The Crucial Need to Modernize Engineering Education

Lyle N. Long  
The Pennsylvania State Univ.  
University Park, PA 16802  
814-865-1172  
lnl@psu.edu

Troy D. Kelley  
U.S. Army Research Laboratory  
Aberdeen, MD 21005  
410-278-5869  
troy.d.kelley6.civ@mail.mil

Stephen Blanchette Jr.  
The Aerospace Corporation  
Chantilly, VA 20151  
571-307-3842  
stephen.blanchette@aero.org

Michael Hohnka  
Applied Research Laboratory  
University Park, PA 16802  
814-867-4145  
mjh147@arl.psu.edu

Abstract—This paper discusses the crucial need to modernize engineering education, and especially curricula. Engineering curricula have hardly changed over the last 30 years, while the world has been changing at an exponential rate. Students are being taught primarily applied physics, which is very mature, when they should also be learning about computing, software, systems, artificial intelligence, statistics, and big data. A review of job employment sites, federal reports, and industry needs supports these claims. Russia and China are modernizing rapidly, and educating millions of students in modern disciplines. The U.S. will be left behind if we do not change.

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1. Introduction
Modern university education in the US, across all engineering disciplines, looks very much like the educational programs of the last century. And most existing engineering programs are still based upon 20th century needs, processes, and assumptions, and still focus on applied physics as the foundation of learning. Meanwhile, many systems being engineered today are cyber-physical systems, controlled and monitored by sophisticated algorithms and software and often networked together. Most existing computer science and engineering departments at major universities do not offer the skill set needed for jobs in the 21st century. Engineering education needs to adapt much more rapidly to keep pace with the cybersystems jobs of the future by including topics such as programming, autonomy, artificial intelligence (AI), statistics, computation, automation, systems, and software.

Computer power has been growing exponentially according to Amdahl's law, information has been doubling every year, networking speeds are over 100 Gb/second, AI is proving more and more capable [1, 2], and entire job categories within the engineering field are being eliminated. Yet curricula at universities have hardly changed over the last 30 (or more) years [3-5]. And, in general, humans are having difficulty adapting to exponential changes [6].

A March 2017 survey by the Rockefeller Foundation [7] noted that half of recent college graduates are not using skills they learned in college at work, and 86 percent are learning new skills outside of college.

The bureaucracy and vested interests of faculty, administrators, funding agencies, etc. work against modernizing the curricula. The students assume they are being trained for modern jobs, but the education they receive is often outdated. This means they are not only poorly prepared for the modern workforce, but also poorly trained to enter graduate school.

Universities are highly stove-piped as well, while most modern problems are interdisciplinary. The miniaturization of computers and the prevalence of computing systems has grown at incredible rates from stage three of the industrial revolution [8]. As a result, almost every modern device or system in the present (fourth) stage of the industrial revolution is a cyber-physical system, which are engineered systems that are built from, and depend upon, the seamless integration of computation and physical components. (see Figure 1).

How can university curricula remain unchanged while technology has been changing at an exponential rate? Most industrial careers last about 10 years now before the person...
must retool and learn new skills, but college professors teach for 30-40 years.

Engineering education is much different than science education. In areas such as physics, chemistry, or mathematics, the students learn the wide array of material in those fields. Engineering education is different, in that it is about designing and building things, and it must be up-to-date with the latest techniques, technologies, and trends. Topics should not be included in the curricula for historical purposes. Four years is a very short time, and the material presented should be carefully chosen and relevant to the 21st century.

The problem is not limited to undergraduate engineering programs, either. There are Ph.D. programs that have not changed in 30 or more years, too. A recent Ph.D. qualifying exam in mechanical engineering listed these topics:

- Fundamentals of Engineering Analysis
- Fluid Mechanics
- Heat Transfer
- Rigid Body Mechanics
- Solid Mechanics
- System Dynamics
- Thermodynamics

A recent Ph.D. exam in aerospace engineering listed these topics:

- Fluids
- Structures
- Dynamics and Control
- Mathematics

Neither of these exams mention computing or software, and are essentially unchanged from 30 years ago (or more). Students are expected to learn cyber skills on their own, even though they are more difficult to learn (and more important) than the mature applied physics material.

