Global J. of Engng. Educ., Vol.7, No.1
Published in Australia

The Education of Engineers: the Uneasy Relationship between Engineering, Science and Technology*

Graham Hills
David Tedford
Scottish Academic Consultants
2B Strathearn Road, Edinburgh, EH9 2AH, Scotland, United Kingdom

The article discusses the ingredients of the effective education and training of professional engineers. It is mainly concerned with the quality of that education, bearing in mind that, within the context of mass higher education, it is essential that engineering as a discipline should be attractive enough to appeal to significant numbers of gifted young people. The nature of engineering education has also to reflect another context, that of global problems, human values and the technologies to cope with these. This will require a new set of learning tools and a new vocabulary to go with them. Central to this paper is, therefore, the epistemology of engineering knowledge, scientific knowledge and technology. The outcome is a better prospect for engineering as a profession and a much wider appreciation of what engineering has to offer to society as a whole.

THE STATUS QUO: IS THERE A PROBLEM?

The status of engineering as a profession and as an academic discipline is a cause for concern. World-wide, there has been a fall in the number of applicants for university courses in engineering. In the UK, several departments or even faculties of engineering have been closed for the want of student numbers. Sadly and ironically, many such closures have occurred in one-time polytechnics established specifically to nurture technology – and therefore also engineering. The simple fact that there have been so many meetings, conferences and publications to consider these matters is evidence enough of the existence of a problem.

The problem then is real and, as it transpires, larger than simply a question of student numbers or even student quality. Related matters include the poor status of the profession as evidenced by embarrassingly low salaries. University departments themselves are invariably under-funded, their laboratories resembling museums rather than state-of-the-art technology. More subtly, the competition for resources ensures that to meet funding criteria, departments and entire universities are increasingly obliged to conform to standardised research-based criteria. There are no *brownie points* for virtuosity and diversity. That is bad news for any profession. Eccentricity and innovation are not too far apart and thus industry as a whole is the long-term casualty of the uniformity imposed on the university scene.

That this problem for the UK is not just a recent eruption is evident in the setting up in the late 1970s of a thoroughgoing government inquiry into the engineering profession [1]. Under the chairmanship of Sir Monty Finniston, and with the *double-entendre* title *Engineering Our Future*, it looked into every aspect of engineering, but especially into the formation of graduate engineers.

The recommendations were radical and aimed at shaking up the whole range of engineering professional institutions. The education and training of engineers was to become much more thorough as well as being longer. Steps were proposed for the deliberate training in engineering skills, many of them craft skills of the kind that a professional engineer would need to supervise with authority. The outcome of the report

*A revised and expanded version of a keynote address presented at the 3rd *Global Congress on Engineering Education*, held in Glasgow, Scotland, UK, from 30 June to 5 July 2002. This paper was awarded the UICEE diamond award (first grade) by popular vote of Congress participants for the most significant contribution to the field of engineering education.

published in 1980 was disappointing to say the least. It was formally accepted by the Government but pigeonholed by everyone else. In influential circles, Finniston became a dirty word and the downstream effects of the report were, if anything, malign.

For example, under the influence of the Cambridge School of Engineering, engineering science became evermore prominent. Its inclination to explicit research-based knowledge grew at the expense of experiential, tacit knowledge such that, in the ensuing decades, engineers and scientists were competing for the same kind of blue skies research funding from a single research council. The advent of computer simulation would add to this flight from reality and to the relative downgrading of technology.

The failure of the engineering profession to endorse the Finniston Report with enthusiasm says much about the professional leaders involved. There was stiff resistance from engineering professors who, one must suppose, had most to lose from the reforms, namely their privileged positions as leaders of their subject. The gap between what was taught and the reality of a swiftly changing industry would grow as science increasingly commanded the intellectual high ground. In this way, engineering would slip into the easy ways of oversimplification and pay for it by being also caught up in the social concern with scientific irresponsibility. At the end of the Millennium, some challenging books appeared such as *Rethinking Science* and even *The End of Science*, none of which helped the cause of engineering [2][3].

CLEARING THE DECKS

In many peoples' minds, it seemed that at least a part of the problem was semantic. Words like engineering science, technology, knowledge society, innovation and even science and engineering themselves were being used in an indiscriminate way. What follows then, at the risk of repetition, are some hopefully unambiguous definitions of the entities involved. These are given in Table 1.

The definitions resonate with UNESCO's view of

Table 1: Scientific knowledge in general, and engineering knowledge in particular, comes in several forms.

Know-what	Scientific and engineering knowledge describing the material world and its theoretical representations.
Know-how	The application of all kinds of knowledge to solve problems ie technology.
Know-how-to-do	The practical and intellectual skills of applying knowledge, ie techniques.

the new learning objectives throughout education, namely:

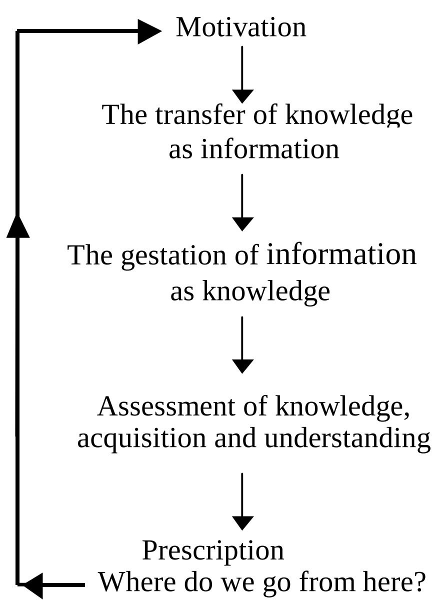
- Learning to know;
- Learning to do;
- Learning to be [4].

