TOWARDS THE ACHIEVEMENT OF SCIENTIFIC CAPABILITY

TOM BRYCE

SYNOPSIS
In a recent report, the Scottish Consultative Council on the Curriculum (SCCC, 1996) has set out a number of principles for effective science education centred on the overall goal of 'scientific capability'. This article examines the five aspects of capability from theoretical and empirical perspectives, including findings from research and changes made, and to-be-made, to the school curriculum in Scotland.

INTRODUCTION
In a recent consultation document Science Education in Scottish Schools — Looking to the Future (SCCC, 1996), the Curriculum Council’s Science Review Group has set out a number of principles to underpin appropriate and effective science education for all young people in Scottish schools. Central to these principles is the overall goal of scientific capability. Like the more commonly used 'scientific literacy', the expression has a multi-dimensional ring to it (skills, knowledge and dispositions) but, perhaps better than it, conveys the 'flavour of science education for action as well as for personal enlightenment and satisfaction' (SCCC, 1996, p. 15). Scientific capability is defined in terms of five, distinct but inter-related aspects:

Scientific curiosity — willingness to explore scientific observations and issues, and to investigate; openness to alternative ideas and questions; ...

Scientific competence — ability to pose and test ideas in rigorous, investigative ways, gathering evidence from a variety of sources; ...

Scientific understanding — using scientific ideas to make sense of the world and to explain phenomena; insight into the nature of science; ...

Scientific creativity — developing new approaches when solving problems; being resourceful, linking scientific and other forms of knowledge; ...

Scientific sensitivity — appreciating the impact of science on people and the environment; developing reasoned opinion and being willing to take on board evidence; ...

While it is conceded that the relative importance of these aspects may vary according to curriculum context and (st)age, it is argued that they should all be developed in a coherent way at every (st)age. Although a strong case is made for practical outcomes under these five headings (and each is exemplified with learning outcomes), the report stops short of curricular prescription or recommendations for change to existing courses. Given the frequency of change in the last decade and its effects upon teachers, it is perhaps useful that broader, long-term questions about the purposes and characteristics of science education for all in the 5–18 year range be debated now.
The central argument, that all youngsters should become more scientifically capable as part of their education, can be considered from theoretical perspectives which have informed the literature in recent years but which are looked at in the context of curriculum development and set against research findings concerning known pupil achievements in science, teaching methodologies and assessment.

THEORETICAL PERSPECTIVES

Constructivism and knowing science

‘Learning science as an active process of constructing ideas.’ (SCCC. 1996, p. 10)

Prominent in the literature of science education is the work done on constructivism (e.g. Driver and Oldham, 1985), an approach to learning which takes seriously the view that meaning (idiosyncratic, personal meaning) is constructed by the learner on the basis of what he/she already knows — so much so that, very often, learners create distortions to (temporarily held) new ideas or inter-connect different ideas. Thus constructivists dwell upon the activity necessary by learners and the understanding required by teachers of learners’ constructs during learning. Trusted old ideas are very hard to shift and research has steadily revealed the wealth of ideas, half-baked and bizarre though some may be, which require unpacking and modification through enquiry, investigation and discussion. Even those who are now somewhat critical of constructivism — for example, Solomon (1994) and Osborne (1996) — admit to the significant body of knowledge we now have about the difficulties encountered in learning science, so much of which is counter-intuitive to pupils.

In the Scottish context, what is striking in science curriculum development is the absence of references to this powerful view of learning and its significance in the rationale for key activities and strategies which produce useful learning. Several writers have expressed their concern — for example, Harlen (1991), Brown (1992) and Bryce (1993) — that course descriptions having closer links to behaviourism and the objectives model (now embedded in the notion of (stage related targets in national curricula), with Bryce (1994) attributing the phenomenon in Scotland to the conservative consensus-driven practice of curriculum development. Because ‘theory’ has been eschewed in materials for teachers we have the ironic omission of researched ideas and findings likely to be of considerable use to professionals in the classroom.

