150 Years of Engineering Education in Scotland
A Critique

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Introduction

There is, I believe, much disquiet about the outcomes of engineering education in the UK. It is not that the teaching is of a low standard; the problem lies in the basic philosophy that engineering education should be mainly based on engineering science and that learning to use the science should be done in practice. While this is a very simplified analysis of the situation, it highlights a major feature of the lack of balance in engineering education. In this paper the historical context is outlined, issues which characterise the lack of balance are discussed followed by proposals as to how a new balance may be achieved.

The Chair of Engineering and degree course at Glasgow University

In 1840 the appointment of Lewis Gordon as Professor of Engineering at the University of Glasgow was the first in the UK. The appointment was by the Crown; it was, and still is, a regius chair. Why was Glasgow was chosen for this appointment? There was not much choice. The University of London and the University of Wales had only recently been established and it is unlikely that Oxford or Cambridge would have welcomed it. That left the four Scottish Universities and the University of Glasgow was in a city which represented a powerhouse of the industrial revolution.

But the Glasgow University Senate did not welcome the appointment. Engineering was not considered to be a suitable university discipline. Even today this attitude inhibits the development of engineering curricula.

During his 15 year tenure of the chair of engineering Lewis Gordon, had no success in raising the profile of engineering education within the university. Not only were the members of the Senate hostile to engineering but the profession did not want engineering to be taught there. Apprentice professional engineers paid for their indentures and therefore practitioners were reluctant to relinquish such a favourable situation.

While Lewis Gordon had a 'quite brilliant'[1] career as a practising civil engineer, the next incumbent of the chair of engineering - James Macquorn Rankine - was a genius, considered to be the father of engineering science in the UK. He too struggled to establish a degree in engineering.


James MacQuorn Rankine

But in 1872, the year of his death, a BSc in Engineering Science was introduced at Glasgow University.

Rankine emphasised the "mutual dependence and harmony between sound theory and good practice" but in his justification for the engineering science degree he stated "…by supplying the student with that scientific knowledge which he cannot well acquire in an office or workshop, and avoiding any pretensions to give him that skill in the conduct of actual business which is to be gained by practice alone". I suspect that Rankine himself did not support the separation of practice and scientific knowledge but had to promote this philosophy for acceptance of the degree course.

While the teaching in the new degree course was deeply focused on engineering science, Rankine arranged for a 'sandwich' component where experience in practice was interlaced with the academic learning. This resulted in a learning regime, which though not optimum, was quite well balanced.

Milestones in engineering education

In 1840 the new chair was in Civil Engineering and Mechanics; the sub-disciplines of engineering were only nascent. In the 1890s the engineering degree at Glasgow divided after the second (of four) years into civil, mechanical, electrical and naval architecture streams with aeronautical being added later. This regime pertained until 1960 when the general nature of the curriculum in the first and second years and the practical training element were discontinued. The fundamental reason for discarding the sandwich structure was that the burgeoning of technical information required more time to be spent on knowledge assimilation. This reasoning was false because (a) the need to learn how to apply technical knowledge needs more emphasis in education and (b) despite the increase in the length of the academic sessions it was still not possible to cover all the issues that may need to be addressed by a professional engineer (see page 8)

In 1979 the Finniston Report[2] recommended that (a) engineering degrees should be re-designated as Bachelor of Engineering (BEng) rather than as Bachelor of Science, (b) that a further year of study leading to and MEng degree be added for those students who have potential to take leading roles in engineering and (c) that the integrated concept of 'formation' be applied to the education and training of professional engineers. The change to BEng/MEng has now been fully implemented but the concept of formation which does have potential to support a new balance, has not been adopted.

Although many of the changes made in recent decades have been about stirring of the existing pot, engineering education has developed. A more holistic view of design is being adopted and learning via project work including group projects is being introduced. But the balance between engineering science and other important professional engineering issues and between the basic principles and their application, tends not to be addressed in a satisfactory manner. I now put forward arguments as to why this balance needs to changed.

Knowledge and Information

The following definitions are not taken directly from a dictionary but (a) they are consistent with a way in which the words are used and (b) they are useful for the arguments which I am making:

- *Knowledge* - what the brain contains
- *Information* - a representation of knowledge outside the brain

Modes of representing information include: speech, text, graphics, etc.

