Effecting Principled Improvement in STEM Education: Research-based pedagogical development for student engagement and learning in early secondary-school physical science and mathematics

Kenneth Ruthven, Christine Howe, Neil Mercer, Keith Taber, Stefanie Luthman, Riikka Hofmann and Fran Riga

University of Cambridge

The *epiSTEMe* project forms part of a national initiative researching means of improving young people's participation and achievement in mathematics and science education. The project involves collaboration between researchers and teachers to devise an intervention, suitable for widespread dissemination, to enhance student engagement and learning in early secondary-school physical science and mathematics. Drawing on the now extensive research base examining US experience of *Standards*-based reform, and parallel research and development efforts in the UK and elsewhere, the project aims to translate promising pedagogical principles into an operational apparatus for viable professional practice.

effective teaching methods; mathematics and science education; redesign research; researcher-practitioner collaboration; secondary schools; student engagement and learning

Introduction

This paper presents the rationale for the *Effecting Principled Improvement in STEM Education* [*epiSTEMe*] project as part of a current research initiative (Economic and Social Research Council [ESRC] 2006) intended to inform ongoing efforts to secure significant enhancements in young people's school achievement in science and mathematics, and significant increases in their participation in further study and employment in these areas. The *epiSTEMe* project is undertaking research-based pedagogical development aimed at improving student engagement and learning in early secondary-school physical science and mathematics, in a form suited to implementation at scale within the English educational system.

From an initial proposal made in January 2007, the project has been funded to run from August 2008 to January 2012. It is organised in three main phases, associated with consecutive school years. During Phase 1 (2008/09) we worked with science and mathematics teachers from partner schools to devise a classroom intervention, including trialling and refining components of teaching modules and research instruments. During Phase 2 (2009/10) we are studying classroom implementation of the full modules by the participating teachers, and the functioning of the research instruments, with a view to finalising both for Phase 3 (2010/11). We are currently recruiting further schools and teachers to be involved in implementation and research during this forthcoming phase. The focus of this research is on evaluating the effectiveness of the intervention – in terms of changes in student attitude and growth in student knowledge – and analysing its operation – in terms of core classroom processes identified by the integrative theory informing its design.

From key questions to a research goal

The call for the ESRC Initiative posed, in general terms, four key questions to the research community (ESRC 2006, 2):

> RQ1) What are the key factors that shape patterns of participation, engagement and achievement in science and/or mathematics education by children and young people and what does this tell us about the kinds of intervention that are likely to have greatest impact on participation, engagement and achievement?
>
> RQ2) What can we learn from the effectiveness of past and current interventions, initiatives and practice to inform the design and development of more effective future interventions, initiatives and practice?
>
> RQ3) How can research-informed approaches help to understand and address key challenges in enhancing participation, engagement and achievement in science / mathematics [in particular to address differences linked to socio-economic status, gender, and ethnicity]?
>
> RQ4) What specific new interventions, or changes in policy or practice, offer the greatest potential to improve engagement and learning in science / mathematics and how could their potential effectiveness and feasibility be assessed more fully?

In response to these questions, the *epiSTEMe* proposal was developed by an interdisciplinary team made up of colleagues with specialisms in psychology of education (Howe), language in education (Mercer), mathematics education (Ruthven), and science education (Taber). Had it proved possible within the timespan and personnel available, it would also have been desirable to call at this formative stage on expertise in sociology of education and in educational improvement. The goal was to draw on a spectrum of relevant research fields to fashion a cogent proposal that integrated their insights to exemplify a more strongly interdisciplinary and cross-subject approach to research in the emerging area known as STEM [Science, Technology, Engineering and Mathematics] education. The proposal aimed to achieve this through deriving promising principles from prior research and development, and applying these to design a classroom intervention (and associated teacher training) suitable for wide-scale implementation. The research envisaged not only evaluating this intervention but creating and testing integrative theory to explain its mechanisms.

