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Laying the Foundation for Education 4.0: Access, Value and Accountability

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The best time to plant a tree is 20 years ago. The second best time is today.
(ancient proverb)

The complexity of the global problems engineers are working to solve has long been discussed in both engineering and engineering education circles. The Grand Challenges for Engineering [1] are grand *because* of the complexity of the challenges. While the challenges stand over a decade later, the speed at which the terms in which they are described, the shift from Industry 3.0 to Industry 4.0, has been slow. As the world becomes more deeply connected, as the internet of things becomes more commonplace in all parts of our lives, as technologies like machine learning and cyber physical systems become accessible to even small businesses, the potential solutions to the current and future grand challenges change in ways we cannot yet predict and will require language to describe what we have not yet invented.

This paper is a call to conversation, reflection, and action. Not only is the world for which we educate engineers changing at an increasingly rapid pace, both internal and external pressures are changing the structure and business model of higher education. If we are to thrive in this evolving world, we need a community-wide consideration of the value proposition of higher education as whole, and engineering education in particular.

How We Got Here: A Brief History

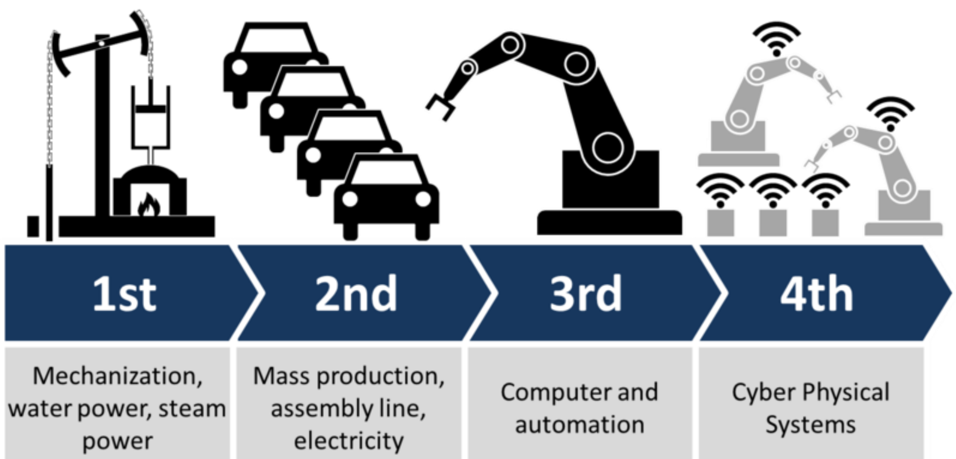

Figure 1. Industry 1.0 to 4.0 Summary [2, Creative Commons License]

Industry 4.0 is built on the achievements of the previous three Industrial revolutions. The first great shift involved the agrarian revolution when people from hunter-gather or nomadic herding societies began to farm and domesticate animals such as cows and pigs. With more stable food sources, populations were able to expand, and this in turn allowed for the first specialization in work. Societies developed primarily agrarian based economies where "industry" was centered around village- or regional-based production and trade. In the early Middle Ages in Europe, this developed into the guild apprenticeship/journeyman/master craftsman systems seen throughout that period. The Renaissance marked increased interest in science and mathematics and ultimately culminated in the Enlightenment period of the 17th and 18th centuries. It was during the end of the Enlightenment that *the* Industrial Revolution occurred, which is now being termed Industry 1.0.

The Industrial Revolution began in England and involved a shift from human-animal powered industry to mechanized industry. These new machines used coal and steam to power them and allowed for the development of more elaborate and step-based manufacturing processes. These technologies spread through the world as part of British expansionism during the colonial era. One could argue that at the base of these inventions was the idea of machine's doing work for people and this had the effect of magnifying the output of people, making them more productive. They also can be seen as a result of the connection between resource production and the production of finished goods ready to go to market, as well as the connection between a power source and what can be done with that power source.

Industry 2.0 was the next leap forward when electricity was discovered and began to spread throughout cities, and with it the telegraph and the network of railroads began to connect distinctly different geographic areas. Manufacturing also advanced with Henry Ford's invention of the mechanized assembly line. Two roots could be said to have given rise to this great leap forward: railroads and electricity. It was the development of rail lines that allowed for the stringing of the telegraph and eventually, electrical lines that formed a spiderweb of connectivity across countries. Industry 1.0 and 2.0 also saw changes in formal education mechanisms, with expectations of basic literacy and numeracy skills alongside expectations to "civilize" newer and poor parts of society [3, 4] and to prepare students for repetitive factory jobs [5].

