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Practising Practice by Design*

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There is a compelling case for cultural change in the engineering profession if it is to continue to have an important and central role in the technological world it has helped create. Such a change must begin in the educational experiences that shape and prepare students of engineering for professional practice. But any change to better equip graduates for practice has to recognise and address the reality that, at heart, the fundamental purposes of the academy and the profession-in-action are different. This paper proposes that studies in design are an effective and productive way of addressing this central dilemma in professional engineering education. It draws on reflected experience in teaching mechanical engineering design at the University of Queensland to set up a framework for learning design. It is argued that, in professional education, the academy must be committed to the requirements of life outside and that the disciplines informing the proper practices of academe and of the profession share a common purpose. Both enquiry and application are important in every activity of life. This paper, therefore, constructs a map of the relationship between practice as performance in academe and the profession. It transforms the map to apply specifically to design, defining two distinct but contiguous regions featuring problem-solving and problem-setting. A learning experience/time path is charted on this map to plot the directions a design-as-preparation journey needs to follow. At each phase of this journey, the general approaches adopted at the University of Queensland are related. The paper concludes with reflections of some recently graduated students as they end one journey and prepare to start another.

INTRODUCTION

THE MOST COMMON path to professional engineering practice is through a four-year baccalaureate degree programme at a tertiary institution. While there are variants on this idea—three-year programmes, sandwich courses (periods at university interspersed with time in industry) and part-time courses, for example—preparation for practice in engineering mostly takes place in an academic setting, removed from the workplace. The dilemma in education arises simply and starkly from this separation. The would-be engineer learns about engineering and seeks to gain the special knowledge and skills judged necessary to engage in it in an environment that purposefully differs from that of professional practice. It is not the purpose of the academy to do engineering. And, while it is true that the practising engineer learns by doing, the purpose of industry employment is not to teach but to engineer.

This difference in purpose is clearly evident to those different groups who attend the academy. The majority of each year's graduates of engineering schools seek and find employment in industry. A small percentage of each group may embark on postgraduate studies immediately and therefore remain in academe, but most are eager to depart that familiar environment to take up the challenges of an engineering career outside the academy; that has been their goal throughout the course, and that was their reason for studying engineering in the first place. To most students, their time at the university is to prepare them for employment as a professional engineer. Their interactions with lecturers and tutors are more or less continually conditioned by this expectation. To students, the university experience is something of a rite of passage, leading to induction into another world. It is an experience limited in time, sometimes interesting, sometimes pleasurable, often to be simply endured, but always leading away from the academic world.

For the faculty, on the other hand, that world is their life. To them, the departure of each group of graduates to an outside world is an occasion for pride, tinged with some sadness. There is the satisfaction of a job well done, but very soon the proper demands of the next group of students command their attention. The faculty's experience of academe is conditioned by a sense of continuity. While their interactions with individual students have a short time-span and lead inevitably towards a parting of the ways, the pattern of their professional lives remains fairly stable. It is in the academy that their careers are set. What they achieve within the academy is the measure of their success, while for their graduating students success is measured by what they achieve after the academy is left behind.

Green [1], however, in a contribution to the *Modern American College* on the acquisition of purpose and the educational process, claimed

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that this 'peculiarity of the academic institution' appears to have to satisfy two different and perhaps contrary purposes, and marks in fact an essential tension rather than some kind of failing. He argued that professional education, that prepares students for professional practice, requires a setting in which practice, in the sense of preparation, is permitted to exist alongside practice in the sense of performance. More positively, it is the performance of faculty in their practice in academe that creates a learning environment in which students can develop the intellectual qualities required for their practice in industry. Green acknowledged that this fact indeed presents dilemmas for the student, the teacher and the academy and asked 'how can the academy foster the acquisition of (different) human purpose in the face of such a fundamental difference?' He framed his answer on the notion of purpose in terms of competence, discipline, practice, service and the exercise of judgement.

