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# Technological Innovation and Engineering Education: Beware the Da Vinci Requirement*

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How best can one educate the engineer of 2020 and beyond? How can institutions meet increasing demands to produce graduates with sound scientific fundamentals and essential non-technical skills, while ensuring they are knowledgeable of state of the art advances in technology? To better frame the discussion, I present an analysis of historical technical innovation and engineering knowledge trends, and provide a perspective on the practice of parsing technological knowledge to define new engineering disciplines. Evidence suggests that the emergence of new engineering disciplines has historically matched the pace of increases in technological innovations, with both the number of disciplines and technological innovation doubling at a rate of between 31 and 35 years. Continued success of the parsing strategy requires increased emphasis on certain engineering education trends such as instilling communication and teaming skills, an emphasis on life-long learning skills, and mechanisms for interdisciplinary integration. Lastly, I recommend that a proactive and thoughtful mapping of future disciplinary demarcations could prove more beneficial than the current ad hoc process.

**Keywords:** engineering education; innovation; curriculum; communication

## 1. Introduction

Graduating engineers today face an environment that is increasingly complex. Global competition has heightened the need to reduce product and process development time. A continuous stream of technological breakthroughs greatly reduces product lifecycles. Steady improvements in features, functionality and quality have increased customer expectations. Complex combinations of multiple technologies in single products or systems require knowledge from multiple engineering disciplines to design, manufacture and maintain.

Educational institutions must cope with an environment where engineering knowledge requirements increase rapidly. Any engineering student can attest to a few of the strategies that have become ubiquitous:

- an increase in the number of required units for engineering majors relative to other majors;
- few elective units permitted, with often very limited choices for those electives;
- engineering classes with substantial workloads regularly earn fewer units than courses in other disciplines with less substantial workloads.

These strategies are less than satisfactory, and are exacerbated as the engineering knowledge base increases. The high workload facing engineering students relative to many other majors is a likely contributor to the high attrition rates of engineers. Such attrition has become a problem of national importance, with roughly 50% of entering engineering students not completing an engineering degree [1]. Many of the students leaving engineering are academically capable, but choose to transfer to an academically less demanding major [2].

Recently, a number of newer strategies and practices have emerged regarding how engineering education should be transformed [3]. These include extending educational contact, use of teams, focus on communication and innovation skills, problem-based learning, increasing international exposure, development of learning communities and communities of practice, use of case studies, hands-on projects and promotion of life-long learning.

A key driver of these practices is the rate of increase in the engineering knowledge base and technological innovations. Consequently, a measure of the rate of change of engineering knowledge and technological innovations should be beneficial for educators and education policy makers to consider in contemplating how to transform engineering education.

### 1.1 A measure of engineering knowledge and technological innovation

Engineering can be defined simply as 'The application of scientific knowledge towards some purpose.' Educating engineers, then, is concerned primarily with imparting knowledge about science and the process of creatively and ethically employing the sciences in purposeful applications. The ways in

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which basic scientific principles are applied using novel approaches, new materials, and better designs, is the heart of engineering.

While scientific principles rarely become obsolete, most engineering applications eventually do. The advance of new innovations makes older applications obsolete. Educators need to ensure that the scientific principles are imparted, while staying abreast of new applications. Engineering faculty face a never ending task of deciding which new applications are important enough to include, and which older applications are made obsolete by recent advances. Consequently, the rate of advances in new and innovative applications is of paramount importance to the ability of educators to adequately prepare engineers for professional practice.

Let us focus on a high level view and ask the question, 'How can we measure the rate of change in technological innovation, and how can the engineering educational system adequately accommodate such change?'

Chronicling technological advances and monitoring obsolescence across multiple disciplines could raise more questions than it would answer. What is an appropriate measure of technological advancement? What innovations should be included and what excluded? Should the complexity or the impact of the innovation be considered? Penetration and decline of technologies often occurs on a continuum. At what point does a technological innovation emerge, and when does it become obsolete? When is a new advance made as opposed to a 'new packaging' of an existing technology? Does necessary historical information exist regarding these issues for past advances in technological innovation?

While admittedly not perfect, patent data appears to be the best readily available information on historical technological innovations that serves to at least partially address many of the above questions.

