists (Di Trocchio, 1997)! However, as has been pointed out, there are a number of reasons that justify the importance of imaginative thinking in the context of science education.

The first reason emerges from the notion of scientific literacy. Although the debate about that notion is not exactly settled, there is an agreement that a person who is scientifically literate should be able to apply scientific knowledge for both personal and social purposes (OECD, n.d.; UNESCO, 2000). It is quite evident that the ability to apply scientific knowledge can, by itself, justify the use of pupils' imagination. Given that the application of knowledge to novel situations, to real world problems, requires both convergent and divergent thinking, and that creativity and imagination are intricately linked, the development of scientific literacy requires imaginative thinking.

The second reason is provided by the notion of narrative thinking. This term was proposed by Bruner (1986), who argued that there are two distinct but complementary modes of thinking: the paradigmatic (or logico-mathematical) and the narrative mode. The former is concerned with the formation of hypotheses, the development of arguments, and generally with rational thought. The latter, on the other hand, is concerned with verisimilitude (i.e., life-likeness or truth-likeness and the creation of meaning) and it employs similes, analogies, metaphors, and even irrational thinking (e.g., paradoxes). Because these two modes are complementary, such processes as hypothesis formation, generation of analogies, and modeling--central processes in the development of scientific knowledge--cannot rely exclusively on the paradigmatic mode. Therefore, in the context of science education, pupils should be given opportunities to use their two modes of thinking. Bruner's hypothesis is certainly very bold but it sheds light on the fact that the development of scientific knowledge cannot be explained solely in terms of paradigmatic thinking. Both the irrational character of scientific thinking (Di Trocchio, 1997; Feyerabend, 1993) and the idea that scientific theories start their life as myths (Popper, 1972) support Bruner's theory about the two modes of thought. Story-telling can be considered a good means for helping pupils understand science ideas, if these are embedded in the plot of a story (Banister & Charly, 2001; Egan, 1986; Hadzigeorgiou, 2006a), and story-telling can also help pupils convey their thoughts (Bruner, 1986). There is even evidence that scientists' personal stories (i.e., stories based on events from their everyday lives) can help scientists think about their own work (Martin & Brouwer, 1991).

It deserves to be pointed out that such notions as myth, story-telling, and narrative thinking may make some scientists and science educators raise their eyebrows. Given that rationality and reality are closely intertwined in our mental lexicon (Egan, 1997), a story or myth could be viewed as the cause of the construction of unreal or even impossible worlds. Yet it is important to consider two points here. First, narrative thinking is not unconstrainedly imaginative, since there is the paradigmatic or logico-mathematical mode of thought which complements, and therefore restrains, the former. Second, there is historical evidence that contemporary science is built upon yesterday's science, and yesterday's science upon the oldest scientific theories which, in turn, are built on pre-scientific myths (Hadzigeorgiou & Stefanich, 2001). In fact, Bruner (1986) did point out that "many scientific theories . . . start their life as myths or metaphors" (p. 12).

The third reason comes from the nature of science itself. Over the past 3 decades, work in the philosophy of science has led to a reconsideration of what could be called the scientific method and the view of science as a rational activity (Duschl, 1994; Trefil, 2003). Gell-Mann, a Nobel laureate in Physics, said: "Rationality is one of the many factors governing human behaviour, and it is by no means always the dominant factor" (cited in Jenkins, 1996, p.147). Although the effort by philosophers of science to arrive at a satisfactory definition of science has not been fruitful, there has been agreement that imagination is an important ingredient of the scientific process, complementing observation, reason, and experiment (Hadzigeorgiou, 2005). This imaginative element is stressed by Richard Feynman (1995):

> The test of all knowledge is experiment. Experiment is the sole judge of scientific "truth." But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws, in the sense that it gives us hints. But also needed is imagination to create from these hints the great generalizations – to guess at the wonderful, simple, but very strange patterns beneath them all, and then to experiment to check again whether we have made the right guess. (p. 2)

Although science is a social activity--"constitutively social," as Woolgar (1993, p. 13) put it--the personal, imaginative dimension of science needs to be recognized (in the same way that we need to recognize the elements of chance and serendipity and their role in scientific discovery). This dimension should also be sought in the area of aesthetics. Science, in fact, might have a greater commonality with art than was originally thought in a more positivist era (Tauber, 1996). The philosopher and historian Thomas Kuhn (1970) has stressed the importance of the aesthetic element in scientific revolutions: "Aesthetic considerations can be decisive. Though they often attract only a few scientists to a new theory, it is upon those few that its ultimate triumph may depend" (p. 156). The history of science provides evidence that aesthetic factors did play a major role in theory construction and in influencing scientific practice in general (Hadzigeorgiou, 2005).