Industry 3.0 began with the rise of basic computing machines such as the Turing Machine invented by Alan Turing in 1935-36 [6]. These expanded over the next two decades and eventually gave rise to the modern computer. Both Microsoft (in conjunction with IBM and others) and Apple had produced affordable models by the early 1980s. Apple even went so far as to begin offering them to middle and high schools in the 1980s. The computer was only part of the formula for Industry 3.0; the other most significant part was the creation of the Internet and the proliferation of mechanisms that can be used to connect to it. Other mechanisms such as fax machines and teletypes also contributed to connecting computers to each other and to other machines. These tools in turn gave rise to the ability to automate processes in a new manner that was more accurate, efficient, and had the ability to be directed or monitored via connections to the internet and telephone networks The changes in technology-supported another change, the relative decrease in manual labor and rise of knowledge work or adding value to information [7]. Similar efforts appear throughout formal education, with research, instructor training, and resources provided to modernize pedagogical choices with more active learning [e.g., 8, 9] and other high-impact pedagogical practices [e.g., 10, 11], which support the behaviors and expectations of successful knowledge workers.

Klaus Schwab introduced the term Industry 4.0 via *Foreign Affairs* at the close of 2015 [12]. He described the seven defining characteristics of Industry 4.0 as: machine learning, big data/big data analytics, the internet of things, remote sensing, cyber-physical systems, manufacturing processes, and value. These are distinctly different in their implementation and impact from what was seen in Industry 3.0 because of the geometric increase in the level of connectivity between them. The Internet of Things means that almost anything can be connected to anything else via remote sensing. This in turn enabled the collection of big data, which can then be interpreted and analyzed via machine learning. We refer to these four aspects as value generators or value creators, while the remaining two pieces we categorize as value manifesters – the places where we commonly see the value of the other four components interacting to create innovations. In our model, as summarized in Figure 2, the creation of value is then seen as the primary output of Industry 4.0 which in turn leads to innovation, the significant impact of Industry 4.0. Like the earlier industrial revolutions, the changes of Industry 4.0, and the speed at which they are occurring, also changes both the base technological literacy needed by the population at large and some of the skills needed for engineers in particular.

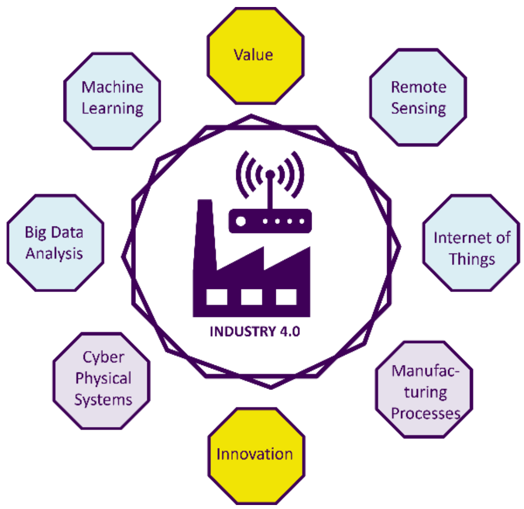

Figure 2. Expanded Model of Industry 4.0

Engineering education, like all of our formal education mechanisms, is living in a similar period of tumult. Many of the engineering tools and methods we have been relying on and teaching are of limited use in the Industry 4.0 world [e.g., 13], and will be of even less value in an Industry 5.0 world. Over the past few years, a sprinkling of scholarship has begun to define Engineering Education 4.0 in terms of teaching Industry 4.0 concepts [e.g., 14, 15, 16] and/or as pedagogical techniques such as video-based internet accessible instruction [e.g., 17] and collaborative virtual learning environments [e.g., 18]. While it is good that there is increasing recognition that the move to Industry 4.0 has reverberations on what and how we teach, it is concerning that the scholarship so far leans toward what we call the 'Bundle of Tools' view.

