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# Disrupting Engineering Education

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## 1 Introduction

In 2004, Richard Riley, former US Secretary for Education, famously said (Gunderson et al., 2004, p. 506):

> We are currently preparing students for jobs that don't yet exist, using technologies that haven't been invented, in order to solve problems, we don't even know are problems yet.

This statement is as true now as it was in 2004. Future-proofing engineering graduates is a goal of engineering schools across the globe and an ongoing requirement of industry and society. We need our graduates to be able to continuously think outside the box, upskill in emerging technologies, processes, and systems, all while meeting the day-to-day demands of their jobs. We strive to produce engineers of the future for workplaces of the future. So how do we continue to innovate engineering education to produce these future-proofed graduates? What process do we follow? How do we disrupt our current models?

Firstly, when we speak about disrupting engineering education, there are misinterpretations of what *disruption* is. This is a mistake commonly encountered, as the core concepts of disruption theory remain widely misunderstood (Christensen et al., 2018). However, we can start by understanding that while all disruptions are innovative, not all innovations are disruptive. Disruption theory essentially describes "the phenomenon by which an innovation transforms an existing market or sector by introducing simplicity, convenience, accessibility, and affordability, where complication and high cost are the status quo" (Christensen Institute, 2022).

Christensen identifies that there are two types of innovations seen in organizations (including education) – disruptive and sustaining innovations (Christensen et al., 2003). Disruptive innovations are "innovations that make products and services more accessible and affordable, thereby making them available to a larger population" (Christensen et al., 2018; Christensen et al., 2015), with sustaining innovation targeted to "improve products and services along dimensions of performance that mainstream customers care about and that markets have historically valued" (Christensen et al., 2018).

Essentially, disruptive innovation tends to create "good enough" products, while sustaining innovation creates "superior products." Arguably, sustaining innovations are more frequently seen in engineering education, rather than disrupting innovations, with the field using the term "disruption" in

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a more colloquial sense as opposed to being aligned to Christensen's disruption innovation theory. This is a misconception commonly seen in the literature (Christensen et al., 2018).

From a strategic perspective, it is likely that a blend of both types of innovation is important in higher education, with a structured approach to identifying innovation opportunities being crucial. Therefore, to address this requirement, we have considered Doblin's 10 types of innovation as a framework to identify areas in which engineering education could innovate. This chapter presents a theoretical framework to categorize and present such innovations. Examples of innovation are identified not only from the affiliated organizations of the authors of this chapter (identified as emerging leaders in engineering education (Graham, 2018)) but also from the extensive literature in this space.

## 2 The Emerging Themes of Disruption

In 2018, Ruth Graham identified recent innovators in engineering education – *the global state of the art* (Graham, 2018). Three interesting trends identified were that there is a shift in innovation from the Global North to the Global South, there is a shift to programs that emphasize socially relevant, outward-facing curricula, and there is a new generation of leaders who can deliver programs at scale.

Graham identified the current leaders as Olin College (USA), MIT, Stanford, Aalborg University (DK), TU Delft (Netherlands), UCL (UK), Purdue, NUS (Singapore), Cambridge (UK), and Chalmers (Sweden). Emerging leaders identified were Singapore University of Technology and Design (SUTD), Iron Range Engineering (USA), Charles Sturt University (Australia), Tsinghua University (China), and Arizona State University (USA). Graham's report also identified "places to watch" (Box 2, page 12).

Project-based learning plays a key role in all these institutions, building students' practice skills as well as broadening engineering programs to include multidisciplinary problem-solving to engage students in engineering-like activity as early in the curriculum as possible. The second significant trend is the move to online content delivery and assurance. This forces careful thought about what is core and what is elective. What do students need to learn before they tackle a given project? Teaching students to seek the expertise they need is an important skill needed for their future workplaces, where lectures will not be available. Designing curricula around these two key innovations requires other changes to the normal university practices.

Key engineering education innovations use more than one kind of innovation. This includes the many forms of practice-based learning and flexible curricula, which are supported by modified learning environments and staffing structures, leading to gradual changes in perceptions and expectations by both students and academics.

Looking at our own innovations and those referenced by Graham (2018), we propose five themes that are emergent, unifying ideas, giving shape to the changes we see in contemporary engineering programs; they are also predictors of future changes that might better deliver the requirements for industry and for students:

1 Developing the *student engineer* identity from early in the program (a logical extension of practice-based curricula).
2 Understanding *perceptions and expectations* from students, employers, academics, and others.
3 Adopting a *flexible curriculum*.
4 Modifying the *learning environment*.
5 Starting with a *greenfield site* – entirely new programs.

### *2.1 The "Student Engineer" Identity*

In general, engineering programs are evolving from content-centric models of what the students should *know* towards capability-centric models of what graduates should be able to *do*. Students are expected to be undertaking a rich engineering learning experience – the whole is greater than the sum of the parts. This disruption occurs where the focus is on ingraining the identity of the engineer. Identity can be powerful (Tonso, 2014), as the individual traverses the trajectory of "what I think I want to be" to "what I am." Authentic educational experiences that align that identity with the practice of the profession lead to more robust motivation, confidence, and passion, all of which lead to improved performance. Authentic problems involve the kinds of problems engineers face in the workplace in contrast with the less-valuable kinds they face in a traditional classroom (Jonassen, 2014).