In connection with these ideas, romantic understanding can be offered as another reason for justifying imaginative thinking. Although the idea of romance in the context of education appears to have made a debut with the philosopher Alfred North Whitehead (who argued that pupils need first to engage in any subject in a romantic way, before they can study its details and before they go into some depth), the notion of romantic understanding was introduced by Kieran Egan (1990) as one of the various forms of understanding that people have developed in the course of cultural history (with the other forms being somatic, mythic, philosophic, and ironic). The educational process can be conceived as a process of recapitulating these forms of understanding. Egan, although not giving a definition of romantic understanding, argued for a number of features associated with it: preoccupation with the extremes of reality, desire to transcend everyday reality, mystery, wonder, meaning, and inspiration. These features point to the fact that romantic understanding is not achieved by just mastering any particular body of knowledge. The following quotation is an example of Richard Feynman's experience of romantic understanding:

> The world looks so different after learning science. For example, trees are made of air, primarily. When they are burned, they go back to air, and in the flaming heat is released the flaming heat of the sun which was bound in to convert the air into tree. [A]nd in the ash is the small remnant of the part which did not come from air, that came from the solid earth, instead. These are beautiful things, and the content of science is wonderfully full of them. They are very inspiring, and they can be used to inspire others. (cited in Girod, Ran, & Schepige, 2003, p. 575)

Feynman's ideas, no doubt, point to how science can inspire pupils to see the world differently. But does this inspiration lead to a conceptual, and not simply a romantic, understanding? The answer is not simple, since there are differences between these two forms of understanding. But a philosophical exploration of the notion of *wonder*, and some historical evidence, can lead one to consider romantic understanding as a prerequisite for conceptual understanding (Hadzigeorgiou, 2005). Wonder, in fact, can be seen as a connecting ring between these two forms of understanding. It is interesting to note that many renowned scientists (e.g., Einstein, Schrodinger, and Dirac) did say that their work was driven and sustained by both an appreciation of beauty and a sense of awe and wonder (Tauber, 1996). Although it is beyond the scope of the present paper to explore the nature of wonder, it is important to stress that a *wonder at* attitude or state of mind, which a) signals the limitations of one's present understanding (Opdal, 2001), b) makes one aware of the mysterious nature of some phenomena or ideas (Hadzigeorgiou, 1999), and c) makes one aware that some phenomena exist at all (Hadzigeorgiou, 2006b) does excite the imagination. It is no wonder then that such a wonder at attitude is recommended for the teaching and learning of science (Goodwin, 2001; Hadzigeorgiou, 2001).

Capturing and Developing Imagination in the Science Classroom

Despite the blows that empiricist and logical positivist philosophies have suffered during the last 3 decades (Duschl, 1994), it is still difficult for both pupils and science teachers to completely abandon such philosophies (Monk & Dillon, 2000). It is very common for them to be engaged in laboratory work involving the investigation of the relationships among various variables and, at times, the confirmation--through an experiment--of an idea (e.g., a law or principle). However, if a true constructivist philosophy was to be considered the foundation for science education, then pupils should be given opportunities to propose hypotheses and to test them and to be involved in modelling, problem solving, finding diverse connections among ideas, and generally opportunities for divergent thinking. From such a perspective, imagination, evidently, becomes an important factor to be considered. In science education, of course, thought experiments, modelling, and problem solving requiring divergent thinking (e.g., calculating the density of a proton or a black hole) can be considered good ways to develop pupils' imagination. However, there are other strategies to do so. In the light of what has been discussed so far, the following strategies/activities can be considered:

