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ABSTRACT

This paper explores the mathematical education of electronic engineering students through an analysis of how mathematics is constituted for the purpose of learning in a university setting. The nature and role of mathematics, offered to students via implicit and explicit messages within mathematics and engineering discourse, is described. Implications for student development are also considered. Contains 16 references. (Author/NB)

Messages from the Front and Other Places: How Engineering Students are Enculturated into Mathematics

by
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Messages from the front and other places: how engineering students are enculturated into mathematics

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Abstract

In this paper, the mathematical education of electronic engineering students will be explored through an analysis of how mathematics is constituted for the purpose of learning in a university setting. The nature and role of mathematics, offered to students via implicit and explicit messages within mathematics and engineering discourse will be described, and the implications for student development considered.

Introduction

It is generally accepted that mathematics is an integral part of science-related activity. Indeed, Feynman (1992) offered a view of mathematics as " *the language nature was written in ... if you want to learn about nature .. it is necessary to understand the language she speaks in*" (p 58). Mathematics can provide one of the most powerful means of solving problems in science and engineering, and thus is considered an important aspect of students' education. However, the issue of the nature and form of mathematical education to offer future scientists and engineers remains problematic (Sutherland & Pozzi, 1995). Surveys of science and engineering departments' mathematical needs have provided long lists of mathematical topics (Dewhurst & Sutherland, 1998) but a consideration of how mathematics is actually being used within the science-related domains is rarely apparent.

The mathematics-in-practice research community has investigated the use of mathematics in out-of-education settings, such as the home (Lave, 1988) and workplaces (Noss & Hoyles, 1996; Smith & Douglas, 1997; Hall, 1999). These studies have pointed to the ways in which these practices are distinct from practices within mathematics communities. Thus a 'situated cognition' view, which

suggests that mathematical knowledge is somehow tied to the context in which it was developed has been gaining currency. However, formal education - particularly at the university level - is largely premised on students successfully making links between generalised mathematical ideas and their specific contexts of use.

With this in mind, a research study of the university setting was undertaken to ascertain the nature of science students' mathematical experiences and their re-production of mathematical practices. The study forms part of a larger research programme, conducted with groups of post-16 students, studying science-related subjects at school, college and university levels in the UK. The approach preferenced in this work is one of aiming to understand learners' progression as *a process of enculturation into scientific communities of practice*, with mathematical work viewed as an integral aspect of this enculturation process.

Many studies in the sociology of science have focused on 'science as a practice', that is, on what scientists actually do, and how a person becomes enculturated into the practice (Collins, 1982; Pickering, 1992). However studies which connect the practices of professional scientists with the initial stages of this enculturation are few (Laws, 1996). An enculturation perspective on learning implies that the learning of subject content matter is only one aspect of many to be attended to in students' development. Other aspects would include the skills and techniques of the domain, the 'ways of knowing', as well as the relationships between these elements. In the current study, the enculturation model demands an analysis of the nature and role of mathematics in relation to science and engineering, that is presented to students. These epistemological messages can be expected to impact on students' development through what is learnt and how it is re-produced.

Students' mathematical and scientific experiences at university are primarily via the formal instructional situations of lecture, tutorial and laboratory. Within these instructional situations, students experience *authoritative discourse* (Bahktin, 1981),

> "The authoritative word demands that we acknowledge it, that we make it our own; ... we encounter it with its authority fused to it".

By studying the epistemological messages posited within the authoritative texts of mathematics and engineering programmes, through lectures, textbooks etc., we can explore the images of mathematics presented to students. That the discourse is authoritative implies that students would be expected to accept the messages and images offered.

