Strategic Perspectives on Engineering Education[1]

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Much is said about what should be included in engineering syllabuses, but less about the strategic aspects of engineering education. Yet, the effects of how a syllabus is structured, and how its delivery is administered, on students their maturation into engineers, can be significant. Strategic planning is crucial.

We need to consider what we want our engineers and engineering students to be and not merely what we want them to know. Planning a curriculum to impart knowledge is one aspect of education. Another is planning the delivery of the knowledge so that its accumulation facilitates both further learning and the development of persons, personalities, and professionalism. This is not more difficult, but it requires additional planning, particularly at the strategic level.

The order in which courses are taught and information conveyed is also important in another respect. Without particular pre-knowledge, a student does not possess the appropriate background to grasp certain information. The result can easily be misunderstandings and the 'learning' of incorrect 'facts', and, when it is, later corrections may be difficult to effect.

The need to fit graduates for industry is a major determinant of what is taught to students, and this can lead to a syllabus being packed with self-contained subjects, often delivered when circumstances allow rather than in a strategically planned order. However, Midwinter (1) says, 'The first degree provides at best an overview of a part of our subject field coupled with a foundation in some of its enduring principles.' Between these two 'realities' there is a tension that can only be balanced by taking a strategic perspective of the curriculum.

The extent to which those with strategic responsibility delegate curriculum planning to those who will do the teaching also has considerable influence. Not only does it introduce the biases of the teachers and, in many cases, limit what is taught to what they already know, but it also reduces the eagerness and, in many cases, the ability to carry out strategic planning.

Emphasising the importance of strategic thinking, this paper proposes a basis for planning an engineering curriculum to facilitate both the learning process and the development of professional engineers.

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A STRATEGIC PERSPECTIVE OF THE ENGINEERING CURRICULUM

Teaching is sometimes thought of only as imparting knowledge. But the education of engineers should be as much about the evolutionary development of people as about the transfer of technical information. 'What do we want students and graduates to know?' is a valid question. But so is, 'What do we want them to be?'

It is possible to identify three roles that engineering graduates are expected to fulfil: competent technician, responsible engineer, and professional engineer. To be a technician, a student or graduate must possess the skills and knowledge to *do* things, in the field and in the laboratory. To be a responsible engineer the graduate must have superior knowledge, at least in a particular field, and be capable of accepting responsibility, exerting authority, and making decisions. To be a professional, the graduate must, in addition to fulfilling the former two roles, adhere to high standards of integrity and behaviour, be able to manage higher levels of responsibility and authority, be ethically aware, and be capable of seeing their work in a broad social context. Although recent graduates are not considered to be Professionals (with a capital 'P'), they are expected to be professional - for example, in their judgement and behaviour. Yet in our curriculum it is unusual to groom students in professionalism.

The three roles are not mutually exclusive. Technicians must have knowledge, engineers must possess skills, and both are expected to display professionalism. But while knowledge needs to be disseminated throughout the curriculum, and discipline and professionalism should be inculcated from the start, there is a discernible evolutionary path. The roles define three stages of a process, and the basis of strategic planning. They also provide identifiable targets in educational and professional development. They are 'targets' rather than 'landmarks' because, although the stages are qualitatively distinct, they cannot be bounded precisely in either content or time. At no point in the curriculum does a student become a perfect technician or engineer; the acquisition of skills, knowledge and the ability to apply it, as well as professionalism, are all career-long processes.

But skills form a basis for later learning, and their development should be planned to facilitate it. Learning builds on what is already known, and the order in which information is presented can be optimised.

For planning purposes, the three stages may be considered sequential, but there is also concurrency. None of the roles should be neglected in any of the stages, but there should be a greater emphasis on inculcating technician's skills in the first stage, engineering knowledge and discipline in the second, and professionalism in the third.

The three stages do not need to be of equal duration, but defining them as one year each in a three-year course would seem convenient and probably about right, always recognising that they will overlap and that they signify changes of emphasis rather than mutual exclusivity. When apprenticeships were the order of the day, they lasted for several years, and, in the current plan, laying an adequate technical foundation would take at least the first year.

Temptation to make the skills stage short for the convenience of lecturers who prefer to concentrate on theory should not be considered.

The engineering stage could not be completed in a year, for the theoretical content, having begun in the first stage, would run into the third. Similarly, third-stage topics need to be introduced in the first stage, increased in the second, and included in all subjects as a matter of course in the third.