- *Presenting ideas that conflict with everyday common-sense* (e.g., the uniform, straight-line motion of a spaceship at thousands of kilometres per second in the absence of an external force, the equivalence of rest and straight-line motion at constant speed, the "emptiness" of solid matter, and the increase in mass of an object with an increase of its speed).
- *Presenting ideas through mysteries, paradoxes, and the extremes of reality* (e.g., the fate of the earth after the total disappearance of the sun, the mystery of universal attraction, the twins paradox in the special theory of relativity, the transmission of electromagnetic radiation through a freezing and empty space, radiation that penetrates matter and makes it visible, the smallest and the biggest molecule, and the fastest particle).
- *Investigating topics from everyday life that call for a creative approach to inquiry* (e.g., investigating possible factors that might have an effect on the illumination of a room, the construction of a flashlight from simple materials, ways to produce electricity for the house in a case of emergency, and ways to heat water in the absence of metallic containers).
- *Investigating topics and problems that might confront humankind in the future* (e.g., investigating alternative sources of energy, the possible effects of new technologies on the production of electricity, and ways to protect the planet from various kinds of dangers).
- *Presenting the great ideas of science through real events from the history of science and through story-telling* (e.g., the idea of the nature of electricity through the Galvani-Volta conflict, the idea of energy through a historical evolution of events that led to the abandonment of caloric theory, the idea of the atom, the discovery of X-rays, and the magnetic effects of an electric current).
- *Having pupils keep daily journals in which they record, and write about, their everyday experiences--their personal stories--which can illustrate science ideas* (e.g., the reverse thrust they experienced while riding the bus, the spectacular colours of a sunset, and the breathtaking twisting somersault of a gymnast).
- *Using questions that challenge pupils to find connections among apparently unconnected facts and ideas* (e.g., how would a thief, the police, and the speed of light be connected? What would be a connection between Newton's laws, a nurse, and a soccer player? Between light, electrons, and a surgeon? Between a glass of wine, the age of the universe, and the evolution of stars?).
- *Encouraging pupils to create their own analogies to understand phenomena and ideas* (e.g., the phenomenon of resonance and the ideas of nuclear fission, nuclear fusion, and chemical bonding).
- *Approaching the teaching and learning of science through the arts* (e.g., using photography and making a collage to present the different states of water or the effects of acid rain or modern technology on everyday life, using sculpture and technologies to construct scientific models, and using drawing to represent a phenomenon such as photosynthesis or the water cycle).
- *Approaching the teaching and learning of science through poetry* (e.g., writing a poem on the elements of the periodic table, conservation of energy, pollution, or action and reaction).
- *Using science fiction* (e.g., speculating about possible applications based on established principles).

Some strategies appeal more to the imagination than others. For example, speculating on new science ideas, constructing a scientific model, or investigating a problem that humankind might face in the near or distant future appear to be more appropriate than having pupils discuss some of their own experiences in connection with their science course. However, even in this case, both the narrative element and the attempt on pupils' part to try to identify from an everyday experience the application of a scientific idea (e.g., the law of conservation of energy or momentum) help develop their imagination.

Regarding the presentation of ideas, it would be naive on anyone's part to believe, for example, that the presentation of an idea alone, in a way that it conflicts with everyday experience, is of itself sufficient to develop romantic understanding. While conflict with everyday experience, or even conflict with accepted beliefs, is crucial in capturing the pupils' imagination, it is the discussion that will follow that will lead to an understanding. The way questions are posed, the opportunities given to pupils to respond, and the discussion that ensues are all crucial for romantic understanding. Any exciting experience, even at a science museum, will remain simply an experience if it is not followed by a discussion. The historical development of ideas, as presented through the various exhibits, should be followed by a discussion of the possibilities these ideas can open for humankind. For example, pupils should discuss the various possibilities of applying the idea of radio waves. If it was the possibility of sending messages to the other side of the Atlantic, or to the other side of the world, that had captured Marconi's imagination, and the imagination of people who had become aware of the power of the idea of radio waves, then pupils should also share in, and extend, that discussion.