This neglect in itself has never reflected teachers from their devotion to knowledge as the core of their work with pupils. At all stages, ‘Knowledge and Understanding’ remains high on the agenda. When Standard Grade courses were developed during the 1980s for S3 and S4, it took time and persuasion to get teachers to accept equal weighting to Knowledge and Understanding for ‘Problem Solving’ and for ‘Practical Abilities’, the latter being assessed internally by teachers. Following the implementation of Standard Grade, curriculum guidelines for the earlier stages gave similar emphasis to process, with various investigative science strands running through the curriculum (5–14 has Science as part of Environmental Studies — SOED (1993)). Yet syllabus writers for later stages (to Higher Grade and beyond) have found no solution to the shortage of time and practical assessment does not feature in Revised Higher science courses. While HMI write positively about the state of secondary science teaching (SOED, 1994a) and can point to the popularity of the Higher Grade sciences — Physics, Chemistry and Biology are the most popular Higher Grade subjects after English and Mathematics: see SEB (1994) for example — there is nothing to indicate that Scotland fares any better than the rest of the U.K. in achieving good public understanding of science. That is what the Scottish Office Report of 1994, Turning The Light On Science, unhappily reflected. Adults know little about scientific theories; they have surprising gaps in their
knowledge about the physical world and, worst of all, they have little idea about how scientists do their work (SOED, 1994b). Referring to England and Wales, the OFSTED Report of 1994 (Science and Mathematics in Schools: a Review) quotes:

...there is a large body of evidence, both in this country and in many others, that the understanding of the ideas of science which school pupils develop within and at the end of their courses is alarmingly poor and that the apparently acceptable level of examination performance hides disturbingly widespread areas of gross and damaging confusion. At the same time, there is also evidence that pupils regard the sciences, and the physical sciences in particular, to be too demanding and to lack either relevance or excitement.

It is tempting, therefore, to argue that secondary school science is still dominated by the need to cover the syllabus, this despite the fact that with Standard Grade, revisions to content gave more emphasis to scientific applications rather than principles, particularly in Physics. Constructivists’ ideas are neither fully recognised nor utilised at any of the school stages, and much of secondary science teaching is constrained through perceived lack of time and via pressures from examinations (of the wrong type). Crucially, much of the content coverage is deemed important because Biology, Chemistry and Physics courses are geared to the education of future specialists. In Scotland, as elsewhere, we tend to have science for scientists, not science for public use.

Scientific skills

‘Developing skills and understanding through investigative work.’ (SCCC, 1996, p. 11)

Equally prominent in science education literature is the debate about practical work and projects and the role of investigative practical science. It seems accepted now that the use of practical work which encourages pupils genuinely to investigate, rather than practical work which is merely illustrative of concepts or outcomes, constitutes a significant teaching strategy. Handled well (cf. Bryce et al., 1991, Hodson, 1993) with effective teacher questioning, pupils’ own ideas can be made the subject-matter of investigation and their practical skills and scientific methodology improved. An appropriate stress can be placed upon setting out testable hypotheses, operationalising variables, using controls and specific techniques, sorting out inferences in relation to evidence, recording and reporting techniques, etc. Useful strategies are ones where activities for pupils require them to use their ideas (as opposed to filling in worksheets — cf Bryce (1995)) and, in due course, to connect these ideas to scientists’ ideas. Arguably, such strategies resolve the ‘process-product’ and ‘parts-vs-whole’ problems which have featured in the last fifteen or so years (cf. Hodson, 1991, Bryce, 1991, Millar and Driver, 1987, Bryce and Robertson, 1988). The issue remains live in relationship to assessment where the amount of structure to be imposed on tasks is still contentious. Particularly at formative stages, structuring (or ‘scaffolding’) is required to ensure that assessment strategies will be valid and reliable. In order to check for genuine problem-solving ability, however, a degree of openness must apply to the problems posed and to the questions set for pupils to investigate, again in the interests of validity.

