Engineering R & d

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Engineering is the application of science. Scientists conduct academic interrogations and analysis of nature. Engineers bring scientist's discoveries into physical reality as structures, machinery and devices. Both professions are inexorably connected in requiring analysis and creativity to accomplish innovation and invention, but are separated by a reality that scientists favor research and discovery while engineers favor development and design.

American engineering education, for the most part, has seen a blurring of the distinction between and the roles of scientists and engineers. This has occurred to such a degree that engineering research now mostly culminates with thesis and research papers rather than physical manifestation of the science. A situation not too far afield of the mathematician who upon being given a problem to solve must already know the solution and by so doing only begrudgingly will labor to present a worked solution. It's all in the abstract not the physical. However, engineering works are not truly realized until there are mechanisms, machines, engines, etc.

As a semi-retired consulting engineer, observing over almost fifty years the progressive displacement of American products by works of other industrial nations, it has been painful to witness the withering of our commercial and industrial product pipeline. Especially poignant is that too much of our industrial, infrastructure, transportation and military components are now foreign sourced. Our domestic development and production capability is being forfeited on account of engineering research culminating as no more than paper.

The acceptance of paper solutions as an academic R&d end game has led to development and production increasingly occurring outside the U.S., where our academic work products are developed, scaled, and put into production overseas [1]. The National Science Foundation (NSF) report to the President and Congress *The State of U.S. Science & Engineering 2020* [2], contains some ominous warnings relative to the state of our national science and engineering enterprise, which states:

> "Increasingly the United States is seen globally as an important leader rather than the uncontested leader."

and

> ". . . the United States is playing a less dominant role in many areas of S&E activity."

Our future rests with today's undergraduate engineers, who are initiated to the profession through coursework in science, mathematics and engineering fundamentals. In the not too distant past, the fundamentals included a fair amount of engineering technology. Many of today's four year engineering programs disdain the technical side of engineering, openly critical that their curricula are assuredly *not a technology program*; favoring instead a more extensive focus on derivation and theoretical work with expected continuity into graduate level research.

This has diminished efforts to teach the means and methods of bringing scientific discovery and engineering inspiration into material practice.

Engineering firms and manufacturers who employ new graduates lament that a majority of early career engineers require excessive mentoring and educating to make them productive as designers. Their education made them great analysts, but sold them short on design and fabrication skills. This lament is common knowledge among engineering principals, but only shared through private discussions between peers. However, it has surfaced in anonymously conducted surveys, a major one as part of a report sponsored by the Governing Board of the National Research Council (NRC), *Education of Architects and Engineers for Careers in Facility Design and Construction* [3]. The findings included substantial agreement among high level officers of academic and non-academic organizations, stating:

> "The overwhelming majority of the professionals interviewed agreed that a significant percentage of the members of their organizations believe that there are serious problems with the current system for educating both engineers and architects. This view was expressed by both academics and non-academics and by respondents who did not themselves necessarily agree with the idea that problems exist."

Specifically calling out,

> " . . . the failure of schools to give students enough practical knowledge and instruction in solving real world problems."

and volunteering,

> "Two solutions to the problem of students getting insufficient practical training were proposed by a number of the people interviewed:
> (1) include more professionals with practical industry experience on the faculty and
> (2) revise the curriculum to provide more emphasis on design, practice, and practical problem-solving techniques.

There are numerous other studies that speak to this concern, as the debate is not new; best summarized by John Alic of the Congressional Office of Technology Assessment in his 1990 letter published in *Issues in Science and Technology* [4]:

> "Engineering educators in the United States . . . have long since won the 100-year-old debate with those, mostly in industry, who would have the schools turn out more practically oriented graduates. Since the 1960s, the theoretically based engineering science perspective has remained unchallenged."