EMPHASIS IN STAGE ONE

It is likely that strategic planners (and others) in departments of the more traditional engineering disciplines (electrical, mechanical, civil) will be more familiar with the notion of a 'technician' and what it implies than those in software engineering departments. In software engineering generally, there appears to be little differentiation between the technician and the engineer, and many who do no more than write code or test systems are referred to as 'software engineers'.

It is neither trivial nor the purpose of this paper to define exactly what a technician (or an engineer) is. Further, an attempt to lay out a definitive syllabus would be counter-productive, for each educational institution needs to develop its own curriculum based on its specialities, the goals of its curriculum, and the branch of engineering concerned. However, stage one needs to include a substantial amount of practical work, to expose students to the components of which systems in their field of engineering are composed, develop their expertise in combining them to create systems, and give them experience in the use of tools, such as measuring equipment. The following list suggests a few first-stage topics, and the subsequent paragraphs offer explanations and notes on how they may be built on in later stages.

- Knowledge of components and their use in building systems;
- Testing;
- The theory and practice of measurement;
- The theoretical bases and practical applications of tools;
- Maintenance;
- Quality assurance.

In the first stage students should be taught about the components used in the construction of systems in their field of engineering. Technicians need to understand their characteristics and functions, be practised in their use and interconnection, and be competent in using them in designing and constructing simple systems. In the second stage, the focus should turn from the technician's knowledge of components to the engineering function of design, whose goals should not be taught only as the achievement of technical functions, but as including other attributes such as safety and reliability, and the importance of architecture, and the need to meet well defined and well understood objectives. This requires decision-making based on an understanding of risks and trade-offs. In stage three the subject could be taken further by the consideration of the ethical, political and societal aspects of modern technological decision-making.

Testing is recognised as a fundamental requirement in many engineering curricula, but this is not invariable. In second-year (software engineering) projects with which I have been associated, it is not uncommon for there to be no emphasis on testing and no requirement for test plans or results to be included in group-project reports. Such neglect reinforces the notion that testing is an extra activity, not necessary if it is supposed that the job has been done well in the first place. Yet it is important for every technician (and engineer) not only to be competent in testing the sub-systems and systems that they build, but also to understand the engineering need to do so. The twin goals, of meeting a requirement and demonstrating that the requirement has been met to the necessary tolerance, demand this. The engineering management requirement, to plan testing (and its budget) to be commensurate with system design goals and with the criticality of meeting them, should be the subject of the second stage. Indeed, the importance of integrating the planning of integration testing and system design, so as to facilitate the efficiency and effectiveness of testing, should be emphasised from the start.

An essential engineering principle is feedback, and all technicians need to know this and to be competent in acquiring the necessary feedback through measurement. In stage one, they should be taught the theory of measurement and given practice in how to measure (in their particular field). They should be taught to distinguish between direct and indirect measurement, to recognise the assumptions implicit in the measurements that they make, to question their suitability for the task in hand, and to understand their limitations. The technician's role is not merely that of doing practical things but also of learning to think about how and why they are done and how appropriate they are to what is needed. Practical work should be designed to engender such thinking. In the second stage the subject should be taken further by giving measurement a higher-level purpose, for example planning its use to determine if design goals have been achieved, or to gain confidence that design measures have reduced certain risks. Measurement is a key element not only in the proving of systems but also in experimentation, and in stage three its use in research and the furtherance of knowledge may be emphasised.

Carrying out testing and measurement raises the need for technicians to develop an understanding of planning processes. For example, in software development it is not possible to acquire adequate confidence in a system through testing, so emphasis is placed on 'measuring' and controlling the development process. If students are instructed to do this without being taught the reasons for, and limitations of, their actions, they will form the wrong conclusions about what they can derive from them. Learning to recognise and question assumptions is a necessary part of a technician's education process - though one not always inculcated.

Tools are a significant part of a technician's armoury, and no technician's education can be considered complete without instruction on tools. However, such instruction needs to fit the technician to select appropriate tools and not merely to use tools provided by others. Each tool is designed for a purpose and, by definition, is limited when applied outside its scope. Education must guide students to enquire into the principles and assumptions behind tools as well as to be dextrous in using them. It should make them both capable of selecting the right tool for the job and ready to reject those that are not. Yet, many graduates (certainly in software engineering) are not taught to be discerning, and are introduced to tools as though they can replace fundamental principles. Fundamentals of engineering are the ability and inclination to think and to make decisions, and if education does not set out to inculcate these, it is not engineering education.

To omit maintenance from an engineering curriculum is to suggest that design is always perfect and permanent. Yet, recognising and observing symptoms, reasoning about them, diagnosing their causes, identifying and analysing the options for correction, and choosing, implementing and testing corrective actions, are not often taught. They should be, in stage one, for they provide an essential foundation for an understanding of the crucial stage-two engineering function of design.