For Green, the competent exercise of any art or craft requires the acquisition of its disciplines. Discipline is the rule that provides order in the way things are done. Being good at any practice implies both the acquisition and exercise of its corresponding discipline. Each practice is given form and structure by a discipline and each discipline specifies a set of virtues or operating principles required for excellence—that is, for competence—in that practice. He then suggested that, for students to acquire competence in the disciplines of any practice, they need a setting in which errors of judgement, skill and inference are without serious social consequences, and added: 'The academic institution is just that kind of setting' [1]. Nevertheless, preparation and performance are brought closer together if the opportunities for both entail: (1) 'a discipline to be acquired, (2) a problem that is 'real' and not merely 'made up', and . . . (3) some audience beyond the student's immediate academic community, a public prepared to take notice of the work undertaken and to act on it' [1]. Professional education should thus be concerned with the acquisition of purpose, but one that makes sense within the context of a public. Green argued that it is this idea of service that unites the purposes of students to the purposes of those already within the academy. To him, service is the fundamental purpose of the academy, whether the purposes of students are aimed at the practices contained within it or at those beyond it.

This suggests that students of engineering might best acquire the disciplines that are essential to practice in industry by working within the academy on tasks that are of direct interest and consequence to the wider community. Furthermore, those learning experiences must at the same time engage the discipline of practice of a faculty focused on academic pursuits; that is, the disciplines of professional practice themselves become the object of study. The contemporary research-based university culture is not really conducive to either of these things. Service is commonly defined as an abstract search for truth and research is predominantly restricted by a science worldview to an absorption with knowledge [2]. This paper proposes that, together, learning and scholarship in engineering design can productively exploit Green's 'essential tension'. This premise is based on experiences in mechanical design teaching in the Department of Mechanical Engineering at the University of Queensland. The Department has maintained a commitment to undergraduate design through several decades and also has a strong research group whose primary interest in 'practice' is interpreted to mean in both performance and preparation, and in the links between industry and academe that promote mutual learning [3].

This paper will now look at the disciplines underpinning the practice of design, first as performance and then as preparation. Given the unity of purpose attending educational programmes that seek to engage community issues, it will seek to show that design studies bring together the practices normally separately identified with the academy and the profession-in-action to form a seamless interface on the fabric of service.

DESIGN AS PERFORMANCE

For an academy committed to the fundamental requirements of life outside its confines, its disciplines are not merely the various bodies of knowledge, although academic disciplines are often conceived this way, but rather are also related to a practice like any other discipline. In this case, the related practice is enquiry and the disciplines specify a set of virtues or operating principles required for competence as human beings engage in enquiry. As Green said, the virtues cultivated by the practices of enquiry are important in every activity of life. Similarly, the disciplines of the profession-in-action are not only associated with the possession of specialised knowledge, although again professionalism is often defined so, but are also related to a practice, in this case the practice of application. Since that practice is concerned with what ought to be done (rather than what can be known), it too cultivates virtues of utility in all walks of life.

So, while enquiry might be the special province of academe, and application the special province of the profession, practice in each employs the disciplines of both. The two disciplines share a common purpose in ordering intellectual engagement on an issue of consequence. Fig. 1 illustrates this relationship between practice and performance.

The virtues of the disciplines which order the conduct of enquiry might include assiduous attention to fact, a concern for truth, a search for organising principle and a willingness to delay formulation until all the data are gathered in [1].