It is very difficult to respond to exponential technology changes at universities when the faculty have tenure. These institutions cannot be run like traditional businesses. It is a zero-sum game. If new programs are added to address modern needs, they often take students from the other disciplines. This is especially true for brick and mortar institutions, but online programs do not have the same restrictions. While most universities have all the students they can accept on campus, the online programs are free to expand and grow.

“Much of what children learn in schools today was designed for the era of paper-and-pencil,” said Massachusetts Institute of Technology professor Mitchel Resnick [9], who argues that most education reforms fall short because they

Figure 1. The Four Stages of the Industrial Revolution [8]
fail to overhaul existing curricula and teaching strategies.

In this paper, we will discuss the need and the difficulty in keeping engineering education relevant as technology changes exponentially fast.

2. The Problem

Susskind and Susskind [10, 11] reference a study that estimates 50% of US jobs could be automated within 20 years, while the World Bank [12] estimates that around 57 percent of jobs could be automated within the next 20 years. Jobs that are especially susceptible to automation are those that involve big data or can be automated using machine learning or robotics. Even professional jobs such as doctors, lawyers, teachers, etc. will be dramatically changed. Jobs that will be more difficult to automate involve skills such as: complex communications, social intelligence, creativity, and perception and manipulation.

Arum and Roksa [13] state that “the U.S. higher-education system has in recent years arguably been living off its reputation.” Further:

- Software pervades virtually every newly engineered system today
- In many domains, complex capability supersedes individual system function
- Most systems must interact/interface/interoperate with other systems to be useful
- The Internet of Things (IoT) is enabling complex capability (and introducing new challenges, e.g., cyber vulnerabilities)
- Autonomy is the currency for reducing the complexity burden on human users (but it increases the complexity of the systems themselves)
- Cyberspace is now one of the most important military areas

U.S. Universities are graduating engineering and computer science students that employers are utilizing in the job market, but we suspect they require significant on-the-job training. A significant number of U.S. Universities will need to realign their curricula to accommodate changing technology. The consequences of not acting may be dire for the U.S.

The problem is acutely visible in the aeronautical and aerospace engineering domains. Trends over the last 50 years clearly demonstrate the dramatic growth of software especially—in terms of size, functionality, and cost—across space, commercial, and military platforms [5]. Yet, aeronautical/aerospace engineering programs typically provide, at most, a required introductory course in software, with the possibility of a later, elective course that may offer more in-depth learning [4]. Most of the students cannot program, and do not understand software engineering [3]. Conversely, anecdotal evidence from interns and students returning from internships indicates that computer science and software engineering students have little background in aeronautical or aerospace systems. Clearly, the stove-piped approach to engineering education is not serving students or their future employers well.

The focus of this paper is targeted towards US universities and their need to change their curricula to meet future employment demands. The driving force behind the change in academic curricula is the rapid rate and infusion of advanced technology across business, government, and social circles. This rapid technological growth reveals two apparently paradoxical problems for those who want to engage effectively in the future job market. First, there is a need to consume, analyze and sift through large amounts of information and knowledge. Second, because new knowledge is replacing current knowledge, there is a need to determine how long knowledge remains useful. This is termed the half-life of knowledge. Graduates who desire to engage effectively in the future job market need to be trained and equipped for these changes. If they are not trained, then there will exist a mismatch in employment demands and graduate capabilities which will subsequently lead to job-related ineffectiveness and costly inefficiencies.

Universities often state that they teach students “how to learn,” but that isn’t good enough in a highly technical field. While a “learning to learn” pedagogy might be appropriate for high school students, or freshman college students, the teaching technique falls short at the graduate level, where science has become increasingly specialized, requiring more and more specific skills to develop expertise in a narrow scientific domain. To teach students material from the previous century and then expect them to learn what is needed in the 21st century is ineffective, misleading, and inefficient. In an age when technology is changing at an exponential rate, there is no time to retrain students after they graduate. In addition, people under estimate the time required to become experts in software, systems, and computing. If students leave universities unprepared for the 21st century, they may never catch up due to the rapidly changing world.