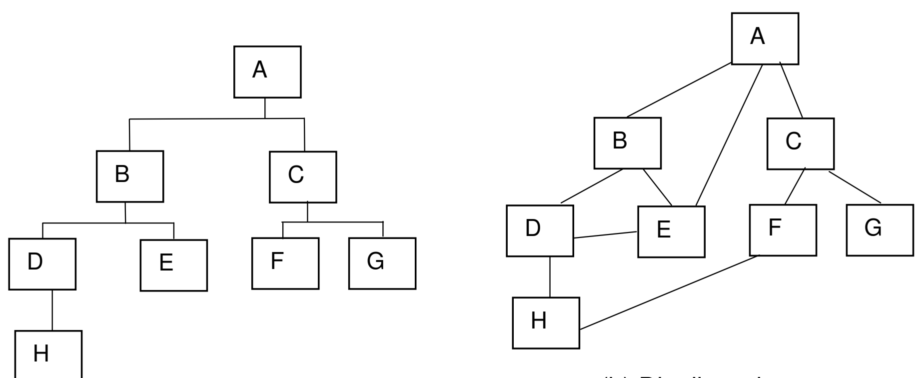
Two types of knowledge are:

- *Explicit knowledge* - that which can be expressed as information
- *Tacit knowledge* - that which cannot, or has not yet been, expressed as information

Tacit knowledge cannot, by definition be taught; it is constructed in a brain. Nor can it be measured directly. It therefore does not appear to be a good concept for incorporation into an educational curriculum. But it is very important. Gibbons et al.[3] state that "In technological knowledge, the tacit component may be larger than the codified (i.e. explicit) one."

Tacit knowledge can only be identified by its reflections – by outcomes which result from its use. Such reflections include:

Associativity Items of knowledge within a brain have a degree of interconnectivity the totality of which cannot be expressed as information. Typically we find it easy to express a hierarchy which has no connection across the branches - Figure 1(a). But we find it difficult to express situations where there is no clear pattern to the links – such as in Figure 1(b). It is one of the great powers of a human brain to tacitly interpret complex patterns of associativity with ease. Computers are, as yet, unable to remotely match such performance.



(a) Hierearchy (b) Distributed net

Figure 1 Associative structures

One of the reflections of our skill in associativity is our ability to deal with homonyms (words with the same sound but different meanings). Interpreting such words is a major problem in machine translation but the human brain can effortlessly identify the correct meaning by association. For example if someone said that a draught came in under the door one would not expect a small black or red disk to appear.

Intuition A main reflection of tacit knowledge is intuition which some people believe is underused[4]. A feature of successful professional engineering is to produce good results in situations of uncertainty. The outcomes from uncertain situations rely heavily on judgement based on intuition.

Judgement is therefore a reflection of tacit knowledge.

Understanding can be defined as the structuring of knowledge in the brain in a way that it can be used. Some people infer that this structuring is a necessary feature of 'knowledge'. Indeed if saying to someone that "I know you" infers that I know more about the person than the fact of his existence. But alternatively if I tell you that the

Universal Gravity Constant is 6.67 x 10^{11} $m^3/kg/sec^2$ and you memorise this number, then you would claim that you *know* the value of the constant. That you could not relate the number to the interacting forces between masses would detract from your understanding but not from the knowledge of the actual value. Therefore understanding is not always treated as a necessary a feature of knowledge. Understanding relates to the degree of associativity of an item of knowledge in the brain. A main goal of education is to develop understanding. Some of it can be measured but there is a strong tacit element in understanding.

Understanding and the information task engine

Figure 2 shows an engine model of competence. The engine performs information tasks i.e. where both the input and the output are in the form of information - the normal type of task carried out by professional engineers. The 'fuel' for the engine is knowledge. The input information, converted to explicit knowledge, is added to the tank and the engine can be started up. Running the engine (by thinking) generates understanding which is a reflection of tacit knowledge. The tacit and explicit components get mixed together in the tank. Some of the tacit components may be made explicit and new tacit knowledge is formed. Unlike combustion engines, rather than consume the fuel, running this engine improves its quality.

In order to develop tacit knowledge, the engine needs to be driven hard under load. One needs to focus on complex problems, analysing, synthesising, reflecting, inferencing, conceptualising, evaluating. The main learning environments at school and university tend to focus on the acquisition of explicit knowledge and cause the task engine to run at low performance levels which are not conducive to the development of tacit knowledge.

