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Monitoring Trends in Academic Programs: Engineering

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SERIES INTRODUCTION

HESA's Monitoring Trends in Academic Programming series provides a high-level overview of programming trends in a thematic area. The goal of the series, which began in 2019, is to provide readers with information concerning pan-Canadian educational trends, to provoke ideas about new program design approaches, and to highlight new or innovative programs around the world. It is meant for a wide readership—both people with connections to a field and to those outside the field who want a quick review of some trends in an area.

It is also a small sample of the program surveying and review capacities at HESA—contact us at info@higheredstrategy.com for more on our program review and analysis services.

ABOUT THE COMPANY

Higher Education Strategy Associates (HESA) is a Toronto-based firm providing strategic insight and guidance to governments, postsecondary institutions, and agencies through excellence and expertise in policy analysis, monitoring and evaluation, and strategic consulting services. Through these activities, HESA strives to improve the quality, efficacy, and fairness of higher education systems in Canada and worldwide.

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Introduction to Monitoring Trends

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WELCOME

This is the fifth issue in Higher Education Strategy Associate's ongoing series, Monitoring Trends in Academic Programming (MTAP). Previous issues have largely focused on areas that bring in several faculties, such as our report on *Water* or on *Agriculture and Food*. This is our first issue that focuses on a single faculty: Engineering.

Why Engineering? Because significant rethinking about engineering undergraduate education should attract the attention of faculties across post-secondary. As a discipline that has long ties to external and professional groups, engineering faculties have often been more attuned to societal demands than other fields. They are demonstrating this by revising their curriculum in ways that more readily train people for the roles and challenges they will face in the future. Students are being asked to solve problems that have no clear solution and work in groups with people who may not have the same academic background as them.

This issue has three main sections:

1. **The First Year** provides a summary of significant changes to first year engineering experiences both in Canada and abroad. The impact of the Olin College of Innovation is noted, and more recent examples of reforms in Canada are celebrated.

2. **Challenge Based Learning** traces how engineering programs around the world are re-thinking their curriculum and allowing students to tackle major challenges in labs and maker spaces. The reforms align with several pedagogical innovations, including flipped classrooms and encouraging the interplay of different learning styles.

3. **Identifying Engineers** explores how engineering departments try to shape the engineering mindset and assess initial steps being taken to improve recruitment of women and other underrepresented groups into engineering programs.

While these are presented as three discrete sections, the themes addressed in this issue: significant and challenging revisions to curriculum, fostering and nurturing different learning styles and perspectives, and engaging students with major social problems surface throughout the discussion.

The audience for this publication consists equally of people outside engineering as it is of people who teach or learn within the field. A core thesis of this issue is that faculties across post-secondary should seriously consider the reforms that we are seeing at Engineering faculties. There is a refreshing willingness to radically overhaul program structures and teaching approaches, and a sense that much of the learning in engineering is becoming mission-driven and committed to training people who will do their utmost to tackle and develop solutions to global crises around sustainability and responsible planning.

Further, this issue advances MTAPs general view that many of the best pedagogical reforms occur when disciplines seriously consider the influence and input of other disciplines. Many of the shifts outlined here are happening because many engineering faculties have decided to seriously incorporate other faculties into their programming (or, at the very least, create bridges between different engineering disciplines).

Unlike other issues, this version is focused primarily on university undergraduate experiences, primarily in the interest of maintaining a coherent thematic discussion. Future issues of MTAP will look closely at trends in polytechnics and colleges, as these institutions are also major incubators of pedagogical change.

Recruiting and Identifying Engineers

This section considers the relationship between academic programming and identity making. Effective programming can deeply shape a person's outlook and mindset, and few have a greater power in doing this than engineering. Engineering is both a discipline and a profession, where links between education and career are more blurred than in most other fields. Many programs are also accredited by organizations like Engineers Canada, which reinforces the link between engineering as a program and as a profession.

Therefore, engineering programs have more of an onus than most academic disciplines in understanding the characteristics of a good engineer. This section considers how engineering programming can be dedicated towards identifying and cultivating the engineering mindset.

