The fundamentals are important…but what are they?

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SESSION C2: Interdisciplinary and cross-disciplinary engineering programs and learning environments

CONTEXT The development of an engineering practice degree in which students learn entirely through industry projects has decoupled the curriculum, where curriculum is considered to be the comprehensive list of skills, content and achievement standards that students must achieve as they progress through their degree, from the unit-based structure of the course. This means that rather than taking a series of units such as 'calculus' and 'thermodynamics', students learn the fundamental maths, physics and engineering concepts when they become relevant in the context of a project. However there are still certain bodies of knowledge and skills that all students must master if they are to work as engineers and it is crucial that 'the fundamentals' are learnt by all students regardless of the specific projects that they work on. A hierarchical learning structure is also still essential, as students must master certain basic concepts before progressing to more complex ideas, but the paths through this new structure will be more fluid, and different for each student depending on the projects they undertake, their particular roles in each group project, and their personal learning goals.

PURPOSE To identify what the key fundamental knowledge is that all graduate engineers must have mastered to become engineers capable to contribute in 21st century practice.

APPROACH Several approaches are being used to identify the fundamentals. The first is to consult the industry partners who are co-designing and co-delivering the practice-based course. They have been very clear about the broad skills they require from graduates and can provide insight into what knowledge is essential and assumed for students entering their practice. The second is to map current engineering curricula, looking at the core knowledge blocks and with an emphasis on the flow through the topics. If a particular topic is required for a project, the previous mastered knowledge must be identified and student attainment tracked to ensure students have sufficient grounding to access the content and apply it in the project context. This mapping process will also identify which areas currently taught do not lead into any other topics are not required for projects or used in industry.

RESULTS Digital disruption and a rapidly changing world have rendered many traditional techniques unnecessary while necessitating the development of many other skill and knowledge sets by engineering students, and it is not yet clear exactly what these will be. It is anticipated that while some knowledge is perpetually fundamental, much of what is traditionally taught may no longer be relevant to modern and future practices of engineering.

CONCLUSIONS Early consultation with industry partners indicates a greater focus on budgeting and financial maths is important, along with a greater emphasis on mathematical modelling and programming skills. 'Basic' maths and physics are considered fundamental but more detailed research is needed to identify specific key topics areas.

KEYWORDS Fundamental knowledge, practice-based learning.

Introduction

Changes in society and technology have radically altered 21st century engineering practice and graduate engineers increasingly require different skills and knowledge to be employable. However engineering courses, while attempting to make headway in addressing the need for the development of key transferable skills such as communication, have not changed in terms of fundamental content for a number of years. This raises a number of questions such as has the fundamental knowledge required of engineers changed? What do engineers still need to understand and be able to calculate from first principles and what has been replaced by technology? Do we need to teach how to use software tools and if yes, which ones? Do all engineering graduates need the same technical depth in fields or is there scope to produce different kinds of engineers, some with technical depth, others with a broader background?

One of the greatest criticisms of traditional engineering pedagogy is that it is a theory based science model that does not prepare students for the ‘practice of engineering’ (Felder, Woods, Stice, & Rugarcia, 2000). In most engineering courses it is traditional that in first year engineering, the majority of student time is spent on the mathematical and scientific basics that underpin all engineering disciplines. In the second and third year, students may work on industry and/or community projects, and industry practice takes place in the final year (Jawitz, Shay, & Moore, 2002; Ku & Goh, 2010; Webster, 2000) or as a work placement during the course. In a course based entirely around projects the course must be defined and structured to allow students to obtain the required fundamental knowledge. Previous research studies suggest that engineers should experience a broad base of fundamental knowledge, skills, and engineering applications in practice within an undergraduate course and later develop their specialist skills through professional practice in their selected discipline (Lima, Carvalho, Assunção Flores, & Van Hattum-Janssen, 2007).

To address these issues a practice-based approach has been developed in which students work in teams on industry-set projects from day one of their course and throughout, with all content being taught in the context of these projects. The curriculum is being co-designed with industry partners through consultation process ensuring it is relevant to current engineering practices (Cook, 2017), a process adapted from the “Design your Discipline (DYD)” stakeholder consultation process created to facilitate curriculum renewal in undergraduate programs (Dowling & Hadgraft, 2013). The practice-based approach is designed to motivate future engineers by establishing relevance in using the fundamentals at appropriate places where it is needed in industry projects from day one of their course, as establishing relevance is one of the main factors which induces students to adopt a deep learning approach (Ramsden & Entwistle, 1981).