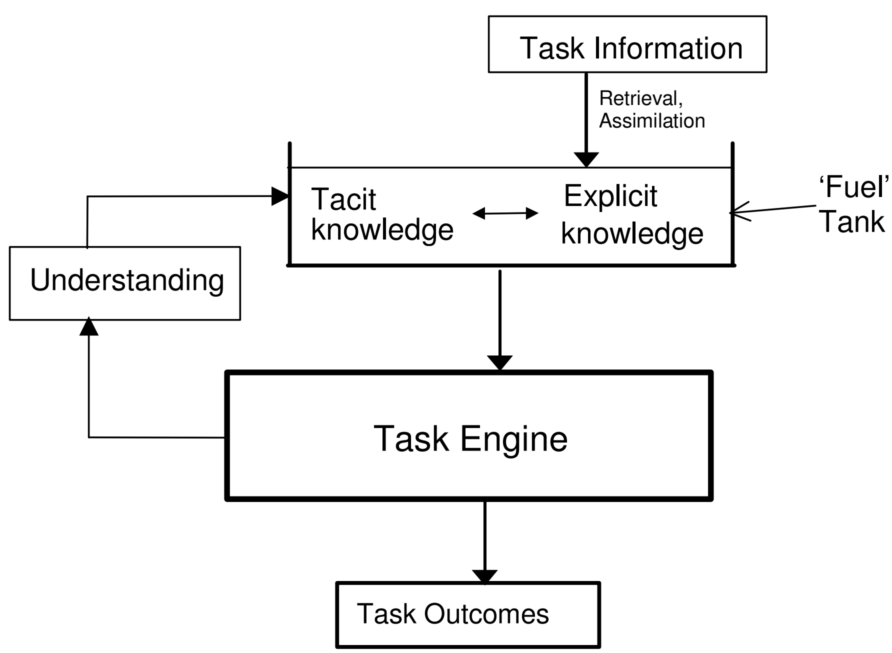


Figure 2 An engine model for information tasks

Dualities

I use the term ‘duality’ to represent a pair of concepts which can be identified as ends to a spectrum. For example tacit and explicit knowledge form a duality:

Explicit knowledge	↔	Tacit knowledge

The ‘↔’ symbol represents the treatment of the pair of concepts as a duality. The two concepts can be interpreted as separate entities but a particular context may involve attributes from both ends of the spectrum. In some circumstances the distinction between explicit and tacit knowledge is fuzzy. This is a main characteristic of a duality.

In education it is important to ‘balance’ such dualities. This balance is fundamental to the arguments presented about education in this paper.

Theories	↔	Applications

The word ‘theories’ refers here to the information/explicit knowledge needed to perform information tasks.

Achieving a satisfactory balance between theories - how things are done, and applications - experience in using them, is one of the most important issues in education.

Determinate processes	↔	Non-determinate processes

A determinate process is one for which there is a unique outcome whereas a non-determinate process does not have a unique outcome; several valid outcomes may be possible. This is also a very important distinction for education. It is normal for university tasks in science and engineering to be determinate. But the use of predictive scientific models (and most engineering tasks) is fundamentally non-determinate with determinate sub-tasks. When dealing with a non-determinate process a main issue is *uncertainty*. The corresponding issue with determinate processes is *error*. With determinate processes one either achieves the correct, unique answer or there is a degree of error in the outcome. With non-determinate processes acceptance of the outcomes requires judgement: measurement of adequacy of the outcome cannot be stated in terms of error alone. In a given situation both error and uncertainty may be present and therefore they also form a duality pair:

Error	↔	Uncertainty

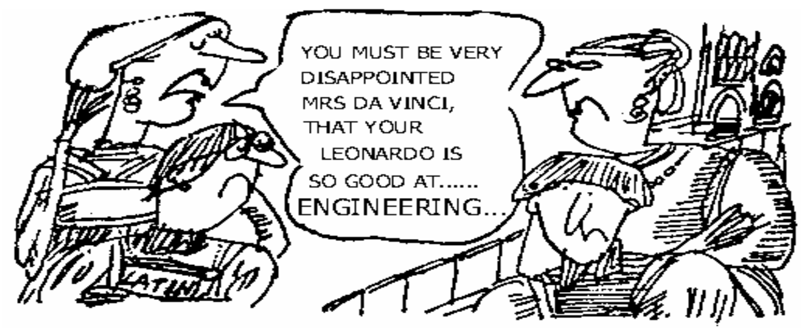
I use here two terms which define types of ability:

- *intuis* is to have tacit knowledge and be able to work with non-determinate processes and uncertainty
- *technis* is to have explicit knowledge and be able to work with determinate processes and error

(Note that these terms are defined here with some minor differences from when I first coined them[5].)