Table 1. School Rankings

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<tr>
<th>Source</th>
<th>No. of Schools Ranked in Top 10</th>
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<tr>
<td>QS World Univ. Rankings</td>
<td>5</td>
</tr>
<tr>
<td>Times Higher Educ. Rankings</td>
<td>6</td>
</tr>
<tr>
<td>U.S. News and World Report</td>
<td>8</td>
</tr>
<tr>
<td>Engineering (U.S. News)</td>
<td>2</td>
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<tr>
<td>Computer Science (U.S. News)</td>
<td>5</td>
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Current U.S. higher education is generally ranked as very good, but it is rapidly becoming out-of-date. Interestingly, the methods used for ranking schools appear to be based on publications and do not address how well the students are prepared for the 21st century. As shown in Table 1, China is rapidly catching up, especially in engineering and computer science. In the U.S. News and World Report rankings of global engineering universities [14], Tsinghua University is ranked number one; and six of the top 10 are in Asia. In Computer Science, Tsinghua is also number one, and two other Chinese universities are in the top ten, ranking above Carnegie-Mellon, Princeton, Georgia Tech, Cambridge, Oxford, Illinois, Michigan, and Caltech.

Figure 2 shows a job distribution from indeed.com compared to the distribution of engineering students at The Pennsylvania State University. Of the job openings shown, roughly 75% are in software, computers, or systems; while only about 9% of the students are studying in those areas. In fact, there are no software engineering, systems engineering, robotics, or artificial intelligence programs at many universities, so students often cannot choose those options even if they wanted. As the need for engineers in intelligent automation and autonomy grows, engineers trained in older traditional disciplines will be needed less and less. Engineering programs must move beyond 20th century applied physics curricula. Applied physics is very mature compared to modern computing and software. At indeed.com, there were 500,000 jobs that mention software, twice as many as all engineering disciplines combined.

While the previous figure shows job and enrollment figures per discipline, Figure 3 shows current job openings from the three largest online job search sites (indeed.com, monster.com, and jobs.com) according to keyword. Aerospace engineers (as an example) are being trained in areas that are not highly sought after. Aerospace curricula have hardly changed in 50 years [4]. Students learn about structures, fluids, propulsion, and control (i.e. applied physics). This material is all very mature, and should be cut-back dramatically to make room for software, systems, programming, etc.

A recent study stated that 50% of U.S. jobs could be automated within 20 years [10, 11]. Brynjolfsson and McAfee [15] state that: “In the next twenty-four months, the planet will add more computer power than it did in all previous history. Over the next twenty-four years, the increase will likely be over a thousand-fold.” The White House (in 2016) [16] emphasized the need for Americans to be educated and trained for the jobs of the future (software and autonomy-related).

A National Academy of Sciences report [25] states:

“Recommendation 2.3: To prepare their graduates for this new data driven era, academic institutions should encourage the development of a basic understanding of data science in all undergraduates.”

The World Economic Forum (WEF) recently released important insights related to how jobs will change in the near future. It is titled, The Future of Jobs Report 2018 [17]. In this report, the WEF describes the impacts that the fourth industrial revolution will have on companies and employees as they reach higher levels of efficiency of production, expand into new markets, and compete with new products. The WEF report presents the following key findings:

- Four specific technological advances will affect the global economy from 2018-2022: high speed mobile internet, artificial intelligence, widespread
adoption of big data analytics and cloud technology.

- Accelerated technology adoption – internet of things, machine learning and augmented/virtual reality, etc.
- Trends in autonomous systems – a broader range of robotic technologies including aerial drones, machine learning algorithms and artificial intelligence, etc.
- Changing employment types – increased automation will lead to some reductions in the full-time workforce as well as to some new productivity-enhancing roles.
- A new human-machine frontier within existing tasks, the shift in tasks from human to machine will accelerate including those tasks that have been considered overwhelmingly human such as communicating and interacting, coordinating, developing, managing, advising, reasoning and decision-making.
- Growing skills instability – a change in the division of labor between workers and machines transforming current job profiles will of necessity require the skills of most jobs to shift considerably.
- A reskilling imperative – by 2022, no less than 54% of all employees will require significant reskilling. Sharply increasing importance of skills such as technology design and programming. Proficiency in new technologies will grow. Human skills such as creativity, originality and critical thinking will increase their value.
- Current strategies for addressing skills gap – 1. Hire wholly new permanent staff already possessing skills relevant to new technologies, 2. Seek to completely automate the work tasks, 3. Retrain existing employees.
- Insufficient reskilling – companies state they intend to target high-performing employees for primary key roles that will be using relevant new technologies while simultaneously prioritizing at-risk employees in roles expected to be most affected by technological disruption (in other words, those most in need of reskilling are least likely to receive such training).