### *1.2 Patents as an indicator of technological innovation*

Patents (utility patents) serve the dual purposes of reserving rights of use of innovations to those that first identify the innovation, while simultaneously adding to the body of public knowledge by making public the details of innovations so that the state of the art will be advanced over time. In this way, prospective innovators are fully informed on the current state of the art so they can concentrate on advancing the state of the art rather than replicating it.

Patents are issued to any applicant who '. . . invents or discovers any new and useful process, machine, article of manufacture, or composition of matter, or any new and useful improvement thereof' [4]. Patents must be applied for, and are issued only after each application undergoes a rigorous review process by the patent office. Key emphasis is on 'new' and 'useful,' and most patent requests are not granted on the first application. Once granted, a patent protects the interests of the patentee for 20 years from the date of filing the patent application, and the patents are published in a publicly available report. The guiding logic is that, after 20 years, the state of the art will have surpassed that originally described in the patent.

For our purposes of capturing the 'rate of change in technological innovation,' the patent office can serve as an important screen. Their review process ensures that patents are issued only for innovations that are new as compared with the current state of the art. Innovations also must be useful, i.e., an actual advance, in order to qualify for a patent, assuring that there is a 'purpose' associated with the innovation. A new innovation that is not useful will not be issued a patent. By these requirements the patent office has consistently determined what is and is not a technological advance. Similarly, the patent office determines a specific and consistent time for acknowledgement of the 'birth' of the innovation. Lastly, patents have a predetermined time-specific obsolescence based on the date of issuance of the patent. While not necessarily true for all innovations, for most patents the state of the art should have progressed sufficiently to make obsolescence a reasonable assumption, with new patents building on and surpassing the knowledge contained in expiring patents.

However, in utilizing patent data as a proxy for engineering knowledge and technological innovation, it is important to acknowledge the following:

- Not all innovations are patented.
- Not all patents are useful enough to become economically viable.
- Individual patents may have only a very narrow application.
- The obsolescence of the knowledge and innovations embedded in some patents may not coincide with patent expiration (i.e., could become obsolete before or after expiration date).

While acknowledging these limitations, we can conclude that patents are the most consistent, inclusive and publicly available proxy for a historical measure of the rate of advance in technological innovation. So as a measure of existing engineering knowledge and innovation at a particular point in time, we take the patents granted in a given year plus the patents granted in each of the preceding 16