Perhaps the most challenging idea in regard to capturing and developing imagination is the speculation about new ideas. How can these ideas be taken seriously? If the development of imagination is not an end in itself, as has already been pointed out, what point is there in encouraging the pupils to come up with "crazy" ideas? Two arguments can be advanced here. First, the history of the evolution of ideas in physics shows that ideas that appeared not simply revolutionary, but very irrational indeed, did prove to be great ideas. Planck had advised Einstein not to try to include gravity in his theory of relativity because that was an almost impossible task. He also told Einstein that even if such an attempt was to be successful, no one would pay any attention. Poincare did believe that the transmission of radio waves on the surface of the earth to a distance more than 300 km was impossible, and Lord Rutherford initially thought that the idea of deriving energy from splitting an atom was absurd (Di Trocchio, 1997). Second, the hypothetical ideas (or principles) can be introduced in such a way that they don't contradict accepted ideas or principles that have been directly tested (Schmidt, 1980).

In Conclusion

The strategies/activities proposed in this article to develop imaginative thinking have been implemented by 12 science teachers who work in suburban (primary and secondary) schools in a European capital, and who have formed an action group committed to the important role of imagination in the learning of science. Their action research (which is part of a larger international project on imaginative education directed by Professor Kieran Egan at Simon Fraser University in Canada) has reported changes in pupils' behaviour in connection with science leaning. These changes refer mainly to discussions outside the classroom, students' comments in their journals, and the seeking of opportunities to learn more about what was presented in the classroom. Female students, in particular, who were the "outsiders" in the science class, were motivated to participate in science activities, and especially those that connected science and the arts.

Of course, one might raise a question about the opportunities pupils have for improving their ability to learn science. It sounds quite reasonable that pupils' engagement in an activity connecting science and the arts or poetry is no guarantee for learning science. But what needs to be pointed out is that the activities proposed here, and which were implemented in real classroom settings (e.g., the use of photography and the making of a collage to present the different states of water, the effects of acid rain, or the effects of modern technology on everyday life, the drawing of models to represent phenomena such as photosynthesis and the water cycle, and the writing of a poem about action and reaction), apart from engaging pupils' imagination, did result in the acquisition of scientific knowledge (e.g., elementary school students did learn that water exists in different states and did learn about the chemical substances involved in photosynthesis), as this was assessed at the end of the unit. Even a poem on Newton's third law became the means through which pupils revised their view that action and reaction are exerted on the same object. An interesting finding by a ninth-grade teacher was that, although the pupils' initial motivation to compose a poem on Newton's third law, and the actual writing of that poem, did not result in a conceptual understanding of action and reaction, poetry did play a catalytic role in involving the pupils--especially the females--with both science, as an object of study, and the events of instruction. This finding provides evidence that school science can be both a scientific and a literary experience, an idea that should be given more thought by science teachers and science educators (Midgley, 2000; Watts, 2001).

What also needs to be pointed out is that activities connecting science with poetry or the arts represent immersion activities, which do not provide pupils simply with opportunities to approach science in a nontraditional way, but with opportunities for self-exploration and self-actualization. If we conceive of education as a possibility, as Maxine Greene (2000) has contended, and if in a school classroom all possibilities exist until a pupil decides to actualize one of them (Liston, 2001), then pupils should participate in activities that give them the opportunity to explore their "unexplored selves." Is it not possible for a girl engaging in the creation of a collage on the effects of a tsunami, or the effects of environmental pollution, to develop an interest in science? Is it not possible for a boy engaging in the creation of a collage on the states of water to become curious about whether ice floats in water or generally about whether matter in its solid state sinks or floats in its liquid state? If we conceive of education in general, and science education in particular, as a possibility, then these questions should always be raised.