In the Scottish context, it is interesting to reflect on the revisions currently being contemplated by the Scottish Examination Board concerning the grading procedures for pupils’ Practical Abilities at Standard Grade (certification at S4). For some time teachers have worked with fairly detailed criteria and structured investigation booklets when handling assessed, open-ended, practical investigations (mostly drawing from the TAPS 3 Assessment Pack — Bryce et al, 1991). These internal assessment procedures have positively influenced teaching as well as ensuring
robust arrangements for assessment where moderation can be professionally conducted. A ‘problem’ has arisen, however, in that the national trend in grades for Practical Abilities is such that they are viewed by some as being too high, and influencing pupils’ science choices beyond Standard Grade (encouraging entry by pupils whose Knowledge and Understanding grades are deemed too low). While fuller details are given in Bryce, MacGregor and Robertson (1995) and Bryce (1996), it is disappointing to know that some people would wish to solve this ‘problem’ by dispensing with detailed criteria and structured pupil booklets in order to increase the demands on pupils; in short to move away from criterion-referenced assessment in order to ensure lower pupil numbers in content-dominated Higher Grade courses. While the SEB is still deliberating the issues, it is certainly true that it is difficult to distinguish between good practice where high pupil grades are achieved as a result of good assessment, good remediation and progress genuinely made by pupils, and practice where high pupil grades are awarded because pupils simply copy corrections into submitted work without understanding and improved skill. It is to be hoped that wisdom prevails.

The general point is that, even at those school stages (S3 and S4) where Scottish science teaching took a significant step forward in respect of Practical Abilities, there are counter-preserves in favour of traditional content emphases to secondary science courses. Inevitably, such pressures would maintain Biology, Chemistry and Physics for the sake of future specialists rather than for general educational purposes. Assuming that science education should make all youngsters more actively scientific in their thinking, in their lives, then current courses, and likely versions in the near future, fall short of the desirable. What will happen in the long run may of course depend upon the fuller implementation of 5–14, for an investigative thrust features strongly in many of the science strands. In secondary schools meantime, investigations have spilled down from Standard Grade to S1, S2. Unfortunately, local government reorganisation, combined with budget cuts, has considerably reduced the provision of in-service staff development for teachers in both sectors. While Scotland has national curriculum guidelines in the shape of 5–14 (as opposed to a mandatory ‘National Curriculum’), implementation and progress does require support!

**PUPIL ACHIEVEMENTS AND TEACHERS’ CONCERNS**

The guidelines for 5–14 have of course brought detailed science specification (for content and process) to the primary sector where, until recently, considerable freedom has been enjoyed by teachers and schools (though this is viewed as having resulted in neglect in some quarters). The content specification, in particular, has raised anxiety amongst primary teachers (who are of course generalists and not specifically qualified in science). This lack of confidence has been well-documented in research by Harlen et al. (1995) with the implications for teacher education drawn out by Holroyd and Harlen (1995). They note, amongst other things, that primary teachers, predominantly women, are much less likely to have any science or technical subject at SCE Higher Grade than they are to have Higher French. Yet SOEID has put substantial resources (certainly necessary) into preparations for primary modern languages. Whatever the Euro-imperatives, it is difficult to see why science should not similarly benefit. Anxieties amongst teachers notwithstanding, it must be said that the recent national surveys of pupils’ science achievements as part of the Assessment of Achievement Programme, AAP (carried out at P4, P7 and S2), show generally good performance across a range of assessed science at P4 and P7, with somewhat disappointing performance at S2 (at least, disappointing given the two years of specialist teaching). These surveys have been conducted at three-yearly intervals, in 1987, 1990, 1993 and 1996, the most recent
still being the subject of analysis. (For AAP Science, see, for example, Stark, Bryce, McPherson and Gray, 1994, SOED, 1994c, and SOED, 1995.) The surveys may soon reveal something of the effects of implementing the government’s 5–14 guidelines.