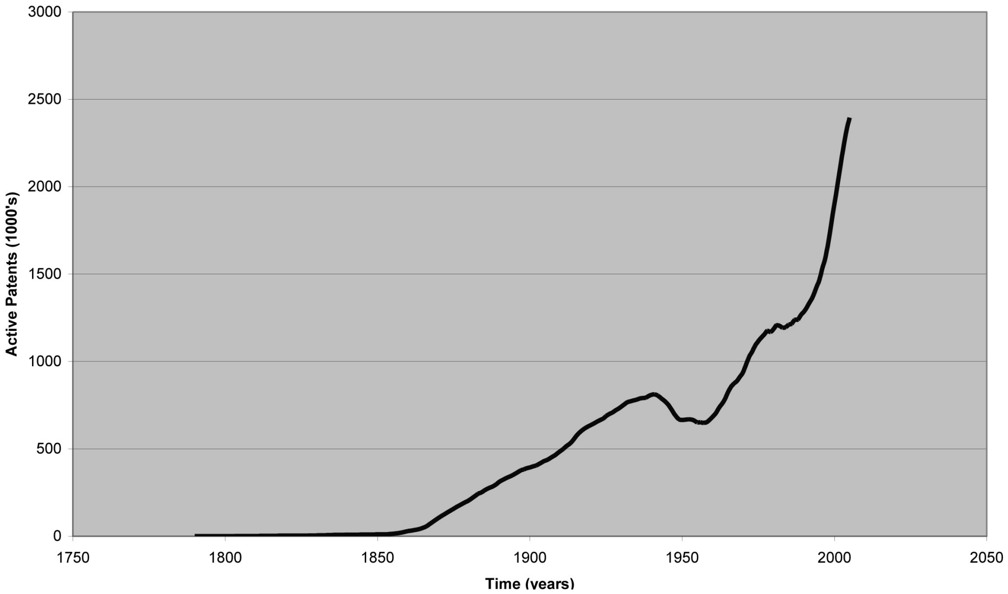

**Fig. 1**. Active patents 1790 to 2005. (Data source: United States Patent Office [5].)

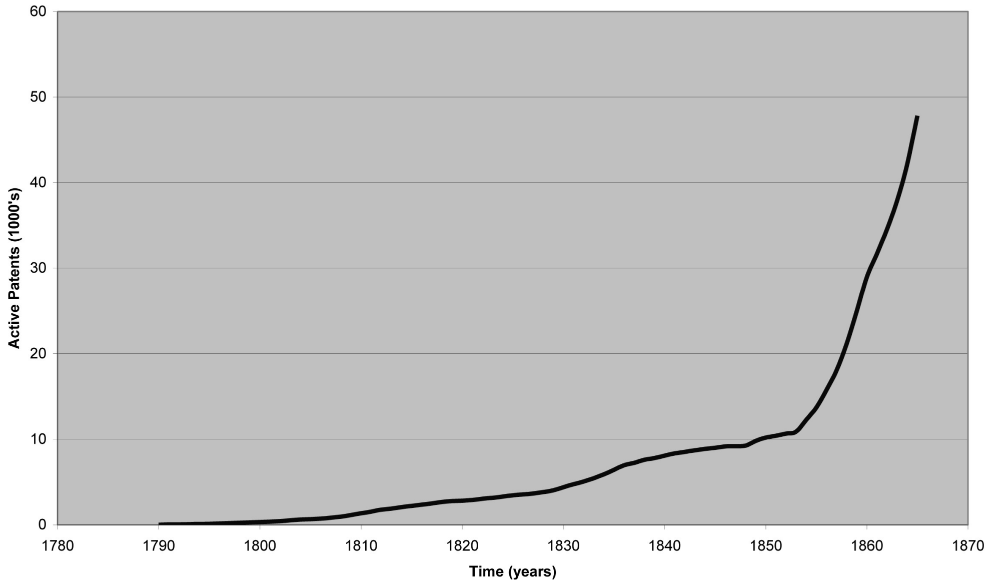

**Fig. 2.** Active patents 1790 to 1865.

years.[1] In this way we capture all patents that are potentially 'active' at any given time.

The data on patents are publicly available on the US Patent Office website [5], with a history dating back to the three patents issued in the year 1790, to approximately 2.4 million patents that were potentially active in 2005. An analysis of active patents since the beginning of record keeping in 1790 to the most recent records of 2005 produces Fig. 1. The shape of the resulting curve suggests exponential growth in active patents.

The scale of Fig. 1 tends to mask the growth in the early years, from 1790 to about 1865. Though not visible in Fig. 1, exponential growth is also exhibited in these early years, with a sharp increase beginning in approximately the year 1854, as shown in Fig. 2.

A characteristic of the exponential functional form is that the 'doubling time,' in this case the time for the total number of active patents to double, is constant. The best fitting exponential

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[1] Current United States law provides patent rights for 20 years from the date of first filing. The exact number of active patents at any point in time is dependent on a number of factors, including whether and how many times a patent holder renews a patent, which cannot extend the patent rights beyond 20 years. Alternatively, the patent holder could allow the rights to lapse. Prior to 1995, patents were potentially active for 17 years from the date of issue rather than the current 20 years from date of first application. For purposes of data represented in the graphs of this paper, we do not include any renewal data, and treat each issued patent as active for 17 years [4].

model for the entire data set from 1790 to 2005 provides a doubling time of approximately 16 years ($N = 216$, with an R-squared of 0.85). In spite of the fairly high R-squared value, the deviation between the exponential model and the actual data in more recent years becomes pronounced, starting from about 1947. The reasons for this appear to be twofold; very rapid, un-sustained growth in the early years (1790 to 1865) coupled with a period of stagnation and decline beginning in 1933. This significant disruption in the historical pattern of patents bears further scrutiny.

The year 1932 saw a local maximum in the number of annual patents issued at over 56 000. After this year, the data show evidence of a significant period of stagnation, decline and then recovery. Beginning in 1933 and through the depression era (1933 to 1941) there is stagnation, where the number of active patents is relatively flat. The impact of a contraction in the capital necessary to foster and apply innovations, combined with a simultaneous reduction of consumer purchasing power needed to provide market demand for innovations, could explain this stagnation in the rate of growth of active patents.