Quality assurance, in its fullest sense, is not easily appreciated by first-year students, so it is as well to defer it as a formal subject until later in the curriculum. However, the culture of demonstrating that goals have been achieved should be inculcated from the start, and an essential aspect of this is the collection, structuring, storage, and use of appropriate evidence. It is from testing and measurement that much of the evidence is derived, so it is in the context of these disciplines that the essentials of quality assurance should be taught - without ever mentioning the word 'quality'. First-stage courses need to be designed to lay the foundations for later courses, by introducing the principles to be explained theoretically in them.

The above are only examples of stage-one education. The topics mentioned may not comprise formal subject modules, though in some cases they would. What is most important is that fundamental principles should be taught, so that right from the start students develop an understanding, not for this or that subject but for *engineering*. Practical work should be used to develop skills that reinforce and inculcate the principles, and the planning and execution should have clear goals - of developing competent technicians and paving the way for later stages.

EMPHASIS IN STAGES TWO AND THREE

Just as the development of technicians' competence does not cease at the end of stage one, the development of an engineer does not commence at stage two. As mentioned above, the seeds of the main focus of the second stage - topics such as design and the planning of measurement and testing, not merely to achieve technical results but also to gain efficiency and effectiveness - should already have been sown. In addition, specialist subjects will no doubt also have been presented.

University education often gives the impression that design is a function to be carried out by an individual. But the notion of subsystems reveals a strong requirement for planning, delegation, negotiation, teamwork, co-ordination, and documentation. It also emphasises the importance of architecture. Identifying options, understanding their merits and disadvantages, and making choices between them are also called for. Thus, addressing design, testing and measurement at the second stage demands a focus on responsibility and authority, project management and management in general, and decision-making. Further, subsystems raise questions about the interfaces between them, the assumptions on which they are based, and the need for interaction and communication. Thus, the concepts of communication protocols and layered communication models arise naturally and may be taught in context.

In addition, stage-two education should develop the stage-one diagnostic skills into the ability to identify, define, and express problems, and to specify and design solutions. This is closer to engineering than the small ability to solve theoretical problems set by others on which so many examination questions are founded. In industry it is frequently the case that problems once specified are trivial to solve, but engineering education fixes on a problem-solving ability, with the result that graduates are not educated, cultured, or confident to tackle real industrial problems (Redmill (2)).

The development of engineering knowledge and ability does not end with stage two, but in the third stage there needs to be a leaning towards the inculcation of professional values. This should be done not merely by introducing new subjects, such as ethics, but, importantly, by making explicit, in different contexts, the ethical, legal, political, and societal issues involved in engineering. The Institute of Education, in research carried out for the Welcome Trust (3), emphasised the need for ethical issues regarding the use of modern technology to be discussed in schools. Clearly such discussion should be continued in engineering degree courses and, by stage three, should have arrived at a point of informed debate.

Risk issues are a significant part of such debate, and a risk course at stage two should not be limited to quantitative risk analysis but should include the topics of risk perception and risk communication that arise from research in the social sciences. It is necessary for a modern engineering curriculum not merely to instil technical competence but also to prepare graduates both to fulfil the engineering profession's responsibilities to society and to understand and respect society's expectations of engineers. At stage three, the issue of professionalism should be included in all subjects, and not merely in non-examinable liberal studies.

Other topics that should be covered by the end of stage three are systems engineering and human factors (2). It is important to be able not only to see systems in the large - in both their technical and social contexts - but also to recognise the multi-disciplinary nature of successful socio-technological systems. Familiarity with the psychology of human behaviour is essential to design, the assessment of risks, and dealing with customers. 'Sustainability' is also a topic of current concern and would seem appropriate to stage three.

The emphasis of each stage should be reflected in its examinations. For example, stage-two questions might require students to state the assumptions made in designing a subsystem in isolation, or in planning its testing. They could be asked to describe the risks and advantages implicit in the assumptions, or to show how planned and methodical integration testing may reduce the risks at the expense of time. At stage three, questions on design might require a consideration of environmental factors.

The above is not an attempt to define a syllabus but merely to propose a basis for strategic planning and to show how it might be carried out and focused. Specialist technical subjects will, of course, be delivered in stages one and three, as well as in stage two, but these are not discussed here, except to mention the need for them to include the emphasis of the stage and for their delivery to be carefully planned. There are good reasons why the progression of engineering education should be planned, and these are considered in the next section.