A key decision was to focus on the early secondary years. It is during this phase of schooling that students meet specialist study of mathematics and science for the first time, and it is known to be particularly important in forming young people's orientation towards further study of these subjects (Osborne, Simon and Collins 2003). In addition, from the point of view of implementation, this phase of schooling is the earliest one in which reform becomes possible through working with relatively small cohorts of specialist secondary teachers rather than a very large cohort of generalist primary teachers. Moreover, because this phase is relatively distant from the pressures of high-stakes external assessment, it offers better prospects of teachers, students and parents being willing to explore new approaches, providing a foundation for change to subsequently work its way upwards through secondary education.

From research base to a pedagogical proposal

Examining the research base at the start of 2007, the amount of relevant British work was limited. While we were aware of a range of interesting development activity, much of this proved to be un- or under-researched. However, the Evidence for Policy and Practice Initiative [EPPI] (Bennett et al. 2005) had conducted some useful systematic reviews. These were highly focused: several of the science teaching reviews, for example, examined small group discussion in relation to particular types of learning process or outcome (now summarised in Bennett et al. 2010), while a mathematics teaching review had examined strategies to raise pupils' motivational effort at mid-secondary level (Kyriacou and Goulding 2006). These reviews, too, had had to face the lack of relevant British studies. For example, while Kyriacou and Goulding identified 25 such studies related to their topic, they judged "relevance of the focus of the study for the review question" to be "low" in 19 cases and "high" in none; likewise, the "appropriateness of design and analysis for the review question" was judged to be "low" in 19 cases and "high" in only one.

Nevertheless, in scoping *epiSTEMe*, there was relevant British research and development that deserved attention. In particular, previous work had sought to develop well-theorised pedagogical approaches running across science and mathematics teaching. One longstanding programme had developed a pedagogical model for lessons aimed at "cognitive acceleration" (Shayer and Adey 2002). Reflecting on this programme, Shayer and Adhami (2007) reported that the original intention was to use periodic lessons within science or mathematics as a context for more fundamental cognitive acceleration that would then support conventional instruction. In the light of experience, however, they suggested that the intervention had been most successful where it had served not as a complement to conventional instruction but as a constructive critique of it, leading teachers to incorporate elements of the new pedagogical model into their normal teaching. Another longstanding programme had developed a discourse-based approach that teachers had used successfully to promote "thinking together" in science (Mercer et al. 2004) and mathematics (Mercer and Sams 2006). Findings indicated that students could be enabled to use talk more effectively as a tool for reasoning; and that talk-based group activities could help develop individuals' mathematical and scientific reasoning, understanding and problem-solving.

In early 2007, too, recent developmental research had given rise to widely circulated professional materials aimed at improving the quality of teaching and learning in secondary mathematics. Drawing on earlier precedents, Watson and De Geest (2005) had worked with teachers to develop pedagogical strategies to raise the quality of learning of lower-attaining students at early-secondary level. Respecting the professional autonomy and pedagogical preferences of participating teachers, this project emphasised personal innovation rather than collective development of common methods. But, while the project found important differences in teaching strategies, it identified a common commitment to offer students an inclusive and empowering engagement with mathematical thinking. While systematic evaluation proved difficult, available findings were encouraging. Building on previous research into diagnostic teaching, Swan (2006) had carried out design research around the development of resources to support teachers in improving the quality of learning in retake examination courses in further education. The underlying pedagogical model emphasised the use of collaborative discussion to elicit and reshape students' existing knowledge and understanding. A systematic evaluation indicated that learning gains were greatest when the resources were used in such more student-centred ways.

However, by far the largest corpus of directly relevant research had arisen from long-term, programmatic efforts in the United States to formulate *Principles and Standards for School Mathematics* (NCTM 1989; NCTM 2000) and *National Science Education Standards* (NAS 1995). These principles had been operationalised in "*Standards*-based" programs intended to foster coherent understanding of fundamental ideas and their relationships, by helping students to explore and make sense of the material that they are learning, and showing that knowledge is a tool for solving problems (Trafton et al. 2001). Thus, in response to the ESRC RQ2*,* the *epiSTEMe* proposal sought to take account of pedagogical principles common to well researched programs that had been judged "exemplary" (by a Mathematics and Science Expert Panel of the US Department of Education) on the basis of evidence of effectiveness in multiple sites (on a large scale, in rural and urban locations, across US states) for multiple subpopulations (by age, gender, ethnicity, ability).