Among some of the detailed findings from the third survey in 1993 were the differences between practical and written assessment — the differential is that the practical favours the least able — and that gender differences surface with age, with Physics/Technology knowledge favouring boys and Biology process favouring girls (Stark, Bryce and Gray, 1994). Worryingly there are substantial overlaps between P7 and S2 performances nationally, a phenomenon not peculiar to Scotland — Western Australia’s findings are similar (EDWA, 1994). This may relate to the observations (in Scotland) that S1, S2 pupils view science as relatively unchallenging (Simpson and Ure, 1994). Together with the discontinuity of process from P7 to S2, the lack of challenge from current versions of Integrated Science in many schools may indeed account for the rather modest increase in achievements between P7 and S2. Some practitioners wonder whether that which constitutes ‘science’ is too remote from pupils’ real interests (and current state of understandings) and too out of line with what is socially acceptable for teenagers to be bothered with. With respect to England and Wales, Duggan and Gott (1996) have recently suggested that pupils’ ability to conduct investigations may be declining and they argue against ritualistic investigative practical work which loses sight of the purpose of collecting scientific evidence. North and South of the Border then, there are significant, if different, indicators that all is not well in science teaching and that we may indeed have imbalances amongst the aspects of capability which we would wish to be realised.

Concerns for science and its role in society have of course been put strongly, both negatively by influential writers like Appleyard (1992) and positively by leading exponents like Dawkins (1995). Dunbar’s judgement is that antipathy to science has deepened, not lessened, since the days of Snow’s Two Cultures, his chief concern being that too many people are actively turned off science, particularly at school (Dunbar, 1995). Like a number of other commentators, Dunbar links contemporary dissatisfaction with science to the dramatic resurgence of fundamentalist attitudes and beliefs, ‘many of which are either self-consciously anti-science or actively seek to constrain its activities in radical ways’ and to ‘the emergence of philosophies of despair among the intellectual elites within the humanities’ (p. 5). As a proponent of education through science, Dunbar contrasts the rigours of thinking scientifically with the ease of conventional social discourse. He concludes that science is essentially ‘a method for finding out about the world that combines empirical observation with causal inference’, not a body of theory which results from such method at any particular point in time (p. 55). The rigour of scientific method, despite its derivation from common sense, is nonetheless unnatural and contrasts significantly with that which does come naturally (as a result of our evolution, according to Dunbar), namely rules of thumb, jumping to conclusions, quick-fix ‘theory’ in the form of socially-derived beliefs, and religious turns of mind. Whether or not Scottish teachers would strike the same balance between content and process as would Dunbar, they would probably share his concerns for the anti-science pressures which abound in modern society.

AN APPROPRIATE PEDAGOGY?
The Harlen et al. (1995) report requires us to ask to what extent Primary teachers’ anxieties about their knowledge of science

- suggest knowledge deficiencies to be made good;
• underestimate process accomplishments to be developed (and progressed into secondary);
• deflect us from concerns about pedagogy.

Considering the first implication, that primary teachers need to know more, it is tempting to speculate whether, had the research been targeted on teachers’ understanding of English literature or history, we would come to the same conclusion. Do they know enough about the subject to be adequate teachers of pupils in their care? Wouldn’t teachers always be found to need to know more, irrespective of subject or field of knowledge? (Don’t we all?) However, this would miss the point that the second and third questions are equally if not more significant. Given the extent of pupil achievements in process skills and knowledge by the end of P7, evident from AAP surveys, shouldn’t purposeful, investigative practical work be taken forward into, and throughout, secondary school? The key point in any such change would be to convince teachers that teaching can both do this and help pupils to understand scientists’ ideas. The latter must be achieved (for all pupils) to an extent which will ensure that pupils remain positively inclined and skilled in acting scientifically. There is no mileage in cramming pupils’ heads with ideas which are ill-understood in the real world context or rapidly become redundant in pupils’ minds, especially if at the same time they become less inclined to act scientifically in their real worlds. ‘Scientists’ ideas should be chosen therefore to have maximum impact on young people’s lives, not derived from principled considerations of scientific knowledge as embedded in subjects.

