The *epiSTEMe* project: Devising a pedagogical intervention to support development of a dialogic teaching approach to early-secondary-school mathematics and science

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Abstract

The *epiSTEMe* project has devised a pedagogical intervention designed to help mathematics and science teachers at early-secondary-school level develop a *dialogic* teaching approach. This type of approach makes use of exploratory dialogue – in small groups and whole class – to elicit and examine differing points of view on problem situations which have been carefully crafted to support pupils in making key conceptual advances in a topic. Design of the intervention has been informed by the now extensive bodies of research on the effective teaching of mathematics and science, and on conceptual development and learning in these subject areas. With a view to the intervention being suitable for implementation at scale across the English educational system, the design process has involved close collaboration with classroom teachers in a range of schools, and has taken account of the recent evolution and current situation of mathematics and science teaching in this context. Trialling of the intervention by teachers collaborating in the development process has found that average achievement in classes which undertook any of the 6 to 10-hour *epiSTEMe* topic modules rose by around 0.8 of a standard deviation between unannounced tests taken immediately before starting a module and then a month after completing the module.

The systemic context

Perhaps the major influence on school mathematics and science teaching in England over the last decade has been the pedagogical model promoted by the *National Strategies* for school improvement. This model emphasises the importance of "lessons hav[ing] clear objectives and [being] suitably paced" and of "a high proportion of each lesson [being] spent on direct teaching" (DfEE, 2001, pp. 6 & 26). Alongside this emphasis on explicitness, directness and pace, however, is recognition of the importance of interaction with pupils and consequent adaptation, shown in recommendations such as:

> Through whole-class discussion teachers question pupils effectively, give them time to think, expect them to demonstrate and explain their reasoning, and explore reasons for any wrong answers.
>
> Teachers use pupils' contributions to assess their strengths and difficulties, to set group and individual targets for pupils to achieve and to plan the next stage of work.
>
> (DfEE, 2001, p. 6)

Indications that these recommendations regarding interaction and adaptation have not been as widely followed as those regarding explicitness, directness and pace come from overviews of the impact of the *National Strategies* on mathematics and science teaching provided by the English schools inspectorate. In science, serious concerns have been expressed about the quality of pupil engagement and learning:

> [M]uch teaching paid scant regard to what and how pupils were learning. In many lessons, teachers simply passed on information without any expectation of pupils' direct

> engagement in the process. The objective appeared to be to get notes into books, and then leave the learning to the pupils.
>
> (OfStEd, 2008a, p. 17)

In mathematics too, there have been similar observations:

> A remarkable degree of consistency existed in much of what pupils said about their experience of learning mathematics… Many pupils, especially in secondary schools, described a lack of variety, which they found dull. Typically, their lessons concentrated on the acquisition of skills, solution of routine exercises and preparation for tests and examinations.
>
> (OfStEd, 2008b, p. 53)

Though not conceding the part that official policies might have played in creating such a state of affairs (Prestage & Perks, 2008), the report points to the impact of an overly reductive teaching approach on pupil understanding as well as attitude:

> The fundamental issue for teachers is how better to develop pupils' mathematical understanding. Too often, pupils are expected to remember methods, rules and facts without grasping the underpinning concepts, making connections with earlier learning and other topics, and making sense of the mathematics so that they can use it independently.
>
> (OfStEd, 2008b, p. 5)

Publication of these inspection surveys presaged major shifts in government education policy that were introduced or announced over the following year. Key policy changes included a revision of the national curriculum to reduce its degree of prescriptiveness; the abolition of compulsory national testing at the end of lower-secondary education; and the abandonment of a centrally-driven school improvement strategy.