Bundle of Tools

Gathered from the research and lived experiences of the authors, Bundle of Tools is a perspective that sees specific technologies, content, or tools as the focus, rather than the system in which they live or the whole that is created when they interact. This is not a new phenomenon. For example, the shift from mass production (Industry 2.0) to more operationally effective methods like lean thinking (Industry 3.0) famously saw managers from mass production firms in Western nations visit Toyota plants in Japan (early adopters of what we now call lean manufacturing) and misunderstand the tools they saw. These managers would often bring home a bundle of tools, such as employees starting their day standing in a circle to talk about quality and light boards on the walls with the current production status, and then implement them as stand-alone features that lacked the systems-level connections and inter-support necessary to make the tools meaningful and functional. When employees pushed back at the bundle of tools and productivity and/or quality did not increase, all too often the firms would decide that these new methods just didn't work, rather than reflecting on their level of understanding or their methods of implementation [e.g., 19].

The Bundle of Tools approach does have some advantages for change agents in higher education. It is often easier and faster to update courses with new tools than to fundamentally change a curricular approach. An individual instructor is more likely to have the ability to discuss new or different tools and/or applications in their own course, while changing the curriculum often requires building buy-in across the department, college, and, possibly, even the university levels. Well-written course catalog descriptions allow instructors to bring new tools into their classrooms without having to go through the catalog and curriculum committee process. It is often easier for individuals new to the concept to grasp individual tools than a systems view and thus make initial steps towards larger change.

These aforementioned advantages, however, require over-simplifying a complex system, and most often losing value in the process. Those initial steps toward change made through the Bundle of Tools approach may have pushed the overall change in a direction that suboptimizes or otherwise harms the progress of the system. These pitfalls include:

- Reinventing the wheel – When focusing on a particular bundle of tools without understanding the system you are trying to implement, it is easy to forget other tools that may have been dismissed in the past but, with the current changes in context, are now feasible alternatives. This is particularly the case with tools that were too complex or expensive when originally considered, but have continued to evolve and/or decrease in price.
- Not re-examining the wheel – new technologies mean that new teaching tools may be incorporated into them to increase the potential learning opportunities for students. Many faculty were still using large lecture hall-based delivery mechanisms when the courses shifted to being offered remotely. Rather than re-examining the efficacy of this delivery method and incorporating new tools like break out rooms or online whiteboards, Flip-Grid, or shared collaborative tools like an editable spreadsheet hosted in OneDrive, Google Drive or a shared network folder, some instructors continued to deliver their lectures by reading them into the camera instead of at the podium.
- Every tool is a hammer – This is the assumption that the tools one has are not just necessary, but also sufficient for all of one's work. It closes the mind to possible new tools to borrow or create that may add much more value to a particular situation.
- Punctuated equilibrium – This is when an organization goes through a significant improvement and then iterates around that improvement for some time after. The strategic advantage this would have provided in earlier industrial revolutions continues to degrade as the pace of change increases; an organization has less and less time to live on their past laurels in the marketplace and doing so can result in losing their place in the market.
- Punctuated Leap Frogging – This is when a company make a change or innovation, and does not wait sufficient time to completely explore the impact of this change before

moving on to the next iteration of change. This is the mirror of punctuated equilibrium and carries risks in expanding or leaving a niche too quickly as well as ratcheting up the organizational pressure to innovate and change, potentially causing suboptimization and extreme stress on the organizational structure and the employees in the organization.

- Discounting risks – When looking only at a bundle of tools, it is easy to miss foreseeable and unknown risks that appear or are otherwise indicated only at interaction points in the system. This is both problematic for industry (e.g., changes to the number and type of workers needed and their skillsets when the technologies change; new players in the marketplace; potential materials shortages or other supply constraints) and for education (e.g., changes to the skillsets needed for graduates; needs for reskilling programs; new players in the marketplace; changing recruitment needs).

How, then, do we respect the need to teach new tools to prepare students for Industry 4.0 while not falling into the trap of Bundle of Tools thinking? One way is to leverage the dual core model of organizational innovation [20] -- technical core and administrative core. The technical core are the tools, procedures, processes, and equipment needed to turn organizational inputs into organizational outputs (hopefully, creating value in the process). The administrative core is the organization itself, including the culture, supporting policies and procedures, and functions that enable the technical core to do its job. This model can be applied at whatever unit of analysis is appropriate – you can draw the boundary line of an organization around a class, department, college, or any other level. This means that anyone and everyone can be a change agent for Education 4.0 in their own sphere of influence. Both cores are vital to a healthy, functioning organization, though each core moves at its own pace, has its own goals, and performs its own activities. The value generators and value manifesters are part of the fast-changing technical core. They can be divided into discrete tools sets that can be taught in for-credit courses as well as through industry outreach opportunities. Every time a new technology tool becomes available, we can update our learning environments to include new labs, new content, and open ourselves to new connections based on the application of the new tools. The technical core keeps us up-to-date with changes in industry practice and clarifies the content for reskilling and upskilling needs. The technical core is the basis for our definitions of minimum technical literacy.

