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New curricula for engineering education: experiences, engagement, e-resources

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ABSTRACT: In an increasingly complex world, engineering students need to learn innovation and complex problem-solving in socio-technical contexts, combining fundamental knowledge of many disciplines, not just mathematics and physics. Our job as educators is to create engaging learning experiences to take students on a learning journey from high school student to proto-engineer. These learning experiences increasingly draw upon industry-relevant project work. There are now several Australian examples of curricula that combine student immersion in projects, supported by on-line learning. Fortunately, the fundamentals of engineering are being made available (and assessed) on-line, e.g. Khan Academy and numerous MOOCs. Engineering curricula are being flipped from *first teach the fundamentals* to *first engage with the engineering problems* and use these problems as motivators for students to learn the fundamentals. This is also assisted by the availability of extraordinary design software to solve the governing equations for most routine engineering tasks. E-learning has morphed from electronic learning in the last 20 years to experiential and engaged learning. This is the future of engineering curricula.

Keywords: Engineering curriculum design, e-learning, flipped learning, experiential learning, problem-solving

INTRODUCTION

The future of work is demanding that universities educate engineers differently than they have in the past. The Institute for the Future at the University of Phoenix has named six key drivers in their Future Work Skills 2020 report: extreme longevity, a computational world, superstructured organisation, rise of smart machines and systems, new media ecology, and a globally-connected world [1]. Of these, engineers and IT professionals are responsible for the computational world of AI and big data, as well as the rise of smart machines and systems that will provide the data for the algorithms and will be driven by the outputs of those algorithms. This is future engineering and IT, which will operate in an increasingly globalised world. The big question for universities is: how do they educate the technology professionals for this future? Is a grounding in mathematics and physics enough? Will this lead to the kinds of innovators who will shape the 21st Century?

The Future Work Skills report lists the key skills of the future workforce: sense-making, trans-disciplinarity, design mindset, novel and adaptive thinking, virtual collaboration, cross-cultural competency, social intelligence, new media literacy and computational thinking. These skills will be applied across the range of Grand Challenges as identified by the National Academy of Engineering [2]: solar energy, virtual reality, reverse-engineering the brain, better medicines, health informatics, urban infrastructure, cybersecurity, clean water (for all), fusion energy, prevention of nuclear terror, managing the nitrogen cycle, carbon sequestration, and tools for scientific discovery. Are the graduates ready for these grand challenges?

Similarly, the World Economic Forum's sustainable development goals are: no poverty, zero hunger, good health, quality education, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry innovation and infrastructure, reduced inequalities, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land, peace, justice and strong institutions, and partnerships for these goals [3]. Will present graduates be equipped to contribute to these goals?

NEW CURRICULUM MODELS

In the old model of curriculum design, one would make separate subjects or units for the future work skills, perhaps sending students to various faculties to learn these skills in the hope that they would see the connections and integrate the skills into a set of professional competencies. However, the past experience suggests that students do not see the value of a fragmented curriculum, preferring to forget anything that they needed to learn other than their major (engineering/IT) subjects. One needs a different approach that balances understanding the fundamentals with learning the process skills of engineering practice (systems engineering principles).

One needs to educate for complexity. Students need to think in systems rather than assuming that there are textbook answers for simplified problems. Students will need a broad set of skills, as well as the ability to work effectively with many disciplines in order to address these complex, global challenges.

CURRENT TEACHING PRACTICES AND THE TECHNOLOGICAL REVOLUTION

Astoundingly, some of present teaching practices are little changed from the Middle Ages. Lecturers address students in lecture halls only slightly updated since the 14th Century, even though the lecture is well past its use-by-date. It seems built on the premise that students cannot read or that they cannot access the teaching materials. In the 21st Century, this seems absurd. In fact, the lecture was superseded by the printed book in 1439 [4]. However, teaching methods did not change, relying on the authority of the teacher as the primary source of knowledge, despite the ready availability of textbooks.

Through its Learning.Futures programme UTS has embarked on a university-wide change to embed active, authentic, blended and collaborative learning [5]. All faculties have been asked to de-emphasise lectures (put them on-line if necessary) and, instead, to emphasise active engagement of students in the classroom through collaborative learning, authentic tasks and assessment supported by blended and flipped learning methods, e.g. [6].

As one might expect, this has been a major challenge for some academic staff who have taught in more traditional ways for many years. The focus, however, is on engagement, authentic experience and e-learning - what one might call e3-learning.