The concerns expressed in these inspection surveys are supported to some degree by trends in the profile of English lower-secondary pupils in international comparative studies over a period spanning the introduction and institutionalisation of the reforms of which the *National Strategies* formed the core (Ruthven, 2011a). On attainment, while the reforms appear to have raised attainment in tests focusing on curricular content and skills (TIMSS) in mathematics, there has not been a similar effect in science; and, in both subjects, attainment on tests emphasising subject literacy and application (PISA) has been unchanged. On attitude, while these reforms appear to have modestly improved attitude towards each subject on a measure of whether pupils appreciate the value of studying the subject, both subjects have seen dramatic declines on a measure of whether pupils like the subject and enjoy learning it.

This, then, was the context in which, in late 2008, the *epiSTEMe* project embarked on developmental research aimed at devising a pedagogical intervention designed to help mathematics and science teachers at early-secondary-school level enhance pupil engagement and learning.

The research base

Since the international explosion in government interest in improving science and mathematics education which took place during the 1960s, there has been half a century of research on the effective teaching of these subjects at school level. These efforts have often drawn, in turn, on an even longer tradition of research on conceptual development and learning in these areas. Over recent years, there have been significant attempts to synthesise the resulting knowledge in ways that provide guidance for policy and practice.

These efforts have been particularly extensive in the United States where the National Academy of Sciences has commissioned a sequence of expert panels to prepare authoritative reports on the advances in research-based knowledge about thinking, learning and teaching (Bransford, Brown & Cocking, 2000; Duschl, Schweingruber & Shouse, 2007; Kilpatrick, Swafford & Findell, 2001) which have also influenced the sustained development of *National Science Education Standards* (NAS, 1995) and *Principles and Standards for School Mathematics* (NCTM, 1989, 2000). Equally, the National Science Foundation has supported the development of innovative '*Standards*-based curricula' which seek to help pupils explore and make sense of the material that they are learning, show that knowledge is a tool for solving problems, and foster coherent understanding of fundamental ideas and their relationships (Trafton et al., 2001). In particular, several of these programs have been judged "exemplary" on the basis of evidence of effectiveness in multiple sites for multiple subpopulations (Department of Education, 1999).

Recent meta-analyses of the accumulated corpus of research on effective teaching have examined teaching components in mathematics and science (Seidel & Shavelson, 2007), teaching strategies in science (Schroeder et al., 2007), and teaching programs in mathematics (Slavin & Lake, 2008; Slavin, Lake & Groff, 2009). While these meta-analyses display important differences in their governing frameworks and specific criteria, and their results reveal significant gaps in the corpus of research available, they do also provide clear indications of the relative effectiveness of some types of teaching component (Ruthven 2011b). These highly effective types of teaching component are as follows:

- *Domain-specific enquiry* (in which classroom activity is organised around types of problem solving which focus on disciplinary concepts and gives serious attention to the pupil thinking that this stimulates) is highly effective for attainment in both subjects and attitude in science (but is underinvestigated for attitude in mathematics).
- *Co-operative group-work* is relatively effective for attainment in both subjects and attitude in science (but not mathematics), as long as pupils have been properly prepared and activity is well structured.
- *Enhanced context* (in which teaching makes strong links to pupil experiences and interests) is particularly effective for science attainment (but is underinvestigated in relation to attitude, and for mathematics).
- *Direct instruction* or *active teaching* is relatively effective for more traditional measures of attainment in mathematics (and is underinvestigated in relation to attitude, and for science).

It was this last teaching component of *direct instruction* or *active teaching* that provided the core model for "the whole-class 'interactive' model of maths teaching" (Reynolds & Muijs, 1999, p. 274) promoted by the *National Strategies* (DfEE, 1998). Support for this model came particularly from an American tradition of "process-product" research on effective mathematics teaching (Good, Grouws, & Ebmeier, 1983), claimed to accord both with a much smaller body of British research, and with the judgement of English school inspectors in their contemporary reports on the school system (Reynolds & Muijs, 1999). However, recognising that this model had been validated primarily in relation to the teaching of basic skills, the relevance of more recent research which indicated a need for other teaching components was acknowledged:

