Teaching and Learning Chemistry in the Laboratory: A Critical Look at the Research

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Introduction

For more than 100 years, teachers in British schools have been encouraged to give practical work [1] a central role in science education, though this tradition is not so well established everywhere (Gee & Clackson, 1992; Jenkins, 1979; Lock, 1988). Not surprisingly, those countries with a strong and continuing tradition of practical work generate the most rigorous and vigorous criticism of its rationale and practice. These criticisms should be regarded with extreme caution. They are not so much an attack on practical work *per se* as a criticism of the kind of practical work we choose to do, and the way in which we implement it. Seen in this light, the criticisms can be helpful to those working towards the establishment of practical work. They may assist teachers elsewhere in avoiding some of the pitfalls. This brief article focuses on why we use practical work, how we use it, and how successful it is in bringing about the kind of learning we seek. It also makes a case for action research as a means of changing classroom and laboratory practice to ensure more and better opportunities for practical work to be used for learning in science.

Exploring the Rationale and its Validity

When asked about their reasons for using practical work, most teachers claim that it assists and promotes both conceptual and procedural understanding. The former argument is sometimes expressed in terms of "what you see and do for yourself, you understand" or "practical work provides concrete reinforcement of abstract ideas". The latter cluster of cognitive arguments is directed towards understanding the nature of scientific inquiry (i.e., 'scientific method') and learning about the design and conduct of experiments. In addition, some teachers assert that practical work gives students experience of problem solving and provides opportunities for creativity. Many teachers proffer *affective* arguments. Put simply, students enjoy practical work; it motivates students and generates interest. It is also commonly argued that it promotes certain attitudes and habits of mind considered valuable in their own right and regarded by some as essential to the proper practice of science, such as paying close attention to detail, persistence and intellectual integrity. Then there are the *skills* arguments: practical work develops both laboratory skills (using equipment safely and accurately) and process skills (observing, measuring, classifying, hypothesizing, etc.). Moreover, because practical work is usually carried out in group settings, it is claimed to assist the development of social and interpersonal skills. Finally, there is a cluster of arguments that I refer to as the *class management* rationale–usually expressed in terms of providing variety of learning stimulus, thus ensuring what teachers in North America often call 'on-task behaviour'.

In Kerr's (1963) questionnaire study of the aims of practical work in secondary school science, there was substantial agreement among the teachers' rankings, though there was less agreement about the purposes of practical work for the 'sixth form' (the last two years of secondary schooling in England and Wales–equivalent to grades 11 and 12 in North America) than for earlier stages, especially among chemistry and biology teachers. It is noteworthy also that the rationale seemed to change with grade level: aims concerned with interest in science were considered the most important for 11-13 year olds; aims concerned with scientific method were seen as the most important for 13-16 year olds; aims concerned with developing observational skills and using practical work as an aid to learning were most valued for 16-18 year olds. In the intervening 40+ years, teachers' motives for using practical work have remained largely unchanged, although relative priorities

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[1] The term "practical work" is used here for any classroom, laboratory or field activity that involves the use of scientific apparatus, chemicals, biological specimens or scientific models, either by students or by teachers. This definition includes computer simulations and computer-supported laboratory work but excludes 'cut and paste' activities, text-based work, drama or dance — valuable though these activities may be in bringing about learning.

have shifted somewhat (Kreitler & Kreitler, 1974; Thompson, 1975; Beatty& Woolnough, 1982; Woolnough & Allsop, 1985; Gayford, 1988; Hegarty-Hazel, 1990;Tamir, 1991; Lazarowitz &Tamir, 1994; Wellington, 1998;Trumper, 2003).

I have recently used questionnaires to collect information about the priorities that Ontario science teachers have for practical work. The five top ranking reasons cited by secondary school teachers were:

1. To assist concept acquisition and development.
2. To motivate, by stimulating interest and enjoyment.
3. To teach laboratory skills.
4. To give insight into scientific method and to develop expertise in using it.
5. To develop certain 'scientific attitudes', such as curiosity, open-mindedness, objectivity and willingness to suspend judgement.