The administrative core includes the organization itself, as well as the organizational culture, and changes much more slowly. This pace of change has both positives (e.g., when an organization has a healthy culture, slow movement in the administrative core gives more opportunities to see anything that might harm the culture and move in to fix it) and negatives (e.g., when there are structural barriers to success for some groups or implicit biases built into the culture, it takes longer to find and remove them then we would want). It is in the administrative core that we learn to understand the system in which we are operating and how to transform changes in the technical core into strategic wins for all of our stakeholders. The mind sets and professional skills necessary for success are in the administrative core. Industry is asking for these mind sets, especially around growth, stochastic thinking, and value co-creation, in our graduates because of how vital they are for both individuals and organizations to thrive in Industry 4.0 and to be prepared for Industry 5.0 [21].

Asking Uncomfortable Questions

Given what we know so far of the increased rate of change from one industrial revolution to the next, the types of tools, mind sets, and more in the dual cores for innovation in Industry 4.0, and impact on engineering education – and higher education in general – so far, it is clear that there are many changes on the horizon. We don't have the answers for these questions about the new business model for post-high school engineering education. Rather, through this paper we are inviting the rest of community into an uncomfortable conversation. In order to survive, or preferably thrive, in Engineering Education 4.0, we need to have serious discussions about what value we bring, what assumptions need to be let go, and what biases we have yet to acknowledge. Given the increasing pace of change, we need to start these conversations immediately, before bundle of tools thinking has a chance to take root and our ability to change the dual cores becomes hampered. The following is a starting list of questions, in no particular order:

How do we leverage new technologies to ensure access to engineering education when the infrastructure available to students is uneven at best? The shift to emergency remote teaching at the beginning of the recent global pandemic made glaringly obvious what many in education already knew: we can *not* assume that students (or instructors) have access to a stable (much less high speed) internet connection and the devices necessary to use an internet connection for digitally mediated learning. While remote and other forms of digitally mediated learning have huge potential to meet students where they are both geographically and in their learning journey, there are significant barriers to entry that must be overcome. Further, approximately 31% of Americans do not have geographical access to lower division or upper division engineering education [22] and uneven enrollments may mean that a two-year college with a solid pre-engineering program has to cancel sections of courses like circuits or statics. The combined impact of barriers to local and digital engineering education not only impacts access to future engineers, it also reduces opportunities for increasing technical literacy among all people while the bar for basic technical literacy is raising due to the shift to Industry 4.0.

How does higher education, and engineering higher education in particular, define its place in a changing marketplace with new players? The days have past where colleges and universities were the default option for skilling, reskilling, and upskilling workers. There are new players in the marketplace: private companies, professional and industry organizations, and free resources posted on platforms like YouTube and LinkdIn. While community colleges have long recognized their important role in the reskilling and upskilling components of workforce development, their four-year counterparts have been much slower to enter this portion of the market. At the same time, the rise of micro-credentialing and increasing acceptance by employers of badges, certificates, and other credentials from non-academic sources is creating competition that colleges and universities are largely not prepared for and/or not responding to at a pace that keeps them relevant in the marketplace.

Freely available technical content placed online has additional implications for the future of engineering education. Videos, articles, blog posts, and open educational resources (OER) are available on many platforms and with varying levels of both production value and (not necessarily connected) accuracy. Particularly in the fast-changing technical core, how do we assure the credibility and accuracy of content? When faculty are using content as part of their courses, it is reasonable to place the onus on the instructor. When students are doing independent study, are we helping them develop their own capacity for ensuring credibility of their sources? How do we help students build their own standards for judging the accuracy of content long after they have graduated and the types of content have continued to change? Where are procedures like academic peer review the most valuable and where does crowd-sourced review become more appropriate? Who qualifies to be a 'peer' or part of the 'crowd'? How does membership in either the peer group or the crowd impact diversity of experiences and thinking? Who is being left out of the conversation and how do draw them in? How do we handle innovations on the bleeding edge where we have limited practical experience to consider? How does the upholding the "safety, health, and welfare of the public" [23] potentially change the answers to these questions? Does this mean that those hiring engineers will rely only on quantitative/measurable things when hiring? Someone is able to do X task and knows Y thing. If we have to rely on those types of assessments, we just end back up at the 'Bundle of Tools' scenario rather than looking at talent holistically.