Research in the area of engineering identity has increased in recent years (Morelock, 2017). Morelock identified several things that contribute to the establishment of the student engineer identity. These are exposure to experiences and the connection of these to a student's "aspects of self." The "aspects of self" can relate to gender, academic identity, race, or one's beliefs or values and, indeed, the experiences one encounters throughout one's life. It is not yet clear how students can connect these aspects of themselves to the engineering profession.

If the profession can be thought of in the *three domains* of technical, professional (transversal/social), and design, then educational experiences that either emulate or directly encounter the environments in which those domains are practiced will provide the opportunity of building their engineer identity. Reflective practice (Schön, 1983) is where the student engineer spends focused time processing the learning experiences, engaging their beliefs and values with the lived actions of engineering practice, across all three of the aforementioned domains.

Through structured and purposeful reflection activities, identity is developed (Johnson et al., 2015; Morelock, 2017). Furthermore, Duarte et al. (2016) found that students' own characteristics (e.g., motivation, self-efficacy) were more important when it comes to the development of self-learning skills (learner autonomy) compared to a particular teaching–learning transaction, and teaching strategies should account for this. Therefore, by applying a heutagogical teaching strategy, capability, capacity, and autonomy can be amplified in students, making them more prepared for the complex and ever-changing work environment (Blaschke, 2012).

### 2.2 Perceptions and Expectations

Disruption can also occur across the many ways that people perceive the profession and the educational processes. The stakeholders in engineering education, from industry to students, from faculty to accrediting bodies, have perceptions of what engineering education is and what it should be. The gaps between these expectations afford opportunities to innovate and disrupt. An example is bringing consulting engineers into the academic setting to work side by side with students while meeting the needs of the client (Mann et al., 2021).

Contemporary students, whose lives have been shaped by ubiquitous availability of information and entertainment, have neither the patience nor the desire to be "taught" in the traditional lecture and problem set model. Conversely, 13 years of school that have focused on face-to-face teacher-led education has left them oddly unprepared for new models of active learning. A transition semester is required to shift students from passive to active, self-directed learners. This is a critical transition for all learners in the 21st century, with lifelong learning identified as one of the top 10 critical skills for all workers (World Economic Forum, 2020).

### 2.3 The Flexible Curriculum

Few things have changed as much as how students engage with the content that underpins the process of becoming an engineer. Each discipline has its own specialized knowledge (fluid mechanics, thermodynamics, circuit analysis, etc.), and every engineering discipline also relies on a broad collection of common knowledge, such as systems engineering, project management, and people management.

For the last 500 years or so, we relied on textbooks and lectures as the dominant modes for knowledge transmission. Students practiced new skills in tutorials, laboratories, and design classes. In the last 30 years, knowledge has moved online. However, many academics and students still cling to the old methods, assuming there will be lectures, problem sets, and textbooks, when we have moved into a world of knowledge at our fingertips. Learning can now happen just in time (JIT) as well as just in case (JIC) (Killi & Morrison, 2015; Liberatore et al., 2017; Riskowski, 2015; Wilkie, 2013).

However, Killi and Morrison have shown that it is important to couple this JIT teaching and learning approach with the optimum time (just in need, JIN) when students' motivation is highest to learn the particular content (Killi & Morrison, 2015). This JIT/JIN learning is fundamentally transforming how to become an engineer. Students will progress more quickly from student to engineer, on a constant trajectory of learning on the job. Universities will need to disrupt their education programs to cater to this rapid acceleration into the workplace. The four- or five-year full-time, on-campus curriculum may be a thing of the past.

Further, drastic step changes in modes of learning, as enacted during the global COVID-19 pandemic, will continue to accelerate this change. Students have realized the benefits as well as the difficulties of remote learning. Universities are also adapting pathways into and out of engineering programs, enabling students to take a variety of routes both before and after university study. Recognition of prior learning is being adapted to cater for microcredentials and MOOCs (Rampelt & Suter, 2017; Shimson & Verstelle, 2017), as well as more formal, long-form programs of study.

In relation to MOOCs, since their emergence in 2011, they have continued to offer opportunities for learners to develop and enhance their knowledge (Rivas et al., 2020; Shimson & Verstelle, 2017). Presumed to have reached their pinnacle towards the end of the last decade, with academics believing the craze had passed, the pandemic has resulted in a resurgence of MOOCs. They have, for many, been part of an important educational response to the pandemic (Impey & Formanek, 2021; Van Melle & de Bie; Yang & Lee, 2021).

## *2.4 The Learning Environment*

Despite parts of the curriculum moving online, most universities still see the face-to-face experience as an important part of university life. In fact, this is where students begin to learn the collaboration skills that will be essential to their future success (Trevelyan, 2014). Most Western universities have invested enormous sums of money into new learning spaces, learning commons, pervasive Wi-Fi, coffee carts, microwaves, and other features to make the campus experience attractive to students (Fraser, 2014).

Layered on top of these new learning spaces are matching social processes that are changing the way that students learn. Student societies are available in a bewildering variety, from social purposes to professionally focused ones, helping students develop their skills beyond the curriculum (e.g., the robotics club and the space society). Student societies that extend across multiple institutions are also prevalent, such as the Golden Key Honor Society, IEEE Eta Kappa Nu, and the Board of European Students of Technology (BEST). Start-ups are multiplying at many universities, with structured support through staffed centers (Miller & Dorning, 2018).