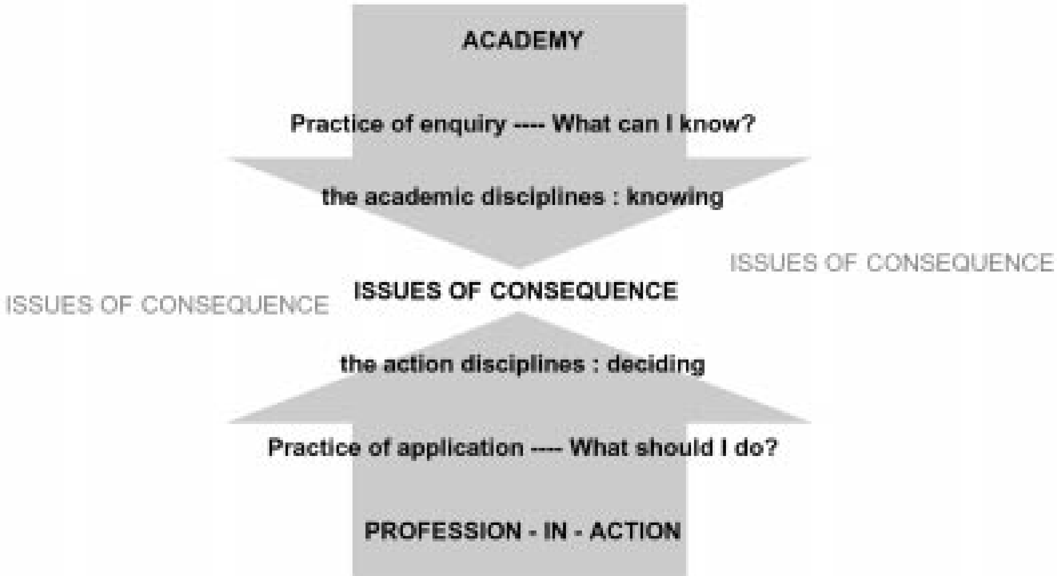

Fig. 1. Practice as performance.

The virtues of the action disciplines which order application stem from a pervasive uncertainty and include the ability to choose and take action without full knowledge, to assess the risk of such action, to make sufficient sense of confusion and, above all, to exercise sound judgement. While each set of virtues can be thought of as belonging to and defining a different practice, it is also clear that each practice demands, to a significant degree, the possession and cultivation of the virtues of the other. It is also worth noting that a virtue in one practice may be a vice in the other; for example, as Green remarked, waiting until all the data are in to make a decision is a virtue in enquiry but can be a vice in application because, in those circumstances, the data are never all in. In any case, though, it is apparent that there is no exclusive realm for practices and the exercise of their different disciplines. In addressing matters of interest to the wider community, performance in academe necessarily overlaps and merges with performance in application.

The same qualities of distinctiveness and connectedness characterise the relation between enquiry and application, if the general picture of Fig. 1 is transformed to the specific, to that perhaps most distinguishing activity of engineering, design. Both knowing and deciding are central to design. A design grows out of what has gone before. The process is fundamentally evolutionary and knowledge enshrined as good practice and guiding principle conditions and directs its advance. However, that advance is always through uncertain territory, for design intends what has never before existed: a new artefact or system of utility. It goes beyond the security of the known, otherwise it is not design but reproduction. To do that demands the exercise of principle, judgement and choice. Design builds solidly on the past and, imagining the future, engages the practices of enquiry and application to bridge the two. The essential structural elements of that bridge can be usefully defined as problem-solving and problem-setting, underpinning, respectively, enquiry and application. Problem-solving, or the discipline of theoretical reason [1], focuses on the process and content of enquiry to reveal things that are known and knowable. Problem-setting, or the discipline of practical reason, seeks to express purpose and meaning, not to solve problems but to find them, to decide where the future must be. Fig. 2 shows the design transform of Fig. 1 to produce a practice-as-performance map for design.

While the upper and lower regions of the map are contiguous, with no clearly defined separating boundary fence, the two parts do have distinctive ‘topographical’ features. Schon [4], in illustration, colourfully described a high ground occupied by instrumental problem-solving where ‘manageable problems lend themselves to solution through the application of research-based theory and technique’ and a swampy lowland where ‘messy, confusing problems defy technical solution’. The intellectual qualities which feature on the problem-solving high ground are primarily associated with method and content. As such, they are essentially analytical. Kolb [5] reported that hemisphere-dominance brain research has found that the brain seems to operate on two distinct and dialectically opposed ways of understanding the world. One way of functioning, described as left-mode, is abstract, symbolic, analytical and verbal. It is this approach that seems to dominate in theoretical reason. It is solidly grounded on certain competencies (viz. specialised knowledge and operating skill) and its concerns are often mainly epistemological, seeking appropriate ways of enquiring. In the problem-setting swamp, in contrast, meaning and purpose constitute the prominent features. Right-brain functioning, which is occupied with