Let us take a few examples.

Youngsters need to know a lot about dietary considerations, exercise and health. Our national health statistics make that embarrassingly plain. Relevant biology and chemistry offer plenty of useful material but it must be engaged with to leave pupils inquisitive as well as informed about food content and able to exercise choice (as well as to be aware of what manufacturers actually do and their motives for it). Investigative, demanding practical work should be able to address such topics.

Similarly, youngsters need to be able to make wise and informed choices concerning medicine and contraception. The side-effects of drugs and treatments which they may subject themselves to in the near future must be understood to the point where pupils can read and act upon studies of field trials, experimental vs control group comparisons and so forth. As with diet and health, useful learning is only likely if science teachers are prepared to enter territory involving important human values and sensitivities. We can’t afford to stick with traditional, value-free (so-called ‘objective’) approaches.

Environmental pollution needs to be understood with emphases upon factors which pupils themselves encounter and to which they are subjected via the media. To take a very specific example: most teenagers know about holes in the ozone layer. They learn about the damage to the Earth’s ozone layer, resulting from chemicals emitted from man-made devices and processes not so much from school science as from the media. The most curious among them will ask why these holes don’t fill by diffusion, that being the most obvious implication from studying ‘matter as particles’ so intensively. Sadly, if understandably, most teachers (and recent science graduates) can’t say why…! Yet damage to the Earth’s atmosphere must be in the science syllabus. If traditional key principles can’t get us there, and if informal media-driven learning gets us nearly there, then school science must take an appropriate investigative approach (in this case with secondary sources) to provide useful learning.
LEARNING SCIENCE AND LEARNING ABOUT SCIENCE

‘Learning about the nature of science.’ (SCCC, 1996, p. 11)
‘The importance of being able to relate to scientific ideas and issues.’ (SCCC, 1996, p. 12)

Hodson (1993) has made useful distinctions between learning science, learning to do science and learning about science. The third of these refers to how scientists work and the contexts in which scientific thinking and practice actually operates. Traditionally, school courses have under-emphasised this dimension and the SCCC (1996) argument is that pupils ought to learn something of this at every stage. Hence ‘scientific sensitivity’ is reckoned as a fifth crucial aspect to capability. A comparison can be made here with recent science curriculum development in the USA. The SCCC’s goal of ‘scientific capability’ is not dissimilar to the view of scientific literacy recommended by the American Association for the Advancement of Science (AAAS) (See Rutherford and Ahlgren, 1990). In her report of recent reforms of the science curriculum in American schools, Raizen states that such a goal is ‘ambitious ….. and far from the science taught and tested in today’s classrooms’ (Raizen, 1993, p.52). Noting the extent of the implementation by state of the AAAS’ vision and framework, Raizen reckons a new chemistry course developed by the American Chemical Society signals the current directions of change, for the text ‘rather than being organized along traditional disciplinary lines, concentrates on eight chemistry-related technological issues, for example water needs, chemistry and health, understanding food. The units stress problem-solving and decision-making, in addition to major chemical concepts and laboratory skills.’ (Raizen, 1993, p. 49)

In the Scottish context, many traditional topics and examples are likely to be useful in connection with ‘scientific sensitivity’ (including energy sources and transformation, food, chemical production, pollution treatment, etc.) but the pedagogical emphasis must move into values and purposes. The recent controversy over the disposal of the Brent Star oil platform and the actions by Greenpeace provide examples of how scientists and technologists actually operate and the difficulties encountered in dealing with hard problems. Rather than avoiding the difficulties, science teaching should face up to science in its real context. Leaving it to other subjects (Modern Studies?) risks a lack of interest in science and an ignorance of what has to be considered; squaring up to problems never turns pupils off, quite the reverse.3