Students are also encouraged to learn collaboratively outside of class through formalized peer learning, such as PASS (peer-assisted study sessions), where trained student leaders help less-experienced students master difficult topics (Arendale, 2016). Students are assisted in other ways, through pastoral support, aided by learning analytics, which can detect non-engagement early, enabling a student to be given a helping hand long before they have failed a key assessment task. Students are also assisted by an increasing trend to bring industry adjuncts on campus in various roles – guest lectures, project and studio leaders and clients, engineers-in-residence, professors of practice, and so on. These industry colleagues boost student engagement and motivation and keep the academic program connected to essential topics, skills, and examples.

### 2.5 The Greenfield Environment

Many of the examples of disruption have taken place in a greenfield environment – those where new models could be established from scratch. This occurs reasonably regularly, although the pathways to that founding vary from philanthropy (Miller & Dorning, 2018) to government support (Magnanti, 2018) to industry patronage (Grose, 2016) to serving as an external sandbox for established institutions (TEDI, n.d.). Greenfield programs are much more able to innovate in the structure of their programs and the processes they change around it, but they do so at the cost of additional challenges to their brand and profit model (key issues in Doblin, to be explained shortly). While these schools are free of the need to subsidize other colleges, or a research agenda, they are also not able to amortize governance and administrative costs across the rest of the institution.

Working in a greenfield environment allows for some parts of the disruption trajectory to be accelerated. New programs and ideas can be developed without the "baggage" of existing habits and cultures. The price for this is that some of the "baggage" is actually "luggage" – useful practices that must, instead, be invented from scratch rather than just simply applied through existing, supportive work practices. This is the trade-off made by most start-up organizations, balancing the benefits of agility with those of scale. It is significant to note that the emerging leaders identified in Graham (2018) are almost all greenfield sites, introducing engineering as a new discipline to their institution or creating an entirely new institution.

A consequence of establishing a new program is that by their nature, they start small. Small programs share many advantages with new programs; there is a smaller footprint involved when the structure, process, and systems innovations are required. Many key disruptions initially emerge as small innovations in large institutions; it is then their trajectory through configuration innovations that see them move to scale. Some institutions keep their programs deliberately small, embracing the value of the learning environment for those students who can pay the fees required to make such programs viable. Other institutions see themselves as not yet large, investing upfront in their programs in the belief that the students and the revenues will flow once the advantages of their offering become well-known.

## 3 Matching Innovation to Disruption – Applying the Doblin Framework

There are many institutions doing innovative things in the engineering space. While there are themes emerging at the frontiers of engineering education, one theme that is missing in the literature is explicit reflection about the innovation process. There are many models of innovation present in the business literature. It is clear from inspection that many of the engineering education innovators are intuitively aligning with these models, but there is little evidence that there has been explicit thinking about the innovation process.

We saw an opportunity to address this absence, particularly in the hope of showing how innovation could be transferred between contexts. The "it won't work here" mindset can be very powerful in resisting change in the face of successful exemplars, and the opportunity to decouple an innovation from the specific operating environment by viewing it through the lens of a framework of innovation was too strong to resist.

We chose the Doblin 10 types of innovation framework as our lens (Doblin, 2021). The Doblin model is not the only model of innovation, but it resonated with us when we used it as a reflective

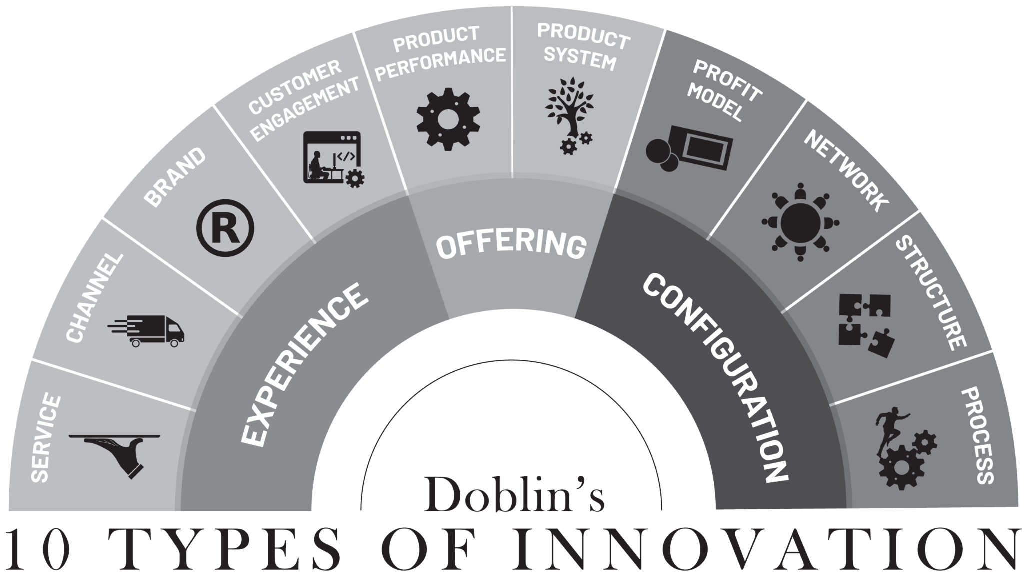


*Figure 6.1* The Doblin innovation framework.

tool. We found it very useful in identifying explicitly many of the things that we were already doing implicitly and for providing a vocabulary to explain the different dimensions of innovation that we have observed in engineering education. It also provided useful insights into why our innovations had been successful when others had failed, and a pathway forward to the transferability of contexts that we seek.