> [A] number of additional classroom processes may be needed to enhance higher order thinking: a focus on meaning and understanding in mathematics, direct teaching of higher level cognitive strategies and problem-solving, and co-operative small group work.
>
> (Reynolds & Muijs, 1999, p. 281)

Although not using identical terminology, the findings of the more recent meta-analyses discussed above confirm the importance of these teaching components, in the form of *domain-specific enquiry* and *co-operative group-work*. In the UK too, more highly focused systematic reviews of research have highlighted not just the importance of such teaching components but the conditions required for their successful implementation. These are particularly illuminating in respect of the conduct of *co-operative group-work* and the kinds of classroom dialogue necessary to support *domain-specific enquiry.*

In relation to the conduct of *co-operative group-work*, Bennett et al. (2010) examined research studies of the use of small group discussions in secondary-school science teaching. The available evidence "suggest[ed] that":

> groups function more purposefully, and understanding improves most, when specifically constituted such that differing views are represented, when some form of training is provided for students on effective group work, and when help in structuring discussions is provided
>
> (Bennett et al., 2010, p. 69);

and "demonstrate[d] very clearly" that:

> for small group discussions to be effective, teachers and students need to be given explicit teaching in the skills associated with the development of arguments and the characteristics associated with effective group discussions
>
> (Bennett et al., 2010, p. 69).

Likewise, relevant to the kinds of classroom dialogue necessary to support *domain-specific enquiry*, Kyriacou and Issit (2008) examined what characterises effective teacher-initiated teacher-pupil dialogue to promote conceptual understanding in mathematics at upper-primary and lower-secondary school levels. They identified "eight possible characteristics of effective teacher-initiated teacher-pupil dialogue":

> going beyond [traditional initiation-response-feedback discourse]; focusing attention on mathematics rather than performativity; working collaboratively with pupils; transformative listening; scaffolding; enhancing pupils' self-knowledge of how to make use of teacher-pupil dialogue as a learning experience; encouraging high quality pupil dialogue; and inclusive teaching
>
> (Kyriacou & Issit, 2008, p. 13).

Noting, however, that there was still limited evidence in support of many of these characteristics, they highlighted how:

> The strongest evidence of the promotion of pupils' conceptual understanding of mathematics came from studies that focused on the enhancement of pupils' self-knowledge concerning how to make use of teacher-pupil dialogue as a learning experience
>
> (Kyriacou & Issit, 2008, p. 14).

The **epiSTEMe** *pedagogical model*

The name *epiSTEMe* functions both as an acronym and an allusion. As an acronym it stands for ***E****ffecting* ***P****rincipled* ***I****mprovement in* ***STEM*** ***E****ducation*. The focus of the project is on principled improvement of teaching and learning in the two core curricular subjects – mathematics and science – that provide a foundation of knowledge and skill for all areas of STEM. As an allusion, the name refers to a term of Greek origin which has broadened its meaning over time from indicating knowledge itself to also referring to some way of knowing or coming to know. An overarching aim of the *epiSTEMe* project has been to produce a corresponding broadening in the concerns of classroom teaching, to focus not just on the target knowledge which is the objective of instruction but on fostering a dialogic process through which pupils can come to know it more deeply.

With this intent, and following the pattern of several of those *Standards*-based programs that have been judged exemplary, the *epiSTEMe* project employs a pedagogical model organised around carefully crafted problem situations. In view of the promising research findings for *enhanced context*, these problems are posed and managed so as to appeal to widely shared pupil experiences and interests, while, at the same time, to inculcate ideas of acting as mathematicians/scientists. Equally, curricular prescriptions are filled out to support the building of strong conceptual foundations: in particular, account is taken of what is known about informal knowledge and thinking related to a topic, and means provided of deconstructing common forms of fallacious reasoning. All these features are intended to provide a stronger basis for the more interactive and adaptive components of teaching which (on the evidence of the inspection surveys quoted in an earlier section) are underdeveloped in current practice. A further aspiration is to establish productive connections between mathematical and scientific ideas.