As in several earlier studies, there were notable differences between secondary school teachers and elementary school teachers: the latter being more inclined to favour nature of science arguments (rank order: 2, 4, 5, 1, 3) and the former subscribing to arguments focused on concept acquisition and development.

Once we know *why* science teachers use practical work, it is pertinent to inquire into whether the predicted educational goals are achieved. In other words, we should seek to answer a number of questions.

- Does practical work assist students in acquiring and developing an understanding of scientific concepts?
- Does practical work motivate students?
- Do students acquire laboratory skills from engaging in school practical work?
- Do students acquire a robust and authentic view of science and scientific activity from engaging in laboratory work?
- Are the so-called 'scientific attitudes' fostered by the practical work we provide?

A number of reviews of practical work suggest that the research evidence is not particularly encouraging (Hofstein & Lunetta, 1982, 2004; Millar, 1989; Klopfer, 1990;Tobin, 1990; Hodson, 1990, 1993a; Lazarowitz & Tamir, 1994). It seems that practical work does not always produce the motivation, learning gains, skills and attitudes we seek. The best that can be said is that *some* teachers use it successfully with *some* students to achieve *some* of their goals.

These research findings are extremely disappointing to teachers, teacher educators and curriculum developers because they are counter-intuitive. Many science educators feel that practical work *ought* to be successful; it *should* be enjoyable and *should* bring about conceptual understanding; it *should* help students develop laboratory skills and *should* give them insight into scientific inquiry. Unfortunately, research suggests that motivation levels sometimes fall as the extent of practical work increases and students don't always acquire the laboratory skills we intend. Moreover, students seem not to learn scientific knowledge any better through hands-on activity than via other methods and, in many cases, students are just as confused about scientific inquiry *after* the practical work as they were before it.

Re-interpreting and Re-orienting the Research

Faced with a conflict between theory and evidence, scientists are supposed to respect the evidence and reject the theory – at least that is what we tell students in school and university science courses. In practice, as I have argued elsewhere (Hodson, 1998a,b), scientists don't always do that. Often they seek to reinterpret the evidence, search for new or alternative evidence or shift the focus of an experiment, maybe even asking different questions. In effect, they ask: "Why is the evidence wrong?" and "Why does it not support what we firmly believe is a good theory?"

I believe there are a number of reasons why the research evidence does not support our belief that practical work brings about the range of learning goals listed earlier in this paper.

- Reason 1: 'Practical work' is too gross a term, too large a category.
- Reason 2 : Practical work is often both poorly designed (in the sense that the goals are ill-defined) and poorly executed (in the sense that current research findings relating to effective learning are ignored).
- Reason 3: Teachers do not always do what they say they will do. In other words, there is a significant mismatch between rhetoric and practice.
- Reason 4 : Students do not always do what the teacher intends or expects. They may misread or misunderstand instructions, fail to distinguish between what is significant and what is unimportant,

lack the necessary skills to collect reliable data, or just get bored and fail to finish. These difficulties are compounded by shoddy laboratory equipment and by constraints on laboratory time. Differences among students in terms of existing knowledge, understanding of the nature of science and scientific evidence, attitudes, motivation levels and laboratory bench skills complicate research findings even further.

- Reason 5 : Practical work frequently 'doesn't work', in the sense that it gives unexpected, inconsistent or inconclusive results, and sometimes no results at all.
- Reason 6: Assessment methods on which conclusions about the efficacy of practical work are based often focus on the less significant aspects of the work, while ignoring valuable learning in other areas. Clearly, assessment should concentrate on what we value and aim to provide rapid and meaningful feedback to both students and teachers (Hodson, 1992, 1993b,c; Yung, 2001).