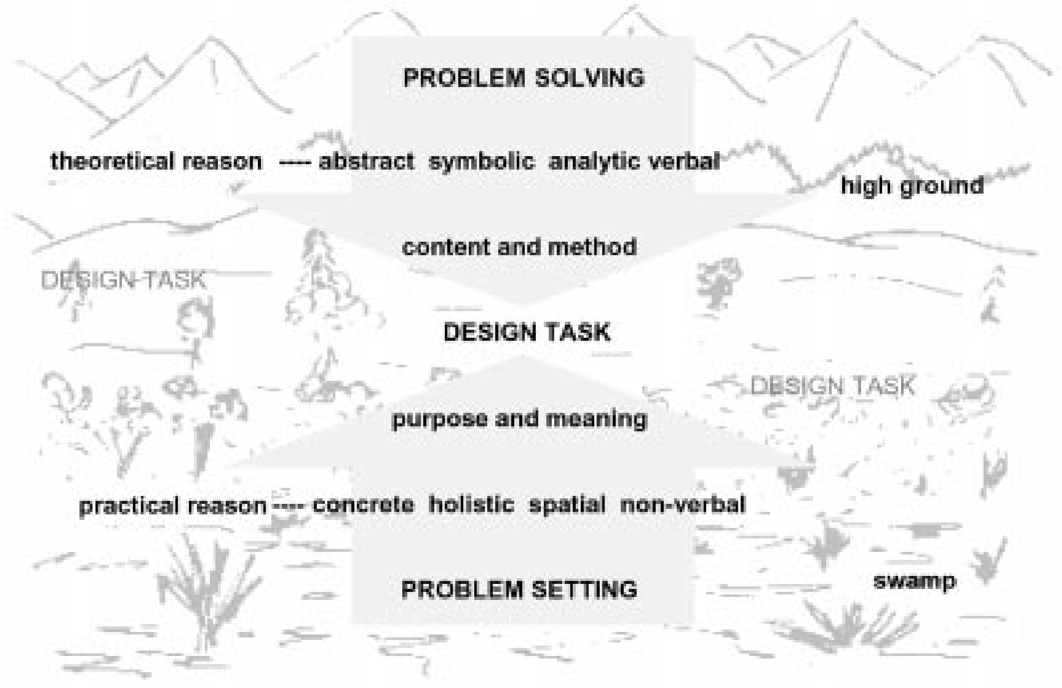

Fig. 2. Design as performance.

concrete, holistic, spatial and non-verbal processes, predominates in practical reason. Its special competencies are sense-making, good judgement and wise direction [6], and its concerns are ontological, aiming to uncover the nature of things.

Design as performance can thus be imagined as a journey through this varied landscape. Often and necessarily the path leads through the swamp, because it is here that uncertainties in direction must be resolved. Equally, the designer must also travel the high ground, where those decisions about direction can be subjected to scrutiny from the more abstracted perspective of enquiry. Importantly, though, real progress can be made only from a willingness and ability to journey through both domains. The designer-in-action has to be able to move freely and with confidence from swamp to hill and back. Turning now to the preparation of students of engineering for professional work, it is precisely this particular quality of design, the seamless conjunction of problem-setting and problem-solving, that makes it so effective as a vehicle for building 'the common purpose' in engineering education that links the academy to the wider community.

DESIGN AS PREPARATION

During their time in the academy, students also make another sort of journey. From studies at Harvard over a period of 20 years, Perry [7] and his fellow researchers were able to describe the typical course of development of students' patterns of thought. They suggested that students construct coherent interpretative frameworks through which they make sense of their educational experiences and that these frameworks are constantly revised over time. The revisions, although exhibiting great variability between students as to rate and extent, fit into an orderly sequence of structuring of meaning from the relatively simple to the more complex. The resulting scheme of intellectual development was envisaged as a map of reinterpretations of the world and of the challenges that precipitated them. The journey that individual students embark on takes them a greater or lesser distance along a path traversing the map, through various positions, or 'evolving ways of seeing the world, knowledge and education, values and oneself' [7]. Subsequently, the scheme has been found to be characteristic of the development of students' thinking throughout a variety of educational settings, including engineering.

Perry's scheme of cognitive and ethical development defines nine positions, 'evolving ways of seeing', spread along a development dimension encompassing dualism, multiplicity, relativism and commitment in relativism [7]. Students typically enter academia with a dualistic view of the world in which things are right or wrong, black or white, and truth is known to the Authorities. Some way along the development dimension, this dualism is modified by the discovery that even such Authorities may disagree and that uncertainties and different opinions are real. This leads next to a reactive multiplicity in which uncertainty is pervasive to the extent that everyone's opinion seems to be as good as the next. Relativism grows out of the realisation that this is not so, but knowledge is now seen as qualitative and