Thirty years have passed since Mr. Alic took this position; nothing has changed save for the withering of our development pipeline, chargeable in part to the reason stated in the NRC report:

> "Echoed in educators' complaints, viewpoints, and resistance to the influence of professionals is a staunch defense of the cloistered environment of academia that fosters a young person's growth without the immediate pressures inherent in the directed expectation of the work world." [3]

A study by the National Academy of Engineering (NAE), *Educating the Engineer of 2020* [6] reinforces the xenophobic cloistering that has evolved, with recommendations that engineering students be restrained from exposure to engineering practice, stating:

> "The B.S. degree should be considered as a pre-engineering or "engineer in training" degree.", and "Engineering programs should be accredited at both the B.S. and M.S. levels, so that the M.S. degree can be recognized as the engineering "professional" degree."

Otherwise interpreted as 'let's make them all like us' in a real life version of the movie *The Firm*, where once you become part of the organization you can never leave.

Nevertheless, upon joining the profession, and under mentorship by experienced practitioners, young engineers do grow into becoming productive designers. However, there is a consequence whereby a great majority of practicing engineers do not return to graduate school or academic work, seeing no relevance to their career path and calling into question the merit of graduate programs. The NAE report included a recommendation that reinforces this reality:

> "Institutions should encourage domestic students to obtain M.S. and Ph.D. degrees."[6]

The absence of practice experienced engineers brings an unfortunate reality in depriving our academic and research community of an essential resource, exacting a terrible toll on America's pipeline of innovation and technology. The fallout of this evolution is that today's research and development is conducted with a capital "R", but a lower case "d". Research institutions pursue R&d and go wanting for the motivation and skills for true R&D to occur.

Visiting the founding institutions of engineering education tells of a different place and time, for one a building at Syracuse University, repurposed today, but bearing an inscription over its entryway as "Machinery Hall Lyman Cornelius Smith College of Applied Science". Erected early in America's exceptional 20th century industrial expansion, endowed by an industrialist made famous by Smith-Corona typewriters, it was filled with so much manufacturing technology its design floor loading was 500 pounds per square foot. Student engineers learned to make real things in a big way, and the city of Syracuse into a robust industrial concentration. Students at similar institutions doing the same for their cities; the most successful graduates endowing their institutions in a cycle of synergistic prosperity borne of engineers making commercial the applications of scientists work. More often than not academic-industrial collaborations saw many cities and regions develop industrial concentrations leading to significant wealth generation. Today's Silicon Valley offering one of the few modern examples, whereby alumni who develop products and become wealthy endow their universities, often participating as faculty or providing leadership of their engineering programs. For example, Stanford University professor and past president John Hennessy had founded one of the first companies to provide WiFi communication technology.

Today's engineering schools remain endowed by alumni, yet too often the wealth is derived from non-engineering pursuits, e.g., Harvard's engineering school endowed by hedge fund profits, Johns Hopkins and Yale's engineering schools endowed by communications media derived wealth. Leadership of our most major engineering initiatives, such as the commercialization of space, or advanced transportation systems has not been motivated by our educational system producing visionary aeronautical or automotive engineers, but instead by gifted dot.com billionaires such as Elon Musk, Jeff Bezos and Paul Allen.

How is it that engineering programs are short on producing engineer-industrialists?

Unique practitioners, such as student prodigies Paul Allen and Bill Gates, who conducted practice oriented work, were banned from the University of Washington computer lab; Allen dropped out, Gates attended Harvard and dropped out too. Had real world participation been a part of their curricula, their university communities would have benefitted far more than by rigid adherence to a purely theoretical PhD program. Elon Musk dropped out of Stanford two days after beginning a PhD. The terminal degree has become an aversion to the highly gifted; for capable others, it has evolved to often brilliant thesis papers rarely progressing into physical work, followed by teaching others to repeat the cycle. Perhaps more important than those who disdain terminal degrees is the attrition rate for undergraduate engineering students, which various sources report as high as 60%. Acknowledging that a lack of primary school preparation for engineering surely is a part of the attrition, a University of West Virginia survey found the most common reason for students to give up on pursuit of an engineering degree is “Engineering majors do not match my interests” [5]. How many inspired and inventive potential engineers are lost to the profession due to the failure of programs to support applications oriented exposure that would capture the interest of young visionaries? Rather than having them depart from academics and go their own way, the curricula should be empowering them to find new avenues.