With respect to reason 1, I consider that much of the uncertainty, ambiguity and confusion of research findings concerning practical work is a consequence of sloppy research that uses the term 'practical work' as a single category of activity, as though all practical work is the same. As a classroom observer, it is often difficult to ascertain the specific intention underpinning a particular lesson because teachers use worksheet-driven practical work simply as a matter of course, with the same approach being used to meet a variety of needs–often with conspicuous lack of success. Researchers usually draw a distinction between teacher demonstration and hands-on work by students, but not always between hands-on exercises (often using worksheets) and holistic investigations (under varying degrees of student control), nor between those activities with a specific and clearly defined and articulated purpose ('to ascertain the concentration of substance x required to bring about…' or 'to investigate the effect of varying y and z on the value of…'; etc.) and those which are simply an opportunity to experience a phenomenon, view an event or 'to see what happens when …'. In short, practical work is both *over-used* and *under-used*. It is over-used in the sense that teachers engage in practical work as a matter of course, expecting it to assist the attainment of *all* learning goals. It is under-used in the sense that its real potential is only rarely fully exploited. Instead, much that we provide is ill-conceived, muddled and lacking in real educational value.

Turning to reason 2, we need to be clear about the purpose of a particular lesson and to choose an activity that suits it. My own research in Ontario indicates that not all teachers appreciate that a learning experience intended to assist concept acquisition or development will almost certainly need to be very different in design from one that aims to help students develop an understanding of particular aspects of scientific method, generate interest in science or give some insight into the history, development and social impact of an idea, process or artifact. Much would be gained by thinking more carefully about different styles of practical work in relation to the crucial distinctions among: (i) *learning science* - acquiring and developing conceptual and theoretical knowledge; (ii) *learning about science* - developing an understanding of the nature and methods of science, and an awareness of the complex interactions among science, technology, society and environment; and (iii) *doing science* – engaging in and developing expertise in scientific inquiry and problem-solving. They are different, though clearly inter-related, purposes; they need to be approached by different kinds of activities. Some recent work by Millar *et al.* (1999, 2001) offers enormous promise for ascertaining how successful particular *kinds* of practical work are in bringing about particular learning goals. In their ingenious and very detailed *Profile of Laboratory Activities*, the authors match eleven intended learning outcomes (5 × content goals; 6 × process goals) against three major design characteristics: the cognitive structure of the task (3 major categories, divided into 3 subcategories and 29 sub-subcategories); the level and nature of student involvement (2 subcategories and 9 sub-subcategories); and the practical context of the activity (6 subcategories and 24 sub-subcategories). Despite a level of detail that at first glance may appear daunting, the *Profile* has enormous potential as a research tool and as an aide memoire and planning tool for teachers and curriculum developers. Science teacher educators, both pre-service and in-service, will find it invaluable in raising awareness of the range and scope of practical activities in science education.

How is Practical Work Deployed?

All science education researchers quickly realize that there is often a mismatch between what teachers say they do and what they actually do. There is also the potential for mismatch between what teachers *think* they do (or think they *have done*) and what a researcher or observer sees them doing. In addition, students may have significantly different views from teachers about what is taking place or has occurred. In other words, classroom events are subject to more than one interpretation, depending on the knowledge, beliefs and values that the various participants and observers use to rationalize their experiences and observations. Also, as mentioned previously, students do not always carry out the teacher's instructions as intended. This array of problems, cited above as my third and fourth reasons for research findings about the efficacy of practical work frequently being confused and confusing, has prompted the reorientation of my own research on practical work towards more extensive classroom observation and discussion with teachers and students during and subsequent to practical work. This work focuses not only on the *kind* of practical work teachers use in particular circumstances and *how* they deploy it, but also on how they rationalize their actions during and after the lesson, especially in those situations in which a change of plan eventuated. What knowledge do teachers use and how do they deploy this knowledge in the changing circumstances of particular lessons? What knowledge sources do teachers access in their day-to-day work in the classroom as curriculum decision makers? How do teachers make their selections from among the available knowledge resources? Why do they do *this* rather than *that*? How are their decisions influenced by their previous experiences and by the characteristics of the students? Additionally, how can teachers be assisted to broaden the scope and depth of their knowledge resources so that they have a greater range of alternatives at their disposal? How can they be assisted to consider a wider range of alternatives and, thereby, make more appropriate and more effective decisions? What is at issue here is the transition from novice to expert, though 'expert' may have too much of a technical-rationalist flavour to it and the term 'connoisseur' may be better suited to my purposes.