The development of an engineering practice degree in which students learn entirely through industry projects has decoupled the curriculum, where curriculum is considered to be the comprehensive list of skills, content and achievement standards that student must achieve as they progress through their degree, from the unit-based structure of the course. This means that rather than taking a hierarchical set of units such as ‘calculus’ and ‘thermodynamics’, students learn the fundamental maths, physics and engineering concepts as they become relevant in projects. Obviously a hierarchical learning structure is still essential, as students must master certain basic concepts before progressing to more complex ideas, but the paths through this structure will be more fluid, and different for each student depending on the projects they undertake, their particular roles in each group project, and their personal learning goals. While this is laudable in terms of allowing students to have individual learning journeys, there are still certain bodies of knowledge and skills that all students must master if they are to work as engineers, the ‘fundamentals’.

In the context of a new practice-based engineering degree, in which students learn entirely in projects, when curriculum is decoupled from unit structure in this way, core knowledge must be carefully mapped and student attainment tracked. However the new structure of a practice-based course allows many assumptions to be challenged, including exactly what is the fundamentals knowledge required to be an engineer is in the 21st century, both for all engineers and for specific disciplines.

Previous work examining the different skills engineers require in 21st century practice has focussed on determining the generic competencies, with many authors calling for increased recognition of skills such as teamwork and communication, business and enterprise skills and generic engineering competencies around digital literacy. Methods used to determine which competencies are necessary in 21st century engineering are many and varied, spanning literature reviews (Male, 2010), stakeholder consultations (Spinks, Silburn, & Birchall, 2007), surveys and focus groups (Male, Bush, & Chapman, 2011), interviews (van der Wal, Bakker, & Drijvers, 2017) and observations (Cardella, 2008).

Work around the fundamental knowledge required by engineers has often focused on mathematical and digital skills. The universal use of ICT in all sectors changes the nature of the mathematical and technical skills required in the workplace, but does not reduce the need for mathematics (Hoyles, Wolf, Molyneux-Hodgson, & Kent, 2002). Niss (2003) identified eight mathematical competencies, where competency is defined as the ability to understand, judge, do, and use mathematics in a variety of contexts and situations. The competencies identified are: thinking mathematically, reasoning mathematically, problem posing and solving, modelling mathematically, representing mathematically, communicating mathematically, symbolism and formalism language, and using aids and tools. Firouzian (2016) surveyed students, teaching academics and practicing engineers about the perceived importance of Niss's eight mathematical competencies and found a mismatch in the perceptions of academics and practicing engineers. Mathematical modelling was most important to both groups but practicing engineers rated the importance on using tools and software far more highly than academics.

This result agrees with the findings of van der Wal et al. (2017) who use the terminology techo-mathematical literacies as coined by Kent, Bakker, Hoyles, and Noss (2005) to describe the combinations of mathematical, statistical and technological skills necessary for successful performance in the workplace. They used semi-structured interviews of fourteen engineers from a spectrum of technical engineering domains to determine seven main categories of techo-mathematical literacies: data literacy, technical software skills, technical communication skills, sense of error, sense of number, technical creativity and technical drawing skills.

This intersection between mathematical understanding and application and 'using tools and aids' is where what is considered fundamental knowledge is shifting. As one of the participants in van der Wal's study says "I have to say, calculus and such, I have never used it. Most of the time it is hidden in the software, and it would be nonsense to let someone calculate for a whole day what a computer can do in a minute." There are many questions to be answered around what fundamental knowledge is needed in this new technology-driven world where information can be accessed at the touch of a finger and digital tools are ubiquitous.

This paper outlines the start of the process of identifying just what these fundamentals are as they apply to 21st century engineering practice.

Approaches

To identify what the fundamental knowledge is a variety of approaches have been considered. The first approach is the top-down stakeholder consultation approach, which has used the industry consultation framework described in Cook (2017) to develop the broader curriculum for this degree to understand the knowledge, skills and mind-sets industry partners employing graduate engineers are seeking. The second is from the ground up, examining the current topics taught in the first year of an undergraduate engineering degree and seeing how these map to the outcomes required by industry, identifying any branches that do not connect in either direction.