The Research Study

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data collection and analysis

The research study discussed in this paper, involved four departments within the science and engineering faculties of a university in the south-west of England. Here, I report on that part of the study which focused on the experiences of electronic engineering students. Inherent in the theoretical position outlined above is the idea that data collection should be focused within the natural context. To this end, an 'anthropological' approach was adopted in attending the lectures, laboratories and tutorials that electronic engineering students undertook for a number of the modules of their first-year degree programme. Within each formal instructional situation, the model was of 'participant comprehension' (Collins, 1994). Data was collected in both the engineering department and mathematics department which serviced the engineering degree programmes. These departments were the formal arenas in which students encountered mathematical ideas, and within each department data collection included:

- audio recordings and fieldnotes of lecture and tutorial sessions
- video recordings of laboratory sessions
- students laboratory scripts and progress test papers
- a diary of conversations with lecturers, technicians and post-graduate demonstrators

In addition, all paper-based and computer-based resources that engineering students had access to were collected for analysis, for example,

- the first-year prospectus, module descriptions and syllabi information
- the web-based materials resources provided for students on their modules
- the recommended textbooks for the degree courses
- a database of examination papers from several years previous

An holistic approach to data analysis was taken, using an analytical framework that has been developing over the course of three inter-related research projects[1]. The framework is informed by the theoretical ideas described above and includes categories such as,

- how mathematics is presented to students (e.g. in teacher talk, in textbooks; through representations such as graphs, tables, symbolic sign systems)
- how students re-produce mathematical aspects of ongoing science work (e.g. through use of representations; choice of representation; problem-solving approach)
- what resources are drawn on by learners when undertaking scientific-mathematical activity (e.g. technical tools such as calculators and measuring instruments; peers; subject knowledge)

Using this framework, case studies of mathematics-in-practice have been developed, for example, 'mathematical practices in engineering laboratory settings', and, 'the characterisation of the use of

[1] 'The Role of Spreadsheets in School-based Mathematical Practices', Spencer Foundation, Sept.1994 - Oct.1995
'Mathematical Competencies of GNVQ Science Students', Leverhulme Trust, Oct.1995 - Apr.1998
'Mathematical Experiences and Mathematical Practices in H.E. Science Settings', ESRC, Apr.1998 - Aug.1999

mathematical ideas across different learning contexts'. Drawing on these case studies, I will discuss in this paper some of the images of mathematics that engineering students experienced during their initial university studies. The educational implications of the epistemic status afforded to mathematics will also be discussed.

research setting

A degree programme in electronic engineering in England may take either 3 or 4 years, with the end qualification being a Bachelor of Engineering or Master of Engineering degree, respectively. The majority of students enter university aged 18 or 19 years. The university in which the study took place is regarded as prestigious and students who enter the university have high scores in their school leaving examinations. In their first year of study, the students on the electronic engineering programme take 5 modules on engineering topics and one mathematics module. The mathematics module must be passed in order to progress to the second year of their degree programme. For the duration of the research study, the mathematics module occupied 2 hours a week of lecture time and 1 hour of examples class, every week for the 24 weeks of the teaching year, with self-study in addition. Each engineering module also occupied 2 hours of lecture time per week, with tutorial and self-study time on top. The engineering modules also involved associated laboratory work which occupied one whole day a week.

Two first-year engineering modules (Analogue Circuit Systems and Fields & Devices) were attended during the research study, as well as the mathematics module (Engineering Mathematics I). The mathematics module is taught by teachers in the Engineering Mathematics department which is a separate department from the Electronic & Electrical Engineering department.

Images of Mathematics

In this section, an overview of the main messages about mathematics that were offered to electronic engineering students is presented. The messages will be illustrated using descriptive vignettes of actual practice, firstly from students' mathematics programme experiences and then from their engineering programme.

a general tool ?

The generalisable nature of mathematics is seen by the mathematics community as embodying the power of mathematical techniques. This image of mathematics as being general and applicable to a multitude of contexts was evident at the level of the institutional structuring of student experience.

Mathematics programmes are delivered to engineering students by the Engineering Mathematics department which is situated in a separate building from the main Electronic Engineering department. The teachers of the first-year module are all mathematicians. The content of the lectures has remained largely unchanged over the years and in many cases is of little relevance to the students' current studies. For example, students were presented with complex analytical techniques which are not required in the engineering course until the fourth year of study.

Each year there are approximately 60 students on the Electronic Engineering degree, however class sizes are usually much larger than this as teaching is delivered to students on a number of different degrees at the same time. The first-year mathematics module is delivered to students on three different degree programmes at the same time. The module is presented twice[2] by the same professor, in consecutive 1 hour sessions. The professors are often unaware of which set of students they are addressing in any one session.