What is the job of the professor when there is so much content available online, mostly for free? How do faculty define the value we bring in our job? How will this change over time? For whom are we creating value and does that list of persons and industries change when we consider different aspects of the role (e.g., teaching, research/scholarship, service)? When is it worth our time to create new content materials (videos, OER, etc.) versus using the content materials available online? How do we define the value created by coaching and/or guiding learners to spot value in their own work and ideas and to turn that value into potential innovation? How do we evaluate the efficacy of our value creation? How will faculty evaluation systems (annual, tenure, promotion, post-tenure) and their artifacts need to change articulate and make decisions on faculty careers using validated value creation? How do we include in our value creation and evaluation processes the impact of external influences? For example, as the demographics of the workforce change, how do we adopt our teaching methods and environments to recognize the increase in mental health needs requested by the 18-24 year old generation (while also needed by many in previous generations who are grateful for those who are speaking out) and among other adults affected by the COVID pandemic?

What does all of this mean for the business model of higher education? What changes will be necessary for higher education to continue to be relevant in 10, 25, 50 years? *Should* higher education still be relevant in 50 years or should we be working toward a different future? How do we, as a profession and an industry, pivot and build our value if some folks in the professorate are starting with an assumption that the value of higher education is self-evident? How do we talk about what value higher ed brings to different constituencies? Do we have a sufficiently full list of who those constituencies should be? Who is being left behind and who is offered a seat at the table? What are we missing when we deny, by action or omission, some folks a seat at the table? The 2020 EDUCAUSE Horizon Report [24] offers four scenarios for higher education in 2030: growth, constraint, collapse, or transformation; higher education will need to adapt or risk being replaced. In the scenario where higher education collapses, the report predicts increasing costs, lack of trust in higher education, and devaluing of degrees as being key factors. In the scenario where higher education transforms, on the other hand, the report paints a picture of flexibility and equity; college and university business models are adapted to allow students to access learning opportunities for life, higher education is affordable for all through company partnerships, and “personal majors” become the norm. The report also offers some suggestions for higher education: implementing learning analytics, teaching machine learning concepts, and collecting data. However, these suggestions bring us back to a Bundle of Tools situation. In order to adapt, engineering education cannot focus only on teaching and implementing the new tools of Industry 4.0. Instead, larger questions must be asked about the value that higher education brings and what that means for our business models.

How will different types of institutions be impacted by the changes likely to occur? Will an institution’s identity make a difference in those impacts, like research-intensive, minority-serving, primarily undergraduate, community college? What about making a difference in the ability of the institution to respond to or influence the changes? How do the answers to the other questions in this list change by institution type? What are the equity issues involved in how different types of institutions define the value created by professors? How does this impact who is considered a professor and how they are trained and recruited?

Access, Value, and Accountability: A Platform for Continued Discussion

We encourage everyone to add questions we are missing, take issue with the questions we list, unpack concerns in different ways, and push at the boundaries of what Engineering Education 4.0 can be and who it can be for. To help this discussion evolve, we note three important through-lines across all of the questions posed above: access, value, and accountability. Access considers how Engineering Education 4.0 has the potential to increase equitable access to engineering education at all levels and varieties, including formal education, continuous lifelong learning, and informal learning within society. Value describes the benefits to the student, the learning environment (including the teacher), the institution, and society from the activities and results of engineering education. Value is generated through every course or set of micro-credentials in Engineering Education 4.0 and is explicitly articulated as part of the learning process. Accountability is the need at all units of analysis to demonstrate appropriate stewardship of resources to achieve the access and value promise of Engineering Education 4.0. Accountability is part of the credentialing process as well as part of the faculty and institutional evaluation systems. Accountability by its very nature also means holding ourselves accountable for leveraging these changes to right significant biases in the current educational model that has limited access to higher education for minorities in terms of financial, geographical, and physical propinquity.

Access, value, and accountability are areas in which we need to be explicit and intentional in our discussion or we risk changing an opportunity for advancement into an opportunity for harm for some or all part of the engineering ecosystem. These three foundations will form the core of a paradigm that is intended to begin a scholarly dialogue to define Education 4.0 with Education 5.0 hurtling towards us just around the corner.

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