The industry consultation process included a series of ideas workshops, curriculum consultations and deep dive workshops centred around the course pillars of social impact, emerging technologies, research & development and entrepreneurship.

The purpose of the ideas workshops was to explain the practice degree concept to Industry, get their initial feedback and ask what knowledge, skills and mindsets they would like graduate engineers to enter their industry already possessing. The outcomes from the ideas workshops was a list of skills and attributes that was organised into a framework which was presented back to Industry partners in the curriculum development workshops where is was built-out and adapted. This early consultation with industry partners indicated a greater focus was required on business and enterprise skills, that budgeting and financial maths are important, along with a greater emphasis on mathematical modelling and analysis of big data.

The curriculum deep-dive workshops then looked in detail at the curriculum areas connected to the four pillars of the course: social impact, emerging technologies, research & development and entrepreneurship. In these workshops participants were asked to expand on specific curriculum points, what they meant in their industry context and what skills and experiences student engineers would need to be able to demonstrate mastery of these. The content taught in the core units of the current engineering degrees were mapped to produce detailed content trees, indicating the topics taught, the interdependencies of the topics and the pre-requisite knowledge for each topic.

At the time of writing the process of deep-dive industry consultation is ongoing, with some preliminary results presented here.

Results

The process of industry consultation in still ongoing but some key ideas have emerged from the stakeholder consultation process. Some general themes that have emerged from industry workshops suggest an increased focus is required on professional skills, business and finance, understanding organisational values and culture and valuing sustainability and environmental issues (which are not considered further in this paper), coding, data analysis and mathematical modelling. Automation, AI, 3D printing and design were also emphasised as being important broad areas student engineers should be exposed to. Specific areas within these were discussed in the workshops and from these the fundamental knowledge underpinning them mapped out.

The result of the mapping process is a complicated web of topics, with many interdependencies. An example of the outcome from the curriculum mapping is provided in Figure 1. In unpacking the automation area identified in the Emerging Technologies industry workshop, an outcome was that graduates should have the ability to use, select and control actuators. This graduate outcome was linked (by the curriculum development team) to different types of actuators, such as electrical, mechanical, hydraulic and pneumatic actuators. For the purposes of this paper, results are limited to mapping curriculum associated with mechanical and electrical actuators only. The operating principles for electric actuators are also linked to mechanical actuator principles (e.g. gears and drives. The control of these two actuator types was mapped to principles of fluid statics and dynamics for hydraulic actuators, and principles of electromagnetism for electric actuators). Underpinning these engineering principles are the fundamental mathematical and scientific principles and concepts. For the use and control of actuators, the identified fundamentals included basic algebraic expression, differentiation and integration, principles of force, energy and work, substance properties, and measurement (including units).