It is widespread practice for university mathematics departments in the UK to provide 'service'[3] courses for science and engineering departments. Thus, the course organisation described above - of mathematics being provided by a separate department to students' host department - is unsurprising. However this model has received little scrutiny despite students' ongoing difficulties with mathematical work in numerate disciplines at this level (LMS, 1995). Underlying this course organisation is a conception of mathematics as a canonical and coherent body of knowledge.

The content of courses was assumed to not need changing as the techniques are fixed and do not change over time. Thus the same content was delivered each year, to all students. This image of mathematics as unchanging over time extended to the range of content presented in that techniques were taught which may not be needed until much later (if ever). In other words, the mathematics was separated, in distance and time, from its contexts of use.

That students on different programmes attended the same mathematics course implies that the subject of students' study is irrelevant to the teaching of mathematics, that is, the mathematics to be taught is the same regardless of which engineering degree the student is taking. This in part explains

[2] Once to Electronic, Computer Systems, and Mechanical engineering students, and once to Civil, Avionics and Aeronautical engineering students.

[3] In the 'service' model, science and engineering departments fund a mathematics department to organise and deliver mathematics programmes to the science and engineering students.

why the mathematics professors' teaching input was almost devoid of any reference to the engineering contexts it was meant to serve.

The applicability of the generalised techniques taught was not a province of concern of the mathematics professors. Occasionally, a professor would work through an example of a technique in action, not by using a context for use, but by using numerical values (essentially changing the problem from general procedure to numerical calculation). On one occasion, a mathematics professor made reference to the "horrible real numbers". Whilst a mathematician may appreciate the general and abstract form of mathematical representation, a focus on this is unlikely to support the engineering students in their learning endeavour. From a certain learners' perspective, numerical calculations may be viewed as abstract as mathematical symbolism when barren of contextual information.

The issue of an absence of context-of-use was further revealed in the examination papers which are set four times a year (Progress Tests) and in the end-of-year examination. Not a single question on these papers posed a problem set in an engineering context of any description. The marking of the Progress Test papers also pointed to the irrelevance of subject discipline as papers were merely divided equally among the mathematics professors, who did not know what engineering disciplines individual students were taking.

If one considers the everyday use of the word 'tool', a vision of a physical object such as a hammer or spanner, may come to mind. These physical tools are hard, fixed and designed to enable only certain tasks to be carried out with them. In some ways this everyday image was also the image being offered by the formal mathematics input students experienced. As a set of techniques or a tool to be applied in various contexts, the ways in which the tool could be used had to be limited. That is, the mathematical tool demanded to be used in only certain ways. Tool-use was constrained by mathematical rules of some description, verbalised at the start of a lecture on differential equations when the mathematics professor began,

> "I was then forced to introduce the idea, .. I mean I *had* to, .."

and shortly afterwards,

> "What I want you to do is *accept* this .. argument"

Thus, not only is the image of mathematics presented as one of a tool, but as an intractable tool at that. The mathematical techniques presented to students were structured and constraining and required users of the techniques to 'follow the rules'.

The whole emphasis in the presentation (verbal and textual) of the mathematics module was on providing students with a tool-kit of techniques and skills, in which they were expected to gain proficiency. This last point is best illustrated by one professor's hand-outs - which finished each section of mathematical notes with the statement,

You are now able to complete exercises #, # and # on the exercise sheet .

To summarise, the examples presented above give insight to the authoritative discourse of students' mathematics programme experiences. The discourse is indicative of an approach to mathematics which assumes that it is possible to teach and learn mathematics as a tool in situations separate from those in which the tool is to be applied. That is, that the formal mathematical tool can be "transferred" unproblematically between contexts, even though the validity of this metaphor has been questioned for some time (e.g. Seely Brown et.al. 1989). Within this particular university setting, the image of mathematics as a tool, to be picked up and carried off, was evident throughout students experiences within the mathematics programme. In the next section, the images of mathematics offered via students' engineering experiences will be considered.

a flexible friend ?