Barnett and Hodson (2001) attempt to make sense of these issues and questions at a theoretical level through the notion of *pedagogical context knowledge.* Its components include: science knowledge (conceptual and theoretical knowledge in science); nature of science knowledge (history, philosophy and sociology of science); general educational knowledge and general pedagogical knowledge; pedagogical content knowledge (Geddis, 1993; Shulman, 1986, 1987); teacher lore or the 'folk wisdom' of teaching (Schubert, 1992); specific knowledge of individual schools and students, including their sociocultural backgrounds; and craft knowledge of hands-on science. In recent years, I have been engaged in observational and interview work with science teachers, largely in the context of practical work and the critical incidents it generates, in order to test the robustness of this notion of pedagogical context knowledge. I am particularly interested in the contrasts between experienced or connoisseur teachers and newcomers, and between elementary school teachers and secondary school teachers. I am also interested in how newcomers are enculturated into the practices of school science education and from whom they learn the various 'tricks of the trade'. Through observation, discussion with teachers before, during and after practical work sessions, talking with students, and looking at teaching records and assessment data, a picture can be assembled of each teacher's views about science, learning, motivation, science education priorities, and so on, about their skills in deploying practical work effectively, for its various purposes, and about how they deal with problems, handle the unexpected, re-orient their priorities as the lesson proceeds and generally 'think on their feet'. This research seems to confirm what we already know, or *should* know: that different teachers have different areas of strength and weakness, differences that are intimately related to the ways in which they plan practical activities, interact with students as the lesson progresses, deal with critical episodes in the lesson and decide what kind of write-up they require of students. These differences are intimately connected to their (sometimes changing) priorities among *learning science*, *learning about science* and *doing science*, and to the sometimes competing demands of (i) good class managem ent (and what some teachers call 'class discipline'), (ii) getting through an over-crowded syllabus and (iii) meeting the demands of external examinations. Additional constraints on teachers' freedom in making decisions about practical work include excessively large classes (up to 40 students in some Hong Kong classrooms I have observed), having no laboratory technician and only poor facilities and equipment, lacking confidence and feeling vulnerable and 'under pressure'–a common experience for many teachers in elementary school who lack a substantial education in science. One interesting finding is that even teachers who hold clear and coherent views about science, and declare their intention to promote a *doing science* orientation, do not always plan laboratory-based activities consistently in relation to those values, concentrating instead on the immediate concerns of classroom management and on concept acquisition and development (see also Hodson, 1993c).

Priorities among *learning science*, *learning about science* and *doing science* show up most clearly in two aspects of the lesson. First, in the question of who is responsible for deciding the following: the question under investigation, the method to be used (design of the inquiry), the data collection methods (equipment to be used), the style of data presentation (tables, graphs, pie charts, etc.), interpretation of data and formulation of conclusions (especially choice of underlying theoretical perspectives), the nature of the write-up (personal, formal, etc.). Second, in the way teachers deal with the critical moments of a lesson: when insightful questions are asked, when things 'go wrong', when unexpected data are collected, and so on. This ability to 'think on one's feet' is a crucial aspect of science teacher expertise and is the feature of practical work I have been investigating via questionnaires, classroom observation and discussion/interview.

