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Linking the learning of mathematics, science and technology within key stage 4 of the National Curriculum

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Abstract
Both the Science with Technology and Mechanics in Action Projects have been working with schools and developing curriculum materials with the aim of bringing together the learning of Mathematics, Science and Technology. The intention has been to improve the way in which students integrate the knowledge and skills from the different subjects, and hence improve the quality of their learning, by breaking down some of the barriers between the subjects.

This paper discusses some of the subject specific and whole school issues that such attempts at integration raise. The strategies that we, and the schools we are working with, are developing to bring the subjects together for students, and to overcome the curriculum and timetabling problems of such cross-disciplinary work, are described. Some initial evaluative findings are presented.

Background to Science with Technology and the Mechanics in Action Project

The Science with Technology Project is the latest in the Association for Science Education's (ASE's) Science and Technology in Society (SATIS) family. A significant new feature of the Project, with respect to earlier SATIS ventures, is that it is managed jointly with the Design and Technology Association (DATA) and the focus for its materials is students and teachers in technology as well as science (Sage, 1993).

The Mechanics in Action Project (MAP) has its roots in developing practical modelling approaches to the learning of mechanics. This has led, since 1989, to work with schools that aims to develop cross-disciplinary approaches to students' learning in mathematics, science and technology across secondary education (see for example McLachlan and Williams, 1993).

Since the Autumn of 1991 both projects have also been working with the Engineering Council's Technology Enhancement Programme (TEP) to develop curriculum materials that link learning in the three subjects using engineering and industrial contexts.

Benefits of linking learning

A number of arguments for cross-disciplinary work in mathematics science and technology can be, and have been, advanced. Some of these arguments are derived from theoretical considerations of the links between the three disciplines (see for example Layton, 1993, LaPorte & Sanders, 1993,), others are based in various ways on the needs of the learner (see for example Paechter, 1992).

Practical experience of cross-disciplinary work at Key Stage 3 in a number of schools has shown that there are benefits both to students and their teachers (McLachlan and Williams, 1993, Steeg and Williams, In press). These benefits include;

For students:
• Increased motivation.

This can occur when cross-disciplinary projects provide new perspectives on the subject matter of the individual subjects. It is particularly noticeable when these projects link the theoretical and abstract with practical activity, especially when this activity has real personal or social importance and a high status. Additionally projects of this nature often provide new ways for students to work, both with their peers and with the adults around them and this in itself is motivating; this 'Hawthorne effect' is clearly not confined only to projects of this nature.

This increased motivation is recorded as having carried back into the 'normal' curriculum and timetable.

• Enhanced learning.

This operates at a number of different levels: A more coherent approach to a topic that arises in more than one of the subjects can reduce student confusion, and, perhaps, by reducing the time...
spent on the topic, release time for other work. The link of a real and practical context to the problem solving and investigational strands of mathematics and science can improve the acquisition of these skills. Conversely the application of scientific and mathematical approaches to work in technology can improve the rigour and thus the quality of the technological outcome.

- Reduction in assessment load.

The fact that a student activity is drawing on skills and knowledge from more than one subject means that there is the possibility of drawing conclusions about student attainment across those subjects from the single activity. This was the focus of the King's college work at GCSE (Paechter, 1992) and has also been supported by SEAC (1991).

For teachers:
- The benefits to students. Perhaps the most significant benefit to teachers is the improvement in students' learning and motivation when it carries over into the mainstream curriculum and timetable.

Similarly the reduction in assessment load noted above has benefits for teachers as well as students, though this requires very careful planning (SEAC, 1991, Paechter, 1992).

- Improved understanding of other subjects' aims and approaches.

One aspect of this is that insight into how subjects relate to one another can improve a teacher's ability to relate work in one subject to the wider experience of the students - and to relate the wider experience to the work in one subject.

Additionally the experience of students' positive reaction to the different teaching approaches of other subjects can motivate teachers to incorporate such methods into their own classrooms where appropriate.

- Staff development and informal INSET.

Organising, and being involved in, cross-disciplinary projects can give teachers experience of management and enhanced respect for their work within the senior management of the school.

All teachers involved are likely to benefit from the experience of different teaching and learning styles - this can be particularly effective in the case of 'resistant' teachers where the development is not the primary objective and adequate support can be built into the involvement.

It should be noted that most of the cross-disciplinary work from which these conclusions have been drawn has taken place in specially constructed time outside the normal timetable. This permits a great deal of flexibility and highlights the benefits - where it does not help us is in the application of the ideas to the mainstream (National in the UK) curriculum and the normal day to day timetable.