They also spell out the limits to the range of computer-aided learning, especially that of the Internet. The Internet is remarkable in that, by flooding the world with explicit knowledge, it has also supplied the means of handling and organising that knowledge. The implications of this machine knowledge for education are necessarily profound.

Thus, the traditional didactic procedure of teaching by lectures is exposed as the fraudulent, inefficient instrument of learning it always was. This has been known perhaps for centuries but was unavoidably the basis of mass education, and not least mass higher education, simply because there was no alternative. The Internet has shown that now there is.

The arguments in support of this are several. The first is the acceptance of the model of learning, the so-called virtuous cycle of learning, shown in Figure 1. This applies at all levels and all ages of education. All five steps in this cycle are essential for its completion. Failure of one leads to failure of them all. The step most easily neglected because of its human connotations is that of motivation, yet this is at the core of the learning process. It is highly subjective and depends on such unquantifiable factors as mood (of the student), personality (of the teacher) and environment (of the class). The word motivate has the same root as emotion, ie disturbed states of mind. Nowhere in the conventional lexicon of learning factors does

Figure 1: The virtuous cycle of learning.



motivation figure seriously. As a result, the majority of those lectured at easily suffer motivation fatigue; many are bored by such rote teaching.

A student may encounter 20 or more of such cycles in their undergraduate career. If they are sequential, then the failure of one may jeopardise the rest. The most common cause of failure within the undergraduate engineering curriculum is a defeat in one or more cycles of mathematics. This subject, if not well taught, can be a serious obstacle to further progress.

The efficiency of each of the five steps in the virtuous cycle is not a matter for conjecture. This can and has been estimated from sampled observation. The results of one such study are shown in Table 2, which is a pass-fail matrix of the five steps and the different methods of implementing them. The most interesting failure, that of the live teacher's limited ability to convey information, will come as no surprise to anyone with lecturing experience.

The tradition of the lecturer standing at the lectern delivering a lecture intended to be transposed into lecture notes goes back a millennium or so to the arrival of the monasteries and their scriptoria. By a process of dictation, thoughts became words, words became knowledge and knowledge became a source of authority. Not only is this, intrinsically, an inefficient way of conveying information, but for students, it is seldom rewarding. Far from being a place of inspiration, the lecture theatre is often the graveyard of motivation.

The matter has been aggravated, at least for scientists and engineers, by the sudden explosion of the knowledge base. In the hundred years between, say, 1900 and 2000, every aspect of science multiplied, fragmented and then multiplied again.

Table 2: Effectiveness of different learning methods.

	Motivation	Transmission	Understanding	Assessment	Prescription
Live teacher	✓	X	✓	✓	✓
Laboratory Exercises	X	✓	✓	✓	X
Student/peer group	✓	✓	✓	✓	✓
Print	✓	✓	X	✓	X
Audio	✓	✓	X	X	X
Video	✓	✓	X	X	X
Computer offline	✓	✓	✓	✓	X
Videoconferencing, etc	X	X	✓	X	✓

Knowledge behaved like a virus and the different sciences with their different languages swiftly created their own colonies of specialised information. Another Tower of Babel has appeared with all its undesirable consequences. Conventional libraries were overwhelmed with books and periodicals. At the same time, universities themselves doubled in size and also in number in a vain effort to cope with the deluge of knowledge and people. Rescue, in the form of the Internet, arrived in the 1990s and just in time. By 2000, the Internet and the World Wide Web (WWW) were installed to manage the seemingly infinite database. Complexity and volume were no longer a problem to industry, the military and the world at large. Only the universities seemed not to have understood or even read Alvin Toffler's *Third Wave* and to have pondered the consequences [5].

The response of the more farsighted learning fraternity was the New Learning Paradigm shown in Figure 2. This simple reform of the now outmoded procedures of lectures, large lecture theatres, large laboratories and large classes opened the way to better learning, to better motivation and to much more effective management of academic studies.

THE NEW LEARNING PARADIGM

The New Learning Paradigm bears a simple message; it says, in effect, that we should render unto the Internet that which machines can manage and render unto humans that which only they can manage.

All forms of explicit knowledge are, therefore, to be bundled into the computer memory. This machine knowledge includes all of rote teaching and learning as it simultaneously generates swathes of time and energy for the human activities involved, ie for students to expend on comprehension, organisation, innovation, practice and pleasure. In black-and-white terms, this means *goodbye* to lectures and *hello* to tutorials, the latter being the time-honoured procedures of Oxbridge and other institutions able to afford small classes.

The differences between the New Learning Paradigm and the old learning paradigms are profound, as indeed are all paradigm shifts. They are spelt out in greater detail in Table 3.

Both Figure 2 and Table 3 are the handiwork of Alistair MacFarlane who, as Vice-Chancellor of Heriot-Watt University in Edinburgh, guided Scottish universities across the divide between the two kinds of paradigm [6]. His background as an electrical