Nevertheless, while the US exemplary curricula were research-informed in being extensively evaluated (e.g. Reys et al. 2003; Riordan and Noyce 2001), and in appealing to views of learning consonant with theoretical syntheses then available (e.g. Bransford, Brown and Cocking 2000; Kilpatrick, Martin and Schifter 2003), their design had been weakly framed in theoretical terms and their evaluation correspondingly restricted (Confrey 2006; Harwell et al. 2007). Our proposal sought to adapt principles proven in the US, framing them in theoretical terms which dovetail with complementary research undertaken in the UK and elsewhere, and using the resulting principled framework to design an intervention suitable for implementation in England in the first instance (but potentially also other parts of the UK).

The *epiSTEMe* proposal was also designed to throw light on the other three research questions. In relation to RQ4, it sought to illustrate a type of innovation with potential to improve engagement and learning – and hence longer-term participation – and to do this in a way that would exemplify a powerful approach to assessing effectiveness and feasibility of innovations. In relation to RQ3, its background pedagogical principles had already been found to be effective in the US in boosting participation and achievement, and the proposed theory-guided refinements aimed to enhance this further. Finally, in relation to RQ1, the proposed research was based on the hypothesis that those features that make *Standards*-based curricula exemplary are key shapers of engagement and achievement.

From pedagogical principles to operational apparatus

Many of the exemplary US curricula share a pedagogical model organised around carefully-crafted problem situations, posed so as to appeal to students' wider life-experience, to inculcate ideas of acting as mathematicians/scientists, and to develop key disciplinary ideas. Material is developed in lessons that cycle through whole-class introduction by teachers, collaborative problem solving in small groups, whole-class synthesis by teachers, and individual practice and consolidation by students. The *epiSTEMe* project aims to build on this pedagogical model, encouraged by its compatibility with teaching methods and curricular activities that have already been successfully deployed in the earlier British research surveyed above.

In addition to respecting principles that have emerged from research into *Standards*-based curricula, we have sought to refine such principles in the light of insights from broader theorisation and investigation. Central concerns have been how to build on students' interests and experiences (Freudenthal 1983) while also addressing the affective and epistemic complexities of knowledge growth (Pintrich, Marx and Boyle 1993). Activities have been designed to support reflexive, intentional learning (Bereiter and Scardamalia 1989) recognising that this is a process of identity formation as much as cognitive organisation (Sfard and Prusak 2005). Concern with collaborative activity, social interaction and classroom dialogue has been informed by earlier work that has analysed the crucial contribution of these processes in bringing students to engage with differing perspectives so as to support effective learning (e.g. Howe et al. 2007; Mercer et al. 2004; Mortimer and Scott 2003).

These ideas have guided the design of an introductory module intended to help establish the dialogic processes and supporting ground rules fundamental to the intervention. To operationalise key principles further in terms of classroom teaching and learning, they have been translated into design criteria for topic modules:

> To cover those aspects of the topic prescribed for the early secondary (Key Stage 3) curriculum (specifically Year 7 in mathematics).
>
> To fill out these prescriptions to build strong conceptual foundations for the topic.
>
> To show the human interest and social relevance (including, in mathematics, scientific application) of the topic.
>
> To make connections with widely shared student experiences relevant to the topic.
>
> To take account of students' informal knowledge and thinking related to the topic.
>
> To provide means of deconstructing common misconceptions related to the topic.
>
> To provide for the exploration, codification and consolidation of key ideas.
>
> To exploit whole-class, group and pair discussion activity on a dialogic model to support these processes.
>
> To build in individual checks on student understanding with developmental feedback.