Issues raised by linking learning

A Subject 'cultures'

Within each subject there is an understanding of the content and how that content should be taught. Any attempt to bring the learning of the subjects together thus requires an examination of the content of each subject and comparison of the content across the subjects. Examination of the content can conveniently take place under three headings - problem solving and investigative skills, procedural skills and knowledge content;

- Problem solving and investigative skills.

All three subjects require students to, at least some of the time, take an approach that might be broadly described as 'problem solving'. Descriptions of what is expected from students in this area within the three subjects can be found in the Attainment targets of the National Curriculum; in particular in Ma1 (DES, 1991a), Sc1 (DES, 1991b), and Te 1-4 (DES, 1990).

It can be argued that there is a broad similarity across these approaches to problem solving (see figure over);
Problem Definition:

Entry:
- Identifying needs and opportunities

Attack:
- Generating a Design
- Building a model, selecting the maths
- Designing an experiment (variables)
- Planning and Making
- Analysis (using maths)
- Carrying out Scientific investigations

Review:
- Evaluating
- Interpreting and validating
- Interpreting results, validating, drawing conclusions

Note: This figure is not intended to suggest that the process in any of these disciplines is linear, as opposed to a cyclical or even an iterative, one.

and thus that development of the skills in one subject can build on, and be built on, in other subjects. Layton (1993) however has argued that this sort of analysis can be misleading. It is in the differences in their approaches to 'problem solving' that the different disciplines define themselves.

A result of this is that teachers may not be able to use a single activity of this type to meet the requirements of more than one subject. For instance in science a primary concern is the identification of appropriate variables and the employment of strategies to establish relationships between them. In technology, however, optimisation of performance is a key concern. This involves eliminating variables that make no contribution to this objective. These two approaches will result in very different pupil activity and in different assessable outcomes.

Further work needs to be done to outline where it is appropriate to take common approaches to problem solving in the school curriculum as part of a coherent approach to student learning and the development of transferable skills, and where the differences should be made explicit to students to increase their understanding of the culture of the subjects.

Procedural skills.

Each subject also has its own set of procedural skills that students need to gain mastery of if they are to progress. Again it can be seen that though there is considerable overlap between the three subjects in the procedural skills expected there are also significant differences;

(Note that these are not exhaustive lists but are intended to a give a flavour of the range.)

Mathematics:

- Use drawing instruments, use calculators appropriately, use computers, manipulate and use apparatus, measure ...

Science

- Measure, select and use apparatus and instruments, record data, use computer technology, design experiments, interpret mathematical information, display mathematical information ...

Technology

- Use equipment and tools accurately and safely, draw and sketch, use computer technology, research, use mathematics ...

Two points arise from lists such as this.

Firstly there clearly are some overlaps here, for instance measurement skills and appropriate use of apparatus; where this is the case a unified approach to the development of the skill should be sought.

Secondly the interesting fact emerges that some elements that are considered to be procedural skills in science and technology would be regarded as a part of the knowledge base of mathematics, "display mathematical information" for instance. In fact the content of Ma2-5 (the 'knowledge' attainment targets) are things that science and technology often hope for in students as skills. A corollary of this is that the 'content' of science and technology may be used as a context for doing some mathematics, a classic example of this being Newtonian mechanics.

- Knowledge/subject content.
  It's possible to put the knowledge contents of technology and science next to each other and note areas of overlap and complimentarity. For example;

Forces and Structures (examples from KS3)
Science (1991, Sc4) Statements of Attainment

Understand that forces can effect the position, movement and shape of an object.
Know that more than one force can act on an object and that forces act in different directions.
Understand the law of moments.

Technology (1990) Programmes of Study

Use knowledge and understanding of materials to design and make structures which stand up to stress.
Design and make structures to take stationary and moving loads.

Technology (Proposed revision 1992) Programmes of Study

To devise and use methods to reinforce their structures; eg triangulation, gusseting and ribbing; relate these and other techniques to familiar structures.
To calculate loads, forces and their effects using concepts such as moments.

One could list many other similar areas. This is simply a recognition that technology tends to draw quite heavily (though not by any means exclusively) on the ‘facts’ of science - and particularly, within the tradition of school technology, on physics.

The proposed revised Attainment Targets for Technology in the UK attempt to make this link explicit by extensive cross-referencing to the Attainment Targets for Science (maintaining on the way the same narrow focus on physics), as well as those for mathematics and art and design. Such cross-referencing does not of itself lead to integrated approaches to the subjects as Barlex (1991) has pointed out.

