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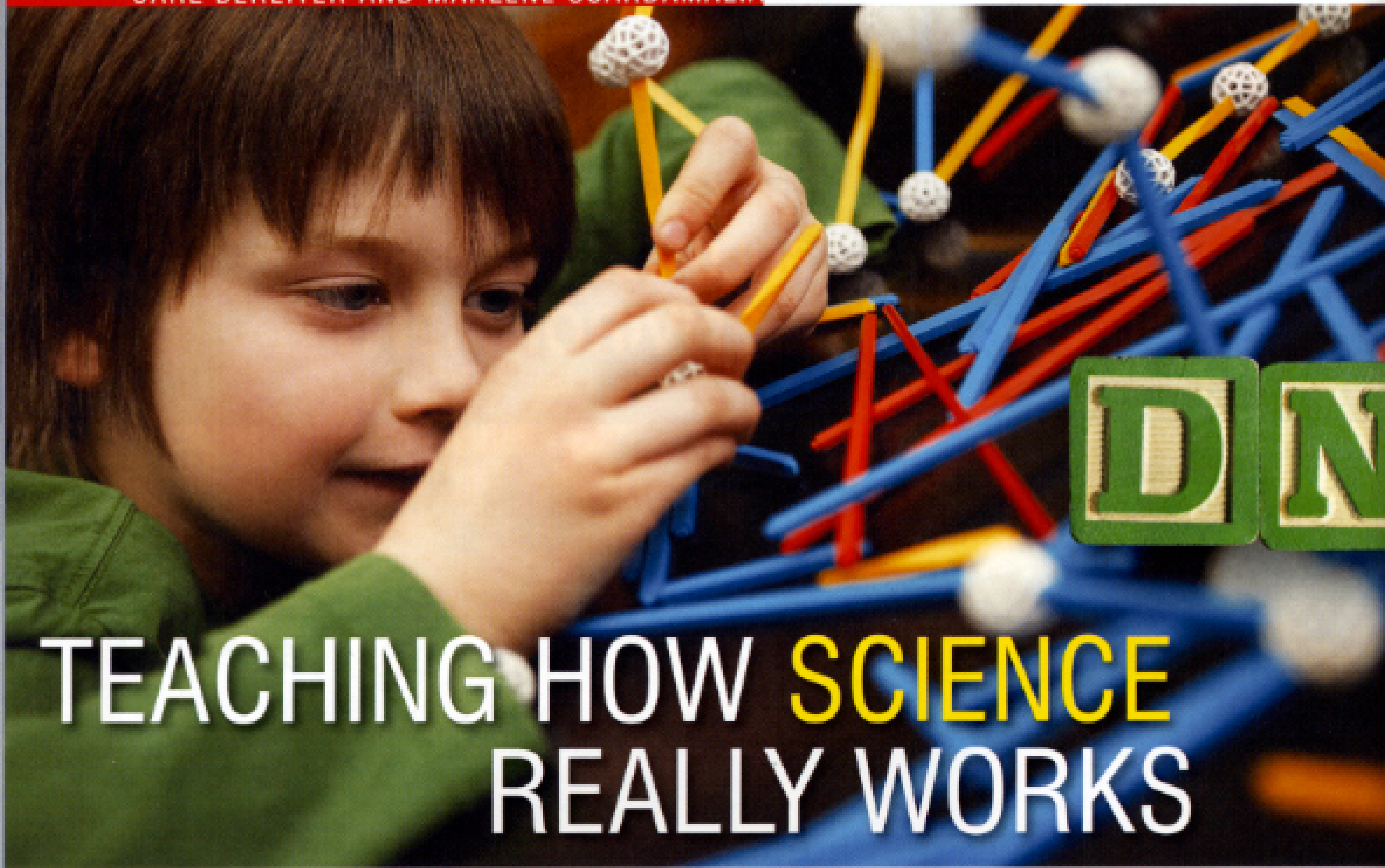