ENGINEERING MINDSET

An important theme in engineering education is the field's interest in understanding what the "engineering mindset" is. Because engineers interact with so many different projects and parts of society, and find themselves in so many different roles, there is a broad interest in understanding what this mindset brings both to the academy and to society. A recent contribution to the Canadian Engineering Education Association articulated that:

> **An engineering mindset *is built on the core belief that solutions to human problems can be designed within the constraints of science, economics, environment, and safety risk management. If the solution can't be found within the bounds of known technology then research and innovation may provide a path forward.*[1]**

This is a helpful definition for two reasons. Firstly, it can be distinguished from other disciplinary mindsets—there are several academic fields and sub-fields that would likely contest this faith in human ability to overcome human problems. Secondly (and more importantly for our purposes), it explicitly connects to several other fields and implies that many engineering projects are conducted in service of projects that have a wide range of interested parties. So, the core question becomes: what does the engineer bring to the table when solutions are being developed?

The scholars whose work is cited above suggest that the engineer needs leadership and management tools to fully

Library, Delft University of Technology (TU Delft) in Delft, Netherlands

function in their societal roles. From a programming perspective, this means acknowledging that emphasizing only technical competency can lead to limitations and to the engineer being unable to fully appreciate the context in which their solutions are being applied.

The project and challenge-based learning highlighted above is a key part of the effort to cultivate leadership skills that allow engineers to share their ideas with people from other academic backgrounds. Students at TU Delft, for instance, are expected to combine a technically rigorous education with student innovations and learning that occurs through extra-curricular activity like their ***Dream Teams***, which are student run groups.

However, there are also more formal course-based approaches to enhancing student leadership skills. The University of Toronto offers a three-course Certificate in Engineering Leadership to its undergraduate students, with courses in areas like ethics, intercultural communication, language and power, and applied psychology. This certificate is comprised of three for-credit courses that can count towards the overall undergraduate degree. Western also allows students to complete a lower-level business administration course and four upper-level engineering leadership courses that count towards their degree. The University of Calgary offers a certificate that is outside of the formal degree structure, but gives their undergraduate students access to six workshops, two networking events, and a leadership conference.

WHO IS AN ENGINEER?

Engineering programs admit and graduate a ***disproportionate number of men*** and struggle to recruit Indigenous students. Programs across Canada and beyond are taking steps to rectify this long-standing imbalance—some of the revisions to the first-year programs and development of CBL and project-based learning are designed in part to attract a wider range of students. Some institutions have also developed environments and collaborative spaces to rethink who engineers are and the conditions they might work in. Engineering Deans Canada has identified Inclusivity and Diversity as a ***fundamental principle*** of engineering education.

One response to this challenge is the development of courses that critically examine the role of engineers in

Water treatment plant

society. Many programs have a course around the Engineering profession that examine ethical requirements, sustainability, and professional conduct, and these courses have also expanded to include some discussion of exclusion and the gendering of work. For instance, the University of Waterloo's Electrical Engineering program's course on Engineering Profession and Practice incorporates diversity training. The University of Ottawa established a STEAM Creation initiative that brought together twelve engineering and twelve arts students to cultivate understanding of different methodological perspectives and create empathy maps that allowed for exploration of different perspectives.[2]

Indigenous peoples are particularly under-represented in engineering—***only 0.73%*** of identified Canadian engineering are Indigenous. There are institutional groups that are devoted to improving access. A key example of this is the Indigenous Futures in Engineering initiative at Queen's University. An important feature of this initiative is how it particularly provides materials, resources and services for children and parents who are part of the K-12 system. They produce booklets and resources for young Indigenous students that help to see themselves in the profession. They also refer to "Ancestral Engineering," which acknowledges how "Indigenous peoples... solved problems relating to transportation, shelter, health, communications and other things in unique and innovative ways." At the University of Manitoba, the Engineering Access Program targeted towards Indigenous learners offers a two-week refresher in math and computer science and also connects some students to introductory courses if they came from schools that did not offer all the pre-requisite courses or if they are adult learners.

Many efforts to facilitate a more inclusive engineering class come from outside of the formal curricula through groups and peer networks. Many institutions now have a Women in Engineering group, which offer peer mentoring, workshops, mental health, and other targeted supports. Purdue University, often boasts having the best public-school engineering department in the United States, has a dedicated site and support for first generation students, including a targeted handbook that provides more detail and explanation of university conventions that a child of university graduates may more readily know. For instance, it includes a simple description of the lecture hall experience and what an honours program is.

In general, efforts to identify a wider range of people who can be engineers are emerging and ongoing, and much of the work is taking place within institutions but outside of formal classes. The next few years should see the spread of courses that specifically address social issues from an engineering perspective—the topics are starting to emerge in general Engineering Practice courses, but they have yet to be fully foregrounded.