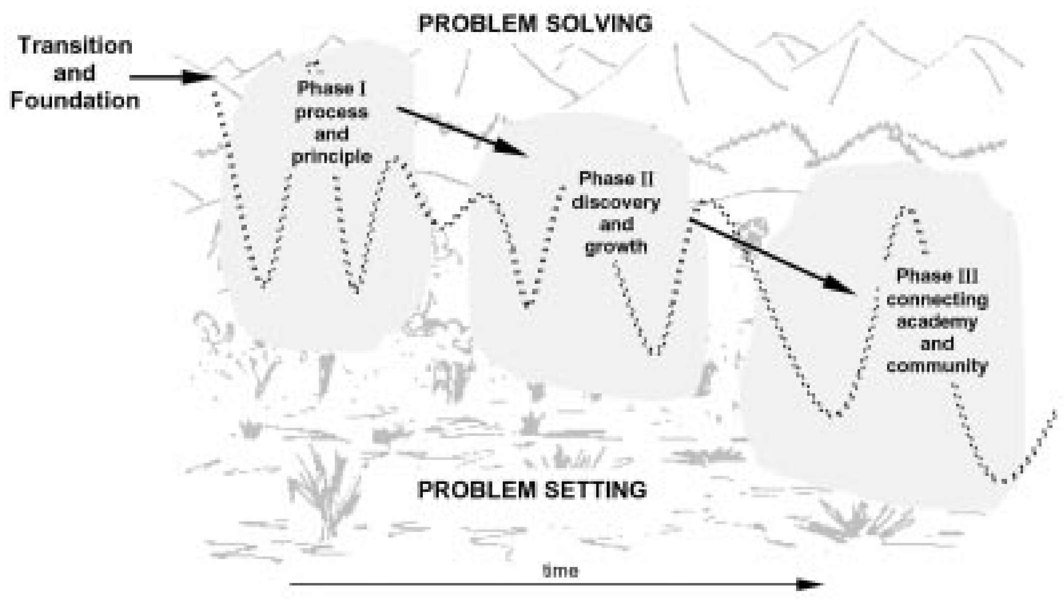

Fig. 3. Design as preparation—the journey.

dependent on context. However, patterns may be discerned which allow for analysis and comparison. Commitment in relativism describes a view in which each may assemble evidence from a variety of sources, including authority, now with a lowercase 'a', to make up his or her own mind. There is an acceptance, too, that new evidence may appear to challenge what has been previously decided.

A journey along this path thus involves the successful resolution of quite fundamental changes in worldview, and the distance travelled is a measure of maturation. It is a significant, formative experience. Of course, not all students will want to make the journey, and of those who do some may not get very far in their time at university, but in general it seems that an expectation of movement along this path underlies much conventional course structure, although perhaps only implicitly. As a consequence, most engineering programmes begin with mathematics and the basic sciences, where truth appears incontrovertible, move on to problem-solving in the engineering sciences, where some doubts creep in, and address the messy uncertainties of actual practice in the later years, if at all. The picture of design as performance that emerges from Fig. 2, however, shows that here lies an opportunity for educators to explicitly match and lead this pattern of intellectual development. The disciplines of design necessarily build on and encourage that journey. Fig. 3, therefore, superimposes a learning experience/time path on the practice-as-performance map of Fig. 2 to serve as a pedagogical guide for design course construction.

The path supposes a four-year programme in which subjects specifically dedicated to design begin in the second year and continue to the fourth and final year. This structure assumes that the first year for students is essentially a time of transition to academic culture. Properly done, it provides a secure base for development by setting the largely mathematical and scientific aptitudes of entering students in an engineering context. The content remains attached to facts and familiar problem-solving techniques but focuses on important basic concepts in the engineering sciences. Expectations, faculty and student basically conform to the dualism positions of Perry's scheme. It is in the second year that the challenge to that way of thinking may begin in earnest.

There are three distinct phases represented on this suggested design-as-preparation path in Fig. 3, more or less corresponding to the second, third and fourth years of a four-year programme. Phase I, building on the transitional first year, is located mainly in the problem-solving region, with occasional excursions into problem-setting. The idea is that students can explore some of the uncertainties always attendant on design from a secure base of accumulated knowledge and familiar analytical techniques. At the University of Queensland (UQ), this phase has, for some time, been approached by engaging students in a sequence of design tasks, mostly individual but at least one a small group effort which purposefully leads them away from single-solution puzzles towards the open-ended satisfying of defined needs set in the context of realistic constraints. Ideas such as force transmission, force flow, design and safety factors, design for cost and safety, design to codes and the use of standard components underscore their experience in learning design by doing, as they follow the design cycle of propose, test, learn and progress.