The *epiSTEMe* model has been particularly influenced by earlier research (which contributed strongly to the systematic reviews discussed in the previous section) that points to the value of dialogic small-group and whole-class discussion in encouraging pupils to talk in an exploratory way and to consider different points of view (Howe & Tolmie, 2003; Howe et al., 2007; Mercer et al. 2004; Mercer & Sams, 2006). Key aspirations for dialogic talk are that it be *collective* in involving all participants, *reciprocal* through considering different viewpoints, *supportive* of free expression and mutual assistance, *cumulative* in chaining and developing ideas, and *purposeful* towards particular curricular goals (Alexander, 2008). However, orchestrating such classroom talk is acknowledged to present significant challenges: facilitating public expression and respectful examination of pupils' thinking; focusing – but not funnelling – discussion to prevent it becoming overly fragmented and incoherent; and guiding pupils towards accepted disciplinary norms of reasoning and communication (Franke, Kazemi & Battey, 2007).

The pedagogical cycle at the core of the *epiSTEMe* model locates such dialogic discussion within a broader structure of phases of exploration, codification and consolidation (Ruthven 1989). In the opening exploratory phase, domain-specific enquiry tasks are employed to support informal development of target concepts. Dialogic small-group and whole-class discussion provides opportunity for pupils to express their thinking about a problem situation and to examine different perspectives on it. During such discussion, the teacher's principal role is to support the dialogic quality of contributions by pupils and exchanges between them.

The cycle continues to a codification phase in which the teacher's role becomes a more authoritative one of explaining accepted mathematico-scientific approaches to the problem situation through active teaching which takes account of the thinking displayed during the earlier exploration phase. In a final consolidation phase, pupils tackle related problem situations more independently, with the teacher's role becoming one of checking pupil understanding and providing developmental feedback.

The **epiSTEMe** *intervention apparatus*

A very concrete aim of the *epiSTEMe* project has been to devise an apparatus to support teachers and departments in developing teaching along the lines of the *epiSTEMe* pedagogical model, without requiring significant reorganisation of work and substantial investment of time on their part. Our orientation has been towards what might be termed "re-design" research that recognises that design for implementation at scale needs to take account of the existing state of the system: notably the people, structures, resources and practices already in place. We have devised a professional development and classroom teaching intervention, relatively modest in scope, and packaged as a viable substitute for modules currently widely taught in schools. The focus is on Year 7, the first year of secondary education (during which pupils reach the age of 12): this is the period most distant from the inhibiting backwash of external assessment, and the one during which teachers are actively shaping norms of classroom participation. It is also believed to mark a particularly important transition period for young people's formulation of their academic futures.

The *epiSTEMe* apparatus consists of the following components. An Introductory Module is designed to build teacher and pupil understanding of the value of talk and dialogue in supporting subject thinking and learning, and to develop rules and processes that support effective small-group and whole-class discussion. This addresses the crucial need, identified in the systematic reviews discussed earlier, to cultivate, amongst both teachers and pupils, productive shared norms of participation in small-group and whole-class discussion, and the capacity to make use of dialogue to promote effective learning. Two further Topic Modules in each subject are designed to support and capitalise on such use of talk and dialogue, and to instantiate the full *epiSTEMe* pedagogical model. These modules are mediated by teaching materials designed to be educative in the sense of supporting teacher development as well as classroom activity (Davis & Krajcik, 2005), and supported by a sequence of two one-day Professional Development events. The first event focuses on dialogic teaching and on how the Introductory Module supports its development. Then, after teachers have undertaken the Introductory Module with one of their classes, the second event debriefs this experience and examines how the Topic Modules in their subject incorporate the pedagogical principles and processes of the *epiSTEMe* model.