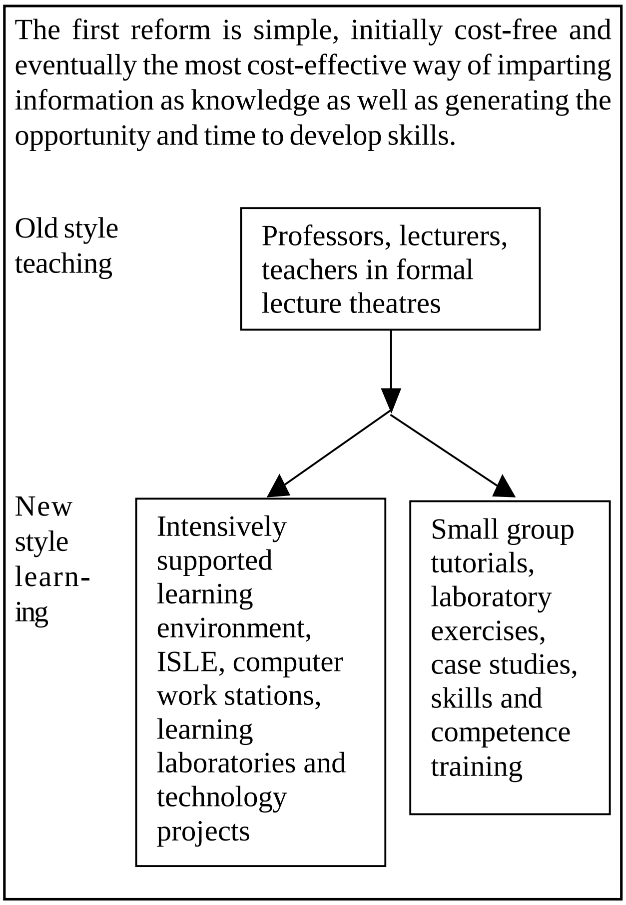


Figure 2: The New Learning Paradigm: a radical reform of higher education.

engineer and communications specialist enabled him to place the shift into its intellectual framework. It opened a door into the future for the science-based universities to enter. Alas, in the main, they did no such thing.

The history of human endeavour has never been the smooth evolutionary path of the kind implied by Darwin. All the evidence suggests instead a series of environmental catastrophes requiring emergency responses just to survive. Sudden changes of this kind that lead to new understandings and new methods are what we mean by paradigm shifts. They are invariably induced by a shock and when any existing paradigm is ousted by a new paradigm, the same struggle for supremacy ensues.

The struggle in this contest is between the Internet and the existing teachers and professors. Many academics cannot see themselves in any other role than delivering knowledge as information. As the Americans put it so succinctly – the professor is no longer *the sage on the stage* but rather *the guide by the side*. To accept this change of role is to enter another kind of pedagogical future where rote learning and rote teaching have given way to discussion, reflection and appreciation. The student and the teacher then stand shoulder-to-shoulder rather than eyeball-to-eyeball. As any student will aver, avoiding the eye of the teacher is a prime consideration.

In any event, even the youngest of pupils is well

Table 3: The development of the New Learning Paradigm.

Traditional	Future	Anticipated benefits
Static	Dynamic	Cheap methods of producing, transmitting and restoring acceptable quality video and animation will have greatly improved the presentation of a wide range of materials.
Impassive	Supportive	Well-designed computer-based learning support systems will have been made highly supportive in dealing with a learner s difficulties. This will provide great scope for remedial teaching.
Single Medium	Multimedia	The imaginative and skilful use of a wide range of media will provide scope for attractive learning, eg audio, video and animation.
Synchronous	Asynchronous	The space and time constraints of traditional presentation methods using lecture and laboratories will have been removed by a shift to self-paced learning using a variety of support mechanisms.
Passive	Active	Learning will be seen as an active process in which concepts are acquired, incorporated into appropriate schemas, and tested in action.
Unidirectional	Interactive	Interactivity offers scope for benefits in clarification, elaboration and consolidation, and is the key to the production of highly supportive learning environments.
Location	Network	Learning can be supported on a network basis across space, rather than in only one location.
Audience	Person	The possibility of developing learning support systems that tailor their response to an individual s needs and performance.
Real	Virtual	The use of virtual objects simulated by computer, and which are interactively accessible, offers considerable scope for linking theory and experiment in teaching and technology.

content to search the Internet for what they want to know. Its passive, uncritical and ever patient stance is all that is desired for the easy availability of knowledge as information. The comprehension of that information, its transformation into knowledge and its integration into a coherent scheme of understanding is, of course, quite another matter. This is the domain of the seminar, of the tutorial, and of Problem-Based Learning (PBL).

The Case Study

Learning by application is the only sound method of learning; it is the justification of project-based learning and, above all else, of the concept of the case study. Case studies are the best learning tool because:

- The case study is important because it always relates knowledge to reality. It contextualises both machine knowledge and tacit knowledge. It involves peoples and opinions. It is inclusive, interesting and motivating.
- It also involves judgemental matters, such as risks, rewards, ethics, morals, responsibilities, environmental issues and other political matters.
- We learn best from our mistakes. We next-best learn from other people's mistakes.

The case study, first championed at Harvard University Business School, is at last permeating other disciplines. It is basically an exercise in integrating the content and the context of a particular branch of knowledge and its specific application. Its merits include:

- Its narrative style;
- Its judgemental incidents;
- Its consistency as a rational exercise;
- The intellectual content of the subject and circumstances involved.

The case study is essentially the novel in reverse. The end is known but not the beginning. The depth and emotional impact of the surprises, the successes and the failings are highly motivating. Its use can be a solo effort or the engagement of a sizeable team. The digestion of the evidence, the presentation of the results and the constant peer review of every aspect all make for satisfactory and satisfying outcomes.

The extension of the case study to areas of activity other than business has been the forté of a small number of forward-looking universities. Several, in order of precedence, McMaster (Canada), Aalborg (Denmark), Maastricht (the Netherlands) and Glasgow (Scotland, UK), have demonstrated its success. Anatomy, perhaps the most fact-laden, rote-learned sector of medicine, has been relegated to a lecture or two, leaving room for other subjects more relevant to the development of doctors and to their social responsibility. Engineering, which resembles medicine in many ways, is bestirring itself, but the financial means of facilitating change are harder to come by.

The generality of one kind of cyclical case study is shown in Figure 3 and taken from the 2001 undergraduate prospectus of the University of Maastricht. The size of teams undertaking these studies is about ten in number. The topics range widely but the skills they imbue are of life-long value. The case study remains the most powerful of learning tools.