Most of the focus of the WEF report was on developing appropriate workforce strategies for the coming technological changes.

Another report [18], from the National Academy of Sciences, states:

“Competence in using computers to solve problems is essential for everyone in an increasingly digital world and is increasingly recognized as a key proficiency for undergraduate success (e.g., Vaz, 2004). As early as 1999, an expert committee proposed that all college graduates should develop information technology (IT) fluency (National Research Council, 1999). That committee proposed, in contrast to more basic computer literacy, IT fluency requires three kinds of knowledge: contemporary skills (to use current technology); foundational concepts (basic principles of computing, networks, and information systems); and intellectual abilities (to apply IT to complex situations and apply higher-level thinking). Although proposed as goals for college graduates, these levels of proficiency are likely important foundations for success throughout undergraduate STEM coursework, which increasingly requires students to use technology to gather and analyze data and solve problems. More recently, researchers have explored how to tap the digital fluency that some students possess to improve the quality of writing in first-year disciplinary courses for non-majors. Most Americans ages 16 to 24 have limited ability to use computers to solve complex problems relative to their peers in other nations. To address this challenge, researchers and faculty practitioners are developing and testing instructional approaches to develop IT fluency and computational thinking. Foundational courses based on the findings from this research will be essential for undergraduate success in STEM.”

The complex problems they refer to in the above relates to problems in digital fluency, computational thinking, mathematics, information technology, and networks.

Meanwhile, industry must continually innovate. They desperately need software engineers, system engineers, and computer scientists. In the aeronautical/aerospace domain, for example, focus is rapidly shifting toward new ways of working. Model-based systems engineering is becoming a standard way of doing business. The U.S. Department of Defense (DoD) is pushing even harder on model-based approaches, embracing the concept of digital engineering. According to the Office of the Deputy Assistant Secretary of Defense for Systems Engineering, Digital Engineering is “an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal.” Further emphasizing the point, Michael Griffin, Under Secretary of Defense for Research and Engineering for DoD, seeks to modernize defense systems [19, 20] by

“...incorporating the use of digital computing, analytical capabilities, and new technologies to conduct engineering in more integrated virtual environments to increase customer and vendor engagement, improve threat response timelines, foster infusion of technology, reduce cost of documentation, and impact sustainment affordability. These comprehensive engineering environments will allow DoD and its industry partners to evolve designs at the
conceptual phase, reducing the need for expensive mock-ups, premature design lock, and physical testing.”

Many U.S. universities don’t even offer software or systems engineering as a program of study. A survey in 2011 showed that 92% of select job openings at Lockheed-Martin were in software engineering, systems engineering, and information technology, and there are very few students coming out of colleges with these degrees. In the U.S. in 2015, however, there were 3800 students who graduated in aerospace engineering. They usually get jobs but often they are in systems or software.

It is illustrative to look at what other countries are doing from an education standpoint. In 2017, China graduated 8 million students, which is 10 times higher than in 1997. The U.S. only graduated 1.9 million [23]. In addition, China is emphasizing Science, Technology, Engineering, and Mathematics (STEM). In 2016, China had 4.7 million STEM graduates, while the U.S. had only 568,000 [23]. In 2015, the top five highest paying jobs in China were related to IT. The U.S. universities still lead in chemistry, physics, and biology; but the importance of these disciplines is now dwarfed by cyber disciplines, and even advances in these fields will be tied to cyber systems. Of course, the government tightly controls education in China, and they can change relatively quickly.

Guarino, Rauhala, and Wan [24] state that:

“The United States spends half a trillion dollars a year on scientific research — more than any other nation on Earth — but China has pulled into second place, with the European Union third and Japan a distant fourth. China is on track to surpass the United States by the end of this year, according to the National Science Board.”