TEACHING HOW SCIENCE REALLY WORKS

TEACHING 'SCIENTIFIC METHOD' has long been a regular part of science education, and many curriculum standards call for it. But it has run into a variety of criticisms, which add up to the charge that it conveys an unrealistic and unappealing view of science. Typical 'nature of science' standards are those from the British Columbia Ministry of Education.[1] They call for students to "identify the methods and principles of science" and "apply the methods and principles of science to specific questions." Suggested student activities for achieving these standards are:

- Present students with situations that help them understand the essential steps in scientific experimentation and research (hypothesis, design of controlled experiments, prediction, repeated testing for generalization and reliability, representation and analysis of data, conclusions, further questions).
- Have students experience the process of science by providing them with simple experiments, or by allowing them to design their own.
- Have students write up laboratory reports.

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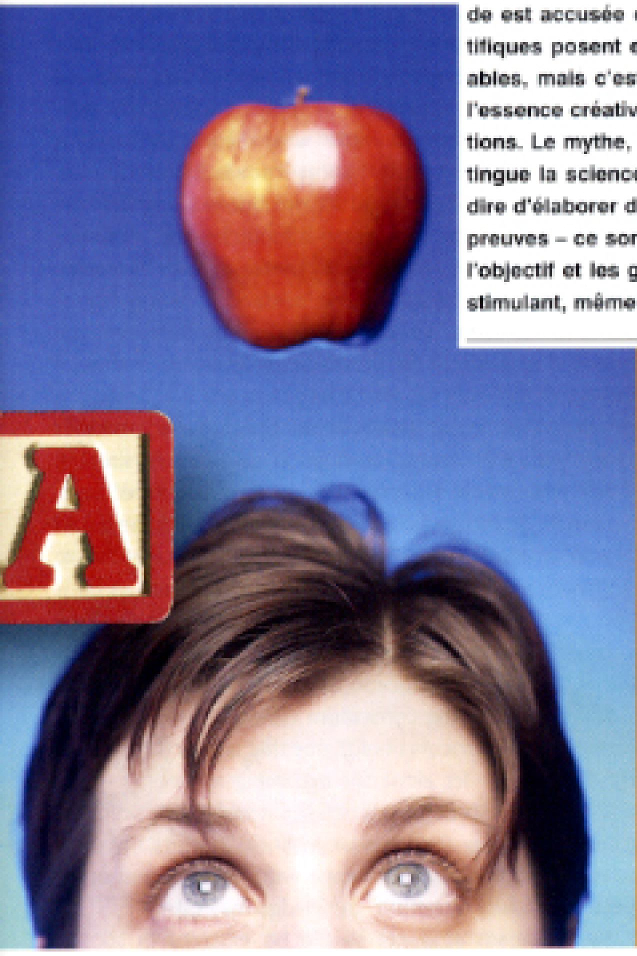
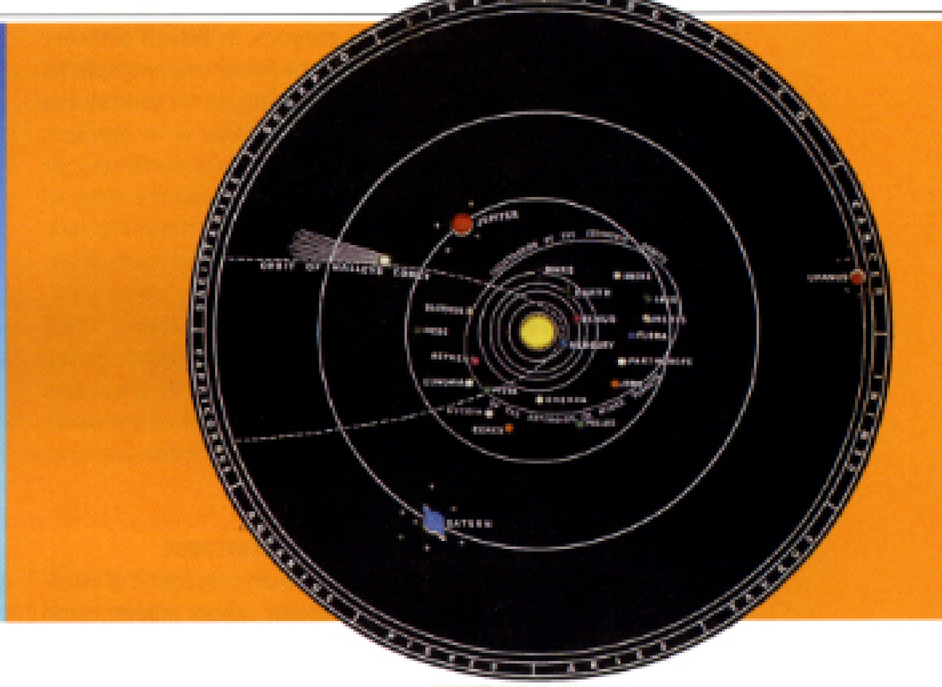
The 'scientific method' is represented here as a step-by-step procedure centered on testing hypotheses. A hypothesis is typically treated as a prediction, and the point of an experiment is to test whether the experimenter's prediction was right. In controlled experiments, one thing at a time is varied while everything else remains the same. This 'control of variables' scheme is often represented as the essence of the scientific method.