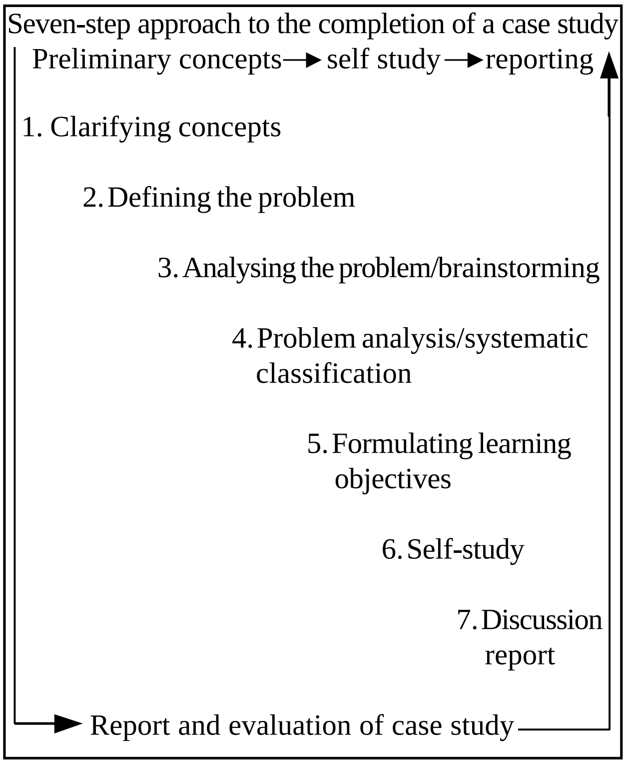


Figure 3: Problem-Based Learning (PBL) in tutorial groups (University of Maastricht).

THE LABORATORY

One of the distinguishing features of the science-based subjects is their involvement with techniques. All techniques are the art of practical exercises in the handling, observation and transformation of materials. The materials may be of natural origin, such as wood, plants, animals and food in general. More likely they will be manufactured materials, such as earthenware, metals, plastics and composites of them. The range of transformations is wide, from the large-scale bludgeoning of structural materials to the intricacies of nano-engineering. The one thing they have in common is that they are learned as skills by the observation and copying of others. Many of the graphic and plastic arts are learned in the same way but in studios rather than laboratories.

The position of skills in the hierarchy of education is not clear and has never been clear. The simple precept of mind over matter has, since Greek times, given cerebral activity a presumed supremacy over mere manual effort. To be described as a hewer of wood or a fetcher of water was not a compliment. The words peasant, serf and mechanic were synonyms for labourer. Refined people behaved in refined ways involving refined skills. These were mainly cerebral and, even so, never considered as skills as such.

In chemistry, physics, biology and medicine, the distinctions were clearer and remain so. However, in engineering, there is a continuous gradation from designing and fabricating micro-circuits to the construction of, say, a nuclear power station. Across this spectrum of activity are, nevertheless, the same considerations of care, precision, safety, risk, reliability and cost, to name just a few of the factors that set engineers apart from scientists. But even within this category of tasks, a division of labour was sought. Craft skills, rude mechanic and mere technician are terms that persist to the present day to confuse the otherwise seamless robe of dextrous and intellectual skills.

A word that cuts across these dichotomies is technology. Although its etymology is evidently ancient, its use is comparatively recent. It is comprehensively defined in Figure 1 but has, in general, only served to confuse still further the relationships between white-coated scientists, white-overalled engineers and blue-collared technicians.

This confusion between technology and engineering is a topic in itself but, in this article, technology is accepted as a bundle of practical and intellectual skills essential to the solution of any kind of practical problem. It is an action word wholly defined by its context and never by its content. It is as implicit as scientific knowledge is explicit. It is experiential, tacit and the source of all wealth. It is a technique only in the most general sense. Technicians and technologists are quite different animals.

Technique, defined in Figure 1 as the know-how-to-do, is the particular skill of performing particular acts to solve particular problems. Traditionally, such skills would be manual, dextrous, explicitly defined but learned by example. Commonly, they would entail precise coordination between hand and eye, as well as between hand and brain as mediated by the eye. Exceptional skills would often be rewarded by the term art. The arts of music making, drawing and sculpting gradually escaped from their peasant origins. Some technical disciplines, such as architecture, entered the rarefied atmosphere of art to the extent of abandoning all of the crafts of the building profession. Only in surgery did reality demand the total and constant coordination of brain, hand and eye to the exclusion of all else.

The place where techniques were mastered was therefore clearly and prominently defined. The operating theatre, the artist's studio, the musician's conservatoire and the stage are places essential to their profession. The chemical laboratory, the physics laboratories, genetic engineering laboratory and the electronics laboratory have not remained the same. They have evolved in the way that the performing arts have not. They may be best practised in academic laboratories, in industrial laboratories or simply on the job. They will change repeatedly during a working lifetime, leaving open the question of what are the essential skills of an engineer.

The argument that the laboratory is the place where academic knowledge is applied and where understanding is best promoted by examples of its use is attractive but archaic. In an unchanging world, the skills of the guild were guarded as unchanging secrets essential to protect their social status. In a changing environment, this attitude is fatal. It is no longer the existing technique that is treasured but rather the ability to acquire new techniques as and when they are needed. The fate of the engineering laboratory is, therefore, that of the drawing office. It is to be mothballed and, as an educational tool, to be forgotten.

Such radical statements are not readily acceptable. To be justified, they have to be set in a wider context of thinking, meaning, learning and the organisation of places of learning. This is the realm of epistemology, a daunting description of territory unfamiliar to engineers.