### *3.1 The Doblin Framework*

Doblin's 10 types of innovation model provides a framework to better conceptualize these transformations (Desjardin, 2020; Keeley et al., 2013). This framework (Figure 6.1) distinguishes three categories of innovation – experience, configuration, and offering – allowing for insights into the ways in which the different curriculum dimensions represent innovation in engineering education.

*Experience* innovations include transforming the services delivered to customers, the channels through which the products or services are delivered, expanding the brand, and improving customer engagement. *Configuration* innovations include reconsidering the profit model, exploiting networks of suppliers and collaborators, changing the structure of the organization, and finding superior processes for doing the work. *Offering* innovations includes addressing product performance and developing complementary products and services to build a product ecosystem.

The five themes discussed so far (the student engineer, expectations and perceptions, flexible curricula, the learning environment, and greenfield sites) can be understood within this framework. The student engineer, in a practice-based learning context, is a change of *experience*. It ticks the customer engagement box, which also requires or implies changes in service and channel and an opportunity for brand enhancement.

Flexible curricula are a natural partner for practice-based learning, providing students with the opportunity to engage in just-in-time learning, as will be the norm in the workplace. Flexible curricula change the student experience, altering the channel through which learning is delivered, with supporting services. Again, this is an opportunity for brand enhancement.

The learning environment must also complement the practice-based learning approach, supported by flexible curricula. Once again, these support the student experience, for example, learning commons provide additional learning services to support the learning channel and may feature in brand marketing.

Greenfield sites, and, indeed, brownfield sites, focus the attention on the configuration and offering aspects of innovation. These are the options that are easy to underestimate when innovation is considered. The profit model must be addressed at some point, networks should be developed with suppliers and collaborators (often neglected as we go it alone), the structure of the academic and administrative team needs consideration, and teaching and administration processes need training and enhancement. Product performance must be designed, and complementary products and services put in place, for example, engagement with industry and internships.

Finally, perceptions and expectations can be (must be) altered across many of the ten dimensions. Students and academics must commit to new ways of learning and new ways of interacting and assessing. These require new skills from both parties. There are opportunities for new branding, to differentiate the new program from its traditional competitors.

Now consider a project-based curriculum and how it requires innovation across all these ten dimensions.

## 3.2 An Example

Each of these ten types of innovation is expressed in educational environments. Impactful change requires innovation across many of the ten Doblin innovation types, as in a project-based learning (PBL) curriculum, which is designed to deliver the kinds of graduate capabilities being requested by engineering employers (ACED, 2021; Kolmos et al., 2004).

1. Altering the curriculum is a change of ***channel*** (*experience innovation*). Students now engage in learning through more design tasks and fewer lectures and tutorials. This may be accompanied by another channel innovation, such as greater reliance on self-directed learning, supported by educational technology.
2. Such curriculum changes are designed to alter the ***product performance***, through graduates with improved workplace capabilities (an *offering* innovation).
3. To achieve these changes, it is also necessary to change our teaching ***processes*** (*configuration*). Our academic staff must develop new skills and confidence to facilitate design-led learning.
4. This shift to a project-based curriculum creates new ***brand*** opportunities, through marketing a new kind of engineering education, attracting those students who are looking for a practice-focused education (*experience*).
5. We might also consider new ways of ***engaging with customers*** through outreach to schools, in-house design competitions for schools, and other means to engage high school students in the new educational model (*experience*). Similarly, we might engage industry through guest lectures, industry-sponsored projects, internships, and so on.
6. There are further opportunities suggested by the ten types of innovation. Students could be provided with better ***service*** to support their learning. Students often struggle with project-based learning at the start. *Service* could include training and handbooks to help them through this first stage of learning. The curriculum might also be structured so that senior students work with junior students, enabling knowledge transfer to the new students.
7. ***Networking*** is another *configuration* opportunity. For example, CDIO is a global network of educators committed to a certain style of project-based learning (CDIO, 2021; Crawley et al., 2014). Through the network, members can access syllabus guidelines and examples of good practice, such as projects, from around the world. Annual conferences support knowledge transfer between individuals and institutions.

8 The ***profit*** *model* must also be considered (*configuration*). Project-based learning is often seen as more expensive than traditional methods, yet some universities have operated successfully for almost 50 years using this curriculum model (Kolmos et al., 2004). Teaching ***processes*** must adapt to make sure that costs are contained. In fact, the greatest value is achieved when students become truly responsible for their own, and each other's, learning. We see this in autonomous teams, such as the Formula SAE competition, where students work together to complete the designated mission (SAE International, 2021).

9 Finally, we come to the ***product system*** (*offering*). Can the project-based curriculum become part of a larger ecosystem of products? The traditional approach would be to develop a follow-on set of postgraduate qualifications. Other approaches could include using the projects as central to engaging with industry in terms of undergraduate projects, postgraduate projects, industry projects, consulting projects. Thus, the engineering school becomes a knowledge factory, engaging with the community on a range of levels, where the project is the central concept and enabling process.

10 As the product system changes, the ***structure*** of the organization can adapt to truly bring teaching and research together in a seamless way (*configuration*). PBL is a research-oriented means of teaching. The undergraduates become part of the research team.

PBL is an example of a mature innovation that has evolved to touch all of Doblin's dimensions. Other innovations are more directly clustered within different parts of the Doblin framework.

### *3.3 Experience Innovations*

Online learning is one innovation currently transforming engineering education. Universally available, online engineering knowledge means students now need ways of knowing what they need to know. We are moving from a "just in case" learning system towards a "just in time" system. Students do need fundamentals, but they don't need four years of fundamentals. Quickly they need to move into problem-solving mode through projects (Prince, 2004; Prince & Felder, 2006).