U.S. universities are not producing the numbers and types of graduates that the digital age requires. Part of the reason is that faculty teach what they know, and the value of what they know often decreases with time. Humans cannot keep up with the exponential growth of computer power [6]. The European model, on which the U.S. university systems are based, have hardly changed in 500 years. It is time to re-evaluate the curricula and approaches to engineering education.

With growing competition from abroad, this constitutes a serious problem for the U.S. We will need enormous teams of experts trained in software, systems, computing, etc. to compete in a world of automation and autonomy. We’ve already seen multi-year delays and cost over-runs in aerospace projects, as well as catastrophic loss of life and equipment, mission failure, and increased cyber vulnerabilities; many of these instances have been traced to software problems [5].

These are serious issues. Academia, industry, and government need to work together to modernize higher education, or it will grow less and less relevant, as will the U.S. Universities need to update and align curricula in all engineering disciplines by offering modern courses for the digital age. Industry needs to take a proactive approach to education. The government needs to increase funding for curriculum change. And academic leaders (Presidents, Provosts, and Deans) need to encourage curriculum modernization.

Some topics that need more extensive coverage in engineering curricula include:

- Systems engineering
- Artificial Intelligence
  - General Intelligence Systems
  - Adaptive Systems
  - Hybrid Systems
- Computational science and engineering
- Cybersecurity
  - Enterprise-level cybersecurity
  - Embedded cybersecurity
  - Code Analysis
  - Penetration Testing
  - Forensics
  - Systems-level cybersecurity
- Cyberphysical systems and robotics
- Data Science
- Computing platforms
  - Basic processor architectures and information
  - Workstation processors
  - Embedded processors and IoT devices
  - Cloud-based processing
- Software Engineering
- Operating systems
  - Real-time operating systems
  - Compilers
  - Operating system hardening
- Programming
  - Assembly Language and Machine Code
  - C/C++
  - Java
  - Python
  - MATLAB
- Software Assurance
- Software Robustness

Large research universities have been especially slow to change their stove-pipe structures, with their focus on research. There is a need for additional new majors, and fewer traditional graduates. Smaller colleges and universities have been more pro-active and often offer more up-to-date curricula. For example, the United States Naval Academy has an aggressive program to build a Cyber Science department, and all the students at the academy
must now take cyber science courses. Another school (Florida Gulf Coast University) eliminated their computer science department and replaced it with a software engineering department.

It is important to point out that curricula must evolve continuously and rapidly. The list of important areas will be different in 10 years. While we can point out some important current topics, these will change with time. Students need to be prepared for current needs and also be ready for a rapidly changing world. And universities must continually evolve to meet those needs.

3. ALIGNING CURRICULA WITH CURRENT AND FUTURE NEEDS

There are several steps to addressing modernized curricula. We assert these steps as essential to maintaining US preeminence in university level technical education in the 21st century.

1) All college students could benefit from a Minor in cyber science, computing, or software. Universities must figure out how to manage this enormous demand. The first author here has successfully created both an undergraduate minor in Information Science and Technology for Aerospace Engineers (www.personal.psu.edu/lnl/ist) and a graduate Minor in Computational Science (www.csci.psu.edu).

2) US engineering curricula must become interdisciplinary

   a. Students must be trained to think and to work in cross-discipline teams to solve problems, just as is done in industry.
   b. Individual disciplines must embrace students from other programs of study in their classes. For example, there is a strong overlap in AI problems with existing Cognitive Psychology research, however cross disciplined pedagogy is rarely ever pursued at the university level.
   c. Faculty must learn to be interdisciplinary as well, and incentivized to do so through existing and new merit and rating structures.
   d. PhD dissertations should be innovative, cutting edge, outside the box research instead of minor modifications or tweaks of the PhD advisor’s existing research.

3) Individual disciplines must embrace additional courses and eliminate old or less important material:

   a. Foundational courses in computing and systems engineering must be added as requisites to existing curricula, and earlier in the system (Associate and Bachelor level). Advanced courses should be encouraged as electives.
   b. Digital concepts must pervade all engineering programs to ensure students have the background and understanding necessary to work in engineering positions without remedial on-the-job training in modern systems, processes, and tools.
   c. All engineering students should be able to program well, in multiple languages (e.g. MATLAB, Python, C/C++, and Java). There should be programming courses every year of a Bachelors degree program.