I have used questionnaires to ascertain what teachers do (or claim to do) when practical work 'goes wrong', in the sense that it produces unexpected results, confusing results or no results at all, and what they do to avoid similar occurrences in the future. For example, what do teachers do or say in order to "talk their way out of the problem" (see Nott & Smith, 1995). What knowledge, experience and pedagogical strategies do teachers use to 'explain away' the results students obtain in favour of the results they should have obtained? Just as important, what expertise (conceptual knowledge, procedural knowledge and craft knowledge) do teachers use in order to obtain 'better' (more reliable or more valid) results next time? I prefer to call this kind of procedural modification *tweaking*–a less pejorative term than Nott and Smith's (1995) term "rigging". In my view, tweaking can be considered the province of connoisseur teachers and, as such, should be regarded as a key aspect of pre-service and in-service teacher education. A different kind of procedure to produce good data, which Nott and Smith (1995) call *conjuring*, involves sleight of hand or manipulation of materials and equipment, such as putting a little dilute hydrochloric acid in the gas jars in which non-metals are to be burned in oxygen or exchanging the rusted nails for untarnished ones (and vice versa) in student experiments left overnight, in order to ensure that rusting occurs (or not) under the 'correct conditions'. In common with Nott and Wellington (1996), I am interested in how often and in what circumstances teachers engage in conjuring. If they conjure, were they introduced to it by other teachers or by lab technicians? Was it part of their pre-service teacher education program? I am interested also in why non-conjurors do not deploy it. Did they not think of it? Do they regard it as unethical?

I have found some interesting cross-cultural differences. Teachers in the UK, New Zealand and Australia often use conjuring as a matter of course, seeing it as no different from using computer simulations to obtain the 'correct results' that lead to the theoretical interpretations and conclusions required by the curriculum. These teachers say that conjuring is justified because it avoids the difficulty of explaining away 'wrong results'–being especially useful with lower ability students, who might be unable to understand the explanation–and because it focuses attention very clearly on the knowledge required for external examinations. Not surprisingly, conjuring is sometimes justified because it eliminates those disheartening situations in which students 'get it wrong'–situations that can quickly lead to loss of self-esteem. It also enables progress to be quicker and may, therefore, have a crucial role in enabling teachers to complete an overcrowded syllabus. Like the student teachers in Nott and Wellington's (1997, 1999) studies, my informants in UK, New Zealand and Australia see conjuring as a "necessary evil" and as a "pragmatic compromise between telling the truth and confusing or discouraging students". In other words, conjuring is in students' best interests, regardless of its dubious ethics. In contrast, many of the Canadian teachers with whom I have worked regard conjuring as a moral-ethical issue and are strongly opposed to it in all circumstances. Interestingly, these same teachers see no ethical dilemma in using computer simulations. Most of the teachers in my Hong Kong SAR contingent were initially opposed to conjuring, though many changed their minds when given opportunities to explore its potential in the specific context of *learning science* (i.e., acquiring particular conceptual knowledge).

It is noteworthy that while priority among Canadian elementary teachers is mainly on *learning about science* and *doing science*, the priority among secondary teachers is firmly in the *learning science* category–largely a consequence of the overloaded secondary school curriculum and the increasing significance of standardized tests of attainment that focus on knowledge acquisition. As both these forces become increasingly significant in elementary school, as they threaten to do, it will be interesting to watch for a shift in priorities among teachers and to examine changes in the kind of practical work they provide. As always, assessment drives the curriculum! It is not surprising, therefore, that conjuring is a much more common practice among secondary teachers than elementary teachers.

It is interesting to speculate on where tertiary level teachers stand on the issue of conjuring. Given their responsibility for inculcating normative scientific behaviour, they may be strongly opposed to it. However, I have no direct research evidence to confirm or refute this supposition. What is interesting is that those who most need to conjure, because they lack the ability to "talk their way out of it" in a scientifically convincing way, are also the least well-equipped to conjure–because they don't know enough science or have insufficient craft expertise.