In the light of the underlying ideas, these criteria have guided the design of illustrative modules on particular curricular topics: proportionality (linked to fractions in mathematics and forces in science); probability (in mathematics); electricity (in science). While all the modules seek to make connections between mathematics and science, this is a particular feature of the modules on proportionality. Proportional reasoning is known to be challenging, yet *Standards*-based approaches have proved to be effective (Ben-Chaim et al. 1998). Indeed, the principle of 'simplification by integration' (Iran-Nejad, McKeachie and Berliner 1990) suggests that an approach which co-ordinates and integrates mathematical and scientific treatments will provide students with additional capital to appreciate and benefit from the significance of engaging problems. Furthermore, quantitative representation may facilitate conceptual growth in science (Schwartz, Martin and Pfaffman 2005).

This operational apparatus of design criteria and illustrative modules is intended to support pedagogical change by scaffolding the professional development of teachers (Ruthven 2005). First, such apparatus has a *symbolic* function, giving visible substance to change. Second, it has a *pragmatic* function, providing concrete frameworks for classroom activity. Third, this apparatus and its associated discourse have an *epistemic* function, crystallising central ideas –as expressed in the design criteria. Finally, inasmuch as such apparatus and its associated discourse explicitly incorporate a degree of flexibility, or are seen as doing so, they can serve a *heuristic* function, assisting thoughtful interpretation and local reformulation of practice. For, while pedagogical apparatus plays an important part in supporting, structuring and spreading good practice, successful reform depends on deeper understanding of, and flexible thinking about, the practice and its apparatus.

From principled apparatus to viable practice

Indeed, although *Standards*-based programs have been shown to have the potential to support effective pedagogical development (Remillard 2005), particularly if classroom materials have been designed to be "educative" for teachers (Davis and Krajcik 2005), they also run a risk of being assimilated to established pedagogies, often by teachers replacing or revising materials to make lessons more skills-oriented and less open-ended, demonstrated to reduce their effectiveness (Schoen et al. 2003). Fundamentally, successful implementation depends on teachers believing that they and their students have the capacity to engage productively with this type of approach (Arbaugh et al. 2006). In particular, teachers and students cannot simply be expected to be able to participate effectively in the necessary forms of interaction: the development of their communicative skills and metacognitive awareness needs to become an explicit goal if it is to be successful, as also does the creation of a classroom environment in which there is clear, shared understanding of the value and functions of dialogue for learning (Alexander 2004).

This represents a considerable challenge for any project which aims to design for implementation at scale. It requires what might best be described as “redesign research”: namely, an approach to design research that recognises that the successful planning of change has to take account of the existing state of affairs as well as an intended one. In particular, such an approach emphasises the need to establish a viable trajectory from the existing state to the intended one; indeed, it makes such a trajectory a condition for the plausibility of any intended state. Furthermore, the viability of such a trajectory depends on identifying what wider institutional change and professional learning are required. Such a trajectory, then, lies in a zone of proximal professional development, conditioned at its leading edge by ideals for intended practice, but at its trailing edge by the current state of practice and thinking (and notably of teachers’ craft knowledge).

Moreover, as emphasised in the New Zealand approach to “best evidence synthesis” (Anthony and Walshaw 1997), reform at scale depends on successful negotiation, across the constituencies forming a professional community, of a new collective understanding of effective practice. Thus, the *epiSTEMe* project is deliberately designed to foster sustained interaction between university-based researchers and school-based practitioners. Huberman (1993, 34) has pointed to the benefits of such interaction “in which researchers defend their findings and some practitioners dismiss them, transform them, or use them selectively and strategically in their own settings”. Reframing ideas in order to collaborate successfully with teachers appears to trigger a decentring process amongst researchers. In particular, it creates a need to address the counter-examples, qualifications and challenges which arise as ideas are tested out by teachers. In doing so, researchers are obliged to go outside the study at hand, to marshal a broader range of scholarly thinking and research experience, and to bring them to bear on these claimed anomalies. In the *epiSTEMe* project to date, the design and trialling of the topic modules has been an important site for such dialogue. Equally, Bromme and Tillema (1995, 262) emphasise the part that scholarly knowledge can play in supporting development of practitioner knowledge when they argue that “from a cognitive point of view, professional knowledge is developed as a product of professional action, and it establishes itself through work and performance in the profession, not merely through accumulation of theoretical knowledge, but through the integration, tuning and restructuring of theoretical knowledge to the demands of practical situations and constraints”. In the *epiSTEMe* project to date, the translation into practice of ideas about dialogic teaching has provided an important focus for such development.