Scientists do test hypotheses using experiments that control variables, but that is like saying that architects make scale drawings. While true, it misses the creative essence. Having students guess the outcome of an experiment and then run it to see if the guess was right may be an entertaining activity for young students, conveying some factual knowledge in the process, but who would want to spend a career guessing and testing? Did any of the great advances in science, from Newton's theory of universal gravitation to Watson and Crick's theory of the structure of DNA, come about through this process? There are examples of scientific advances achieved through testing one variable at a time, perhaps the most striking being Pasteur's demonstration that airborne microbes were responsible for beer turning bad. It is an exciting detective story and one that students from middle school on up might well read in Pasteur's own words. But where did Pasteur get such an outlandish idea? Where did Newton get the idea that the same force that makes objects fall to earth holds the planets in their orbits? Conventional teaching of the scientific method, even if it is done through highly motivating hands-on experimentation, drains science of its excitement and converts it into a plodding one-thing-after-another exercise.

EN BREF La « méthode scientifique » s'inscrit depuis longtemps dans l'enseignement des sciences, mais a fait l'objet de plusieurs critiques qui, pris dans leur ensemble, font que cette méthode est accusée de communiquer une perspective irréaliste et pénible des sciences. Les scientifiques posent effectivement des hypothèses et font des expériences où l'on contrôle les variables, mais c'est comme dire que les architectes font des dessins à l'échelle. C'est vrai, mais l'essence créative est absente. Le véritable rôle de la science est d'obtenir de meilleures explications. Le mythe, le bon sens et l'imagination produisent aussi des explications, mais ce qui distingue la science, c'est l'effort soutenu d'approfondir les explications dont on dispose, c'est-à-dire d'élaborer des théories. L'observation attentive, les essais méthodiques, l'accumulation des preuves – ce sont là d'importants éléments de la pratique scientifique, mais les théories en sont l'objectif et les guides. L'élaboration de théories rend l'enseignement des sciences pertinent et stimulant, même pour les plus petits.





ALTERNATIVES

Two alternatives, which convey different ideas about the nature of science, are:

1) *Science as argumentation*. This is an expansion of traditional work on hypothesis testing. Students investigate rival hypotheses and then engage in evidence-based argument about competing factual claims. Sometimes the argument takes the form of a debate.

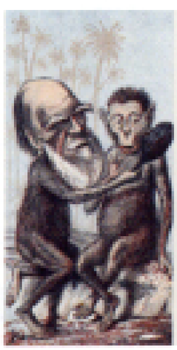
2) *Science as explanation*. The focus here is on developing theories that explain puzzling facts and working to achieve better theories.