The design of modules has tried to ensure that a wide range of teachers and departments will find them readily and robustly usable. In particular, the Topic Modules provide a full set of classroom materials which explicitly target curricular objectives within the typical period of lesson time allotted to the topic in question. They are designed to fit the parameters normally found within the system, but to be sufficiently flexible to be adaptable to other common variants. For example, the normal length of a timetabled session in English secondary schools is around 60 minutes, of which about 50 minutes is typically available for teaching. Lessons are designed to fit such a session length, but are structured as sequences of shorter activities to facilitate adjustment to another session length or to a differing lesson pace. Equipment requirements have been limited to items known to be widely available and easily usable. For example, soundings indicated that classrooms typically had either an interactive whiteboard or computer projection, and that teachers were accustomed to using these, often with prepared displays, usually alongside a traditional whiteboard. This led to Projection Slides becoming the primary support for classroom implementation of lesson sequences. Nevertheless, during trialling it became clear that school computer systems could not be relied on: here the Study Booklet given to each pupil provides an important fallback. Teaching Notes for each module support lesson planning, highlight key aspects of each activity and explain its rationale, and advise on handling pupil responses.

An illustrative dialogic activity

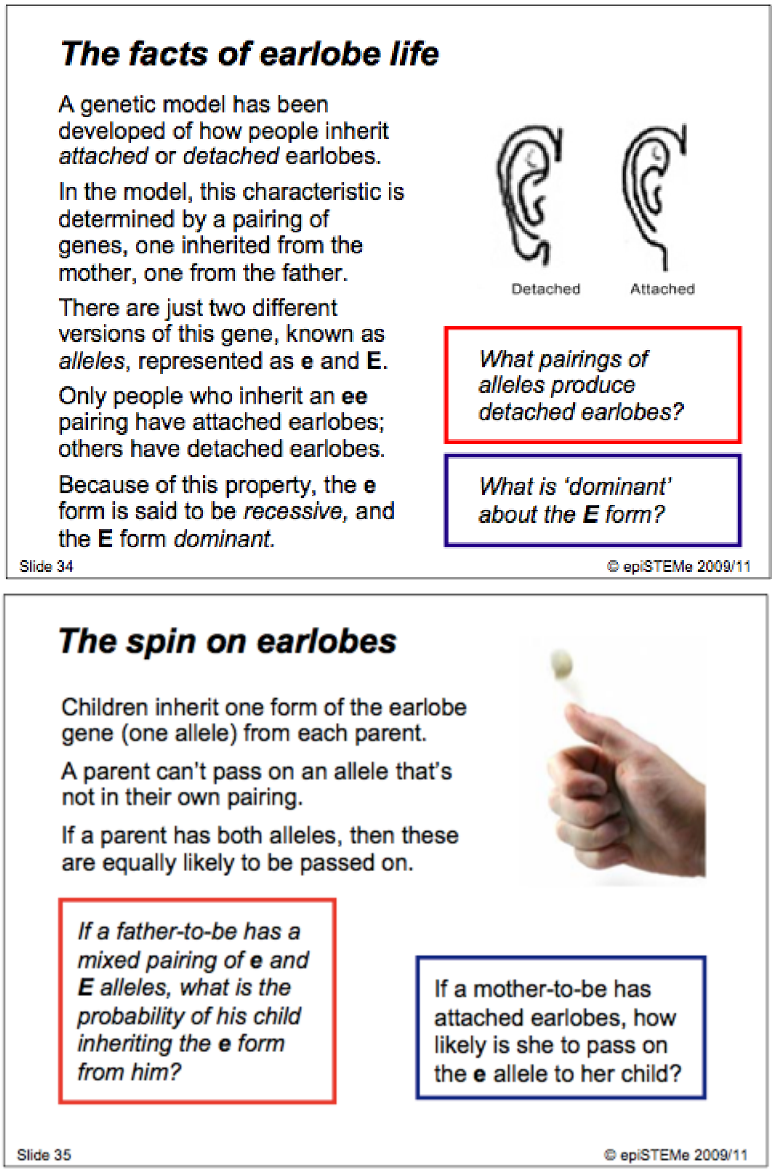

Fig. 1: *The earlobe lottery.*

To illustrate the dialogic dimension of the *epiSTEMe* pedagogical approach more concretely, we will use the example of an activity that examines a simple probabilistic model of genetic inheritance. The key genetic ideas underpinning the model (as shown in the first slide in Fig. 1) are introduced to the class in an interactive style. Pupils are often surprised to learn of the two earlobe types; typically they show great interest in knowing which type they and their classmates have! The questions on the slide are designed to support collective extraction and organisation of information from the text: one that incorporates features of mathematico-scientific writing that pupils need to learn about but which many find challenging at this stage. The probabilistic aspect of the model is then introduced (as shown in the second slide). Over the course of this introduction, the teacher aims for pupils to come to grasp, first the distinction, and second the relation, between allele pattern and earlobe type. It is also not unusual for some pupil to pose the question of whether attached earlobes will eventually die out; this is acknowledged to be an interesting question that it may be possible to address in due course. Typically, too, some pupil asks whether both problems on the second slide concern the same child; this provides a good lead into the problem that pupils are then asked to work on, initially in small groups: *A couple are expecting their first baby. Both parents have a mixed pairing of e and E alleles. How likely is their baby to have this same pairing?*