In any case, the challenge is live among scientists and technologists themselves. One only has to note the address given by the 1995 Nobel Peace Prize Winner, Joseph Rotblat, the physicist involved in the development of the atom bomb who has campaigned ever since for nuclear disarmament:

I hope more scientists will be encouraged to devote a little bit of time to find ways to prevent dangers that come with the progress of science and technology. (Scotsman, 14.10.95.)

The Nobel Committee cited Professor Rotblat and the Pugwash Conferences for their work to diminish the part played by nuclear arms in international politics and in the longer run to eliminate such arms. They had worked behind the scenes to get scientists to take responsibility for their inventions, the citation said.

While there are attempts to defend traditional science and to oppose constructivism, investigative science and ‘scientists-at-work’ — for an entertaining and inspirational dismissal of one source, see Claxton (1996) — the challenge for curriculum development now is to advance teaching strategies which exemplify both ‘science-in-the-making’ and ‘science-as-scientists-do-it-in-practice’. There is good school practice about and those with responsibilities for curriculum develop-

---

1. Claxton, 1996
2. Rotblat, 1995
3. Raizen, 1993
ment should recognise the significance of informed theoretical discussion, infused with evidence from research, among those who lead the way (for example Cosgrove, 1995, and in Bryce, 1995).

IN CONCLUSION
The SCCC (1996) document is right to stress the significance of the five aspects of scientific capability, thereby pointing to parts of the curriculum where imbalance or neglect may be found. There are, at present, probably considerable variations in courses across the sectors and between formal and informal education in science. Likewise, it would be easy to underestimate the variations between teachers, ostensibly following the same courses, concerning the emphases they ensure with learners. Speculating in Scotland just now, it might be fair to suggest that in formal education the emphasis on

Scientific curiosity — wanes as pupils progress through school, largely due to inappropriate content and with diminishing focus upon problems which pupils find interesting.

Scientific competence — is unacceptably patchy throughout school, with unconvincing outcomes for general education (in a public world hell-bent on pushing anti-science).

Scientific understanding — is relatively over-emphasised with unjustified claims for the output of non-specialists from schools.

Scientific creativity — is usually sacrificed because projects/investigative activity is subordinated to content coverage.

Scientific sensitivity — is still significantly under-emphasised at great cost to education....

The arguments mounted in SCCC (1996) are therefore timely and much needs to be done, particularly at a point when a major overhaul of the upper secondary curriculum is underway (Higher Still). The signs are that changes in that quarter are unlikely to be spirited or radical in the ways so surely spelled out in the SCCC document.

NOTES
1 A version of this paper was presented to the 21st Annual Conference of the Association for Teacher Education in Europe, Glasgow, September 1996, and is reproduced here with permission.
2 When it comes to inter-subject collaboration in secondary schools, say between Modern Studies and the Sciences, HMI have not exemptified (cannot exemplify?) good practice. They only hope for it, as evidenced by management checklists in recent HMI reports in the Effective Learning and Teaching series:
   ‘Have purposeful links been established with other departments outwith science, ...?’ SOED, 1994a, checklist for PTs Science, para 6.32.
   ‘Is the department outward-looking in collaboration with cognate (Social) subjects and other departments?...’ SOED, 1992, departmental evaluation, para 7.27.

Where one might expect firm guidance in Environmental Studies, 5–14 (that being constituted by Science, the Social Subjects, Technology, Health Education and IT) only hopes are expressed, its literally final words being concerned with synthesising knowledge and skills: ‘This might be achieved by:

   collaboration between teachers from different subject departments; cooperation with primary colleagues to develop in S1/S2 studies begun in P7’ SOED, 1993, page 110.

REFERENCES