Students' Views

Opinion among the Canadian students with whom I have discussed the *role* of practical work seems to be equally divided between those who see it as *doing science* and those who see it as *learning science*. I have also found numerous examples of students not giving any thought whatsoever to the purpose of the activity or how that purpose has informed the selection of procedures to be adopted. For many students, the primary goal is to complete the tasks, get the right results and complete the report. Berry *et al.*, (1999, 2001) and Wilkinson and Ward (1997) confirm that students in Australian schools are similarly motivated and will even ignore discrepant results in order to finish quickly.

Because they give so little thought to what they are doing, and why they are doing it, students are generally poor at identifying limitations in procedures and recognizing malfunctioning apparatus. In an exercise at grade 10 level in an Ontario school, I gave one group of students a defective thermometer (with a break in the mercury thread). They still managed to obtain the correct data in the experiment. Interestingly, when shown the faulty thermometer away from the laboratory setting, they saw the mercury break immediately. On several other occasions, groups of students were given more apparatus than they needed in order to complete a designated task. After some brief discussion, several of the groups began to incorporate the surplus apparatus into their set-up or introduced additional procedures to make use of it. Sometimes, when they saw what was going on, members of other groups said: "We want what they have got" and "How come they have extra stuff?" What these observations suggest is that many students have become socialized into seeing laboratory activities as a set of procedures for getting the 'right answer'. They don't critique and they don't think; they *just do it*, as the Nike advertizing slogan has it. In consequence, they don't so much *learn science*, *learn about science* and *do science* as learn to be good students and learn the game of 'doing labs'. I have also observed that when faced with *major* difficulties, students often give up, ask other students to supply the missing data, or seek help from the teacher. Only very rarely do they work through the procedure for themselves, adjusting it in the light of what they know and what they have observed so far. However, there is some encouraging evidence that students *can* develop both the confidence and the ability to 'think things through' for themselves when provided with opportunities to design and pursue their own inquiries in a properly supportive environment. It is intriguing that students in Hong Kong, who are so often subjected to highly formal teaching and learning methods, seem more adept at this than Canadian students–though it should be noted that I have only worked with students in Hong Kong's top banded schools.

It follows that we should ensure that students are clear, at the beginning of a practical activity, about its specific purpose and whether its overall thrust is one of *learning science*, *learning about science* or *doing science*. I am also firmly of the view that we should discuss with students all tweaking activities and how they contribute to more successful practical work, whatever its purpose. I am less convinced about the desirability of telling students about conjuring activities, though I do not rule it out–with older students, and retrospectively.

It is gratifying that students in the Ontario classrooms I have studied, at least in grades 11 and 12, are perfectly able to deal with practical work 'going wrong' without losing confidence–many commenting that "It can happen to anyone". However, when asked if they think any less of their teacher when experiments and teacher demonstrations do not work as intended, they are no longer of one voice. Some students show admirable understanding of the teacher's difficulties:

> "Teachers are human like all of us, so we expect it to go wrong now and again."
> "It's just one of those things."
> "It's to be expected."
> "Science isn't as straightforward as it looks."

Other, less forgiving, students lay the blame squarely on the teacher's lack of expertise:

> "I don't think the teacher is doing his job. I think he should do it at home first; that's my impression.
> "If the teacher messes up… I mean if the teacher screws it up, he's supposed to be teaching it, right? Either he's a lousy teacher or it has something to do with the lousy merchandise he's using."

There is strong evidence that student responses are related to their views about the purpose of practical work: those who regard it as an opportunity for *doing science* probably expect things to 'go wrong' from time to time; those who share the view of the grade 11 student who told me that "School science labs are where science is recreated to promote better understanding", may be less understanding and less forgiving.