In contrast to the epistemological messages described above, the image of mathematics in the context of engineering appeared to be more flexible. For example, the image of mathematics as serving the needs of an engineers job - rather than constraining lines of action - was clearly evident in much of the authoritative discourse of students' lecture experiences. The following episode describes one lecture, mid-way through the twenty-week module on Analogue Circuits.

An equation is stated,

$$V_0 = A\left(V_i - \frac{R_1}{R_1 + R_2} \cdot V_0\right)$$

(which is labelled equation (6) on the hand-out) and the professor continues to talk,

"and multiplying that out, and re-grouping, cross-multiplying, we get then an expression for the output voltage divided by the input voltage. This is the gain, the 'closed loop gain' of the circuit. .. And then, what I've done, is just to manipulate it a bit more to get it into a form, which is easier to understand because with all of these expressions you can stare at them and wonder 'what on earth's going on' and after a bit you can, sort of, see a way forward to help you interpret what's going on. So what I've done here, is to push it into a form .."

and after some further substitution and algebraic manipulation,

> "Now, equation (1) is the form we adopted (for the variation of gain with frequency), .. and if we put that equation (1) into equation (8) ... and then, staring at it a bit longer, looking for ways forward, we have .."

Within this episode, the representations and techniques of mathematics were being used in a way to ensure the successful achievement of a specific engineering outcome. The purpose of the mathematical work was to reach a point where the physical variables, represented by symbols, could be arranged in a way that enabled a graphic representation to be produced. To achieve this, the mathematics had to be manipulated, stared at, pushed and re-grouped, in order to move forward and make things "easier to understand". The contrast in the specific discourse of professors was particularly marked,

> compare,
>
> ".. I was forced to .." (maths professor)
>
> with,
>
> ".. what I've done is .. manipulate it .." (engineering professor)

Here, the message from a mathematics professor seems to relate more to being *mastered by*, rather than acquiring *mastery of*, a tool.

The following vignette also illustrates a flexible movement between 'mathematical' and 'physical' objects that appears to be a key skill within engineering practice.

> The lecture was concerned with the effects of 'gain' and 'bandwidth' on the operation of a device called an 'operational amplifier'.
>
> "First of all what I'm doing, is to extract from this, a very important relationship - between f_t and A_0 and f_0 - and we do this by looking at this region where f is a lot greater than f_0 (refers to a graphical representation of gain A versus frequency, f). We're looking, really, over this range here (pointing at a region on a graph on the OHP), from about ten f_0 upwards. And, what we've got then, is this straight line asymptote and that's tantamount to say, that f over f_0 here is going to be rather greater than 1, to the extent that we ignore 1."
>
> The professor then went on to talk through a series of equations constructed from symbols such as A (which represents the gain of an amplifier) and f (which represents the frequency of an input signal to the amplifier). These equations were manipulated using straightforward substitution of other symbols and algebraic manipulation to arrive at a new equation. This new

equation represented a different way of describing the way the amplifier responded to inputs.

> "And we use f_t - as quoted on the data sheets - as a useful 'figure of merit', to compare the capabilities of different amplifiers, towards the higher frequency end. So if we want better high-frequency amplification, we have to use an f_t which is big enough. And this is why in the lab - those of you who are doing the bottle counter project - are not using a 741 because the poor, old 741 doesn't have a high enough gain at 40kHz to make it worthwhile."

In this lecture, students were presented with many ideas related to electronics which they were unlikely to have met before. In contrast, the mathematical ideas were based around school-level substitution and manipulation. The role of the mathematics was to represent an initial state - within the process of designing a circuit - and through manipulation, to arrive at a final state. No complex mathematical techniques (such as those presented in the mathematics module) were required. The purpose of the mathematics was to allow one to shift between alternative views of the response of a particular circuit arrangement. This episode points to the embedded nature of mathematical work in the ongoing engineering practice and the close relation between the mathematical symbolism and specific ideas in the engineering context, rather than the mere application of a general, intractable technique or tool. The process of working through the problem described above was an engineering process. The physical properties and concepts were represented by mathematical symbols and manipulated as if they were mathematical objects, but the physical objects were never 'lost'.