4) Industry should be pro-active in modernizing education. They should partner with universities to transform internships into apprenticeships in order to stay relevant and competitive. If engineering education is not updated, employers will continue to bear the burden of providing more on-the-job training in automation-related disciplines and they will have trouble competing globally.

5) Faculty need to embrace change, retool, and teach 21st century material.

6) In addition to incorporating cyber topics into existing curriculum, entirely new majors, minors, and certificates should be considered.

7) Students in all disciplines should be exposed to various methodologies for staying up to date with technological advances such that they develop this as a habit.

4. CONCLUSIONS

The U.S. needs to modernize engineering education to meet current and future technology demands. And this will not be just a one-time fix. Technology will continue to change exponentially and education must evolve rapidly and continuously. This will require dramatic changes in the educational systems, approaches, and institutions. U.S. engineering education has changed little and is still focused on applied physics, and not cyber. Other countries, including Russia and China, are not sitting idly by, and are preparing for the future of automation and computing. If the U.S. does not respond to the needs of the 21st century, it could easily fall behind other countries.
REFERENCES


18. Indicators for Monitoring Undergraduate STEM Education


Lyle N. Long is a Professor of Aerospace Engineering, Computational Science, Neuroscience, and Mathematics at The Pennsylvania State University. He has a D.Sc. from George Washington University, an M.S. from Stanford University, and a B.M.E. from the University of Minnesota. In 2007-2008 he was a Moore Distinguished Scholar at the Caltech. And has been a visiting scientist at the Army Research Lab, Thinking Machines Corp., and NASA Langley Research Center; and was a Senior Research Scientist at Lockheed California Company. He received the Penn State Outstanding Research Award, the 1993 IEEE Computer Society Gordon Bell Prize for achieving highest performance on a parallel computer, a Lockheed award for excellence in research and development, and the 2017 AIAA Software Engineering award and medal. He is a Fellow of the American Physical Society (APS), and the American Institute of Aeronautics and Astronautics (AIAA). He has written more than 260 journal and conference papers.

Stephen Blanchette Jr. is the Director of Software Systems and Acquisition at The Aerospace Corporation in Chantilly VA. He oversees a team of aerospace professionals providing software engineering and acquisition management support as well as objective technical analyses and assessments to organizations across the space enterprise. Mr. Blanchette has over 30 years of experience in the defense industry with positions in software management and development for various systems including the Apache helicopter and the Bradley family of vehicles. He holds a Master of Arts in Diplomacy from Norwich University and a Bachelor of Science in Computer Science from Embry-Riddle Aeronautical University. Mr. Blanchette is an associate fellow of the AIAA, a senior member of the IEEE, and a longtime member of the ACM, AFCEA, AUSA, and NDIA.

Troy D. Kelley is the leader of the Cognitive Robotics Team and is an Engineering Psychologist at U.S. Army Research Laboratory Aberdeen Proving Ground, MD where he has worked for 25 years. Mr. Kelley received his Master’s degree from Radford University in Industrial Organizational Psychology in 1988 and another Master’s Degree from George Mason University in Applied Human Factors and Cognitive Psychology in 1999. His primary research interests include visual cognition, object recognition, cognitive robotics and computational models of cognition. He has developed the Symbolic and Sub-symbolic Robotics Intelligence Control System (SS-RICS) which is a cognitively inspired robotics control architecture. He has authored or co-authored over forty technical publications, proceedings, and journal articles.

Michael Hohnka, BSEE, is a subject matter expert with 33 years of experience in software and embedded systems. Mr. Hohnka currently serves at the head of the Access & Effects Department within the Cyber Data and Image Sciences Division at Penn State’s Applied Research Lab. In this capacity, he provides leadership of all Access and Effects related programs and has formulated fresh concepts relating to comprehensive penetration testing via the OSI model, performed reverse engineering of complex embedded systems, and conducted research into compiler induced vulnerabilities. These concepts have been proven through several research projects for the U.S. Navy.