There are many successful examples of PBL, and all the most innovative engineering schools engage students in projects, usually from the first semester onwards (Bertel et al., 2021; Froyd et al., 2012). Students also need *real* projects, and they will get these through industry projects on campus and by students working in industry, for example, through internships and work placements.

There are emerging educational models where working is a key part of engineering education (Lindsay & Morgan, 2021; Ulseth et al., 2021; Boyle et al., 2022b; Morris et al., 2022; Fitzgerald et al., 2022). This is a return to cadetships from the 60s and 70s, when students worked full-time and studied part-time (very demanding, with high attrition), or via sandwich programs where they alternated between work and study. Other models are bringing industry on campus so that students are engaged in industry-like situations from week 1 (Mann et al. (2021), Ulseth et al. (2021)).

The REEdI project in Ireland (Boyle et al., 2022a) uses technology to change the student experience, using virtual and augmented reality (VR/AR) experiences into the curriculum to improve both authenticity and accessibility for the students. Similarly, COVID-19 emergency teaching shone a light on the challenge of delivering meaningful hands-on engineering experiences for students learning remotely with technology (Graham, 2022).

Other themes that emerged from Graham's work include the development of transversal skills (Ulseth et al., 2021), student-centered cultures, entrepreneurial mindsets (Svanström et al., 2012), sustainability (van Grunsven et al., 2021), equity and diversity (van Grunsven et al., 2021), ethical development (Lavi et al., 2021; Adams et al., 2021), and creativity and innovation (Loh et al., 2021). All these require changes to the student experience if they are to be implemented successfully.

All these are dimensions of disruption in engineering education. They have the power to create meaningful impact on student learning experiences and bring value to the organizations the graduates will serve. However, *branding* and messaging become essential. Beyond just implementing strategies in any of these areas, there must be effective *communication* to potential future students and their families, as well as to the companies the graduates will serve. Furthermore, we cannot underestimate the importance of bringing the wider academic community within our institutions along with us on the journey. Without acceptance by these stakeholders, the disruption will not be sustainable (Merton et al., 2004).

### 3.4 Configuration Innovations

Networking is probably the most overlooked path to innovation. Despite the significant overlap between the many programs offered by our engineering schools, academics often teach "their" subject in isolation. Consortia could work together to share resources, such as online tutorials, worked examples, projects topics, electives, reducing preparation time, while improving quality and coverage, but for the most part, we only go as far as adopting a textbook to replace bespoke lecture notes.

The CDIO consortium is a successful exception to this rule: an international community of project-based learning practitioners. CDIO has subsequently expanded to over a hundred institutions worldwide, easily the most successful example of networking in engineering education. There have been other consortia, for example, the coalitions funded by the NSF in the 1990s (Borrego, 2007; Coward et al., 2000), and the European Union has also funded many consortia (e.g., Erasmus and similar programs). However, except for CDIO, most fail after funding comes to an end. Are consortia destined to fail? There needs to be a return on investment for these innovations, for example, in the form of decreased costs (more efficient teaching practices), more students (economies of scale), better students (reduced cost of teaching), and so on.

A smaller-scale example is the EWB Challenge (Engineers Without Borders, 2021). Each year, the Challenge focuses on a community in a developing country, requiring first-year students to find engineering solutions to improve the lives of people in that country. This is usually the first chance for students to see the connection between engineering and social benefit. This is an interesting example of networking, given that it was initiated by a non-university organization, somehow overcoming the natural tendency of academics and students to steer away from "not invented here."

A related opportunity is academic development, enabling new pedagogical ideas to be introduced more quickly, such as alternative forms of assessment, group-based collaborative learning, professional skills, reflective practice, project-based learning, studios, and so on. Australia had considerable success through federal government funding of university consortia from 1990 to 2010 (Universities Australia, 2021). Sadly, these programs were discontinued, but they left behind many academics who had upskilled themselves in collaboration with colleagues from other universities. The Human Capital Initiative run by the Higher Education Authority in Ireland is another example of government funding university consortia (Higher Education Authority Ireland, 2022).

Business models are another key challenge for universities to consider. Universities tend to focus on teaching degrees. We recruit students into those degrees and graduate some of them (usually as few as 60% of them). However, at the heart of our degrees are subjects. These are our basic products. Could we make some of our subjects into more profitable products? Further, what are students paying for? They are no longer paying for lectures and tutorials. They may be paying for access to a community of learners and bespoke, block mode learning, on-campus challenges, global opportunities, and so on. Certainly, this is a very different model to delivering content to 500 students in a lecture theater. The teaching needs to be much more student-focused and career-directed. The question is, can this be translated into an offering that students (and governments) can and will pay for?

Other industries have already been through this transformation – gyms do not make their own exercise bikes or free weights but instead focus on the experience and support they can craft around them. In higher education, the textbook is an illustration of a mature disruption of this type; a small handful of publishers (Pearson, Wiley, Macmillan, Cengage, etc.) provides a standardized resource to us all. Many of these publishers are now looking to develop smart online tutorial systems and are competing with a host of new educational start-ups (EdX, Coursera, Khan Academy, Codecademy, etc.) as they do so.

### *3.5 Offering Innovations*

When considered through the Doblin lens, there are few examples of innovations in the offering category. While there is a rich diversity of "product" that different institutions sell – a technical education, a credential, graduate employment, a learning community, a pedigree – most of this differentiation manifests in other forms of innovation. Engineering degrees are somewhat of a commodity: the four- or five-year accredited degree that makes an engineer. The innovations/differentiations seem to be in how institutions deliver that product and in how students experience it.