It is also the case that attempts to link science and technology run the risk of superficiality because of inherent problems in making these links (Layton, 1990);

• the form of the knowledge may not be transferable;
• there are problems of timing and sequencing;
• prefacing work in technology with knowledge in science may close down solutions; however, having inadequate advance knowledge will also close down solutions.

However, it is possible (we work with schools that have done so) to produce a scheme of work that ‘covers’ the requirements of both science and technology for an area such as that above in a completely integrated way.

When we look at mathematics however, we find that one area of knowledge will be useful in many areas of science and technology. An example of this kind (from the many that could have been chosen) of mathematics can be found in Strand (ii) of Ma3 (Algebra; formulae, equations and inequalities):

Level 5; “express a simple function symbolically”. Level 6; “solve simple equations”.

The converse of this is that one area of science or technology might make use of almost the whole mathematics curriculum.

The conclusion of this brief analysis of the content of the three subjects is that very careful planning is required if cross-disciplinary approaches to the curriculum are to successfully support learning in all three subjects and encourage students to transfer their knowledge between the subjects.

It should be noted too that teacher skills and confidence in approaching cross-disciplinary work are important issues. Teachers will need to gain the same understanding of ‘levelness’ and progression in other subjects that they have in their own. In addition it has been recognised (Paechter, 1992) that the understanding of terms such as “evaluation” and “investigation” can be different in different subject cultures.

B Organisational

There are of course many other issues that any attempt to integrate teaching across a number of subjects will need to face. These organisational and practical questions are not analysed here in as much depth as the subject specific questions were, but are nevertheless substantial and cannot be overlooked when planning such work.

Our experience and that of others who have attempted cross-disciplinary work is that these issues will include the following at least (Paechter, 1992, McLachlan and Williams, 1993):

• Timetabling

If cross-disciplinary approaches are going to have a significant effect on students’ learning in Key Stage 4, ways will need to be found to make
them more integral to the normal flow of the timetable than is usual at present.

- GCSE syllabuses

Teachers within the constraints of GCSE need to be confident that anything that they are involved in is contributing to the learning required by the syllabuses.

- Assessment practicalities

If cross-disciplinary work is to contribute to GCSE assessment all teachers involved need to be aware of this from the start and to plan with it in mind. This is to be the subject of further advice from the group at King’s College who ran the Cross-curricular Assessment Through Coursework for GCSE project (Paechter, 1992).

- Time for planning

This is critical and needs to be acknowledged by senior management from the start.

- Involvement of key personnel

Experience has shown that identifying and involving the key people in a school will be what determines success, or lack of it. This will usually include people from senior management with the power to make the necessary decisions on issues such as timetabling and finance.

- Overcoming student resistance

Students can be resistant to new approaches that challenge their perceptions of such things as the established subject boundaries. They can also be powerful change agents. However, it is particularly important that students are not left with the responsibility for overcoming problems raised by the new approaches.

Much further research needs to be done to determine the best strategies for success, both for forging the specific links between subjects and in the wider planning of such work. Some initial approaches from our experience, and that of others, can however be drawn out.

Strategies

In the work we have been engaged in there have been two broad strands to our attempts to encourage and support a greater integration between the three subjects. Firstly, in the written materials we are producing, we have adopted particular organising strategies to provide a framework for the three departments who will be using them. Secondly, we have encouraged the creation of a variety of groups of teachers with specific roles.

1 Written materials

Levels of linking learning

The materials we have been writing have been technology led, that is, the overt motivation for the work has been provided within a technological context. Thus the issue for us has been how best we should link mathematics and science into the materials. From the beginning it has seemed important to us to do this in a way that is not artificial - i.e. mathematics or science should be there for an identifiable reason. This has led us to ask the question “What sort of science or mathematics is it?” and to attempt to answer it by attaching it to one of the following categories:

- Mathematics or science that is essential to the proper fulfilment of a particular technological task.

In this case the maths/science will be seamlessly woven into the task without the students’ attention necessarily being drawn to the fact that it is there.

An example of this is the calibration of an electronic device; the task has been largely written by mathematicians to be used primarily by technology teachers.

- Mathematics or science that is widely useful or ‘generic’.

The criterion here is that the maths/science will be useful more widely than the task in hand. In this case the maths or science in the task, and its usefulness, is focused upon and generalised with the aim of building a transferable ‘skill’.