Technis	↔	Intuis

Engineering education has been deeply focused on the development of technis. Is there evidence to support the view that this is not the best strategy; that a new balance of technis and intuis is needed? The conventional wisdom is that one learns basic principles at university and how to use them in practice.



A bridge too far for high fliers

On the Today programme on Radio Four Timothy Eggar, the education minister, was explaining the newly proposed vocational alternatives to the academic National Curriculum. He said that academic high fliers should be able to study classics or a second foreign language, whereas those of lesser academic ability should be able to study vocational subjects such as design, technology and engineering.
Whilst it may be in character for many Conservative MPs to consider engineering as unsuitable for academic high fliers, it is deplorable for an education minister to show such a lack of understanding of the needs of engineering and of the nation.

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Figure 3 Letter to the Editor with cartoon, The Guardian Nov 1993

The theory first syndrome

Two ways that people approach a learning context are: (a) they want to know the basic principles and then move on to examples or (b) they want to start with an example and then move on to the basic principles. Those in the former category are 'academic' types - a dominant characteristic of teachers. Academic ability is prized in education - see Figure 3. The latter preference appears, understandably, to be common for engineering students and does not necessarily reflect a lower potential for success in engineering.

The examinations that student sit, reflect what they are expected to learn. Traditional exam questions in engineering tend to be dominantly in the form:

- For technical processes requiring calculations, perform say 3 out of 5 tasks in 2/3 hours based on simplified contexts . The tasks tend not to be related to other parts of the engineering process. Their purpose is to demonstrate that knowledge has been gained.

- For knowledge which is not based on calculations, students are required to 'discuss' issues i.e. to write in an essay format about them. Again the topics tend to be within a narrow context.

Controlled by the format of the examinations, curricula are divided into topics on which information is provided via lectures and written material; tutorial questions are provided which are normally related to the examination questions; then the process moves on to the next topic. It is of course not possible to teach more than one topic at a time but it is possible to integrate topics by requiring tasks to be performed which require more than one topic to be addressed - Figure 4.

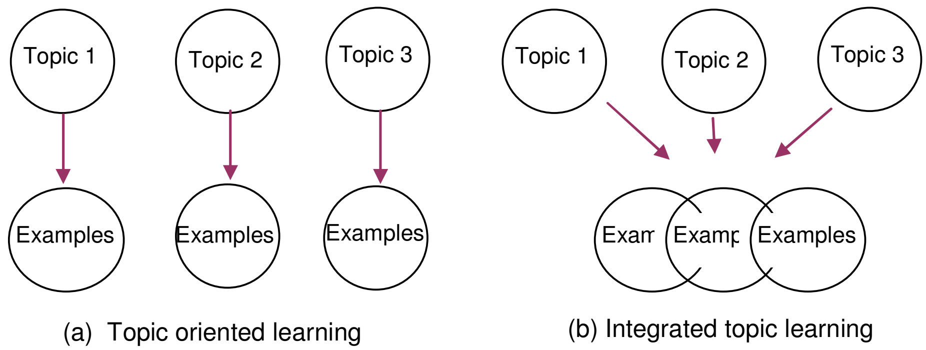

Figure 4 Approaches to the learning of topics

Even for academic types the topic oriented approach is not a good regime. It provides only a low level of opportunity for associativity and therefore low potential for developing tacit knowledge/understanding.

While some project work is being introduced to engineering curricula to provide more balanced learning, formal examinations are still viewed as the core test of ability.

The result is that engineering graduates tend not to be good at doing engineering tasks. The knowledge gained is not deeply rooted in their brains and the foundation that they have developed in fundamental skills - thinking, designing, writing, drawing, sketching, presenting, calculating, validating - is similarly shallow.

It can be argued that examinations are about knowledge acquisition and other features of learning are developed in coursework - and that the dominance of knowledge acquisition is declining. But, in general, the balance is unsatisfactory.