Coinciding with the entrance of the United States into WW2, is the start of an era of decline in the number of annual patents. WW2 is likely to have impacted our measure of innovation primarily in two ways. First, the talents of the most able-minded innovators were in many instances co-opted and redirected towards the war effort, producing innovations that did not result in patents due to concerns over national security. Secondly, many potential able-minded innovators were not developed via a college education and professional engineering career, but were employed in the physical execution of the war effort and its aftermath. This declining trend in the number of active patents eventually reversed in 1955.

To analyze current conditions while excluding the aforementioned disruptions in our measure of rate of innovation, let us now focus on the fifty years of data from 1955 to 2005. Figure 3 shows the active patents from 1955 to 2005. Modeling this data via the best fitting exponential curve produces a 'doubling time' of 31 years, with an R-squared value of 0.97. This means that our best estimate for the doubling time for technological advances at present is 31 years. This estimate takes into account the generation as well as the obsolescence of technological advances.

The doubling of the amount of technical innovation and engineering knowledge every 31 years has potentially important implications for engineering education in a number of facets. We will concentrate and restrict the present discussion to the implications for educational contact, currency, and the organization and integration of engineering knowledge.

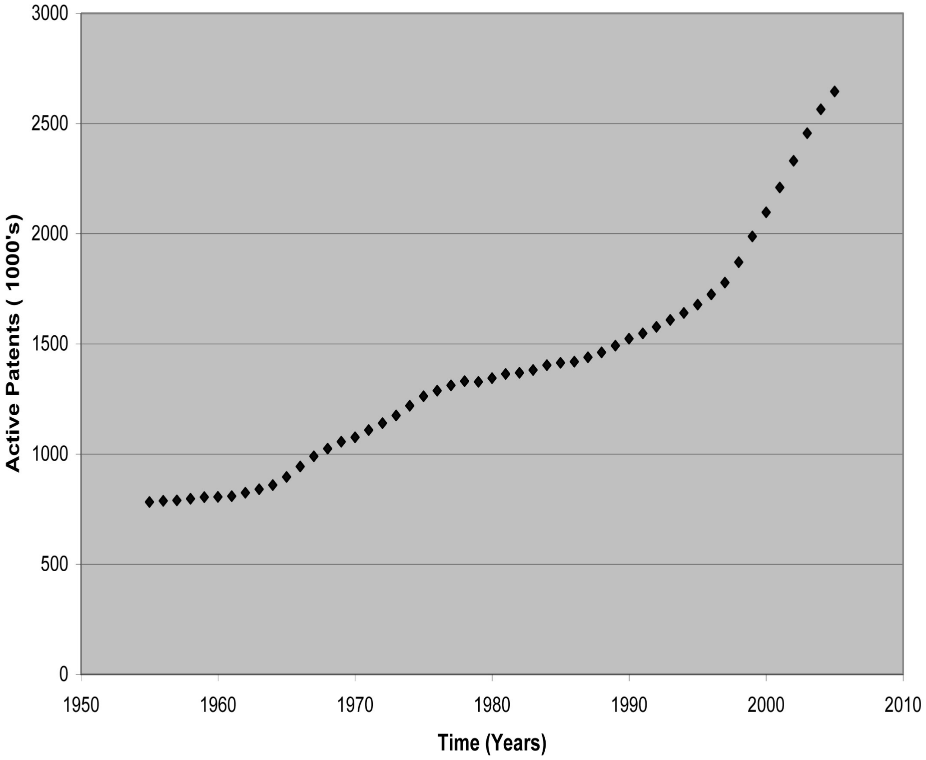

**Fig. 3.** Active patents, 1955 to 2005.

## 2. Coping with innovation acceleration

One option to cope with an increased knowledge base is to increase educational contact requirements. Calls for lengthening the requirements for an engineering degree are not new. In fact Cornell, the University of Minnesota and Ohio State University briefly made the switch to a 5-year degree in the 1940s, but when other universities did not follow suit, they discontinued the practice [6].

It would of course become impractical to double the amount of educational contact required for an engineering degree every 31 years. While the increases in technical innovation and engineering knowledge present many challenges, increasing contact hours required for the degree to keep up with the rate of innovation constitutes an unsatisfactory and self-limiting solution.

At best it would be a stop-gap solution, providing a temporary reduction in the gap between the time available for knowledge acquisition and the amount of knowledge available for acquisition. However, the rate of increase in knowledge would quickly catch up, necessitating a further increase in educational contact hours to close the new gap. Succeeding generations of engineers would eventually have educational contact hour requirements that would make choosing an engineering education/career path increasingly unpopular.