SUMMARY

Engineering programs are taking serious steps to expand their understanding of what makes an engineer and who can be an engineer. Engineering departments have long had a pride that stands apart from most faculties, and the bonds of community that engineering programs can forge should not be abandoned—they are key to what makes engineering a dynamic field.

However, engineering departments are increasingly shifting to a more external focus and thinking rigorously about what it is that they contribute to social and technical problems that other disciplines might not. It also means developing projects and courses that require engineers to work more closely with people from other intellectual backgrounds to improve mutual comprehensibility. The "Ancestral engineering" paradigm is an intriguing step in this direction.

There is clear commitment from multiple levels to improve on the long-standing gender disparity in engineering, as expressed in the Engineering Deans Canada declaration. This commitment has manifested in several studies and the formation or growth of women in engineering groups that help provide mentorship and support for incoming students. Design and challenge-based courses are also in part a response to make programs more welcoming to a wider range of students. However, programming changes are only just emerging.

The First Year

The first year of any post-secondary student's program is critical. It provides fundamental knowledge and skills that students can draw upon for the rest of their program, it attunes students to study habits, and it helps confirm what subjects a student is interested in. A strong first year can help with student retention and completion. This is particularly critical for university Engineering programs, *since they often have lower retention rates* than other programs—in part due to the challenge of giving students training in the various competencies required by the different branches of engineering. This retention issue can be *particularly acute for students who are not white or Asian*; groups who were not traditionally targeted or recruited by engineering departments or who have equal access to the preparatory courses in the K-12 system. Fortunately, this challenge has also led to institutions around the world developing new ways to approach the first year in ways that are engaging and that can help students understand and apply their knowledge earlier in their program.

The hard skills persist—students will still need to brush up on their vector calculus and fundamental physics. However, there are several innovative approaches to creating a first-year experience that both provides core skills while getting students excited about where their studies will take them in the future. The goal is also to set students up for experiential opportunities throughout their undergraduate degree, fostering and foregrounding creativity as much as technical prowess.

THE OLIN SHIFT

Engineering has an unusual advantage in that the traditional first year was strongly challenged by the emergence of the Olin College of Engineering, which had its first cohort of students in 2000. The development of the Olin curriculum through a collaborative effort between their early faculty and the thirty "Olin Partners" students who were in the first cohort has a rather considerable reputation in engineering education annals—the thirty students had the opportunity to help design the original curriculum that was the rolled out to a full class in 2002. The institution also targets having about half of the undergraduate body being women. Despite the relatively short span that Olin has been operating, the institution is considered, along with MIT, as one of *the leaders in engineering education.*

The primary innovation that is associated with Olin is their heavy emphasis on design thinking and hands-on learning from the onset of undergraduate, rather than as a capstone

John Hodgins Engineering Building, McMaster University in Hamilton, Ontario

project in a senior year. Underpinning this approach is a belief that engineering requires more engagement with people with a range of mindsets and intelligences and shifting engineering from an individualistic and competitive culture to a collaborative and connected one.[3] There is an explicit goal at the institution to train people who are interested in confronting societal challenges. In terms of curriculum, this means more teamwork and projects that cut across disciplines, though as Olin has grown, a few concentration options have emerged over time.

The Olin approach has been credited with changes to curriculum at much larger institutions. Notably, the University of Illinois at Urbana-Champaign developed the ***GFX Scholar program*** that allows first-year students to pursue projects and work with students that are similarly interested in themes like technology and innovation or global sustainability. The program demonstrates how a complex programming approach that breaks a number of normal disciplinary routes can be offered as a sizable institution—though notably one must get admitted into the program.

A unique feature of Olin is their willingness to share learning materials widely. They have a website devoted to distributing their teaching and learning material, from guides on effective teaching to modules for their courses. For example, their Principles of Integrated Engineering course provides handouts for all of their projects, notes the various mini-experiments that students can work on to improve their knowledge of the Arduino Uno R3 system, and provides clear information on the different requirements and deliverables expected for the final project. The final project in the course is orientated around a sprint review, which lines up with a common methodology from formal project management systems.

TRENDS IN CANADA

Engineering faculties across Canada have been keenly considering the structure and content of their first year. The tremendous challenge for most faculties is to develop a first-year experience that both allows students to get the tools needed to succeed in a wide range of engineering disciplines, provide exposure to real-world challenges and issues, and give intensive training on challenging and technical topics. This is not an easy balance for any faculty to achieve, but engineering has a particular challenge in juggling a range of topics in a rigorous and coherent way.

This section highlights recent changes at two recently revised programs.