Learning thresholds

Learning threshold - the age at which natural ability start to decline. It is not easy to be confident about relative outcomes of educational tests because of the difficulty of getting representative samples but we can say with confidence that there is a learning threshold for language. Young people, at the age when they start to learn to speak and for a few years after that have an ability to learn language, or languages, that few can match in later life. It is best to learn language from the earliest possible age although this principle is not well supported in the UK.

When it comes to learning to play a musical instrument few would disagree that one should start young - the younger the better especially for those who lack a high level of natural ability. And no one would disagree with the principle that one should not focus on basic theory of music for 4 years before going on to start to play the instrument.

Practising a sport from a young age is also generally accepted as an important strategy for later peak performance.

Thus we are confident that some features of human performance merit early application. What can we infer in this respect for technis and intuis?

Technis, by definition, is dominated by explicit knowledge. While people find that knowledge gained when young tends to be more easily recalled in later life, we do not find that, say before middle age, ability to commit information to memory is in decline. I have heard the opinion ex[pressed that "Unless you learn the basic engineering theory at university, you never properly grasp understand it". This may be a common experience but it is a function of lack of opportunity rather than of innate ability. Those who define engineering curricula try to be inclusive about what is to be learned i.e. they seek to include all the topics that may be needed in practice. This objective is unattainable: the extent of such information is too great in all branches of professional engineering. In Rankine's time it may have been possible to include most of engineering mechanics in a four year curriculum. By the middle of the twentieth century the potential for doing this had dipped below, and is now well below, the horizon. Therefore even if it is better to learn the basic theory at university it is only possible to sample it.

Is intuis subject to a learning threshold? Deep thinking is a main feature of intuis. Is the brain like a muscle which if not developed when young and kept in shape by using it, loses its quality? If "yes" is the answer to this question then neglecting the development of intuis in education is a flawed strategy. Even if the answer is "I do not know" is it worth taking the risk that it is not true? I believe that the answer is "yes".

Basically there is are no good reasons to support the principle that theory should come first followed by application later.

Computer processing and the human brain

Table 1 evaluates the relative strengths of a computer and a human brain in relation to some features of technis and intuis. Whereas a brain cannot match a computer for speed and accuracy of implementing determinate processes - especially doing calculations - it has spectacular ability in relation to intuis. Intuis is not something that we expect computers to have. Therefore education tends to focus on the ability of humans to do things that the computer can, in some circumstances, do better and neglects the development of brain power that goes beyond what computers can do. While Table 1 a very simplified model of complex situation, it does provide further evidence for the need for a new balance in education

Table 1 Basic abilities

Ability	Computer	Brain
Implement determinate processes/algorithm quickly and accurately - technis	High	Low
Interpret complex patterns, make good decisions in conditions of uncertainty - intuis	Very low	High

Delivering a balanced curriculum

The principle that education should not be too heavily focused on technis but should promote the development of other mental attributes is not of recent origin. This is the theme of Charles Dickens novel *Hard Times* published 150 years ago. But assessment of the outcomes of curricula which are structured so as to be 'more interesting and relevant' often fail to be deemed as successful because the outcomes become less easy to measure. Assessors find that learners do not know the basics. The fundamental problem is in balance. A necessary feature of most curricula is that some time should be devoted exclusively to knowledge acquisition. Prospective surgeons have to learn about all the bones, muscles and nerves in the body. This will not be achieved exclusively via examples of surgical contexts. Rote learning is needed. Similarly a ship's captain has to know by heart the meaning of lights displayed by other ships since he may have to interpret them in an emergency. It is less easy to define what a professional engineer *must* know but for example deep knowledge of the principle of equilibrium is a necessary attribute of a structural engineer.

A way of expressing how balance in a curriculum may be achieved is to seek to address the range of issues identified by the dualities. For example it should not be theories or applications; it should be theories and applications. Each duality should represent a two lane highway of learning.

Modes of learning

Two basic modes of learning are:

- *Taught learning* where a teacher talks to a class, the members of which do further study on the subject matter plus coursework. Taught learning is focused on the development of explicit knowledge.
- *Experiential learning* has the following characteristics
  - The learner carries out tasks and activities the main objective of which is to learn (as distinct from tasks outside education where the main objective is to achieve task outcomes).
  - The needed information for tasks is mainly identified and acquired by the learner by reading and via mentor support.
  - The work is carried out by a single learner or by a group

These two modes of learning are not mutually exclusive but may be considered to form a duality:

Experiential learning	↔	Taught learning

Technis can be a feature of both modes of learning but intuis is only weakly developed in taught learning. Balancing taught and experiential learning is the key to balancing technis and intuis.