At worst, increasing the number of years required to obtain an engineering degree would dissuade potential innovators from embarking on the path towards becoming an engineer (in the absence of all other disciplines similarly increasing degree requirements). Recent declines in number of students entering engineering programs [7] would be exacerbated, making this an onerous proposition.

Let us reflect on an apparent paradox: The professional environment that engineers face today was created largely by engineers who were educated yesterday, via traditional curricula and pedagogies culminating in a traditional four year degree. A four year degree requirement has been the standard for over 100 years now, a time during which, according to our measure, the engineering knowledge base has more than octupled.

If engineering knowledge and technological innovations have really been advancing so rapidly, how is it that the educational system's pathological failure to keep pace has not manifested itself in a completely ineffectual system? We observe that other strategies for accommodating the significant increase in knowledge requirements have been utilized that have heretofore been adequate in maintaining a standard four year undergraduate degree while accommodating increased knowledge requirements of the engineering professions. Prominent among these are 'facilitative technologies' and 'growth of disciplines.'

### *2.1 Facilitative technologies*

A progression of increasingly sophisticated facilitative technologies, for example slide rules, then calculators and now computers with extensive CAD and mathematical software, have provided a buffer against an ever increasing knowledge base. These allow for organization, retrieval and exploration of data and information, including almost effortless 'number crunching' capabilities as well as exact, scalable, quickly modified designs. Such activities previously consumed major portions of engineering students' time. Possibly, future technological advances akin to these will continue to mitigate knowledge growth requirements and afford other opportunities for better allocation of student time.

### *2.2 Engineering disciplines*

Engineers historically have been those who have creatively applied scientific principles towards some purpose. Distinctions between engineering foci have traditionally been based on either the science, for example 'chemical' engineers, or the purpose, for example the original distinction of 'civil' engineer denoting a focus on non-military applications. From early in the history of the United States, the advent of new engineering knowledge and technological innovations has resulted in new engineering disciplines being born [6]. These disciplines are largely constructs that serve to parse engineering knowledge into comprehensible and practicable domains. This organization of knowledge into disciplines and specialties is a time tested strategy. The rapid increase in engineering knowledge and technological innovation imposes a need for the creation of more disciplines as a way to divide knowledge into well-defined and 'learnable' domains.

## 3. Growth of engineering disciplines

The Engineers Council for Professional Development (ECPD), later to become the Accreditation Board for Engineering and Technology (ABET), was founded in 1932, and began accrediting United States engineering programs in 1936. In this first year of accreditation, 15 distinct engineering disciplines were accredited, with no new disciplines accredited for a 13 year time span[2].

While accurate for the current measure of number

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[2] Note that this 1936 to 1949 interval is the biggest gap in accreditation of new disciplines in ABET's history, and, similar to innovation and knowledge creation trends discussed earlier, was likely influenced by the great depression and WW2.

of disciplines, the dataset used may not perfectly capture the number of disciplines throughout history due to certain characteristics of the original data source. First, missing from the data would be any previously accredited disciplines that currently do not reside in any accredited department (i.e., 'obsolete' disciplines). Secondly, the date of each discipline's first accreditation was determined from the current list of ABET accredited programs, by selecting the oldest date of initial accreditation from all institutions listed as currently accredited in that specific discipline. This means that it is possible that an institution that originally was the first to be accredited in a particular discipline, but is currently not accredited in that discipline, would not be reflected in the dataset and consequently shift the 'discipline emergence date' to a later year.

Figure 4 shows the cumulative number of accredited engineering disciplines over time, from 1955 to 2005, the same time frame of our previous analysis of patent data. Please note this discussion and timeline is concerned with the first emergence of distinct recognized *disciplines*, not the number of accredited programs or departments. Some of the more recent additions of accredited engineering disciplines include: Software; Information Technology; and Applied Networking and Systems Administration.

An exponential model provides a good fit for this data, with an $R^2$ of 0.97 (slightly better than a linear model, which also provides a good fit with an $R^2$ of 0.95). The exponential model in this case provides a doubling time of 35 years. Recall that our similar analysis for active patents over the same time period yields a doubling time of 31 years. This agreement in doubling times suggests that the rate of technological innovation has historically been matched closely by the parsing of the engineering knowledge into disciplinary domains.