An important ground-rule for small-group discussion is that pupils should try to come to an agreed position; even if they are unable to achieve this goal, honouring it calls for them to engage with points of view other than their own, and to develop an argument in support of their position. Once most groups have formulated some kind of response, the activity switches to a whole-class plenary in which their varying answers and arguments are elicited. Typically, there is a clear need for further whole-class discussion, because different groups have arrived at what are clearly contrasting answers. Moreover, each answer arises from a distinctive pattern of reasoning: an everyday model of inheritance in which “children take after their parents” (leading to an answer of 100%) as well as variant patterns of probabilistic reasoning about the outcome space under the scientific model of genetically-mediated inheritance (leading to answers of 1/3 and 50%). These three responses represent, respectively, the predominant everyday misconception about inheritance of characteristics, the predominant lay misconception about outcomes in a simple repeated trial, and finally the accepted and coordinated mathematico-scientific conceptions.

The first *epiSTEMe* professional development event employs the videotaped example of a plenary review of this problem to examine how teachers can support quality of classroom discussion. Research analysis of this example has helped concretise teaching strategies and tactics that can assist and develop dialogic exchange (Ruthven, Hofmann & Mercer 2011). This analysis informed our choice of a sequence of short video episodes to stimulate discussion with and between teachers, with the classroom dialogue transcribed to encourage attention to the fine grain of pupils’ mathematical thinking and of the teacher’s participation in exchanges. The emphasis is on encouraging teachers to “read” what is taking place as each episode unfolds so as to understand how pupils are responding and reasoning, to analyse the quality of dialogic interaction, and to anticipate accordingly how the teacher might productively shape events and ideas. While the research analysis informs our contributions to the discussion with teachers during professional development, we do not explicitly present it.

Supporting dialogic exchange is the aspect of the *epiSTEMe* pedagogical model that teachers have found particularly challenging. Because this approach emphasises developing mathematico-scientific reasoning as its goal, not simply securing task performance, it requires significant shifts beyond the received ideas and habitual reflexes of established practice. For example, a dialogic approach calls for the teacher to be prepared to give time to multiple pupil contributions which can be persuasively fallacious or poorly formulated. To sustain productive discussion, the teacher must be able to identify and interanimate the thinking behind different pupil responses, and steer progression in reasoning without closing down discussion.