For example, the use of spreadsheets as a tool for modelling and analysis is developed strongly in one area of technology work and the skill is reinforced in others.

- An opportunity for mathematics or science that arises from the materials.

Often a technological task provides a context for the development of further mathematical or scientific work, for example, some extended maths coursework or a science investigation. These opportunities for further work are
described and supported within the teachers', rather than the students', notes.

Identification of generic mathematical tasks
As noted earlier, the mapping of mathematics onto science and technology produces some difficulties. Our response to this has been to look for mathematical tasks that are ‘generic’ in that they arise across a broad range of scientific and technological activities (Steeg and Williams, In press). Examples of such generic tasks include (not all at the same level of complexity or scope):

- Calibration of an instrument or device;
- Making a 2D or 3D model;
- Display of quantitative data;
- Analysis of a relationship between two variables;
- Using and interpreting graphical information;
- Reading scales or instruments appropriately;
- Making a scale drawing;
- Building a mathematical model;
- Ratio;
- Assessing reliability.

Although some of these mathematical tasks might be required almost every time a student is engaged in some science or some technology, our aim has been to make sure that each task is focused upon at least once, in a detailed way, in the materials we are developing - using the expertise of mathematics as well as science and technology educators, and always in the context of some real science or technology.

2 Using groups
A significant feature of our approach to this complex area of curriculum development has been the extensive use of groups of teachers, both to earth our work but also, critically, to provide arenas within which the organisational difficulties noted above can be addressed. We have made use of three broad types of group.

Writing Groups
These have brought together teachers from a range of schools and all three disciplines. The main focus of their work has been the development of curriculum materials and their breadth has helped to ensure that such things as progression, differentiation, National Curriculum ‘levelness’ and attention to GCSE requirements have been given a high profile across all three disciplines.

Simply seen as staff development, the effect on the individuals involved in these groups has often been dramatic. Equally dramatic has been the positive effect on the quality of the materials produced.

School development groups
Each school we have been working with has put together a development or management group for the project. This group has included teachers from all three departments and senior management representation, as well as people from outside agencies involved in the project such as local industry.

These groups have been critical to the success of the project within a school, ensuring such things as coherent planning for progression across and within the subjects, development of timetabling strategies and recognition of staff development.

Working groups
In one area of the country we have piloted a regional working, or ‘user’, group. Run as a fortnightly ‘twilight’ session, this group has had a wide range of effects including support to teachers in our project schools, INSET on items of hardware and software, instant feedback on trialling and ideas for curriculum materials. It is likely that we will extend this idea to all of our schools across the country.

Discussion
Early feedback
Our first materials are currently being distributed to schools for extensive trials over the next sixth months. It is the evaluation of this trial that will provide the first feedback of not only how well the materials work with students, but also how they are being used in schools to support linked work across the three different departments.

Our expectation from the initial development work in schools is that there will be a wide range of results and approaches, from attempts at full integrated timetabling to no more than marginally increased teacher awareness of what goes on behind the doors of other departments.

An important question for us will be the effects of these different kinds of approach to linking the subjects on such things as students achievement and motivation, teacher development and involvement and continued viability in the school. Experience suggests that we may find a development through different approaches over a number of years as teacher (and school) confidence in working across the departmental boundaries grows.

Research questions raised by this kind of
The fundamental question that our work raises is;

- ‘Does the linking of mathematics and science with technology lead to enhanced capability in each of the subjects?"
- Other research questions that are related to this include;
- What is the relationship between technology as practised in industry which includes both mathematics and science, and technology as taught and learnt in schools?
- How do the concepts of mathematics and science need to be reworked to make them useful in technology?
- How does the achievement of technological outcomes contribute to capability in mathematics and science?

Gilbert (1992) also raises a large number of research questions that relate to this area.

Evaluation and research strategies and methodology

The research data that we are collecting comes both from the development of our curriculum materials and from evaluation of how they have worked with students and how they have been used in schools. Feedback from this process will take a number of forms:

- The actual development of curriculum materials that link learning across the three subjects.
- Valuation of these materials through student and teacher proformas and questionnaires, interviews, working in the classroom alongside teachers and students.
- Collecting data about students' performance based on teacher assessment, external assessment and Records of Achievement.
- The use of case studies to analyse how success (or disaster) has been achieved in implementing learning across the subjects. These will also be used to provide models for development for other schools.

We hope that a year from now we will be able to report some results from this initial trials stage.

References