Finally, during the first year of the *epiSTEMe* project, major shifts took place in national policy: notably, revision of the national curriculum to reduce prescriptiveness; abolition of compulsory national testing at lower-secondary level; abandonment of centrally-driven school improvement. These shifts reflected growing recognition that the gains in student achievement achievable through the improvement approaches and pedagogical models associated with the National Strategies had been largely exhausted, as well as increasing awareness that such gains had been at the expense of a marked decline in student attitudes towards mathematics and science, so emphasising the importance of teaching approaches that are effective in terms of affective as well as cognitive outcomes (see Ruthven submitted). These changes have created more favourable conditions for the dissemination and uptake of innovative pedagogical approaches aimed at improving student engagement and learning, such as the one being developed and researched in the *epiSTEMe* project.

References

Alexander, R. 2004. *Towards Dialogic Teaching*. York: Dialogos.

Anthony, G., and M. Walshaw. 2007. *Effective Pedagogy in Mathematics/Pàngarau: Best Evidence Synthesis Iteration.* Wellington NZ: Ministry of Education.

Arbaugh, F., J. Lannin, D. Jones, and M. Park-Rogers. 2006. Examining instructional practices in *Core-Plus* lessons: implications for professional development. *Journal of Mathematics Teacher Education* 9(6): 517-550.

Ben-Chaim, D., J. Fey, W. Fitzgerald, C. Benedetto, and J. Miller. 1998. Proportional reasoning among 7th grade students with different curricular experiences. *Educational Studies in Mathematics* 36(3): 247–273.

Bennett, J., F. Lubben, S. Hogarth, and B. Campbell. 2005. Systematic reviews of research in science education: rigour or rigidity? *International Journal of Science Education* 27(4): 387-406.

Bennett, J., S. Hogarth, F. Lubben, B. Campbell, and A. Robinson. 2010. Talking science: The research evidence on the use of small group discussions in science teaching. *International Journal of Science Education* 32(1): 69-95.

Bereiter, C., and M. Scardamalia. 1989. Intentional learning as a goal of instruction. In *Knowing, Learning, and Instruction*, ed. L. Resnick, 361-392. Hillsdale NJ: Erlbaum.

Bransford, J., A. Brown, and R. Cocking, eds. 2000. *How People Learn: Brain, Mind, Experience, and School.* Washington DC: National Academies Press.

Bromme, R., and H. Tillema. 1995. Fusing experience and theory: The structure of professional knowledge. *Learning and Instruction* 5: 261-267.

Confrey, J. 2006. Comparing and contrasting the National Research Council report on evaluating curricular effectiveness with the What Works Clearinghouse approach. *Educational Evaluation and Policy Analysis* 28(3): 195–213.

Davis, E. A., and J. S. Krajcik. 2005. Designing educative curriculum materials to promote teacher learning. *Educational Researcher* 34(3): 3–14.

Economic and Social Research Council [ESRC]. 2006. *Targeted Research Initiative on Science and Mathematics Education*. Swindon: ESRC.

Freudenthal, H. 1983. *Didactical Phenomenology of Mathematical Structures*. Dordrecht: Kluwer.

Harwell, M., T. Post, Y. Maeda, J. Davis, A. Cutler, E. Andersen, and J. Kahan. 2007. *Standards*-based mathematics curricula and secondary students' performance on standardized achievement tests. *Journal for Research in Mathematics Education* 38(1): 71-101.

Howe, C., A. Tolmie, A. Thurston, K. Topping, D. Christie, K. Livingston, E. Jessiman, and C. Donaldson. 2007. Group work in elementary science: organizational principles for classroom teaching. *Learning and Instruction* 17(5): 549-563.