McMaster's Engineering gave its program revision a compelling name—the Pivot. At the core of this revision was the creation of a year-long class, Integrated Cornerstone Design Projects in Engineering, which combined four separate courses and re-orientated them towards solving four separate design challenges over the course of the year. The projects were selected to show how engineering can help with challenges around health care, sustainability, and other issues facing the community. One of the core elements of the pivot was to encourage different types of learners: readers, listeners, and doers. The curriculum also orientates around five core paired competencies: Discover and Create, Integrate and Solve, Business and Innovate, Global and Diversity, and Citizen and Community. They launched the first-year integrated course in 2020 and have just launched their first second year design project in the winter of 2022. The entire project is documented in ***an engaging and detailed online document***.

The University of Saskatchewan also recently revised its first-year engineering curriculum significantly. An intriguing theme is their shift towards a module course approach, where several courses that would have lasted a full semester are now broken into one- or two-month modules, as shown in their revised first year schedule, pictured below.

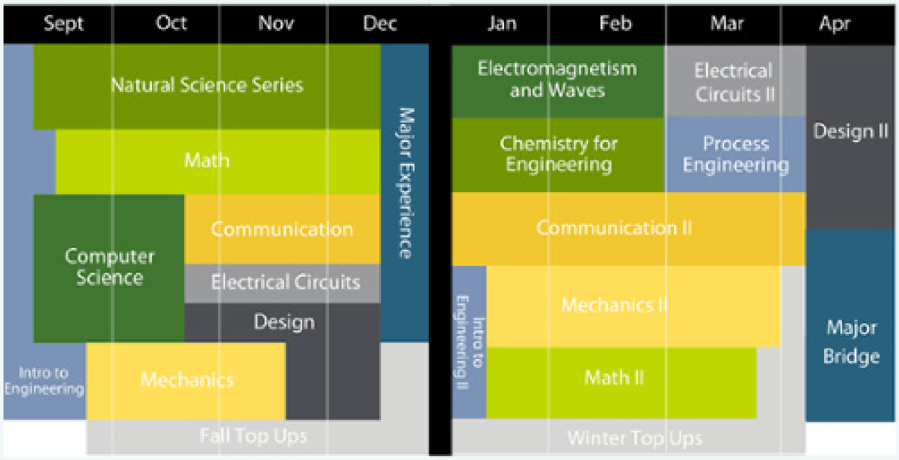
Other shifts in their programming include an introduction of free online "summer top-ups" that help incoming students refresh and enhance their understanding of chemistry, mathematics, and mechanics. Students select their major at the end of the first year (which is relatively common in Canada), but before the end of first year students can take a Major Bridge Course that introduces them to their chosen discipline in a more detailed way.

This reform is remarkable because it fundamentally rethinks how semesters can be formed to help introduce students to the wide range of knowledges needed to succeed in a wide range of engineering fields. ***Students are graded on a competency-based assessment***, and students need to demonstrate a competency in a learning outcome to receive their grade. Students receive at least two opportunities to demonstrate their competency in an outcome, and a better performance will replace any earlier grade.

SUMMARY

McMaster and Saskatchewan are two leaders in the push to revise the first year. Faculties across Canada should keep an eye on engineering departments, as they are completing ambitious plans that should provoke thinking about first year experiences across faculties. The goal is to improve retention, provide a means for students with different levels of STEM preparation to succeed in engineering, and excite students about what it is they will be learning.

First Year Schedule, University of Saskatchewan



Challenge Based Learning

Challenge Based Learning (CBL) has gained considerable traction since emerging in academic literature at the turn of the twenty-first century. While the precise definition of CBL can vary depending on the user or literature, it generally "frames learning with challenges using multidisciplinary actors, technology enhanced learning, multi-stakeholder collaboration and an authentic, real-world focus."[4] It fosters collaboration between students, academics, and external groups. CBL differs from other problem-based learning because it provides students with an *open problem to try to solve* rather than a specific problem or project to complete. Engineering has been one of the earlier adopters of CBL as a pedagogical approach.

Many engineering faculties have developed programs and approaches that encourage students to develop their knowledge of these challenges and to create solutions to them directly within the curriculum within a CBL framework. The primary reference point for this approach is the *UN Sustainable Development Goals*, though other frameworks are possible. For instance, Engineering Deans Canada identified *six Canadian Engineering Grand Challenges* that were framed around the UN SDG. This section examines how different engineering programs organize their curriculum to foster challenge-based learning.