Strategies for experiential learning

Project learning A main strategy in experiential learning is project learning where students work together to address a brief based on a real or potentially real context. The nature of the work can be design, investigation, planning, etc. While there is advantage in some individual project work, the preferred mode is group work. The outcomes of taught learning are mainly from individual effort; group project work provides a context for creating balance between solo and group working - another duality: Project learning also provides opportunities for students to research the necessary information for tasks which provides balance against taught learning where the information is provided by the teacher. This can be a very effective type of experiential learning.

Part-time study While it can be very demanding, part time study - evenings or block release - is a very good learning regime. Good practical experience will normally be superior to the simulated experience of project learning but it can be difficult to integrate the learning of theory with experience in practice.

Sandwich courses The thin sandwich model (6 month periods in practice) tends to be better than thick sandwich (full year in practice) because there is greater potential to integrate the learning. Much depends on the quality of the experience during the periods in practice. It can be very variable despite efforts by academic supervisors to seek to maintain quality. Also there is limited opportunity for planned integration between the academic and practical components

The ideal regime may be to work in practice with part time academic learning integrated, where possible, with the work experience. We need to experiment with methods of treating education, training and practice in more holistic way - the concept of *formation* as promoted in the Finniston Report[2].

Barriers to balanced learning

Attitude of teachers Teachers tend to be 'academic types' more interested in the theories than in applications. This is not a criticism of teachers but it does represent a barrier to balanced learning

Quality assurance A great deal of resource is allocated in education to quality assurance. The focus of theses efforts tends to be on whether educational processes are properly implemented with little attention to the appropriateness of the processes themselves. Consideration of educational quality should pay more attention to the suitability of goals rather than just to optimisation of their achievement.

Deep focus on student performance. While it is essential that student outcomes are assessed, modern education tends to treat student performance as *the* measure of educational success. This results in the curriculum being skewed towards outcomes which can be easily assessed and in particular towards measurement of technis. But when students work in groups, assessment of individuals becomes more difficult; also intuis cannot be measured directly. There should be room in the curriculum for some activities which are evaluated more by the quality of the learning experience than from individual outcomes.

The need to grade students also drives assessment towards assessment of technis which is much more objective than for intuis. Having such objectivity would appear to be fair to the students but it means that those who have higher potential in relation to intuis are disadvantaged.

Attitudes to vocational education That those with academic ability are 'clever' and those with more practical abilities have lesser intellects is a myth - Figure 3. The opposite argument can be made - that intuis is the main source of high intellectual performance. That practical ability is deemed to be secondary to academic ability has been a seriously negative feature of education for over 150 years.

The Research Assessment Exercise The universities are being required to show that the money that they receive for research is being well spent. That they should be so challenged is unarguable; it is the process for doing it that is at fault. The focus on research performance is driving down teaching quality. All academic staff at universities are expected to be research active; departments are penalised for not meeting this criterion. While this is not an unreasonable objective, it tends to militate against good engineering teaching. It is difficult to find staff for whom all the boxes can be ticked and heads of department are inhibited from appointing people with excellent practical experience when they do not have research potential. This is intensifying the academic nature of learning i.e. it is driving the balance in the wrong direction.

Conclusion

We have yet to recover from the lack of balance between theoretical and practical learning established when degree courses in engineering were first introduced in the UK the 19th century. Learning about theories without experiencing how to use them is a bit like going to piano lessons where there is no piano. If you want to be good at carrying out a professional engineering task, the assimilation of the necessary explicit knowledge should be in close association with learning to use it practical contexts. Separation of these components of learning inhibits the development of tacit knowledge which is fundamental to professional engineering competence.

A key issue is *balance*. A proportion of academic learning in the curriculum is necessary; some straight knowledge just has to be assimilated. But it is also essential to learn to use knowledge effectively.

The work of professional engineers in consistently achieving successful outcomes in situations of complex uncertainty requires mental activity at the highest level - representing a pinnacle of intellectual achievement. But the degree to which engineering education fosters such competence is sub-optimal. A new balance is needed.

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