THE EPISTEMOLOGY OF LEARNING

The reform of undergraduate education so far considered here has been concerned to shift the emphasis from didactic lectures, subject-centred teaching, the rote learning of facts, explicit knowledge, and memory-based examinations to the softer world of student-centred learning, tacit, implicit knowledge and continuous assessment. It challenges practices that are centuries old and evokes resistance from every conservative angle. It can easily degenerate into politics in which conservatives of the left and the right unite to defend the old order. Thus, even before the advent of the personal computer and the New Learning Paradigm, there were movements to liberalise the all-important business of education and training. They were defeated by a disparate collection of opponents, including government itself, which, as ever, saw its role as the defender of the *status quo*.

Inevitably, after long periods of retrenchment, the faults of any settled system surface and demand attention. In the matter of higher education, the source of fracture was the continued explosion of the explicit knowledge base. As science, engineering and technology expanded in all directions, the demands they made on the educational system, and not least on the students, became insupportable. The flood of books, articles, conferences, learned papers, PhD theses and new examination requirements grew and grew. It provoked epistemological concern for the nature and future of such knowledge and as to how it might be managed.

Two groups of people emerged to ask salient questions about knowledge itself. The first, more radical (and more difficult to read) was the work of a collection of distinguished educationists led by Michael Gibbons, a one-time member of the Science Policy Research Unit associated with the University of Sussex. Their book, published in 1994, carried the title *The New Production of Knowledge* [7]. A second book by the physicist, John Ziman, also published in 1994, is in a more philosophical vein [8]. Both books set out to categorise all forms of scientific knowledge into two sets termed Mode 1 and Mode 2.

Mode 1 describes the factual knowledge that most people recognise as such. Its salient features are spelt out in Table 4. It lists the triumphal results of some three centuries of scientific enquiry starting with Galileo and Newton and, as yet, with no end in sight. Mode 1 is the world's collection of systematic, explicit, codified knowledge of all kinds still largely in written, printed form but increasingly now in the form of film, tape and computer memory. Its main characteristic is its tendency continually to grow and fragment into more and more specialisations. A subject such as chemistry was not so long ago seen and taught as a coherent whole. Now it is splintered into at least 50 self-contained branches each with its nomenclature, literature and periodicals. Conversation across the divides between these new disciplines is no longer easy or straightforward. The same is true of engineering, but to a lesser extent.

Table 4: The academic ethos.

Social Practice	Epistemic Principle
Subject specialisation	Fragmentation of knowledge
Specialist publications	Homogeneous knowledge bases
Impersonal attitudes, open publication and argument	Objectivity, empiricism and realism
System criticism, orderly controversy, peer review	Consistency, reliability, refutations but also establishment-minded, internally referenced
Open to novelty, personal autonomy	Progress, conjectures
Universality, transcultural	General laws, common unified abstractions
Decisive criterion	Is it right?

Table 4 also includes some social characteristics: some good and some bad. The idea of objectivity has to be good but the denial of human involvement is not. The idea of peer review has much to recommend it but it is not far from cronyism, often the hallmark of the professions. In spite of its limitations, the value and importance of Mode 1 knowledge are clear. Scientific education of all kinds therefore consists of familiarising oneself with the range and content of this explicit knowledge. Everyone reading this article will have been educated on this basis. Examination successes are still judged on the ability to recall the content and its meaning of Mode 1 knowledge. But its drawbacks are real and also important; they include:

- Fragmentation of knowledge (new Tower of Babel).
- Internal referencing, peer review, cronyism and social corruption.
- Absence of context, flight from reality.
- Objectivity taken to extreme, dehumanisation of science.
- Authoritarian attitudes to knowledge and success.
- Competition between knowledge bases leads to internal uniformity and external conformity.
- Academic values prevail, theory prevails over practice.

Not surprisingly, therefore, there is an alternative. It is termed Mode 2 and covers the contextualisation of knowledge; its salient features are as follows:

- Holistic and not reductionist.
- Context driven, not subject driven.
- Mission-oriented research, not blue skies.
- Teamwork, not individual scholar.
- Multi-authored publications and heterogeneous knowledge bases.
- Divergent not convergent thinking.
- Reflexive philosophy rather than objective statements.
- Decisive criterion: does it work?
- This is the world outside academia.

It is the result of putting Mode 1 into context. Context is another word for reality and that reality is inescapable. The imposition of reality on the coherent but theoretical description of the scientific world is illustrated in Figure 4; the second column, Mode 2, being the world of work, the world outside the institutions of education, especially higher education.

In as much as Mode 1 sanctifies objectivity, it consciously or unconsciously seeks to close the door on human emotions, the aspect of fellow humans that we treasure most. It also subconsciously closes the door on personal as opposed to technical skills, the former being, by definition, human attributes. Some of the essential skills of Mode 2 include:

- Personal skills: speaking, writing, debating, reporting and presenting.
- Personality skills: evaluation, criticism, judgemental.
- Intellectual skills: mathematical, language, philosophical.
- Professional skills: computation, keyboard, marketing, financial, design, management.
- Craft skills: drawing, painting, technical, music.

They define each human being and pose the question of which of them comprise the essential skills of the professional engineer. The answer – as many as possible – might be thought to be trite but is justified by two particular aspects of Mode 2.

The first is that Mode 2 emphasises the contextual nature of useful knowledge. Because engineers are problem solvers, they cannot, as do scientists, follow the line of least resistance and simplify the context to suit their convenience. The context is invariably a given and all subsequent considerations of design, production and monitoring will include every aspect of the context involved. Considerations of safety, risk, cost and efficiency may be of overwhelming importance and woe betides the engineer who neglects any of them. Furthermore, context is not a black or white issue. Contextualisation may be weak or it may be strong. It may be constant or it may be ephemeral but it can never be neglected.