Engineering degrees are not usually coupled with a complementary product or service. Double degrees may fall into this category, as do co-op work placements. Lifelong learning has been talked about for 30+ years but has not yet manifested as a complementary product or service. We have not moved from "education as a product" to "education as a lifelong service."

## 4 Disruption Isn't Meant to Be Easy . . .

Disruption happens as the "entrant" delivers a more functional model of learning to small, often neglected, audiences. The entrants are largely ignored by the "incumbents" as they move up market. Disruption occurs when the mainstream audiences begin demanding the disruptive model. One thing that makes it hard is that disruption can take a very long time to occur. By Christensen's definition, it might be argued that disruption isn't occurring yet in engineering education. There certainly are many examples of entrant disruptors and, as stated previously, many functional features of effective models. However, to date, there has not been widespread mainstream demand for or adoption of radical new teaching models (Sorby et al., 2021).

### *4.1 Continuous Improvement Mindset in Disruption*

Implementing disruptive models of education is neither linear nor simple. Often, those looking to implement change want to find a model that works elsewhere and then copy and paste that model. This is a recipe for disaster, as it fails to acknowledge the differences in social context between the two locations. It also assumes that the model being copied is linear and static when in fact disruptive models are non-linear and dynamic. They are, instead, complex adaptive systems.

Complex adaptive systems require an instrumentation and control approach where there is continual monitoring of the system, resulting in appropriate actions from the input – probe, sense, and respond, as Snowden and Boone (2007) have said. Intentionally implementing feedback is a component in any engineering design cycle; thus, disruption, like engineering design, requires such a continuous improvement approach. The effectiveness of the learning can thus be continually improved during the implementation of the disruptive curriculum (Noor, 2013). Thus, those looking to implement should treat any innovation model as a complex adaptive system.

Ruth Graham identified the attributes of emerging and sustaining engineering education world leaders through Graham (2018) and CEEDA (2021). Of the many attributes identified, the focus on continuous improvement aligns with complex adaptive systems.

> Looking across the innovative approaches described in the Special Issue, two features stand out. The first is an emphasis on continuous change. An appreciation that change is not a single moment or stage, but an ongoing process, runs as a thread through the articles, and can be seen in the continuous improvement model adopted at Iron Range Engineering that led to the establishment of the Bell program (Ulseth et al., 2021).
>
> *(Graham, 2021)*

When considering nearly any model of learning, an essential component of the model is reflection (Dewey, 1933; Kolb, 1984; Schön, 1987). Reflection is a metacognitive act whereby the learner connects the learning to prior learning, assesses its value and contexts, and projects its future value. Reflective practice is essential for the ability of emerging engineering practitioners to nimbly meet the ever-changing needs they encounter while tackling the world's complex problems (Sheppard et al., 2008). Yet reflection is woefully missing as an intentionally developed skill in most engineering education (Ulseth & Johnson, 2017). At best, reflection is tacitly developed in traditional engineering models. The act of reflection is core to the engineering design process and the probe-sense-respond approach to complex problem-solving. Therefore, disruptors in engineering education need a level of reflection built not only into the curriculum but also into the continuous improvement processes of the program team.

## 4.2 The Journey of Innovation

Disruptive models need to use multiple Doblin dimensions as they move towards maturity. The kinds of innovation that are necessary to begin a disruption differ from those that are required to maintain it and to scale it; a deliberate trajectory is required. What may start as a different classroom experience may then require different channels to deliver that offering, networks within and beyond the institution to be scalable, and may eventually need to change the processes and even the structure of the institution.

What distinguishes the great from the good are those that provide value when innovating at the configuration level. It is not enough to just innovate to stop your disruption from being squashed; it is necessary that the innovation provides value on the configuration dimensions as well.

It is on these trajectories that the importance of leadership becomes clear. Successful and sustainable disruptions have leaders that work across all of Doblin's innovation types. In some places, this could be a single champion who is able to adapt roles as the project matures, but this is seldom the case. Most disruptions are instead successful with a team who can shepherd the disruption as it evolves through the different types of innovation and different leaders who are accountable for the kinds of work associated with each. Disruption is a journey, a vector that moves from the disruptive idea that manifests on a single dimension to the disruptive model that manifests across multiple dimensions. To make this journey successful, it is essential to approach it with the perspective that it will evolve over time; a continual improvement mindset is required.

## 4.3 Barriers to Disruption

Practicing disruptors encounter common roadblocks. One of the biggest is when the incumbents decide not to ignore but instead seek to eliminate the innovators, a common phenomenon carried out by entrenched and powerful curriculum or accreditation committees. Others include rigid physical infrastructure, technology limitations, enrolment sizes (too big or too small), government regulations, and industry demands. One of the most common barriers to disruption is in fact one of the key themes of disruption – expectations. While those driving the change may have already moved their expectations, other stakeholders can often provide inertia or resistance.

External accreditation is often presented as a roadblock to implementation; the perception that "it will never get accredited" undermines the implementation of change. This perception is in fact particularly pernicious because it is built upon a mistaken understanding of the goals of accrediting bodies. Accrediting bodies desire the better attributes of the newer models and are often dismayed by the lack of change made by those who support the incumbent model. This view is a carry-forward from a previous era of accreditation, where accreditation was more of a "protector of the status quo" (Froyd et al., 2012). Unfortunately, external accreditation is of such value to institutions that they may be unwilling to take risks in this space, even when those risks would be welcome.