Both the lecture course on Analogue Circuits and the accompanying textbook made extensive reference to the ideas of *models* and *modelling*. Here, modelling was an alternate system of representations, which included mathematical symbolism, that could be manipulated either physically or mathematically. The physical and mathematical remained intertwined throughout the modelling process. For example, in working with a particular analogue circuit, an engineering professor would model by producing a different physical system which gave access to an alternative view of the circuit. Thus, modelling in the engineering sense appeared to be about a problem-solving approach, as illustrated below.

At the beginning of a one lecture, the professor moved onto discussing the problems associated with operational amplifiers,

> "Now, at the end of the last lecture, I was telling you about how op-amps in fact have various problems which we have to think (about) from a practical sense, and one of the things we have to do is first of all, is model these non-ideal features to understand what

influence these will have on the design of the circuit .. Then what we'll do is to develop an analysis of the circuit, using our new model - including the (??) effect - .. and find out what happens to the output.

So let's just look at first of all the DC problems associated with the offset voltage. Now the classical manifestation of this is that .. we would ideally expect zero out .. in practise we do have a finite output voltage, and there's nothing we can do about that (because it is due to the industrial fabrication process). What we can do however, is to model that effect and provide an external means of reducing the effect of that offset, to zero. .. Remember this is simply a model that enables us to conveniently carry out further calculations.

Now, it's important to understand that it doesn't matter whether we put this input offset voltage either in the plus input side or the minus input side, and indeed which way round the polarity goes. Because (of) the effect we observe, so long as we've got a mathematical model which corresponds to what we observe, that's fine."

As in the other examples of mathematics-in-engineering practice described above, the modelling approach, involving mathematical symbolism and techniques, is used by engineers to change a problems around, that is, the making of a different problem that enables an engineer to move forward.

The image of mathematics as a flexible tool was re-produced in students' mathematical practices within the engineering programme. The following example is taken from the laboratory project which accompanied the Analogue Circuits module and occupied 18 hours of laboratory time over a five-week period. Students were engaged on a project, in teams of three, to build an ultrasonic bottle counter. The project was essentially one of construction as students were provided with an overall circuit design, however decisions had to be made about the values of circuit components (such as resistors and capacitors) to put into the circuit.

Values for a capacitor and a resistor had to be chosen to fulfil the purpose of enabling a diode detector to work, but were constrained by another element in the circuit (a trigger). Other design constraints were important, for example, the weight, size and cost of the overall device, which meant that the capacitor value ought to be small. The constraint presented by the trigger was presented as a mathematical formalism in the project handbook,

$$C_dR_d = 352 \times 10^6 \text{ s}$$

This product (C_dR_d) was a fixed value and so an arbitrary resistance value could be chosen to then work 'backwards' to find which capacitor to use.

The handbook gave an arbitrary example,

Suppose that Rd = 220kΩ, then $C_d \approx 1.5nF$

The majority of students initially chose a resistor and a capacitor with values very close to this suggestion to put into their circuits. However, when they tested the output of this circuit they found that they did not obtain a large enough output signal to enable the trigger to work. Some groups tried substituting different values of R_d into the equation, to find new values for the capacitor. One group kept the value of the capacitor element constant and, with the rest of the circuit completely wired up, systematically changed the value of the resistor they used, referring constantly to the output trace on an oscilloscope until this output trace gave the output signal they wanted. Other groups used different strategies again. One group made their decision on values for R_d and C_d based on the time aspect of the output signal, another group used the voltage level of the output to make their decision. At the end of the project (i.e. five weeks) values for R_d varied between groups from 22 kΩ to 1MΩ and values of C_d from 1.5nF to 10nF. Some of these values remained the focus of heated debate within the groups of students.

In this vignette, the students abandoned the 'following of (mathematical) rules' in the engineering design context. According to the project handbook, the values of circuit elements, in this case the values of R_d and C_d, were constrained not only by a mathematical expression but by other individual circuit elements and by other design considerations. In practice, the mathematical formalism intended to guide students choice of values was initially used, but then discarded in favour of more practical considerations, such as obtaining the output that was needed. That is, students chose to prioritise design considerations over mathematical rule following. They did not feel 'forced' to stick to using the formalism and instead used the mathematics in a flexible manner, alongside other resources such as the read-out from an oscilloscope.