A final point that deserves stressing is that giving imagination its proper place in science education helps reaffirm the value of liberal education. This is crucial, given that recent reform efforts in science education have placed an emphasis on the notion of the utility of science (OECD, n.d.; UNESCO, 2000). Although utilitarian aims of science are laudable, an appreciation of science as a way of knowing, an appreciation of its beauty, and an understanding of its great ideas should also be an important goal of science education (Girod et al., 2003; Hadzigeorgiou, 2005; Millar & Osborne, 1998). While the applications of science presuppose the workings of imagination, an emphasis on presenting science mainly through applications (technological and practical), because they are relevant to pupils' lives, might result in consolidating a positivist view of science. In reaffirming, of course, the value of liberal education, and in providing pupils with opportunities to connect science and the arts, science education can pave the way toward bringing the humanities and the sciences closer (Hadzigeorgiou, 2006b; Midgley, 2000). This is another reason why new holistic approaches to the learning of science should be welcome. These approaches, apparently, should not contradict what we know about the nature of scientific inquiry.

Although there are no recipes for how a pupil learns science, research suggests that certain ideas, such as misconceptions, social context, dialogue, and conceptual change should be considered in planning a curriculum and instruction. These, no doubt, are important ideas, but they have represented a limited view of how pupils learn science (Girod et al., 2003; Hadzigeorgiou, 2005). They should certainly be considered in developing more holistic models of learning, but they should also allow for a place for imagination. Kieran Egan's (1990) idea that the neglect of imagination might be a reason for pupils' failure in science should be given serious thought.

References

Banister, F. & Charly, R. (2001). Developing science concepts through story telling. *School Science Review, 83,* 75-84.

Bruner, J. (1986). *Actual minds, possible worlds.* Cambridge, MA: Harvard University Press.

Di Trocchio, F. (1997). *Il genio incompresso.* Italy: Mondadori.

Duschl, R. (1994). Research on the history and philosophy of science. In D. Gabel (Ed.), *Handbook of research on science teaching and learning* (pp. 443-465). New York: McMillan.

Egan, K. (1986). *Teaching as story-telling*. Chicago: University of Chicago Press.

Egan, K. (1990). *Romantic understanding*. Chicago: University of Chicago Press.

Egan, K. (1997). *The educated mind: How cognitive tools shape our understanding*. Chicago: University of Chicago Press.

Feyerabend, P. (1993). *Against method*. London: Verso.

Feynman, R. (1995). *Six easy pieces*. Reading, Mass: Helix Books.

Girod, M., Ran, C., & Schepige, A. (2003). Appreciating the beauty of science ideas: Teaching for aesthetic understanding. *Science Education*, *87*, 574-587.

Goodwin, A. (2001). Wonder in science teaching and learning. *School Science Review*, *83*, 69-74.

Greene, M. (2000). Diversity and inclusion: Toward a curriculum for human beings. In F. Parkay & G. Moss (Eds.), *Curriculum planning: A contemporary approach* (pp. 293-300). Boston, MA: Allyn & Bacon.

Hadzigeorgiou, Y. (1999). On problem situations and science learning. *School Science Review, 81,* 43-49.

Hadzigeorgiou, Y. (2001). The role of wonder and "romance" in early childhood science education. *International Journal of Early Years Education, 9,* 63-70.

Hadzigeorgiou, Y. (2005). Romantic understanding and science education. *Teaching Education*, *16,* 23-32.

Hadzigeorgiou, Y. (2006a). Humanizing the teaching of physics through storytelling: The case of current electricity. *Physics Education, 41,* 42-47.

Hadzigeorgiou, Y. (2006b). *On humanistic science education*. Athens, Greece: Grigoris.

Hadzigeorgiou, Y., & Stefanich, G. (2001). Imagination in science education. *Contemporary Education, 71,* 23-29.

Jenkins, E. (1996). The "nature of science" as a curriculum component. *Journal of Curriculum Studies, 28,* 137-150.

Kuhn, T. (1970). *The structure of scientific revolutions.* Chicago: University of Chicago Press.

Liston, D. (2001). *Joy as a metaphor for convergence: A phenomenological and aesthetic investigation of social and educational change.* Cressskill, NJ: Hampton Press.

Martin, B., & Brouwer, W. (1991). The sharing of personal science and the narrative element in science education. *Science Education, 75,* 707-722.

McAllister, J. (1996). *Beauty and revolution in science.* Ithaca, New York: Cornell University Press.

Midgley, M. (2000). *Science and poetry.* London: Routledge.