Figure 4: The transition from Mode 1 to Mode 2.

Mode 1		Mode 2
Communes of homogeneous subjects	→	Multidisciplinary teams; heterogeneous knowledge
Solitary scholar	→	Part of active network
Open publication and freedom of knowledge	→	Intellectual property
Universal themes	→	Mission-led projects, local problem solving and final solutions
Objectivity and disinterestedness	→	Serving practical interests and involving
Fundamental, blue-skies research	→	Context of application, collectivised problem choice
Life-long vocation	→	Professional teams and entrepreneurial insecurity

The second justification of Mode 2 is that it emphasises the heterogeneity of the knowledge base serving any particular context. The range of factors involved may well be burdensome but in them lies the seeds of innovation and invention. On the other hand, a Mode 1 homogeneous knowledge base is by nature convergent, conservative and conforming. It is the enemy of innovation.

Innovation is triggered by a fault of reasoning, observation or prediction. Empiricism, therefore, is the tool of the engineer if nothing else. It is when two self-consistent homogenous knowledge bases collide to produce a result necessarily at odds with both, that the spark of invention or innovation starts a new train of thought, the first step towards change.

Mode 2 then is the treasured home of innovation, and the range of likely novelty can be equated to the range of contextualisation mapped out by the problem, research and mission. Mission-oriented research is as necessarily Mode 2 as blue skies research is necessarily Mode 1. From these considerations some essential truths emerge. They are as follows:

- At the point of comparison, implicit Mode 2 knowledge is always more important than explicit Mode 1 knowledge.
- At the same time, Mode 2 knowledge should contain all Mode 1 knowledge relevant to the context concerned.
- In confronting a problem, it is therefore essential to exhaust the resources of Mode 1 before embarking on its solution.
- Whereas, until the present, Mode 2 skills were acquired incidentally to the acquisition of Mode 1 knowledge, now the requisite Mode 1 knowledge has become incidental to the Mode 2 skills defined by the context.
- Any knowledge base is arbitrarily delineated by its context. Mode 1 knowledge is inescapable. It is the material and lubrication of Mode 2.
- However, in times of change, Mode 1 knowledge can stand in the way of Mode 2. It is then a hindrance, a source of prejudice and the origin of not-invented-here.

- In its extreme forms, Mode 1 becomes the excuse for intellectual constipation and fundamentalism.

ENGINEERING DESIGN AND INNOVATION

In reflecting on the nature of engineering knowledge, as compared with scientific knowledge, it is difficult to escape the conclusion that whereas scientific knowledge is largely Mode 1, engineering knowledge is, or should be, more Mode 2. Necessarily, engineering research, engineering design and engineering innovation are mission-oriented, heavily contextualised and undoubtedly Mode 2. There is a sense in which science is a product and therefore a noun whereas engineering is primarily a process and therefore a verb.

These semantic niceties are not trivial. Above all others, the word design is bedevilled by a range of meanings that faithfully reflect a parallel range of contexts and methods. Institutions, which seek to describe and govern the concept of design as a generality, encounter great difficulty in seeking common ground between, say, an aerofoil designer, a graphic artist or a fashion designer. They are all designers but to a first approximation, there is no common ground and no common language between them because there is no common product and therefore no common context. However, once the context is soft pedalled, design processes emerge that are common to all three.

Put another way, design is intrinsically a Mode 2 process of trial and error. It has no intellectual or knowledge content as such and, in practical terms, is wholly defined by the particular context involved. This delineation of engineering research, design and innovation, as primarily a Mode 2 process rather than a Mode 1 product, is useful in maintaining the distinction between engineering science and engineering practice. They are not unrelated but their separation is essential if false comparisons between them are to be avoided.

But there is another equally compelling reason for insisting on the Mode 2 character of engineering processes and also of science-based processes, both of which are recognisable technologies. It is a simple fact that Mode 1 comprises arrays of explicit knowledge each by definition homogeneous in its knowledge content. These islands of knowledge are not only homogeneous but always increasingly so. Like black holes, they absorb everything into their theoretical frameworks until the burden of so doing leads to fission and re-fragmentation. The novelty in such systems is self-contained and self-reinforcing, paraphrased long ago as knowing more and more about less and less. This kind of knowledge processing goes by the name of reductionism. It is Mode 1 and the enemy of complexity, heterogeneity and innovation that are characteristics of Mode 2.

As noted above, it is the nature of invention that the flash-overs of understanding, whereby a new idea is born, occur at the periphery of one knowledge base as it makes contact with another. All innovations benefit from a cocktail of conflicting ideas, concepts and contexts that breeds the otherwise unthinkable. Innovation may well be another name for the brain wave of a single individual but its roots are external (Mode 2), never just within (Mode 1).

The cultivation of Mode 2 is, therefore, desirable because it offers a broader basis of learning, more engaging and more colourful than the normal Mode 1 fare of intense specialisation. It will appeal to, and therefore select, intellects of this persuasion who will thereby feel comfortable and confident in confronting new contexts. The alternative, Mode 1 in its extreme forms, comes close to narrow-mindedness. It is not an attractive cast of mind and there is no evidence that it benefits individuals or society at large.

However, at some stage, the specialist must emerge. The precision engineer, the brain surgeon and the particle physicist are all needed. Their education and training is reflected in the longer periods over which they are educated; but these will always be a tiny minority. The mistake made by Britain in the training of its engineers was to suppose that such necessarily narrow specialist education and training was appropriate for all engineers. This error was compounded by the further supposition that even the minority of specialists could perform as innovators without a broad basis of general knowledge. Thus Britain, almost uniquely, fell between these two stools. It does so still.