Huberman, M. 1993. Changing minds: The dissemination of research and its effects on practice and theory. In *Research on Teacher Thinking,* ed. C. Day, J. Calderhead and P. Denicolo, 34-52. London: Falmer.

Iran-Nejad, A., W. McKeachie, and D. Berliner. 1990. The multisource nature of learning. *Review of Educational Research* 60(4): 509-515.

Kilpatrick, J, G. Martin, and D. Schifter, eds. 2003. *A Research Companion to Principles and Standards for School Mathematics*. Reston VA: NCTM.

Kyriacou, C., and M. Goulding. (2006). *A systematic review of strategies to raise pupils' motivational effort in Key Stage 4 Mathematics*. London: EPPI-Centre.

Mercer, N., L. Dawes, R. Wegerif, and C. Sams. 2004. Reasoning as a scientist: ways of helping children to use language to learn science. *British Educational Research Journal* 30(3): 367-385.

Mercer, N., and C. Sams. 2006. Teaching children how to use language to solve maths problems. *Language & Education* 20(6): 507-527.

Mortimer, E. F. and P. Scott. 2003. *Meaning Making in Secondary Science Classrooms*. Maidenhead: Open University Press.

National Academy of Sciences 1995. *National Science Education Standards*. Washington DC: National Academies Press.

National Council of Teachers of Mathematics 1989. *Standards for School Mathematics*. Reston VA: NCTM.

——— 2000. *Principles and Standards for School Math*. Reston VA: NCTM.

Osborne, J. F., S. Simon, and S. Collins. 2003. Attitudes towards science: A review of the literature and its implications. *International Journal of Science Education*, 25(9): 1049–1079.

Pintrich, P., R. Marx, and R. Boyle. 1993. Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research* 63(2): 167-199.

Remillard, J. 2005. Examining key concepts in research on teachers' use of mathematics curricula. *Review of Educational Research* 75(2): 211-246.

Reys, R., B. Reys, R. Lapan, G. Holliday, and D. Wasman. 2003. Assessing the impact of *Standards*-based middle grades mathematics curriculum materials on student achievement. *Journal for Research in Mathematics Education* 34(1): 74-95.

Riordan, J., and P. Noyce. The impact of two *Standards*-based mathematics curricula on student achievement in Massachusetts. *Journal for Research in Mathematics Education* 32(4): 368-398.

Ruthven, K. 2005. Improving the development and warranting of good practice in teaching. *Cambridge Journal of Education* 35(3): 407-426.

——— submitted. Using international study series and meta-analytic research syntheses to scope pedagogical development aimed at improving student attitude and achievement in school mathematics and science. *International Journal of Science and Mathematics Education*.

Schoen, H., K. Cebulla, K. Finn, K., and C. Fi. 2003. Teacher variables that relate to student achievement when using a Standards-based curriculum. *Journal for Research in Mathematics Education* 34(3): 228 – 259.

Schwartz, D. L., T. Martin, and J. Pfaffman. 2005. How mathematics propels the development of physical knowledge. *Journal of Cognition and Development*, 6(1): 65-86.

Sfard, A., and A. Prusak. 2005. Telling identities: In search of an analytic tool for investigating learning as a culturally shaped activity. *Educational Researcher* 34 (4): 14-22.

Shayer, M., and P. Adey, eds. 2002. *Learning intelligence: Cognitive acceleration across the curriculum from 5 to 15 years*. Buckingham: Open University Press.

Shayer, M., and M. Adhami. 2007. Fostering cognitive development through the context of mathematics: Results of the CAME project. *Educational Studies in Mathematics* 64(3): 265-291.

Swan, M. 2006. Learning GCSE mathematics through discussion: what are the effects on students? *Journal of Further and Higher Education* 30(3): 229-241.

Trafton, P., B. Reys, and D. Wasman. 2001. Standards-based mathematics curriculum materials: A phrase in search of a definition. *Phi Delta Kappan* 83(3): 259-264.

Watson, A., and E. De Geest. 2005. Principled teaching for deep progress: Improving mathematical learning beyond methods and materials. *Educational Studies in Mathematics* 58(2): 209-24.