To summarise, this series of vignettes exemplifies the ways in which mathematics was presented and utilised as an integral aspect of an engineers' way of working. Not only did the lectures show how an engineer used mathematical techniques and a process of modelling, to learn about electronic circuits - and ultimately improve and design new circuits - they also modelled how an electronic engineer works in practice. The mathematical work was embedded in ongoing engineering practice and was utilised flexibly alongside other resources accessible to the engineering problem-solving process.

Summary

contradictory epistemologies

Within the engineering community, the view of maths appears to be one of a valuable means of achieving particular ends, it can be manipulated in various ways towards those ends, for example, it can be ignored when practical engineering constraints are deemed more important, or is malleable enough to allow us to "push it into a form" which is more useful. Mathematics provides a means for understanding how electronic devices work, that is, it enables an engineer to deconstruct the workings of a circuit, understand the contributing roles played by each circuit element in turn and describes potential outputs of the circuit as a whole. Through a combination of knowledge of physical characteristics and manipulation of mathematical representations, circuits can be re-designed to obtain the outputs required for a particular job.

In contrast to this image of mathematics as malleable in the context of use, students experiences of the mathematics programme was of mathematics as a discipline which forced users into certain ways of working. Whereas the discourse of the engineering professors was of the need to "push it into a form", that of the mathematics professors was of being "forced to introduce the idea" and to acquiescently "accept this plausibility argument". Thus conflicting messages were presented to the students. The professional mathematics community appear to require students to be subordinated to the practice of mathematics whereas the engineering community requires mathematics to be subordinated by students, in order to achieve success in the job at hand.

application of a general tool or situated practice ?

The discourse of mathematics-as-tool was evident at several levels of the students' experience, from the way the degree courses were organised to the presentation of mathematical ideas in the mathematics programme. Thus a global message offered to students is of maths-as-tool, to be learnt somewhere and used somewhere else. However, students' engineering experiences present an image of mathematics in engineering as one of much more than mere tool-use. Whereas the mathematical programme experiences of the engineering students offered an image of the usefulness of mathematics as being a property of the mathematics itself, the engineering experience is one of constructing the usefulness or applicability in-situ.

Evidence is emerging that teachers in some universities are moving away from a maths-as-tool view. For example, within the chemistry department at on UK university they are moving toward a an approach where "chemical intuitions and concepts inform, and are developed in, mathematics, and vice versa" (Templer et.al. 1997). They have questioned whether "the mathematical tools of, say,

Fourier analysis [are] necessarily the same intellectual thing when they are used by chemists as when they are used by mathematicians " (ibid. p.18).

As mentioned previously, the image of the general applicability of mathematics is also at odds with research conducted outside educational settings. The implications arising from this body of work present a challenge for students in education: to make links between mathematical ideas when experienced within different situations. This work is showing that not only are students not supported in this endeavour by the teaching and learning environment experienced at the university, but that they receive contradictory messages about how these links may be formed.

Implications

Epistemological messages were conveyed to engineering students through a multiplicity of means and analysis of these messages has given access to the nature of the community that students were being recruited into. However, conflicting images about the nature and role of mathematics in engineering were being offered. Further exploration of the tensions between these epistemologies may help to understand whether students difficulties with the mathematical elements of their studies relate more to the mixed messages they receive about the nature, purpose and use of mathematics, rather than any failings on the part of students.

The message of 'mathematics as a tool' was evident, however the practice of mathematics in engineering cannot adequately be described as mere 'tool use'. Whilst it would be spurious to view mathematical work in engineering as 'not maths', neither can it be conceptualised as just mathematics applied in a different context . Thus, programmes to encourage students to do better at maths in order to better understand engineering are likely to meet with only limited success.

From an enculturation perspective, formal mathematics instruction is not only about the delivery of mathematical techniques, but also about the shaping of beliefs about the status and nature of these techniques. The need for higher education teachers to reflect on their implicit assumptions of teaching and learning has been gaining strength in the UK. However, this current study is indicating that teachers need also to reflect on the underlying epistemological messages of the subject they advocate.

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