Phase II is the watershed. Here problem-setting, deciding what and why, is given exposure equal to analysis and good practice. Equipped with the foundations of design process and principle cemented by a good understanding of engineering science and technology, students by this stage are (hopefully) now ready for a different sort of challenge, to travel into uncertain territory without having the path set out for them. It offers an opportunity for self-discovery and growth, and indeed experience at UQ indicates that students quickly recognise the changed nature of the thinking that is required of them. Many relish the prospect.

At UQ at this level students work individually on a single, semester-long design task, typically to design, document and draw a complete machine to perform a specified operation. The system usually comprises an effector of some sort driven through a mechanical transmission from an IC engine or electric motor. The lecture series is carefully coordinated with design stages. It is intended to pilot the students' advance across unknown territory through four distinct but integrated modes of thinking. The first, and most eagerly sought by students, is concerned with ideas about how the set task might be accomplished (i.e. what assemblage of components will do the job and what size they ought to be). It begins with estimations of power and space to explore the boundaries of the required system. It canvasses feasible arrangements to satisfy function based on good practice while leaving the actual choice of system to the individual student. Such choices must then be justified, so a model of design is developed on a 'design for function (synthesis)—design against failure (analysis)' framework. Here function and failure may be broadened as necessary to include ergonomic, economic and other factors, as well as physical acceptability. The second mode, at a higher lever of abstraction, has to do with non-verbal thought. The student designer must develop the ability and habit of creating pictures in the mind, for, as Ferguson [8] described in his book *Engineering and the Mind's Eye*, it is as mental images or visions that designs first take form. In the author's experience, engineering students generally have highly developed analytical skills but poorly developed spatial ones. First-level design begins to correct this imbalance by encouraging and requiring design sketches. This second subject takes a further step, aiming by repeated example as well as by requirement to effect, over time, progress through a design of substantial scope by a habitual interplay between pictorial representations and modelling for analysis. At the next level of abstraction, and only episodically made explicit during lectures, are ideas about the design process itself. These interludes are designed to draw out general principles about what defines and distinguishes the intellectual activity of designing by setting the students' experiences within the context of technical, social and personal design domains [9]. At the highest level of abstraction, there is an underlying but express purpose, which permeates the entire delivery and organisation of the course, to promote progress along Perry's path of intellectual development. A disciplined commitment to reaching an individual, prudently examined and satisfyingly complete outcome to a challenging design task is often a memorable experience in students' lives.

Phase III moves the focus further into Schon's swamp, where the design process is dominated by complexity arising from the consequences of its outcomes and the uncertainties through which it must proceed. It is now that the necessity for principle-based practice will become clearly evident as students face design decisions which embrace the full richness of the engineering design environment, wherein competing needs and responsibilities demand respect for differing values and the exercise of sound judgement. The final-year elective subject at UQ, in attempting to realise this focus, makes the connection between design studies within the academy and the wider community. Students work in groups of four over the whole academic year on externally sponsored projects. Prior to the beginning of the academic year, a list of design topics is formulated from consultations with interested industrial contacts or other community representatives, often alumni who well understand what the students will face. Participating students form their own work group and agree on a choice of topic. From then on, each group has an ongoing responsibility to liaise with their sponsor, to define the design task, to construct an appreciation of the design environment and to negotiate deliverables. These might be prototypes, mock-ups, a set of working drawings or a combination of all three, accompanied by a final report to the sponsor comprising recommendations, costings and technical justification. There is always a wide variety in each year's projects; for example, in one year designs were required for a turf aerator, a moving bed truck trailer, a children's gait trainer for a local hospital, an inflatable antenna for satellite communications, a scramjet ignition system and an in-oven compression rig for large transformer construction. While such diversity is intentional because it adds tremendous interest for all concerned, underlying the organisation and operation of the subject there lies a constant expectation that each group, working on its own topic, can learn to make judgements, of consequence to informed others outside of the academic milieu, without the penalties for error that are normally associated with commercial practice. There must be time and opportunity to develop the qualities of sound judgement and this final year capstone subject aims to provide them.