Another perceived barrier to innovation is the issue of scale. Many engineering schools operate at very large scales, with thousands of students. There is a misconception that because these institutions operate at scale, any innovation must also commence at scale. Disruptions must be scalable, but they can start small, even within large institutions, such as the NEET program at MIT (Lavi et al., 2021).

A real challenge is that of the "pioneer cohort." When a disruptive model is implemented, the student engineers in the model are the pioneers that can make or break the success of the innovation. To their benefit, they usually develop a level of resilience that is unparalleled in a traditional program, as they must persist through the constantly changing environment around them – a powerful outcome in transversal skill development. However, they lack a ready-made identity, which is inherent when people before them have succeeded both in the model and after graduation.

This lack of identity often results in a built-in lack of confidence in the new program and the people delivering it. Learning to be an engineer is an inherently difficult quest in any model and requires change and resilience on the part of the students. Being part of a pioneer cohort provides the alternative of making the new model the scapegoat – they can question the validity of the program rather than engage with and overcome the challenges they encounter. Understanding the attributes of pioneer cohorts can lead new disruptors to be ready for and expect these challenges, oftentimes even mitigating the issues before they emerge.

## *4.4 The Role of Faculty in Disruption*

Key stakeholders in the disruption process are the faculty who teach engineering programs. There is a well-entrenched traditional model of teaching engineering which is thoroughly embedded in the processes and structures of the institution. While some innovators will happily be early adopters of any change that comes along, the majority of faculty will be more circumspect in embracing change. Therefore, influence is required to ensure academics have a willingness to embrace and understand the template models of disruptive engineering programs available. They need to have a willingness to change and upskill, to be able to effectively drive the curriculum reforms required in their context. In addition, they need to understand the impact of disruptive technologies in the teaching and learning process and champion the inevitable cultural changes that are required.

We now need faculty to start thinking the way we want our engineering graduates of the future to think. They need a broad knowledge in not only engineering but also socioeconomic factors, they need an entrepreneurial attitude, they need to be disruptive thinkers focused on innovation and value creation for their university, and they need to be capable themselves of working in interdisciplinary teams of specialists, engineers, and stakeholders. If they don't think like this, how can they instill this mindset in our future engineers?

### 4.5 Helpful Change Models

At a more macro level, it is important for us to be aware of how higher education institutes are complex ecosystems and how an understanding of this complexity can help plan and drive innovation across the configuration, offering, and experience for a particular organizational context. Otherwise, we could end up perplexed as to why our organizations, our leaders, our departments, our curricula, our customers, or our teaching strategies remain stagnant and impervious to sustained innovation. Therefore, an understanding of organizational theories can be advantageous. Manning (2017) describes this complexity in higher education and how organizational theory was, and can be, further used to help higher education institutes to reinvent themselves and become more innovative.

Leadership style and change management have critical parts to play in the innovation process. There are many different change and leadership models referenced in the literature (Borrego & Henderson, 2014; Bush, 2015; Froyd, 2014; Kolmos et al., 2016; Vlachopoulos, 2021). Bush describes the linkages between organization theory with different types of leadership in higher education and how the connection (among other things) has an impact on innovation and change management. The author surmises that the four aspects of organizations that theorists study are structure, goals, culture, and context. One could argue that these aspects are closely aligned to Doblin's configuration subdomain, organizational design ("Make form follow function and align infrastructure with core qualities and business processes").

The link between culture, change, innovation, and leadership has been referenced in engineering education reform literature since the early 2000s (Merton et al., 2004) and is consistently identified as an important connection in higher education in general (Blanco-Portela et al., 2017; Borrego & Henderson, 2014; Bush, 2015; Froyd, 2014; Reinholz & Apkarian, 2018; Vlachopoulos, 2021).

## 5 But It Can Be Delightful . . .

### 5.1 A New Mindset for New Challenges

Disruption is a mindset as much as a process. For most of us, we are disrupting our business before someone else does. This may take several years, as we roll in new programs, across multiple disciplines. There will be transition issues, sometimes for hundreds of students, as old subjects are phased out and new ones replace them. There can be turmoil and unhappiness for both students and academics.

However, there is also delight when students see learning in a new light (Hadgraft et al., 2018):

> Open-ended scope, freedom, and creativity. I liked how I had freedom to learn using my own practical experiences, instead of a regimented assessment schedule.

We are training a new mindset that sees the world from a disruptive point of view. Increasingly complex engineering problems require new solutions; there are no old solutions to copy. Disruption must be a habit in every classroom if we are to graduate professionals with this mindset.

Our old programs have, instead, mostly relied on applying known theory to known problems, as if the problems in the world were unchanging. These curricula were inspired by the post–World War II explosion in science and engineering. Our current world faces many challenges, at increasingly large scales. The Sustainable Development Goals (SDGs) (United Nations, 2021) describe the global challenges that we will face over the next 50 years, and we need engineers who can engage with these problems. Engineering graduates need to demonstrate awareness and application of the SDGs and understand their importance for the engineer's role in society. It is important to build the SDGs into individual subjects in engineering degrees. For example, a key part of the REEdI program is that students are required to demonstrate awareness and application of the SDGs in their on-campus projects, workplace tasks, and industry projects (O'Sullivan et al., 2022).