The cold war and frenzied effort to counter thermonuclear Armageddon caused drastic changes in engineering education and industry. The government did two things, first breaking up industrial city concentrations to prevent a single attack taking out a whole industry [7] (eradicating a long standing purely organic industrial-academic synergy), and secondly, as a consequence of Sputnik, putting the NSF in charge of R&D at engineering schools (scientists took command of funding and steering engineering research). University research had only represented one quarter of national research efforts, and industrial research dominated [8]. Once the NSF took command, it became de rigueur for Principal Investigators to hold the terminal degree of scientists, i.e., PhD’s. Development persisted only because a sufficient compliment of practicing engineers remained affiliated and embedded in engineering faculties. However, over time the allure of government funding and “research university” prestige led to exclusive recruitment of PhD engineering-scientists. As practice qualified engineers were attritted, the development pipeline slowed to little or no products brought to implementation. A particular example of the presence of practice qualified engineers, and the impact on true R&D was Vannevar Bush, a founder of Raytheon, Dean of the MIT School of Engineering, and America’s top military science administrator during World War II and into the cold war years. Bush’s R&D initiatives were fostered by a triangular alliance of government, academia and private business [9].

It is significant to note that though Vannevar Bush had chosen to focus his capabilities in the Academic milieu, he was experienced from working as an engineer in General Electric’s factories in Schenectady, NY and Pittsfield, MA as well as at the Brooklyn Navy Yard. An unlikely pedigree for most present day Engineering Academic Deans. Bush effected the NSF’s dominance in directing university R&D, but based on the world he came from, likely could never envision the exclusion of practice experienced engineers from graduate level participation within the university communities.

The exclusive focus on academic research has resulted in little to no advocacy for development funding, causing an evolution of government funded research becoming a poison pill to development. Federal science and technology funding is currently apportioned at >99% to research (academic pure science) and <1% to development (application oriented translational research). Global competitors have government funded research apportioning as much as 30% toward development [1].

Our current production of useful things relative to our R&D efforts are best examined using the economist's metrics of *total factor productivity* and *industrial capacity utilization*. Referencing the figures contained at the back of this paper: Figures 1 and 2, show the relationship between our R&D expenditures and how this contrasts to our capacity utilization and total factor productivity. The ongoing decline of our industrial capacity indicated in Figure 2 covers most industrial sectors, but is particularly illustrated by Figure 3, wherein the shipbuilding sector speaks to how our capacity to conduct large scale manufacturing has become inconsequential relative to global competitors. Though a majority of shipbuilding has been overtaken by low-cost producers, there remains a fair number of European ship-builders regularly executing billion dollar ship orders. Our forfeiture of this multi-billion dollar industry which crosses multiple areas of our industrial base, e.g., primary metals, heavy machinery, large scale fabrication, automation, et. al., also impacts our engineering prowess. The U.S. capacity for shipbuilding had been long ago demonstrated by our having built 700 ships in 1943 during the World War II emergency, utilizing the limited technology of the day.

Practicing engineers must be reinstated as a body of advocacy for rebalancing government funding and bringing motivated industry partners into the R&D process as well. There do exist some practice oriented programs, such as MIT's PhD in Chemical Engineering Practice or Lawrence Technological University's Doctor of Engineering programs. The appreciation of commercial merit will efficiently steer investment in the progression of thoughts into practical physical products, the essence of which is best summarized by Thomas A. Edison's position: "Anything that won't sell, I don't want to invent. It's sale is proof of utility, and utility is success".

In examining the issue of practicing engineers as part of the academic community, it is important to look at the presently accepted governance of engineering education. The Accreditation Board for Engineering and Technology, Inc. (ABET), considers Engineering as programs:

> "that often focus on theory and conceptual design" and Engineering Technology as programs that are: "more practical than theoretical in nature".