Gutenberg's printed books did not usher in a new style of education in the 15th Century, but one can expect rapid change with the availability of the world's knowledge from contemporary mobile devices at any time and in any place. Increasingly, students are avoiding lectures and looking on-line for *best of breed* learning materials. Khan Academy [7], Codecademy, MOOCs such as Udacity, EdX, etc, are making the basic knowledge of an engineering degree freely available. If this is so, and students can learn an engineering degree on their own, what is the competitive advantage of a university?

ENGINEERING PRACTICE

Since 2000, there has been a series of international reviews of engineering education in the UK [8], the US [9-11] and Australia [12]. They have tended to identify similar themes, which continue to go on, largely unaddressed in most curricula. In fact, many of these issues have existed for a very long time [13]. Curricula should provide:

1. Better balance of theory and practice;
2. More industry involvement - authentic experiences;
3. More active learning with hands-on activity;
4. Use available best practice more effectively;
5. More student diversity - in particular, more women.

So, one need to educate for professional practice, but what is professional practice? Each lecturer has an accreditation body that has defined a set of graduate outcomes, e.g. EUR-ACE [14], ABET [15], Engineers Australia [16], and the Washington Accord [17]. These are usually grouped into three sets of outcomes: a) mathematics, computation and the physical sciences; b) design and engineering practice; and c) social and professional skills, such as communication and teamwork, ethics and sustainability. These lists of outcomes do little to give a sense of what it is that engineers actually do.

In 2009, Ian Cameron and the author were charged with the task of writing a simpler list of outcomes, which would become the national Australian Threshold Learning Outcomes [18][19]. The authors' definition, drawn from many meetings with academics and professional engineers, focused on the *nature of engineering work*:

1. Understand the problem in context;
2. Use a design and problem-solving process;
3. Supported by disciplinary knowledge;
4. Teamwork and communication;
5. Manage oneself.

In a subsequent project, David Dowling and the author explored the nature of environmental engineering in considerable detail [20]. Practising engineers were asked: *what is it that graduates DO in your company?* Although the investigators expected a list of technical tasks, such as *environmental engineers work on water, air, soil, noise, energy problems*, they were consistently given sets of *process skills* (in 20+ meetings and 200+ participants):

1. Investigation;
2. Modelling;
3. Design;
4. Impact assessment, risk, sustainability;
5. Planning and management;
6. Audit and compliance.

The investigators recognised that these process skills must be supported by technical skills (in the areas of water, soil, air, noise, energy) and also by professional skills (teamwork, communication, etc). A capability cube was proposed to show the intersection and interdependence of these three sets of skills [21].

James Trevelyan's work has also provided a much richer description of engineering practice [22]. This book should be compulsory reading for all engineering academics and students, because it gets to the heart of the problem to be solved - what needs to be learned to become an engineer. The investigators need to *understand the problem in context*, the first of their threshold learning outcomes (above).

EDUCATING FOR ENGINEERING PRACTICE

Engineering curricula need to be built upon the nature of engineering practice, which requires investigation, modelling, design, management and impact assessment skills. Yes, technical skills are necessary, but they are not the number one priority, as all this research shows. Design and complex problem-solving is the number one priority. This will enable graduates to grapple with the kinds of problems that were identified as being critical in the 21st Century. How can one achieve this?

Various forms of problem-based and project-based learning have been used in engineering programmes, with the longest record that of Aalborg University in Denmark, since 1974 [23]. In another approach, CDIO - conceive, design, implement, operate - is the best organised international community to support PBL-like activities [24]. There are many examples, where PBL is used in parts of the curriculum. However, PBL has never quite taken over in engineering as it did in medical curricula.

PBL curricula typically use a project spine, with the technical (disciplinary) subjects supporting the projects. In traditional curricula, it is the other way around - students are taught knowledge and skills and, then, they apply it in *design* subjects that are often little more than application subjects. In a PBL curriculum, projects occupy between 25% and 50% of the curriculum. In traditional curricula, design-like subjects tend to occupy 10-15% of the curriculum.

STUDIO-BASED LEARNING

At UTS, the idea is to migrate the engineering curricula to what is called a *studio-based* model. A studio is a project-based experience, with a difference. In a studio, the focus is really on each individual student's learning. The project is the means, not the destination. The assessment is portfolio-based rather than relying on artefacts such as project reports. Each student writes a learning contract to identify what is to be learned. Students can be working alongside each other on the same project, but with different intended learning outcomes [25-28].

One of the first test cases is environmental engineering, drawing on the Define Your Discipline work, described above [20]. Five potential studios have been identified, each of which will be half of a semester's work (about 300 hours):

1. Environmental engineering practices (a general introduction in a land and water context);
2. Sustainable urban transport systems;
3. Urban water and waste;
4. Energy engineering (energy efficiency, renewables, bioenergy, embodied energy);
5. Land and water management (at catchment scale).