Science involves both of these, and so both have a legitimate place in science education, but the science-as-argumentation view is by far the more widely accepted among educators. This may be because it is closer to the familiar 'scientific method' and because it is concrete, dealing with observables such as the lengths of pendulums and the exposure of plants to light. However, it has serious limitations. It deals with the testing of scientific ideas, but it has little more to offer than the traditional 'scientific method' about how new scientific ideas originate and develop. Thus it omits the creative core of science. Furthermore, the success of science-as-argumentation depends on making a clear distinction between hypothesis and evidence. This has been found to be inordinately difficult for school students – and no wonder. Science educators themselves have trouble agreeing on whether to classify particular statements as hypotheses or evidence.[2]

Why the neglect of science-as-explanation? The dread word 'abstractness' probably has much to do with it. Can young students really be expected to produce explanatory theories? The answer is decisively yes. Even in Grade 1, children have no trouble understanding that the job of a theory is to explain. Give them any problem of explanation they can understand, and a Grade 1 class will produce a flood of 'theories'. There is even evidence that infants behave in a theory-generating manner.[3]

Can students actually build coherent, factually grounded theories? While that is not so easy, most children have a good intuitive model already available to build on: the model of a well-formed story. Underlying the mathematical models mature scientists build are 'qualitative' theories, which are essentially 'how it works' narratives.[4] The questions one may ask of qualitative theories are essentially the same as those one may ask of a story plot: Does it make sense? Does it hang together? Are there any holes in it? With enough mindful work on stories, young students learn not only how to ask these critical questions but also how to repair a story that fails on these counts.[5] Once they discover they can do the same with scientific theories, they are on the road to doing real knowledge creation in science. And they love it. Who wouldn't?

Unfortunately, science-as-argumentation plays into the hand of those whose approach to knowledge is more ideological than scientific. As reported in the *New York Times*, a new strategy being adopted by anti-evolutionists in the U.S. is to no longer press for the teaching of 'creation science' or 'intelligent design', but to require the schools to



teach the 'strengths and weaknesses' of evolution. To many people this is an unassailable position and opposing it is anti-scientific. As one writer to the *Times* declared, "Any scientist who is afraid of an honest, open discussion and exploration of the weaknesses and strengths on any scientific theory is not a good scientist and should be barred from academic research."[6]

The whole 'strengths and weaknesses' gambit rests on the belief that the business of science is testing truth claims, and this is what 'scientific method' instruction and science-as-argumentation teach. In fact, the business of science is producing better theories. Seldom is a theory abandoned except when there is a better theory to take its place. The story of evolutionary biology in the century and a half following publication of *The Origin of the Species* is only in small part a story of testing and confirming or rejecting Darwin's hypotheses. It is mainly the story of improving on the original theory, incorporating new knowledge of genetics and new findings from many different fields of biology. This is an exciting story. Exposing students to it could make good educational experience in science, and it is decidedly not a story of biologists closing ranks against criticisms and alternative theories. It is a story of progress on a large scale in making sense of the world, progress to which many researchers have made contributions, large and small.

MAKING GOOD USE OF SCIENTIFIC KNOWLEDGE

Some educators argue for a utilitarian conception of scientific literacy. From their standpoint, school science is too much oriented toward making everyone a scientist, whereas what students need is more directly applicable scientific knowledge and abundant practice, through well-designed and socially relevant projects, in applying scientific knowledge. Students need to make wise dietary choices, for instance, and this requires some knowledge of calories, vitamins, types of fats, and so on, but nothing like the knowledge required to become a food chemist. As future householders and voters, they need enough scientific knowledge to understand what conserving energy has to do with reducing carbon emissions, but they can't be expected to work out the details of the total environmental impact of paper versus plastic bags.

It should be recognized, however, that not everyone goes along with this limited conception of scientific literacy. What you can do with knowledge of nutrition, ecology, bacteriology, or psychology depends greatly on the depth of your understanding. True, you can get practical guides to nutrition, energy conservation, child rearing, and so on – and a base level of scientific literacy requires that you have enough knowledge to comprehend and follow such guides. But to focus science education at that base level results in a scattered and boring curriculum (similar to the 'practical mathematics' curricula of old), one that is poor preparation for university – let alone for becoming a scientist – and one that sends students out into the world poorly prepared to make sensible decisions on political matters involving science and ill equipped to cope with the new and unexpected directions scientific knowledge may take.