While the pressures of increased engineering knowledge and technological innovation argue for increased disciplinary parsing of knowledge, the globalization and competitive market pressures increasingly require the integration of more and more knowledge in individual products, processes and projects. This relationship is similar to what Lawrence and Lorsch first observed in their classic study of organizations in different environments; increased environmental complexity requires increased organizational differentiation, while the more differentiation between the various parts of an organization, the more integration mechanisms are required for high performance functioning [9].

These requirements for increased integration of disciplinary knowledge will in turn require increased emphasis on instilling communication and interdisciplinary team skills in graduating engineers. These are, rightly, key components of new ABET requirements, and there has been much recent activity in this area of engineering education research. As technological innovations and the engineering knowledge base continue to accelerate, these non-technical skills will become increasingly

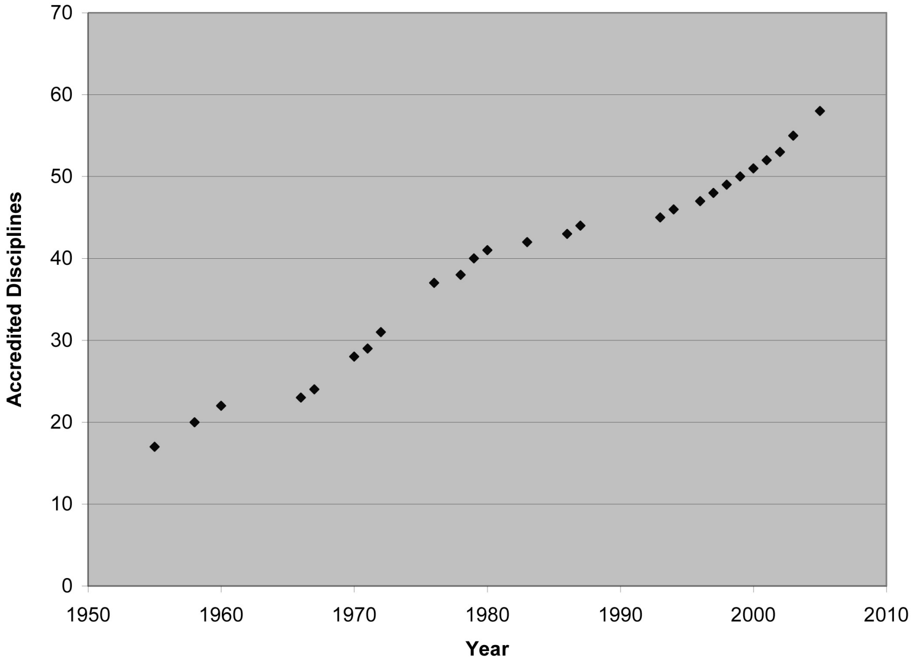

**Fig. 4.** Engineering disciplines accredited by ABET, 1950–2005. Cumulative total by year first accredited. (Source: ABET website [8].)

critical for the successful and efficient integration and application this knowledge.

Other formal mechanisms for providing students with experiences integrating the engineering knowledge from different disciplines is also called for, for example research centers promoting interaction of faculty and students from multiple departments, and application courses where students interact and coordinate contributions with those from other disciplines.

## 4. Discussion

Engineering faculty have continually struggled with what to include in engineering curricula. A steady stream of technological breakthroughs and innovations provides a continuous crop of new materials and the need for curriculum renovation. While it becomes obvious that new material needs inclusion, it is perhaps less obvious when material becomes obsolete and should be removed from the curriculum.

Fundamental decisions regarding the future actuation of engineering education depend in part on the rate of growth of the body of knowledge that engineers need to know. The record of patents issued and expired, by virtue of requirements to be both new and useful, the rigorous screening process, and built in obsolescence, appears to be a useful indicator of the level and rate of change in engineering knowledge and technological innovation.

Analysis of patent data reveals a rate of increase in engineering knowledge that is exciting but challenging from an educator's vantage point. If the amount of engineering knowledge relevant to current practice doubles every 31 years, the educational system needs to be designed to accommodate this trend in educating future engineers.

The continuous increase in engineering knowledge requirements begs the question, 'What is the appropriate content for engineering education, and when are engineers adequately prepared to transition from a primarily learning mode to a primarily performance mode?' Some might argue that the increase in the knowledge base requires a longer time in the learning mode prior to transition to performing mode. However, such a requirement of individuals to spend more time and learn more would provide only a temporary respite from the onslaught of new knowledge.