Millar, R., & Osborne, J. (1998). *Beyond 2000: Science education for the future*. London: King's College.

Monk, M., & Dillon, J., (2000). The nature of scientific knowledge. In M. Monk & J. Osborne (Eds.), *Good practice in science teaching: What research has to say* (pp. 72-87). Buckingham: Open University Press.

OECD. (n.d.). *Program for international student assessment (PISA): Scientific literacy*. Retrieved May 15, 2007, from http://www.pisa.oecd.org/pages/0,2966,en_32252351_32236102_1_1_1_1_1,00.html .

Opdal, P. M. (2001). Curiosity, wonder and education seen as perspective development. *Studies in Philosophy and Education, 20,* 331-344.

Planck, M. (1933). *Where is science going?* (J. Murphy, Trans.) London: Allen & Unwin.

Popper, K. (1972). *Objective knowledge*. Oxford: Clarendon Press.

Schmidt, S. (1980). Science fiction and the science teacher. In J. Williamson (Ed.), *Teaching science fiction: Education for tomorrow* (pp. 110-120). Philadelphia, PA: Owlswick Press.

Shepard, R. (1988). The imagination of the scientists. In K. Egan & D. Nadaner (Eds.), *Imagination and Education* (pp. 153-185). New York: Teachers College Press.

Tauber, A. (1996). *The elusive synthesis. Science and aesthetics.* Boston, London: Kluwer.

Trefil, J. (2003). *The nature of science: An A-Z guide to the laws and principles governing the universe.* Boston, Mass: Houghton-Mifflin.

UNESCO. (2000). *Report of the world conference on science: Framework for action.* Paris: Science Sector, UNESCO.
Van't Hoff, J. (1967). *Imagination in science*. New York: Spriger-Verlag.
Watts, M. (2001). Science and poetry: Passion vs prescription in school science? *International Journal of Science Education*, *23*, 197-208.
Woolgar, S. (1993). *Science: The very idea*. London: Routledge.

Critical Incident

An Invitation

Readers are invited to send, to the Editor at editor@ScienceEducationReview.com , a summary of a critical incident in which you have been involved. A critical incident is an event, or situation, that marks a significant turning point, or change, for a teacher. The majority of critical incidents are not dramatic or obvious, but are rendered critical through the analysis of the teacher (see Volume 3, p. 13 for further detail). You might describe the educational context and the incident (please use pseudonyms), analyse the incident (e.g., provide reasons to explain your observations), and reflect on the impact the incident made on your views about the learning and teaching process. Upon request, authors may remain anonymous.

We have undoubtedly all done things about which we were very pleased, and perhaps done other things about which we did not feel so pleased, and we all need to remain reflexive of our practice. While teachers will view an incident through the lenses of their own professional experiences, and may therefore explain it differently, this does not detract from the potential benefits to be gained from our willingness to share our experiences and thus better inform the practice of other teachers.

Measuring Pi

By: Vladimir D. Yegorenkov, V. N. Karazin Kharkov National University, Kharkov, Ukraine
yegorenkov@univer.kharkov.ua

Once, when my younger son was in the fifth form, he came home from his school with the task from his mathematics teacher to measure pi. I proposed that he find a round object, take a thread, make several turns of the thread around the object, measure the length of the thread, and then determine the circumference of the object. After using the thread to also measure the diameter of the object, he could calculate the required ratio.

He went away to complete the task, but returned in tears. I inquired as to what had happened. He said that his result was 3.12, but that he knew from the book it had to be 3.14. I suggested he repeat the measurements with a different round object he could find in our flat. He obeyed, but came back in complete despair. Through more tears, he reported that he had got 3.16, but that it still had to be 3.14. I congratulated him with the results and said that both his numbers were right.

At first, he couldn't grasp the idea, so I informed him that the first number he got was used by ancient Egyptians, and the second one was in use in Mesopotamia. For everyday, practical purposes it is often quite sufficient to use 3.12 or 3.16; even today. The first theoretical value of 3.14 was obtained only by ancient Greeks (specifically, perhaps, by Archimedes), using mathematical reasoning rather than the measuring that had been used previously, and the kind of