Richard Hodgkinson, The University of Sheffield

The Engineering sector in the UK has seen a dramatic transformation in recent history. This has been driven, in part, through international manufacturing competition and the progression of technology. The engineering sector has become focussed on export of technological design and innovation - highly specialised products in limited quantities - rather than industrial mass-production. Conventional technologies are developed incrementally, whilst innovation and a competitive advantage to the economy is offered by those able to develop novel solutions. Such changes rely on the provision and education of highly skilled employees.

Arthur (2009) provides an insight into the nature and origins of technology, together with how an economy arises from its technologies. When we open up the "black box" of a specific technology, we find it is a combination of sub-assemblies - of existing technologies, each of these relying on underlying principles. New technologies are "self-created" from new combinations of the old ones. These technologies are likened to a "Language", or set of tools, within a specific technological domain. Combination from the elements of this toolbox is key to the creation of novel technologies and more generally, towards technological evolution. Significant advances occur when "redomaining" occurs – for example, the transition from canals to railways. He concludes succinctly that "Innovation...is a constant redomaining of old tasks ... within new worlds of the possible" (p85). It is vital to the UK economy that our next generation of scientists and engineers embrace this opportunity for innovation between domains.

The interaction of domains not only applies to future technology – the evolution and integration of technology throughout our current industries places importance on principles and systems historically considered separate. He emphasises that for technologies to be successful, they must be combined to form a working architecture, each component balanced to work together. Thus, only when these technologies are considered together can these systems be efficiently designed and optimised.

The instrumentation in the field of chemical engineering is such an example. It relies explicitly on the contributions from electronics and computer science. In modern optimised plants the control systems are as crucial as the chemical engineering. The increase of technology complexity has lead to the outsourcing of such systems, whereas in the past, sensors may have been designed, optimised, and implemented in-house by engineers and technicians knowledgeable to the process.

Experience shows that this hands-off approach is problematic, and even more so in research environments. Undoubtedly at this time there will be experiments, in establishments, where readings will be taken from complex systems that are functioning incorrectly, their software incorrectly configured, or their measurements distorted. This data will be taken as accurate, used to formulate and test hypotheses, and published in peer-reviewed literature.

Clearly, fostering interdisciplinary knowledge would aid the economy, retrospectively, within the current fields of technology. However, we should look at the brighter side, and how such knowledge would allow innovation - innovation that would dramatically benefit the economy. Arthur highlights that phenomena and principles echo across domains. "Principle transfer" through mental association occurs with the possession of a "very large quiver of functionalities and principles" (p123) to hand. More specifically, a diverse array of functionalities and principles is important as "Novel technologies...come from experience gained outside the standard domain they apply to" (p108). This is enabled by a period of accumulation and experimentation, where principles are recalled from the past, picked up, suggested by theory, or appropriated from other areas or domains. A second contribution is also essential. A knowledge of the "Grammar" of the field is essential – an unspoken "deep craft" (p159) understanding of the likelihood of technologies to fit together - "rules of allowable combination" or the "cookery of the art". This "Grammar" has a greater importance as "they may start as rules, but they end up as a way of conceptualising technologies, a way of thinking" (p78) – the framework for assembling a separate idea that cannot be gained solely through theoretical teaching. Importantly, this "Grammar" is often localised, causing the resulting national competitiveness of sophisticated technologies (p159).

Opportunities to encourage principle transfer apply not only at discipline level, but at the level of current courses, too. Fundamental to engineering as a discipline is the solution of problems through the interconnection of related concepts, yet the modular structures encourage a segmentation of knowledge. Learning this knowledge for an end of module exam only reinforces this.
A noteworthy area, applicable to all engineering disciplines, is the teaching of mathematical concepts. The paradigm for reframing a mathematical course in an engineering parlance could be greatly improved on; as the material is still restricted, in many cases quite literally, to a non-engineering environment. A set of tools is provided, yet their application is not reinforced. As a result, it remains as

a separate block of knowledge. Central to some of the classic fundamental derivations in engineering is not only the ability to use the tools, but a realisation of how to assemble them to achieve a desired result. An engineer needs to know what tools to use, how to use them, and – specifically – When to use them.

Teaching – and applying - mathematical content simultaneously with engineering material as requirements arose in a module, rather than being a necessary caveat of engineering courses, would produce a very different outcome. Aside from showing how and when to use mathematical tools, these tools would be more pertinent and more effectively retained. Future problems could be "transferred to the domain" of mathematics far more easily and confidently than before. Tools make work easier. Making the use of mathematical tools easier would therefore improve the efficiency of engineering.

The modularisation of "Tools" simplifies the details of design and the education of the field – preventing the designer or student from "drowning in a sea of details". Modularisation is essential. However, for novel technologies, it is essential that we break out beyond it. We must encourage the act of mental association outside of classic domains – so called "joined up thinking".
Whilst interdisciplinary HE courses are becoming more commonplace, course overlap is thus vital for innovation, industry, and research. TCE (Jansen, 2012) highlights a recent graduate claiming ""that there's not enough emphasis" on the engineering side of the degree. "You need more studies with other disciplines – especially electrical and mechanical engineering"".