THE IMPORTANCE OF ORDERED PROGRESSION

Good teaching is facilitated by good planning, and the successful transfer of knowledge is facilitated by the order in which material is taught. 'A great deal of research indicates that, once formed, people's beliefs change very slowly, and are extraordinarily persistent in the face of contrary evidence … New evidence appears reliable and informative if it is consistent with one's initial belief, whereas contrary evidence is dismissed as unreliable, erroneous or unrepresentative' Slovic et al (4).

In teaching, care needs to be taken of how students' beliefs are formed. If something is taught for which they don't have the background, they are likely to form incorrect 'understandings' - with two results. First, the misunderstandings are likely to persist, perhaps throughout life. Second, the misunderstandings will create a foundation on which even greater false certainties may be built.

How much re-teaching does it take for such misunderstandings to be unlearned? I know of no research that provides the answer. But research does suggest that it could be rather a lot. Slovic and Tversky (5) invited subjects to make a choice. Then, having made it, they were presented with strong authoritative arguments against it. When invited to review their original choices in the light of the new information, very few changed them.
We are often deaf to what contradicts what we think we know.

I am not aware that this problem is widely recognised in teaching. To address it, a strategic approach is required for scheduling subjects, not merely within a stage of study but across an entire curriculum. Topics should not be taught until the necessary foundations have been laid via the teaching of prerequisites - for which, the prerequisites must be identified. Courses need to build on each other, and, if taught in the wrong order, they can create false knowledge structures.

INTRODUCING NEW SUBJECTS

The three-stage model (technician, engineer, professional) and the principle of ordered progression together provide means of planning the introduction of new subjects into a curriculum. Subjects such as project management, the psychology of human behaviour, risk, and systems engineering (2) are now appropriate to engineering education. In introducing them, we should not ask, 'Where can we fit them in?' but, 'To which role (or stage) are they first appropriate?' and, 'What needs first to be taught for the principles of the subject in question to be understood?' A further relevant question is, 'What later courses may depend on this course, and what needs to be introduced in this course to facilitate their presentation?' The strategic approach also forces us to examine the necessary credentials of teachers, and to plan their acquisition or development.

DISCUSSION

A curriculum requires strategic planning with a view not only to what students and graduates should know, but also to what they should be.

Three stages of an engineering curriculum may be identified. By the end of the first, the student should be a competent technician, with the skills and understanding on which to base the development of an engineer. The second stage should address the qualities that an engineer requires, over and above those of the typical technician, such as judgement, the evaluation of trade-offs and decision-making, the specification and control of tasks and small projects, design, systems engineering, and the principles and application of quality management. The third stage should introduce those issues that are essential to a modern professional engineer, such as ethics, the effect of technological systems on society, societal decision-making, and the legal and political implications of the field of engineering in question. Theoretical and practical instruction should be planned to meet these ends.

Once a curriculum - in whatever field of engineering - is structured in these stages, the presentation of information can be planned to facilitate the students' development as technicians, engineers, and professionals. Each facilitates the learning and development of the next, so planning the development of the person as well as the presentation of information carries considerable advantages.

Nor are the advantages limited to personal development. If information is presented to students unready for it, they may form misunderstandings, and research shows that these can be extremely difficult to alter. Only strategic planning can prevent this, by ensuring that, at an earlier stage, students receive the necessary prerequisite skills training, personal development, and information. Then the chance is increased of their understanding what is taught and deriving the 'correct' mental models from it.

Strategic planning of the engineering curriculum is not a luxury, to be carried out if time and circumstances allow, but an essential part of the functioning of every engineering-education department. It requires good teachers who must understand, contribute to, and work within the strategy. For this they need to work as a team, which requires the strategic planner to be, as in comparable industrial circumstances, a project manager, leader, and team-builder. Of course, this presupposes that there is a defined strategic planner of the curriculum, who has the authority to do the job and to implement the plans, the will to do so, and a clearly defined responsibility to higher authorities (who, in turn, should enforce the requirement for strategic planning and implementation).

Further, once it is recognised that the goal is for the novices who arrive at the commencement of stage one to leave as professionally-minded graduate engineers at the end of stage three, it becomes obvious that a professional culture needs to be inculcated from the start. Norms can and should be taught, but culture is promulgated by the example of living by the norms. Lecturers are role models, whether they like it or not, and, for an engineering culture to be developed, they must show themselves to live by the norms. They must also place high expectations on the students, and the strategic planners must place high expectations on the lecturers. The quality of engineering education depends on its strategic planners.

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