Conclusions

What I have been arguing is that many of the difficulties associated with practical work arise from the unthinking way in which curriculum developers and teachers utilize it, and the unthinking way in which students carry it out. If we are to construct a science curriculum that is both *philosophically more valid* (portrays a faithful picture of actual scientific practice) and *pedagogically more effective* (ensures that all students learn successfully), we need to use a much wider range of teaching and learning methods than has been usual in secondary school science, and match learning experiences more carefully and more specifically to the goals of particular lessons, being cognizant throughout of the crucial distinctions among *learning science*, *learning about science* and *doing science*. Practical work functions better when teachers are clear about its purpose, design activities to match that purpose, and communicate this information to students. As argued earlier, there is a key role for teachers and for well-written support materials in directing student attention to the significant elements of the activity and ensuring a 'minds-on' approach. It is also clear that the effectiveness of laboratory work and field work can be enormously enhanced by creating more opportunities for students to talk with other students and with the teacher about the purpose of the activity, its design characteristics, and the theoretical significance of the findings (Hodson, 1998c).

Hofstein and Lunetta (2004) argue that "teachers spend large portions of laboratory time in managerial functions, not in soliciting and probing ideas or in teaching that challenges students' ideas" (p. 44), while Marx *et al.* (1998) report that science teachers often have difficulty helping students to ask thoughtful questions, design investigations and draw conclusions from data. My own research shows that many teachers devote considerable attention to the *science* involved in the activity but scant attention to the *learning* issues and how they relate to its design. If this is the case, there is an urgent need for professional development opportunities focused on more purposeful and more effective deployment of practical work. Newcomers to the profession often report that pre-service teacher education in the area of practical work is neither extensive nor particularly useful. As Tamir (1989) comments, policy makers often assume that engaging in laboratory activities as an undergraduate equips future teachers with the knowledge and skills they will need to organize and manage practical work in school science. This is categorically not the case: designing good laboratory activities is a complex and difficult endeavour; teaching well in the laboratory requires considerable expertise, knowledge and skills. Thus, there is an urgent need for professional development. My own view is that action research is the most effective and the most professionally enriching way of effecting significant change in the classroom. It is an approach I have used for many aspects of science education, including gender issues, establishing an STSE perspective, developing multicultural and antiracist education, overcoming 'science anxiety' among elementary school teachers, introducing metacognitive strategies, and so on. Not surprisingly, therefore, I have used it in the context of developing more effective practical work.

The principle underlying action research is fairly simple: groups of teachers subject some aspect of their practice to critical scrutiny, develop some alternative perspective and approach, trial it, evaluate it in action, subject the 'new practice' to critical scrutiny, and begin again. In other words, they engage in successive cycles of critical reflection, planning, action and further reflection. It is this interplay of criticism and practice that enables teachers to gain insight and expertise, and to develop the curriculum in ways that they (collectively) perceive as more worthwhile, desirable and effective. In a collaborative study with Larry Bencze (Bencze & Hodson, 1999; Hodson & Bencze, 1998), a group of teachers addressed the issue of what counts as authentic science in the context of secondary school science education (i.e., shifting to a *doing science* emphasis). The teachers began by studying some ideas in the history, philosophy and sociology of science. Next they devised a new approach which they believed was viable, taking into account the constraints of the classroom, tried out their ideas and evaluated the effectiveness of what they had devised. In the light of this evaluative feedback, the group was able to address a number of constraints on science curriculum change, including the demands imposed by a mandated curriculum, insufficient time, inadequate facilities and high cost (many of the open-ended activities the group wished to implement were time consuming and expensive of materials and equipment). They also had to deal with resistance from other teachers (change that conflicts with common practice is often stoutly resisted, even by those not directly concerned) and the restrictions imposed by the assessment regime ("How do we assess this?" was a common question from teachers, especially Heads of Science). In other words, the action research approach is firmly rooted in the everyday life of the classroom and, therefore, has a much greater chance of success–not least through its capacity to generate feelings of ownership and empowerment. What quickly becomes clear is that when teachers engage in inquiry into their own teaching, they seem better equipped to help students engage in inquiry-based learning. This particular study, together with several related action research studies, are published in Hodson *et al.*, (2002).

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