THE EDUCATION AND TRAINING OF SPECIALIST ENGINEERS

This concluding section seeks to restate the obvious that if engineers are properly to achieve the status enjoyed by, say, medical practitioners or lawyers, then their profession of engineering must strive to be as exclusive in its membership and thorough in its training as it reasonably can. This is not a plea for some exalted elite in the social hierarchy or the first step towards a monopolistic power base. Rather, it is a plea for the exact and demanding training of young people already conversant with the language and principles of engineering and already possessing the personal qualities of the confident professional.

The ingredients of such a career are not a mystery; they are the combination of the well-educated personality and the thoroughly trained specialist, developed in that order. In the language of the previous section, this means a good grounding, Mode 2, followed by a thorough grounding in practice, Mode 1, as shown diagrammatically in Figure 5. The sequential swings between Mode 1 and Mode 2 will, in reality, be much less pronounced. Rather, they are to be seen as changes of emphasis as the student climbs his/her ladder of attainment (proposed by the Dearing Enquiry [9] and now blessed by the Bologna Declaration [10]) as, for example, shown in Figure 6.

Good general grounding is the natural outcome of the New Learning Paradigm. Here, the general skills and the general knowledge of the broadly educated person are honed in subjects of general importance and of particular interest to individual students. Since the undergraduate's inclinations and emotional commitment are at the heart of the New Learning Paradigm, they are usefully stimulated by encounters with successful practitioners with attractive personalities. This is a far cry from the image of the introverted professional specialist whose only interest is to promote his subject so that students can pass his examinations and become his research students. Romantically or otherwise, students only learn what they like from whom they like.

If education is for life, then education must be revered and enjoyed. Training is beneficial because the context of master and apprentice is intrinsically human, two-sided and intimate. It is the task of the professor to enthuse the students, charismatically in a larger audience or personally in a tutorial. There is no other way.

Figure 5: The foundation of graduateness.

In countries other than Britain, professional education and training is more broadly based. It comes later and it takes longer. The broad bases are those of wider skills and a wider knowledge base. Students graduate first and then proceed to graduate school for postgraduate, professional training.

This is the USA Model. Not long ago it was the Scottish Model.

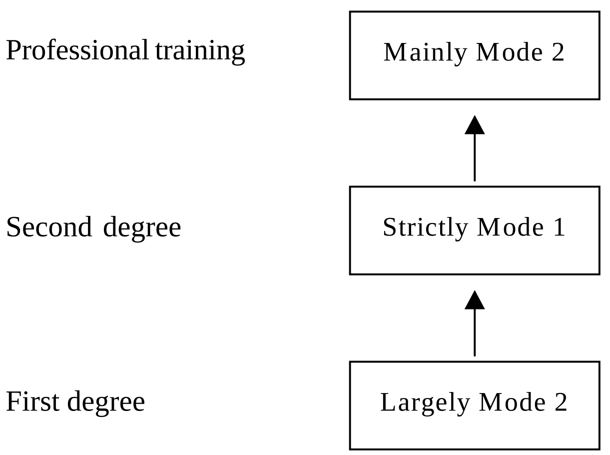
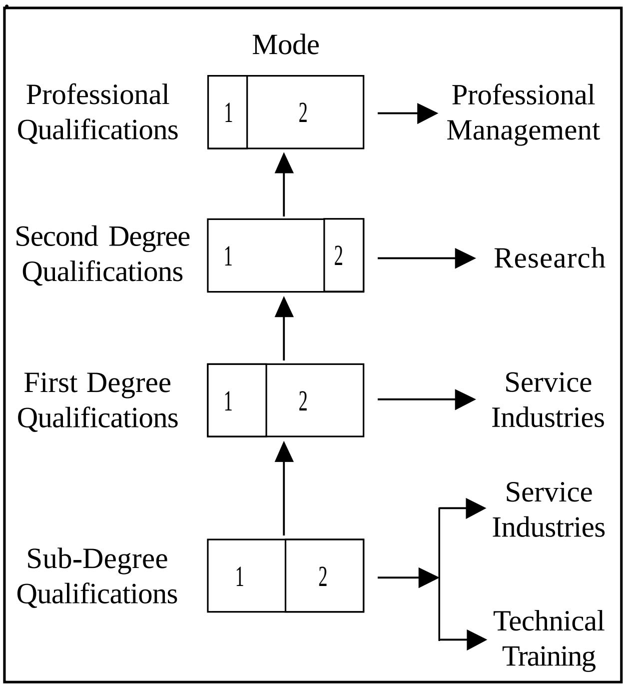


Figure 6: The ladder of professional attainment; this is a progressive ladder for ALL students.



The inclusion of so many personal aspects of education and training is, of course, the death knell of the traditional written examination. The oral examination beloved of continental Europeans is a considerable improvement on that but, best of all, is continuous assessment at the behest of the student and certainly not for the grading of individuals.

Given the pedagogical opportunities of the New Learning Paradigm, there is no room in universities for the death-or-glory hurdles race of the school examination. The concept of sufficient attainment to proceed is that of an infinite series of gently rising steps, each to be climbed in no particular way and in no particular time. And if this seems too idealistic to be credible, it need only be noted that it is the normal practice of undergraduate education in that most successful of democracies, namely the USA.

The procedures to be followed after graduation may also be lifted from that country, where change is welcome and the *can't-be-done* brigade are not entertained. The specialist training of the professional engineer is best carried out in the graduate school where research and training go hand-in-hand with industrial practice. The transformation of the committed graduate into the Masters apprenticeship, the research assistant, the research director and the research manager is as straightforward as needs be.