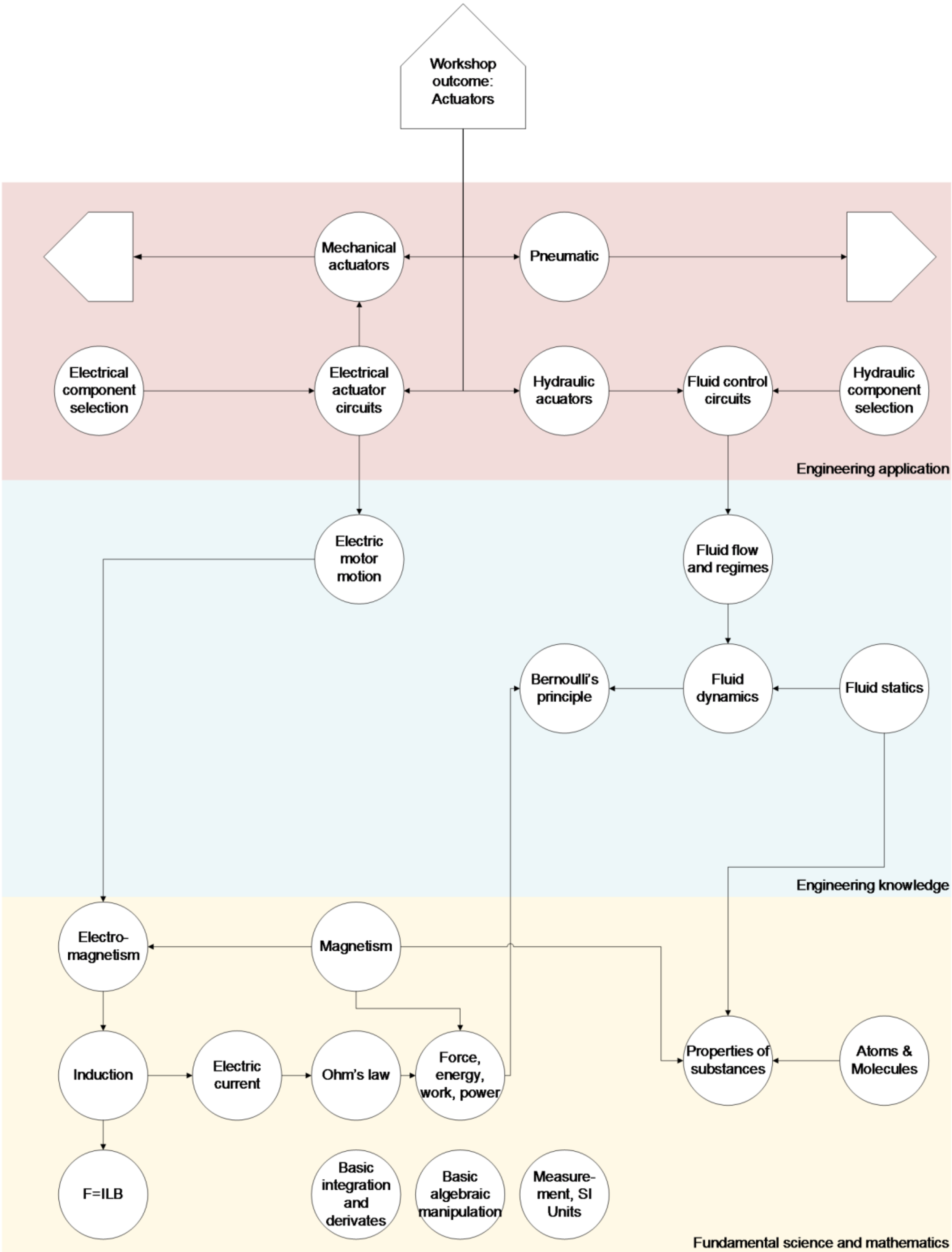

Figure 1. Example of identified linkages between industry outcomes, engineering principles and fundamental science and mathematics for actuators.

The linkages from the engineering principles converged to shared mathematical and scientific principles; these are considered to be the fundamentals. It is expected that further mapping of the top level industry outcomes to engineering principles will identify further shared mathematical and scientific principles. In addition, it is anticipated that many of the fundamentals delivered within traditional engineering curriculum may not be mapped, suggesting that they do not need to be included in the core curriculum. However, these excluded fundamentals may be required within the curriculum for specialist engineering fields, depending on specific industry outcomes.

Discussion & Conclusions

It is apparent that while, in a traditional education system, students are contained to a well-defined convergent problems, industry expects creative and innovative academic practice that provides students valuable practical knowledge. Students require an opportunity to apply engineering knowledge in practice, which means the purpose of engineering education in most cases is to graduate engineers who can demonstrate engineering application in real world scenarios (EA, 2012).

This model of using stakeholder consultation has highlighted broad concepts that are required by engineers and here it has been used to attempt to identify the fundamentals underpinning those concepts in terms of basic of mathematics, physics, electrical energy, electronics circuit theory, environmental and materials science, mechanical design, telecommunication networking, coding and programming etc. In all workshops there was a strong focus in the discussion on the importance of generic competencies such as communication and teamwork, skills as suggested by others (e.g. Male (2010)), often making it challenging to elicit responses from industry participants focussing on more technical competencies.

This process of identifying concepts and unpacking them to determine the key knowledge that underpins them is an involved process, requiring iterative consultations with stakeholders and in-depth mapping of interdependent topics at a detailed level. This work is ongoing. Digital disruption and a rapidly changing world have rendered many traditional techniques unnecessary while necessitating the development of many other skill and knowledge sets by engineering students, and it is not yet clear exactly what these will be. It is anticipated that while some knowledge is perpetually fundamental, much of what is traditionally taught may no longer be relevant to modern and future practices of engineering.

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