The role of the academic, therefore, changes at this senior level. There are no formal lectures; rather each group meets with the lecturer separately, on a regular weekly basis. At these sessions the lecturer is firstly a design coach and professional mentor, seeking to guide and assist each group's journey through a territory most often characterised by the need to make decisions under conditions of uncertainty, and only secondly a technical adviser. In contrast to the first-level subject, where the students' confidence is firmly anchored in technical problem-solving ability, here the focus is on problem-setting to establish competence and confidence in dealing with both the technical and non-technical realities inevitably met in their projects. Cohesion within the wider class is maintained by regular combined progress reports, giving opportunities to persuade a critical audience of peers and gain experience in dealing with their sometimes trenchant criticism. In parallel with group work, each student individually researches and writes two papers over the year, one on design methodologies and the second concerning reflections on their own intellectual growth while in academe, with particular reference to the design course. The structure is thus expressly designed to prepare and empower the individual for transition to a professional career in engineering.

PRACTISING PRACTICE BY DESIGN

There is a very pragmatic conclusion to the engineering design process. The outcome, whether artefact, machine or system, has to pass the ultimate test of fitness for its intended purpose: it has to work! It is entirely proper, then, for the premise set out in this paper to be subjected to the same scrutiny. The paper has expounded on a pedagogical framework for learning design which has emerged from a conjunction of the academic discipline of enquiry and the practical discipline of application to issues of consequence. It claims that this approach fits students of engineering for the practice of engineering. Well, what do the students think? The following are extracts from papers written by a final-year group nearing the end of their journeys of preparation for practice. It seems appropriate to conclude on this note.

Gareth:

'It is particularly important to 'get it right' in design education since understandings that emerge are essential to becoming an engineer. In fact in my opinion most of the learning that I achieved during the study of engineering happened during the design course, despite its being only about 10% of the total credit points gained. I feel that this is so since design developed critical and creative thinking, involved practical exposure to professional engineering practice, introduced the social aspect of engineering through group work, and assimilated the theory of many subjects. I consider the undertaking of the design course right through to 4th year fundamental to my development as an engineer and as a person.'

Peter:

'The academic environment does not lend itself easily to the teaching of the final phase in an engineering design when theoretical ideals must become practical possibilities. Students accustomed to dealing with problems which have well-designed solutions, can too easily be led to believe that the design process ends with a set of neat drawings. Those trying to bridge the credibility gap between design specification and final product are faced with the task of teaching compromise rather than scientific method. By changing the emphasis from paper work to product, however, the lecturer can overcome difficulties of poor student motivation which so often occur in traditional courses. The essential ingredients for such a change are careful planning, industrial collaboration and internal organisation which permits a more central role for the student in both making and execution of decisions. The challenge is indeed enormous. Education cannot meet the challenge alone and its efforts must be complemented and reinforced by an industrial contribution. Industry has to take its responsibilities in this matter much more seriously than it has to date.'

Ben:

'In my opinion, by completing this subject [final year elective], I have matured considerably with regards to design as well as my attitude to mechanical engineering. I believe that many lessons have been learnt which will hold me in good stead for the industrial world. The processes developed allow me to critically examine and analyse ideas with a professional attitude. At present, I feel quite confident in entering the industrial world as a mechanical engineer'.

Nathan:

'From a student's perspective, it has been very refreshing to witness the amount of thought that has gone into the structure of the design course, within this department. Perhaps consequently, it is my opinion that this subject (final year elective) has been both the most effective and enjoyable subject studied throughout the undergraduate degree. However, it has taught the students to always look for areas of improvement and hence some have been raised in the body of this [his] paper.

Within the design subjects, there is room to improve the nature and scope of the problems studied. In particular, it would be beneficial to include the design of processes, and to increase the scope to include design implementation and support services. Outside the design subjects, the inclusion of design assignments should be encouraged in the engineering science subjects. It is important that such assignments be monitored by tutors with design experience and that the students have already been exposed to the design process through a design subject.

Finally, the current design course has led me to the top level of intellectual development, Perry's commitment in relativism, and as such I reserve the right to change my mind on any issues raised herein.'

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