It will be a Mode 1 experience of Mode 2 attitudes to skills and personal achievement. There could be no better basis for the good engineer. The best vehicles, so far, for this kind of educated training are Germany's Fraunhofer institutes.

It is well to remember that education is, like life, irreversible. The Hippocratic oath taken by medics – *do no wrong* – has its counterpart in engineering – *specialise only when you have to*. In acquiring the skills of the professional engineer, it is important not to be burdened by knowledge that would be best discarded. It is further to be remembered, therefore, that knowledge is luggage and that, where possible, we should travel light.

But the last word in this article is to be had not by engineers but by technologists. In a recent publication – *The Universe of Engineering – a UK Perspective*, Sir Robert Malpas defines technology as *an enabling package of knowledge, devices, systems processes and other technologies, created for a special purpose* [11]. Because that special purpose is defined by a context, technology, like design and innovation, is quintessentially Mode 2.

Elsewhere, technology has been described as something between engineering and science. In the absence of an Arabic word for technology, Middle East countries cannot divorce it from technique or technician. It may be for this reason that technology enjoys a lonely status or no status at all in those countries. It is their considerable loss.

As noted in Table 1, technology is simply know-how. It has no substance or meaning outside its context. There is no difference in principle between engineering technology, scientific technology, medical technology, business technology or information technology. They are all about the means of accomplishing a specified end in a specified context.

The single art of technology is the ability to reorganise all the components of a problem into the components of a solution, using whatever knowledge and skills are required. Much of this information may be already known and explicit, ie Mode 1, but however much is known, there remains the frame of mind, the intellectual skill, the tacit knowledge of putting it together, ie Mode 2.

Because this art of know-how has no explicit knowledge content, it is not recognised by the existing educational system. This is because it has no written form and because it cannot be examined and assigned a grade. In the whole of education, from the primary school to the graduate school, that which cannot be examined or measured is without formal value. The task of reinstating technology as the apex of scientific and engineering achievement is therefore a difficult one.

It may be put bluntly that outside Mode 1 (regarded here as the heartland of academia), technology – the tacit knowledge of experience and the comprehensive know-how – is the supreme human achievement. Even outside academia, it necessarily encompasses extensive areas of explicit knowledge but, in engineering at least, that knowledge without the capacity for its application is without value.

This is equivalent to stating that knowledge for its own sake is no more than an indulgence. That statement flies in the face of the idea of a university as pronounced by John Henry Newman in his Victorian justification of Oxford as a seat of learning [12]. Be that as it may, engineering knowledge remains just knowledge until it is placed in context and applied to solve a problem.

Therefore, since the advent of the Internet, the good engineer is not a person filled with engineering knowledge but that person skilled at accessing it and skilled at utilising it. In engineering technology especially, the knowledge is incidental to those skills. The education and training of engineers is the process of imbuing him/her with those skills.

REFERENCES

1. Finnniston, M., Report of the Committee of Enquiry into the Engineering Profession. London: HMSO (1980).
2. Nowotny, H., Scott, P. and Gibbons, M., *Rethinking Science*. Cambridge: Polity Press (2001).
3. Horgan, J., *The End of Science*. Reading: Addison Wesley (1997).
4. UNESCO Task Force on Education for the 21st Century, Report. Paris: UNESCO (1996).
5. Toffler, A., *The Third Wave*. London: Collins (1980).
6. MacFarlane, A., Teaching and learning in an expanded system of higher education. Glasgow: Scottish Higher Education Principals (1997).
7. Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P. and Trow, M., *The New Production of Knowledge*. London: Sage (1994).
8. Ziman, J., *Prometheus Bound: Science in the Steady State*. Cambridge: Cambridge University Press (1994).
9. Dearing, R., Higher Education in the Learning Society (Dearing Report). Norwich: HMSO (1997).
10. http://147.83.29/Salamanca 2001/documents/main_texts/bologna.htm
11. Malpas, R., *The Universe of Engineering*. London: Royal Academy of Engineering (2000).

12. Newman, J.H., *The Idea of a University* (1854). (Republished) Oxford: Oxford Clarendon Press (1976).

BIOGRAPHIES

Sir Graham Hills was born in 1926 and educated in London University leading to BSc (1946), PhD (1950) and DSc (1962) in chemistry. He was lecturer at Imperial College, Professor at Southampton University and Vice-Chancellor at Strathclyde University, Glasgow. He was in between Visiting Professor in Canada 1968, in the USA 1969 (and National Science Foundation Fellow), and in Argentina 1977. His special interests were in electrochemistry, liquid state and molecular thermodynamics. He was a member of the UK Prime Minister's Advisory Council in Science and Technology and a Board Member of BP, the Post Office, BBC National Governor for Scotland (1988-1993). His abiding interest has been technology and technology transfer.

Born in 1931, David Tedford, OBE, graduated ARCST (1952) from Glasgow's Royal College of Science and Technology and BSc (1952), PhD (1955) from the University of Glasgow; and thereafter researched in aircraft guidance systems at Ferranti Ltd, Edinburgh, Scotland, UK, before taking up an academic career at the University of Strathclyde. There, he built up a powerful research group in gaseous insulating systems and dielectric materials, and was appointed to the Foundation Chair of Electrical Engineering in 1972. Later, he became Pro-Vice Chancellor at Strathclyde (1982-1992) and undertook a wide range of activity overseas including a number of visiting appointments. He was Vice-President of the Royal Society of Edinburgh from 1992-1995, and in the mid-1990s, occupied the new post of Chief Scientific Adviser to the Secretary of State for Scotland, dealing with policy, longer term strategy and other general issues concerning science, engineering and technology, including the commercialisation of research. He is presently Chairman of the Court of the University of Abertay Dundee and much involved with the work of the Scottish Science Trust.