Evaluating the intervention

The development, refinement and evaluation of the *epiSTEMe* intervention has been undertaken over 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 and trial classroom activities reflecting the *epiSTEMe* teaching model. Lesson observation and close interaction with participating teachers provided valuable informal feedback and evidence samples during this and the following phase. As illustrated in the previous section, examples and insights gained from these sources helped not only in refining the classroom modules, but in devising professional development activities. In particular, to better assist teachers to translate principled characterisations of dialogic teaching into practical actions, we devised ways of incorporating discussion prompts and supports into classroom materials, and undertook analysis to identify examples and strategies which would enable us to communicate a more powerful operational delineation of dialogic teaching. At the same time, participating teachers reported that the *epiSTEMe* classroom materials and pedagogical guidance helped them to achieve higher quality of pupil experience and outcomes.

Over the course of Phase 2 (2009/10) we studied classroom implementation by participating teachers of successively refined versions of the full modules. In this phase we also had the benefit of further feedback from a suite of pre- and post-tests for each topic module. Because they too were undergoing calibration and refinement, the tests administered to each class were not identical, but were sufficiently similar for the results to be considered comparable. We focused particularly on the learning gains in each module between pre-test and the unannounced deferred post-test, taken a month after module completion; in the few cases where the latter was not administered, we substituted results from the immediate post-test. The class results in Table 1 show the size of the resulting learning gains for each module (taking the standard deviation of test scores as the unit of measurement). Although class effect sizes proved more varied in some modules than others, the mean effect sizes for the four modules were similar. Overall, then, as measured by our topic tests, the average learning gain effect size for a class undertaking a 6 to 10-hour *epiSTEMe* module was 0.78. During Phase 2, some parallel classes following a school's normal module of study for each topic also undertook the test sequences: the average learning gain effect size for such classes was 0.13.

Table 1: Effect sizes of learning gains for the *epiSTEMe* topic modules during Phase 2

Topic module	**Class effect sizes**	**Mean effect**
Fractions, Ratios and Proportions	-0.73 -0.57 0.82 1.24 1.29 1.60 1.95	0.80
Forces and Proportional Relations	0.35 0.50 0.55 0.80 0.91 1.02 1.30	0.78
Electricity	0.51 1.31	0.91
Probability	0.56 0.62 0.66 0.76 0.83 0.98	0.74
All modules	All data above	0.78

For Phase 3 (2010/11), we recruited a further 25 schools to conduct a randomised field trial of the intervention. Schools that applied to participate in the field trial were randomly assigned to the intervention or control group. Teachers in the intervention group completed the training programme at the start of the 2010/11 school year, and then undertook the *epiSTEMe* modules with their Year 7 classes. Teachers in the control group had to wait until the start of the 2011/12 school year to undertake the training. Over the course of the 2010/11 year, a range of data was collected from around 80 participating Year 7 classes and their teachers. This is currently being analysed to compare pupil outcomes from the first implementation of the *epiSTEMe* approach by teachers in the intervention group with the outcomes produced by the established practice of teachers in the control group. The range of pupil outcomes under consideration includes changes in subject attitude over the course of the year, learning gains from the unit of study on each focus topic, and opinions on key aspects of learning experience during each of these units of study. Further analyses will examine how such outcomes may be mediated by pupil-level and class-level characteristics relating to gender, English-language precedence, socio-economic status, home cultural-social capital, and prior attainment. Within the intervention group, classroom observations will also provide measures of the strength of implementation of the dialogic teaching model, with a view to assessing the potential influence of variation in this strength on pupil outcomes. Findings from these analyses are expected to be available for dissemination by early 2013.

If the results of the evaluation justify doing so, both the classroom materials and the training programme comprising the *epiSTEMe* intervention will then be made more widely available. The project also expects to produce research papers reporting on the design, operation and evaluation of the intervention as a whole and of individual modules, and on the conceptualisation, operationalisation and implementation of the dialogic teaching approach which has a key place in the intervention.

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