ABET goes on to state:

> "In general, engineering programs offer more foundational analysis of problems while engineering technology programs stress current industrial design practices that allow students to start developing practical workplace skills." [10].

Any question as to why our engineering programs have evolved to incapacity of development?

Contrary to ABET's categorizations, it is proffered, from many years of experience in the practice of engineering, that the presently accepted convention does not reflect the reality of the engineering and technology disciplines as truly exist.

A better description of who's who in engineering and technology is suggested as follows:

Engineering Scientists:	Academic or research engineers almost invariably holding a doctoral degree.
Engineers:	Private practice licensed professional engineers, or employed engineers holding bachelors or masters degrees.
Engineering Designers:	Technologists holding associate or bachelor degrees in engineering technology.
Engineering Technicians:	Equipment specialists holding manufacturer certificates or associates degrees.
Trade Technicians:	Machinists, millwrights, welders, electricians, et. al. who are trained through apprenticeships.

The above categorizations are from observations made from many years of the private practice of engineering, inclusive of interacting with and providing engineering (facilities, tooling, fixturing, etc.) for academic as well as industrial research institutions. It is important to note that it is not unusual for certain individuals to be able to capably function in more than one skill set, e.g., an engineer that has a talent for designing which is as much an art as a science, or a trade technician who advances their skills upwardly to technician or designer capability.

Engineering development is the action of taking theoretical or conceptual work and creating a physical manifestation, as a working prototype or demonstration device or system. Successful development work is only possible using a combination of engineering and technology skill sets. Academic institutions usually do not have designers or technicians in house and development is most often accomplished through the engagement of trade contractors working with third party engineers to effect the creation of prototypes. Outsourcing prototyping and demonstration work reduces the feedback from experimental discoveries. This process would have been far better served and more likely to lead to a successful outcome if the engineering and design were conducted in concert with the conceptual evolution, i.e., advancing research products into engineering works via a design loop and/or design spiral methodology. The conceptual design originating from initial research, when progressed to development, prototype and demonstration, is very often discovered to have shortcomings, with the benefit of the experimental findings commonly providing the quickest signals of how to adjust the design to yield the desired design outcome.

As one coming of age amidst a family of mechanics and technicians, a youngster not alone in visiting shipyards, power stations and construction sites during an era when a non-litigious society allowed common sense to prevail for safe conduct. The offspring of technologists were made to see the works their parents were very proud to show them, letting first-hand experience build enthusiasm for a career path enabling an independent and prosperous adult life. Observing big and small engineering works raises interest, e.g., seeing the awesome scale of a 1,000 MW power generator or watching a pipefitter annealing copper tubing by heating it to a glow and rapidly quenching in cold water. Hard copper magically becoming malleably soft. Today's best analog are the robotics-mechatronics programs, which provide a limited bandwidth that ought to be much broader. With appropriate planning and supervision, middle and high school age students holding interest in engineering need to experience more than science projects, and see real things being made.

Although the most significant awareness of the importance of a balanced combination of science-based and practice-based methodology to engineering education is coming from industry, it is notable that universities outside of the U.S. are advocating for a rebalancing. In the paper *The Suitability of Problem-based Learning for Engineering Education* [11], the authors discuss the merit of problem-based learning (PBL), giving credit to a cross over from their medical school which adopted this approach from its origination at the medical school of McMaster University in Canada. Their focus was on biomedical and mechanical engineering, specifically using "Design Centred Learning" (DCL) and case studies where DCL forms a bridge between theory and practice. An additional advocacy can be found in the paper *Mind the Gaps: Engineering Education and Practice*, [12]. Speaking to the "misalignment between engineering education and practice" the author makes clear that a "Technical problem-solving model cannot explain practice" and that engineers can only change the world ". . . if they also *deliver* the artefacts represented by their problem solutions and designs."