By all means students should be engaged in socially worthwhile projects, and almost all such projects involve scientific knowledge of some kind (often many kinds). Currently in progress is an international project on global warming, launched in Toronto at a Summer Institute on Knowledge Building that brought together school students from Ontario and Quebec, Hong Kong, and Catalonia. The students are gathering a great deal of information about the environment and causes and consequences of global warming. They are enthusiastic about proposing solutions and about various hands-on activities such as testing water samples. But recognizing scientific issues that need to be understood is a challenge of a different order. Practical and socially beneficial projects like this one, if handled in a thoughtful way, can develop deepening understanding of the social issues or the practical problems being addressed; the problem, we are suggesting, is that such work may not advance scientific understanding. It may even be a way of avoiding difficult scientific ideas. For that reason, we do not see education focused on uses of scientific knowledge as an alternative to science-as-argument or science-as-explanation approaches. However, it can be an important complement, provided it is integrated with the pursuit of scientific understanding.

IDEA-CENTRED SCIENTIFIC LITERACY

There are many different ways of teaching science. They vary according to how much autonomy is given to the learners, how much the teacher acts as an information provider, how responsive the teaching is to students' own questions and ideas, how much use is made of hands-on work and simulations, and so on. Cutting across all these differences, however, is a difference in how much the focus is on ideas – as compared to a focus on facts or activities. Any method of science instruction can be carried out in an essentially idea-free manner or in ways that put ideas at the centre.

The real job of science is to produce better explanations – and no matter how they are formulated, explanations are structures of ideas. Everything else is secondary. Myth, common sense, and imagination also produce explanations. What sets science apart is the sustained effort to improve on the available explanations; in short, science is theory-building. Careful observation, methodical testing, marshaling of evidence – these are all important parts of scientific practice, but theories are the goal and the guides. They are what make patient observing and testing worthwhile and personally rewarding. Can young students grasp this? Yes, but this is not the place to marshal evidence for it.[7] Instead, we end with the words of a Grade 5 girl who we think has as good a sense of what science is about as many a philosopher:

> "...I think that I can tell if I've learned something when I'm able to form substantial theories that seem to fit in with the information that I've already got; so it's not necessarily that I have everything, that I have all the information, but that I'm able to piece things in that make sense and then to form theories on the questions that would all fit together..."

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Notes

1 Accessed, 10/10/2008 http://www.bced.gov.bc.ca/irp/scitech/st11in00.htm

2 M. Ranney, P. Schank, C. Hoadley and J. Neff, "'I Know One When I See One': How (Much) do Hypotheses Differ from Evidence?" in *Advances in Classification Research*, ASIS Monograph Series, vol 5, eds. R. Fidel, B. H. Kwasnik, C. Beghtol, and P. Smith (Learned Information: Medford NJ, 1996), 141-158.

3 A. Gopnik, A.N. Meltzoff and P.K. Kuhl, *The Scientist in the Crib: Minds, Brains and How Children Learn* (Harper Collins: New York, 1999).

4 D. Bobrow (ed.), *Qualitative Reasoning About Physical Systems* (MIT Press: Cambridge MA, 1984).

5 A. McKeough, J. Palmer, M. Jarvey, and S. Bird, "Developmental Approaches to Writing Instruction," in *Best Practices in Writing Instruction*, eds. S. Graham, C. MacArthur and J. Fitzgerald (Guilford Press: New York, 2007, pp. 50-73).

6 L. Beil, "Opponents of Evolution Adopting a New Strategy," *New York Times*, 4 June 2008.

7 See, for instance, M. Scardamalia, "Collective Cognitive Responsibility for the Advancement of Knowledge," in *Liberal Education in a Knowledge Society*, ed. B. Smith. (Chicago: Open Court, 2002); M. Scardamalia and C. Bereiter "Knowledge Building: Theory, Pedagogy, and Technology", in *The Cambridge Handbook of the Learning Sciences*, ed. R.K. Sawyer (Cambridge, UK: Cambridge University Press, 2006).