These studios will explore the key process skills of investigation, modelling, design, impact assessment, management and planning, and audit and compliance. Students will develop these key practice skills across these five contexts.

Studios have also been introduced in software engineering, data engineering, and in a new electronics engineering programme. Each studio is nominally 25% of a semester's work in these programmes, across 7 semesters. The 8th semester contains the capstone project as the final studio. So, studios represent 25% of the programme. These studios:

1. Develop professional capabilities (learning outcomes);
2. Use supporting on-line modules (with on-line assessment);
3. Rely on teamwork;

4. Provide exhibition, presentation and interview of the student work;
5. Use a portfolio as evidence of attainment.

Such curriculum reform is not easy; however, there are small steps for moving to a more-project-based curriculum:

1. Create projects in more courses (subjects). The focus should be to provide an integrative experience for the students.
2. Rethink the sequences of courses, e.g. fluids, structures. What is a small project that can be included in each course in the sequence that builds professional capability in such a way that the projects grow in sophistication?
3. Identify a project course in each semester.
4. Share this project across semesters, linking disparate subjects, e.g. design of a structure could also link to design of its foundations (geomechanics), to project management and to engineering economics.
5. Combine subjects into bigger units with bolder, cross-disciplinary objectives.
6. Introduce multi/transdisciplinary projects.

In the author's experience, Step 1 will yield useful results. Once confidence has been obtained by both staff and students in how to conduct projects; then, Steps 2-6 are easier to take. It is likely that the curriculum will need to adapt to a more project-focused approach.

ENGINEERING DESIGN PROCESS

The engineering design process underpins these studios. A popular version of the design process is design thinking [29][30]. Students begin by understanding the problem - *empathise* in the language of design thinking. This process engages students with the stakeholders of the problem, with the intention of *defining* the problem as clearly as possible. An essential part of the definition is a set of *requirements*, which define what must be delivered. Once agreed with the client, students then *ideate* possible solutions and *prototype* and *test* proposed solutions.

These processes are surrounded by a set of project management and team processes to ensure that a successful solution is delivered on time and budget. Beyond this simple description of design thinking lies systems engineering, which should also be an essential component of any engineering degree [31][32].

Students also need access to sophisticated design software (e.g. Dassault Systemes 3D Experience software), on-line modules (e.g. Lynda.com) and on-line assessment (e.g. Peerwise). This environment mimics the engineering workplace, where graduates need to be self-organising and to operate at a high cognitive level, using sophisticated design tools, using information around them, including their team, surrounding teams, the instructor, the project mentor, and on-line resources.

One key transition is the move to on-line mastery of engineering fundamentals. Subjects such as statics, dynamics, circuits, control, thermodynamics, fluid mechanics, etc., will soon be learned on-line. Statics.com is one existing Web site to support students, including assessing their mastery of the topics. More will follow.

CONCLUSIONS

An engineering world that emphasises *innovation* needs educational processes that will graduate potential innovators. Old methods rely on reproducing past solutions. One needs graduates who will create the solutions of tomorrow.

Fortunately, one now has available the tools to make this work - one can provide *personalised learning* in the age of Google. Students build their portfolio of capability within the studios, working on a series of projects with fellow students.

Thomas Shuell wrote (in 1986):

> *…the teacher's fundamental task is to get students to engage in learning activities … it is helpful to remember that what the student does is actually more important in determining what is learned than what the teacher does* [33].

Academic teachers need to become *designers* and *facilitators* of learning experiences rather than lecturers. This will change who the universities need to hire over the next 10 years.

The common knowledge is that this works. At most campuses, the Formula SAE Racing Team is a shining example of what students can do to develop their capabilities. They do not need intensive supervision. Project work of this kind does not need to be time consuming, contrary to popular belief. One would do well to have every student engaged in such a team.

Students need to become self-organising learners. They will learn to deal with complex problems, access technology as required (both design tools and learning tools) and develop professional practice skills. They will document their capabilities through an e-portfolio and exhibit and defend that work at regular intervals. They will emerge from the university ready for the complex challenges of the future.

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BIOGRAPHY

Roger G. Hadgraft is a civil engineer with more than 25 years of experience in improving engineering education, publishing many papers on problem- and project-based learning (PBL), and the use of on-line technology to support student-centred learning. He was instrumental in introducing a project-based curriculum in civil engineering at Monash University and in several disciplines at the Royal Melbourne Institute of Technology (RMIT). Roger was an Australian Learning and Teaching Council Discipline Scholar and co-author of the Threshold Learning Outcomes for Engineering and IT and he has been a member of several national learning and teaching projects. He is currently Director of Educational Innovation and Research at the University of Technology Sydney.