CBL VERSUS PROBLEM BASED LEARNING

CBL shares much with Problem Based Learning (PBL), which is a somewhat more known approach in Canada. A report from Alex Usher and Robert Crocker explored the *use of PBL in McMaster* back in 2006. PBL asks learners to thinking critically and analyze real world problems—often problems that are taken directly from actual scenarios. Often, PBL projects occur over the course of a term. However, a key difference is that *CBL need not lead to a final solution*. The pedagogical value is in the serious investigation and development of ideas that may tackle a challenge. Further, there is no expectation that the instructor knows the answer to the problem, but rather is best positioned for helping students develop ideas. Therefore, challenges are often major and involve large populations and issues.

A PBL EXPERIMENT IN CANADA

In Canada, a recent implementation of a PBL was attempted at the University of Toronto's Chemical Engineering undergraduate program. The project asked students to analyze copper samples from two different sites, make predictions about copper yield, and project the social, environmental, and economic impact of the work. This work was sequenced over seven deliverables in a term. Intriguingly, the authors found that students wrestled particularly with how to analyze and explain their data in context. Nevertheless, a post-course survey found that students particularly improved their visual and written communication skills over the course, and that many students changed their planning and writing for their lab reporting in response to different challenges. The publication of this report found that while the first year of the course had some operational challenges (such as consistent standards across evaluators), they generally found the approach successful. The department continues to offer the course as of 2021-22.[5]

CBL ABROAD

One of the recognized leaders in CBL is University College London. CBL is a major part of their *Integrated Engineering Framework* (IEL), which foregrounds learning through team based designed exercises, flipped lectures, and IEP Challenges. This IEL approach was developed as a way to attract a wide range of students beyond people who excelled in mathematics and physics in high school. The challenges are completed during the first year, but the intent is to have those projects frame a student's development over the course of their undergraduate degree. Students complete two challenges—one within their discipline (e.g. mechanical engineering) and one with a cross-disciplinary group. Issues tackled within these challenges include creating sound recovery plans following an earthquake or creating solutions for producing and distributes vaccines quickly to remote areas in Sub-Saharan Africa.

The Eindhoven University of Technology (TU/e) has made CBL an important part of their ***overall academic vision for 2030***. Their research-based learning model committed to making challenge-based learning a "distinctive element" of studying at the institution, where bachelor's students will be expected to tackle open-ended problems around issues like energy sustainability, while master's students will engage in more in-depth research into identified challenges. These projects are also expected to bring in external partners and research projects in a dedicated research space.

In ***an explanatory piece***, a collective of educators at TU/e noted that the shift to CBL has impacted several teaching and learning practices. There are experiments in linking challenges across courses and between engineering and elective courses, in developing inter-university collaborations and projects, and in creating lengthy courses for students from a range of programs around particular issues, like improving the sustainability of the famed Dutch dairy industry. In terms of teaching, they note that CBL implementation has enhanced support for students to become more self-directed and allowed instructors to serve a role closer to a coach (or even a partner in more advanced projects).

Intriguingly, the TU/e authors note that few students with a heavy math or physics programming focus have elected to take these CBL projects, which they identify as an ongoing area of research. This speaks to the ongoing challenge in balancing the more open-ended and interdisciplinary CBE approach with more traditional engineering education approaches that prizes advanced knowledge in mathematics and physics. Further, CBE based education takes considerable faculty resources and commitment and high tolerance for failure and experimentation—many reports indicate that students can initially be confused and frustrated with open-ended assignments unless they receive careful guidance and support.

Nevertheless, the potential is significant. A study by scholars at The Tecnologico de Monterery found that students who participated in one of their four CBL projects (that lasted four months) had higher grades on average than students who took only traditional classroom-based courses.[6] Perhaps even more importantly, student surveys found extremely high levels of satisfaction with the projects, despite their reports that they struggled with the level of self-learning and project difficulty. Students in the CBL stream also performed much better in ethics examinations, demonstrating that their engagement with real world problems helped them thinking critically and creatively about quandaries that can emerge during projects.

SUMMARY

CBL is not an entirely new trend in engineering, but it is one that is emerging rapidly at locations around the world. It responds directly to demands that post-secondary institutions work actively to tackle global problems—not abstractly, but directly and urgently. It also combines with several pedagogical trends in a concrete way: empowering students to experiment and make mistakes, removing the professor from the lectern and having them act as hands-on coaches and mentors, and de-emphasising the need to find the one correct answer in favour of teaching students how to develop a process for finding the right answer. The CBL approach being advanced is not a total replacement of traditional lectures and courses— again, that vector calculus is needed! —but it gets students thinking more about what they can do with those raw tools and enables them to make mistakes.