### *5.2 Maintaining the Disruption*

Ongoing disruption is hard to maintain. It's easy to run this year's project like last year's, go through the motions, take it easy. Industry partnerships help us break out of this laziness. Industry problems change regularly and usually have a level of difficulty that stretches students beyond what they think they can achieve. These problems create an edgy environment that can stress some students (and academics!). Our job is to project-manage our students, keep them on track, help them be less stressed, but encourage them to seek novel solutions to these problems. We should encourage excellence through innovation.

This changes how we design subjects, semesters, whole curricula. Our fondness for outcomes-based education has tended to constrain our subject design, handcuffing us with a set of learning outcomes that can be too specific, often focusing only on technical outcomes. Instead, we need meta-learning outcomes that define program-level concepts, not the textbook contents page. For example: engage with stakeholders to identify a problem; apply design and systems thinking to respond to the identified problem; apply technical skills to develop, model, and/or evaluate designs; demonstrate effective collaboration and communication skills; and conduct critical self-, peer-, and group review for continuous improvement (Hadgraft et al., 2018).

Self- and peer review are essential skills for us as much as for our students. We must put our practice under the microscope, seeking constantly to refine and improve our practice. Agile methodology is one approach that relies on constant review of progress (wrike.com, 2022). The semester is broken into a series of sprints, for example, weekly or fortnightly. Teams present their work at each scrum or stand-up meeting to report progress and to state what will be accomplished next. Any difficulties can be quickly resolved at those meetings. This keeps students on track and resolves difficulties that they might have. In this way, the academics project-manage the student teams to completion. This is helpful for those students who might feel a bit lost when confronted with a problem that they have not seen before.

However, we also need to be on the lookout for new possibilities, new ways of disrupting ourselves, before we become too comfortable with how the subject, major, or program works. Students, too, should be on the lookout for new tools and new ways of working together and new people to work with. Diversity brings new challenges as well as new ways of looking at problems. Problems are increasingly transdisciplinary. Without this disruptive mindset, we fall back into old ways of thinking, turning out last year's design, when a new solution is required.

Of course, disruption can be uncomfortable. We know that each problem we face will bring challenges we haven't seen before. However, the key shift is in our problem-solving capabilities. We are shifting from a focus on being able to solve specific technical problems (circuit analysis, thermodynamics) to a focus on multidisciplinary problems, requiring multi-stakeholder input. There are recognized problem-solving processes for these sorts of problems, such as Fleming (2021) or Fogler and LeBlanc (2007); it's just that traditional programs have not taught them. Equipped with these meta-problem-solving skills, new problems are not just less challenging; they become positively exciting!

## 6 And It Never Ends

Higher education is a well-established marketplace, with heavily entrenched traditional models of learning. There is a long history of innovation in higher education, some successful and some less so. The confluence of ever more powerful technology, changing expectations of industry and students, and external shocks, such as pandemics, means that engineering education is ripe for wide-ranging disruption.

Doblin's ten types of innovation provide a framework to consider the ways in which innovation and disruption take place in engineering education. While we may project to the world that we offer a wide range of different offerings to potential students, the Doblin lens shows us that what we offer are mostly different experiences and configurations of a substantially similar offering. Reflecting on the kinds of innovations we pursue assists us in identifying what can truly become disruptive.

Sustainable scalable disruption requires innovation in the configuration domains. Disruptions within existing institutions require innovation in the processes and/or the structures of those institutions, as they reinvent the way they go about their operations. Disruptions beyond an existing institution require innovation in the network dimension, sharing the ideas beyond a single organization.

Disruptions that begin as start-up organizations avoid the challenges of reinventing an existing culture within existing structures and processes, but they do so at the expense of a lack of existing infrastructure and with the significant challenge of having to innovate (often unsuccessfully) in the profit model dimension. A blank page is by no means essential for disruption – it merely changes the nature of the disruption trajectory.

What is essential is the mindset of continuous improvement. Disruption can only progress when there is a commitment to making the experience, configuration, and offering better and a willingness to adapt to the different needs and risks of innovating in each of these dimensions. For the early adopters among us, change is comfortable, and we are willing to try and fail and try again. The late adopters among us support the sustainable disruptions that have the full spectrum of innovations covered. Fortunately, the mindset for disrupting engineering education is the engineering design mindset – the mindset that we want to instill in our graduates. Continuously improving what we do will enable our graduates to continuously improve what they do and to better serve their profession, their communities, and their societies as they practice as professional engineers.

## 7 Lastly, We Leave You With This Thought . . .

Being disruptive is not about a single product – it is much more. We have shown through this chapter that a combination of innovations, inspired by Doblin's framework, will produce impactful and powerful results. We suggest that action research is the paradigm that best fits the insights from the Doblin model. Disruption changes over time, and so does the kind of innovation that you need.

Whether you are an academic, an action researcher, or tasked with a change management initiative at your organization, we encourage you to take this framework and utilize it as a diagnostic tool to analyze your current state or use it to formulate a proposed new endeavor. No doubt the opportunities uncovered will look different depending on the context of your institution. Let Doblin's framework give you insights, let it highlight the opportunities, and let it illuminate the research questions that are ready to be explored. The value of this new model is the novelty of applying the Doblin lens. Our "call to action" is to use a deliberate process for innovation. As we've shown, successful innovators have disrupted across many dimensions, though from all appearances they have done so intuitively. Now, the intuitive approach is no longer necessary. The Doblin framework is available for future disruptors to use as a guide, deliberately and explicitly.

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