The advance of technology results in ever-successive layers of sub-domains to an existing technology. Perhaps 50 years ago, the inside of an electronic device was clearly visible. The working principles of locomotives could clearly be seen. The sub domains within the "Black box" were visible. It is no longer possible to delve into modern technology without specialist equipment or an a priori knowledge. Even providing an appreciation of what the public considers a basic piece of technology - for example, a mobile phone - and explaining the underlying creativity and elegance, is virtually impossible today. Arthur offers a pointer as to the change in image of engineering. "The reason engineering is held in less esteem than other creative fields, is that, unlike music or architecture, the public has not been trained to appreciate a particularly well-executed piece of technology" (p98). Extending this, practical interests or appreciation in engineering design is evidently bracketed as unusual, and thus unfashionable, for this very reason. The cycle is deeper, however, as degrees are typified by blackboards, lectures, exams and coursework. A creative element appears to be lacking that would propagate to the public level and change this view.

It would be impractical to suggest that technology should be less layered in nature. Thus we must emphasise the creativity of technology by "opening up" the black box of technology and show to young students – and the public – it is creative reconfigurability: The "wonder that thousands of phenomena all work together" (Arthur, p52). Practical industrial visits go some way to this. Teaching goes further, however it is insufficient to teach the fundamentals – the practical creativity must be engendered. Students must be allowed to create, only then can the wonder of technology be appreciated. This has two obvious benefits. It engenders the mindset for linking and association needed for innovation – the "Grammar" of engineering, the intangible knowledge of assembly. Secondly it encourages students to become future engineers.

Perhaps some skilled engineers and scientists reading this, will, at some point in their lives, have experienced the creative side of engineering, perhaps developed a hobby and then found themselves fostered by this to become engineers later in life. The practical experience is fundamental.

It has been highlighted recently (Perkins, J. 2013. p.37) that despite a perceived skills shortage in industry, many graduates remain unemployed, or employed in a different area, once they graduate. Issues surrounding a shortage of practical skills are often mentioned, yet the opportunities in education appear to be limited. In the writer's experience at secondary school, where the lathes in the corner of every technology room were used regularly in the past, they stood silent. It can be argued that modern production techniques render the use of manual tools obsolete, and such equipment as manual lathes, are redundant. Indeed, vocational courses do not always adequately address future production techniques (Perkins, J. 2013. p27). But in this, something was lost, particularly at younger ages - the creative hands on psychological connection so important to inspiring the next generation, and not so much the raw knowledge as the origins of the "Grammar" of engineering. It also creates a mindset that everything can be produced though CAD and CNC without realising it is a physical process, each variation with benefits and limitations.

Whilst at Higher Education level graduates will have made the choice to follow engineering, gaining the practical knowledge desired by industry is an issue at degree level – to quote "principally because degrees do not adequately develop practical skills and/or lack specific technical content" (Perkins, J. 2013. p39). The previous TCE article highlights "that the shortages in vital professions are, at least in part, down to the "variable quality of UK graduates' practical laboratory skills."" Certainly, pre-defined, "button-press" style scripted laboratory practical tasks, whilst the most convenient to the university and least daunting to the student, might not be the most helpful, and certainly not the most engaging and creative. Some compromise should be sought. Students are quoted saying that there is "too much focus on book work and theory, not enough on practical work" and that there was "one workshop to show us 'this is a spanner'".

At the level of a research PhD, students are encouraged to learn new skills towards their research activities. Some students may also wish to learn simply to further their own interest. However students from both degree and PhD level have found that gaining experience on, for example machine tools, to be difficult – despite the keenness of expert technical staff to share their knowledge – perhaps some of the best "industrial" teachers. This was due to sensible, accessible frameworks not being in place to permit this. These students were chemical engineering based – such an experience would have contributed as interdisciplinary practical knowledge. If this issue extends through the educational system, particularly to secondary school level, what message does this send to our next generation of keen engineers wishing to explore their creativity?

Something needs to be done. In brief, it can be. The Georgia Institute of Technology features a well-equipped unique "Invention Studio" (http://inventionstudio.gatech.edu/) available for student project and personal work. Students from across the engineering disciplines share their ideas. Creative problem solving is inherently encouraged. The centre has expanded from one room at its outset to five.
At MIT, an undergraduate course sets students a challenge to design and build an electric go-kart in the space of a semester with a budget and workshop access (Guan, C. 2013) – a realistic ill-posed design problem that demands more than just theoretical knowledge.

In conclusion, in order to provide the innovative engineering base required by the economy, interdisciplinary knowledge is key. Application of this knowledge requires mental connection, which is fostered by creativity. Creativity is linked to practical skills and problem solving, both of which are important in fostering the next generation. Practical skills build the art of engineering, which cannot be taught. And students are willing to engage – the question is, will the education system provide a framework to enable this?

References:

- Arthur, W. B., 2009. *The Nature of Technology*. New York: Free Press
- Jansen, R. June 2012. *A matter of perspective.* The Chemical Engineer (852), p. 62.
- Perkins, J. November 2013. *Professor John Perkins' Review of Engineering Skills.* [pdf] Department for Business Innovation & Skills. Available at http://epc.ac.uk/wp-content/uploads/2013/11/11-2013-9808-BIS-Prof-John-Perkins-Review_Accessible.pdf
- Georgia Institute of Technology "Georgia Tech Invention Studio". Accessed from http://inventionstudio.gatech.edu/ (01/2014)
- Guan, C. 2013. *ON 2.00GOKART; OR, DESIGNING A DESIGN CLASS TO DISRUPT DESIGN CLASSES AS WE KNOW IT; OR, HOW TO MAKE MIT UNDERGRADUATES BUILD SILLY GO-KARTS SO YOU DON'T HAVE TO*. Accessed from http://www.etotheipiplusone.net/?p=3035 (01/2014)