In Conclusion

Engineering faculties are making some ambitious changes that should be considered closely by faculties and departments across academia. These are some key observations:

- **Curriculum design can inform recruitment.** By thinking deeply about who an engineer is, faculties and programs have rethought how to deliver programming in ways that can reach different audiences. Recruitment and curriculum design are often siloed, but changes in engineering demonstrate that there is considerable utility in thinking about how they might relate to each other. Most of all, it is vital that different types of people "see" themselves in program design and delivery.

- **Bring students in.** The challenge of orientating students to the demands of higher education is common across effectively all programs. The trend of engineering programs offering free and optional courses and refresher courses and modules prior to the formal beginning of the program, typically online, is a way to ensure that students from a range of backgrounds begin on a more equal footing.

- **First year programming should let students test new ideas.** There is a decisive shift towards introducing challenging and thought-provoking projects to students during the first year and beyond. Beyond providing skill development in research design, teamwork, and independent thinking, these programs help students immediately connect their studies to vital problems that vex the world today.

- **Rethink course structures.** A remarkable feature of course design at places like Olin and the University of Saskatchewan is how they have rethought course structures in ways that allow for more targeted learning and development of essential skills. Curriculum revision need not be fully confined to the traditional course and semester model and many disciplines have core 'toolboxes' of varying complexity that are fundamental for students.

- **Challenge Based Learning is difficult to design—but worth implementing.** Almost any employer survey tells us that people are looking for people who have advanced problem solving and communication skills. CBL projects help cultivate those skills in students organically—and they also allow some space for students to not come to a resolution for their problem, yet still learn (and get reasonable grades!) from the experience. CBL can also get professors to clearly demonstrate how their research and contributions apply beyond academia.

- **Mission driven learning is changing curriculum.** This is one of the clearest examples of a discipline that is taking calls for post-secondary to have a greater impact outside of the institution seriously. This helps to re-affirm the importance of the system to society at large and can help prompt new thinking about seemingly intractable problems.

- **Curriculum design can be collaborative across institutions.** Olin shares their learning material and hosts symposiums to share ideas across institutions. In Canada, an active conference on engineering education provided many of the cases studies used for this report. This willingness to share material should be adopted widely.

Overall, what this overview demonstrates is the extraordinary breadth and depth of curriculum re-thinking that is occurring in the filed of engineering, ranging from admissions, to pedagogy, to curriculum design. Few other fields of study in higher education are attempting this level of re-imagination. And, perhaps surprisingly, this is happening in a field which is governed in part through a system of external accreditation which is commonly thought to make programs more conservative in their thinking.

Other fields of study are certainly innovating; over the previous editions of MTAP we have documented many initiatives across a variety of fields. However, to a large extent what we are seeing in these fields are new combinations of programming; that is, attempts to cover new ground by bringing together insights across multiple fields of study. What we are seeing in Engineering, however, is something different: a deeper and more fundamental interrogation of how a field's practices can be brought up to date. This is not something that is not evident across the rest of the academia, and one is tempted to ask why. Perhaps Engineering can act as a model and an inspiration for other fields to engage in deep redesign.

Endnotes

[1] Marnie Jamieson and John Donald, (2020) "Building the Engineering Mindset: Developing Leadership and Management Competencies in the Engineering Curriculum." *Proceedings 2020 CEEA-ACEG20 Conference.*
[2] Chantal Rodier, Mohamed Galaledin, Justine Boudreau, Hanan Anis and Liam Peyton, (2020) "STEAM-Arts Integration Frameworks for Transdisciplinarity," *Proceedings 2020 CEEA-ACEG20 Conference.*
[3] More on this shift may be found in David E. Goldberg and Mark Somerville, *A Whole New Engineer.*
[4] Silvia Elena Gallagher and Timothy Savage (2020), "Challenge-based learning in higher education: an exploratory literature review," *Teaching in Higher Education.*
[5] See Jennifer L. Farmer and Lydia Wilkinson (2018), "Engineering Success: Using Problem-Based Learning to Develop Critical Thinking and Communication Skills," *Proceedings 2018 CEEA-ACEG20 Conference.*
[6] Jorge Membrillo-Hernández et al (2019), "Challenge based learning: the importance of world leading companies as training partners," *International Journal on Interactive Design and Manufacturing* 13.

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