Periodically, the ever increasing knowledge base would require a subsequent increase in length of formal education. Requiring each new generation of engineering students to master more and more material is akin to requiring all graduates to be super engineers, what one might call the 'da Vinci Requirement.'

Leonardo da Vinci's name is still instantly familiar now, almost 500 years after his life time of innovations. This is because his work as an inventor and artist was extraordinary and largely unequalled. Da Vinci was a 'super engineer' who simultaneously exhibited competencies across multiple engineering disciplines (see, e.g., [10–12]). "Beware the da Vinci Requirement" is cautionary advice, as history has produced very few such 'super engineers' through the centuries. While creating such 'super engineers' is laudable as an aspiration, it is unrealistic as a graduation requirement.

Seen in this light, the extension of engineering to a five-year (or more) degree seems at best a stop-gap measure to temporarily allow more material to be taught and learned during the undergraduate educational process, but that does not sustainably address the fundamental nature of technological innovation acceleration. At the same time, such a strategy is quite likely to reduce recruitment and retention rates, exacerbating already worrisome trends.

More promising strategies appear to be an increased emphasis on development and utilization of facilitative technologies, an increased effort to construct an advantageous parsing of engineering knowledge into engineering disciplines, and a consequent increased emphasis on developing strong communication and team skills for interdisciplinary communication. Additionally, the vigorous pursuit of post graduation life-long learning becomes an important strategy.

Over the course of just the last generation, computers and engineering software have become ubiquitous in the education of engineers. Great strides have been made in creating tools for engineers to efficiently create designs, solve problems, and access, collect, filter and sort information. Advances in such tools could be similarly dramatic over the course of the next generation. Engineering educational institutions will need to focus more and more effort on staying abreast of these new developments and incorporating them into the education of engineering students. A positive trend in this area is the increased emphasis on development of engineering education centers and research consortia.

There are some important potential limits to the use of patent data to measure innovation, and to the applicability of the study results to other regions that are worth mentioning. First, it is possible that other factors, such as changing cultural attitudes emphasizing litigation and economic enrichment, influence the number of patents granted rather than any actual increase in innovation. The second is that the patent data and the data regarding engineering disciplines are both from the USA, and therefore may not be representative or be applicable to other locations. Regarding the first limitation, one could also argue that changing cultural emphases on litigation and economic enrichment play a large role in driving actual increases in innovation, in creating new innovations where there is no question of intellectual property rights, and in seeking new economic opportunities. Regarding the second limitation, it would be a worthwhile research endeavor to study other regions to see if the same relationship between patent data and engineering disciplines holds. Of particular interest would be the identification of regions that are particularly rich in technological innovations and those that are stagnant, and then to compare the engineering educational systems in both to see if similar innovation and stagnation trends can be found regarding rate of discipline creation.

## 5. Conclusions

The current study argues that US Patent data is a reasonable, well-defined, historical and readily available proxy for chronicling innovative technological advances. Similarly, 'active patents' serves as a proxy for 'technological advances that are current,' accounting for innovations that are current as well as those that become obsolete. Technologies that are current are the 'state of the art' that engineering education systems need to equip graduates for at any given point in time. When this active patents data is juxtaposed with ABET data for accreditation of engineering disciplines, we find that the rate of increase of engineering disciplines largely keeps pace with the measure of rate of increase in innovative technological advances. This result leads to a number of interesting conclusions.

First, requiring a fifth year of undergraduate engineering education to keep pace with increased knowledge requirements is at best a stop-gap measure, only briefly relieving the pressure of 'too much information and too little time.' At worst such a practice would likely drive a significant number of potential engineers away from pursuing such an arduous academic path.

Second, the emerging significance of non-technical skills that are becoming essential for engineers are better understood. When portions of knowledge become compartmentalized into distinct disciplines, the criticality of communication skills and teaming skills to access that information becomes readily apparent. When the amount of knowledge is vast and rapidly increasing, the benefits of 'life-long learning' to maintain currency, even within a single discipline, also become readily apparent.

Lastly, a deliberate long term plan for the parsing of engineering disciplines could well facilitate efficient anticipation and coverage of emerging technological advances. Creating a plan that anticipates and pushes knowledge advancements through discipline creation could provide benefits as compared to reactive ad hoc development. Most notable among these benefits would be the preparation of engineers ready to contribute immediately upon graduation.

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