Engineering education urgently needs to revisit how Science, Engineering and Technology are ordered and especially how practicing engineers are essential to R&D programs. Practitioners are empowered with an acute awareness of what is commercially practical as to materials, manufacturing processes, and how to employ what is available to be able to create what was unavailable, compounded and driven by an awareness of what the marketplace wants and needs. Resurrecting development will reverse the decline of our industrial base. Restoring a robust industrial ecosystem will also draw inspired young people having a predisposition for applied science into engineering by letting them witness material science and fabrication early on. Albert Einstein is reported to have opined on the criticality of imagination and inspiration. The paradigm of recruiting students into engineering who are proficient in science and math needs a modification to add in a natural curiosity and drive for technology.

Some specific recommendations proffered for the betterment of engineering education:

1. Rebalance engineering curricula to restore technology into the programs.

2. Correctly define the roles and differences between engineering-scientist vs. engineer vs. engineering designer, and align them in collaboration to advance theory and conceptual design into accomplishing demonstration.

3. Revise faculty reward criteria from 'publish or perish' research papers into 'demonstrate or perish', i.e., advancing concepts into development and demonstration of engineered products.

4. Retitle 'Research Universities' as 'Research and Development Universities', and require R&D faculty to conduct teaching as relates to the process of development and demonstration, especially through interpreting and analyzing experimental discoveries during the conduct of the R&D work.

5. Restore the presence of engineering practice-experienced engineers into academia, and recognize the most accomplished ones as "Professors of the Practice of Engineering".

Only when practicing engineers are brought back into our engineering schools, as participants in research and development – will R&d rightfully be R&D, and our nation return to leadership as an industrial society in support of our economic and national security.

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Figures:

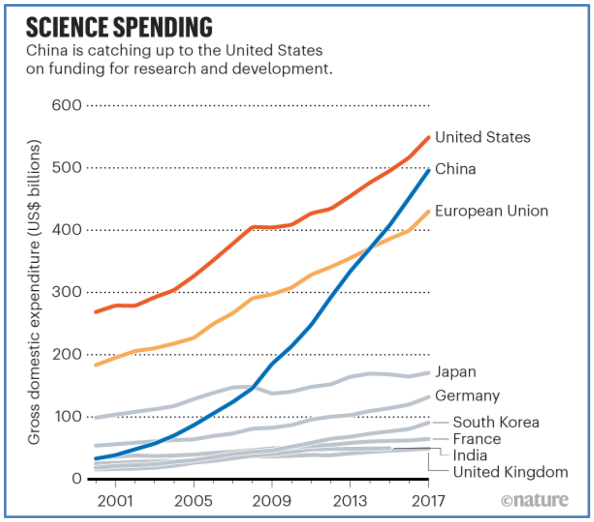

Figure 1
R&D Spending by Country
Source: nature

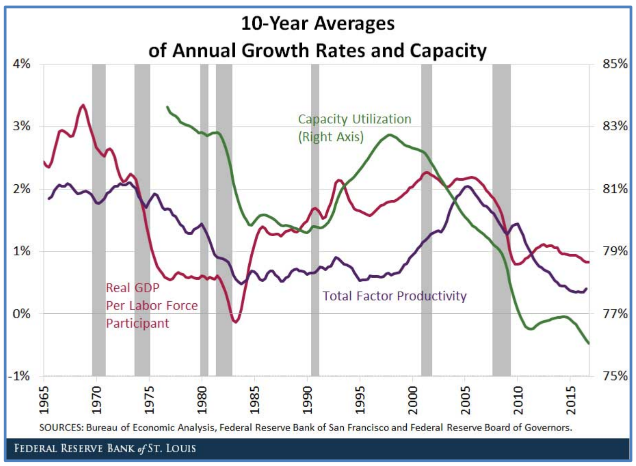

Figure 2
U.S. Growth Rates
GDP Per Labor Force,
Capacity Utilization, and
Total Factor Productivity
Source: U.S. Federal Reserve

Figure 3
Shipbuilding by Country
Source: VesselsValue

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