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Electrical and Computer Engineering: Past, Present, and Future

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The field of electrical and computer engineering (ECE) has had an enormously successful history. This field has pushed the frontiers of fundamental research, led to the emergence of entirely new disciplines, and revolutionized our daily lives. ECE departments[2] are found in nearly every engineering school and have historically been one of the larger departments both in terms of faculty and student enrollments. Academically, a strong ECE department is highly correlated with the reputation of an engineering school. Of the top 10 engineering schools in the latest *US News and World Report* rankings of graduate programs, nine have top 10 ranked ECE programs.

Nevertheless, ECE is a field that finds itself facing challenges. In this paper, we will look to the field's past issues and note how the field repeatedly reinvented itself to push to new heights. Finally, we argue that the time is ripe for another reinvention and show how aspects of such a reinvention are already emerging. Areas such as machine learning and data science, the Internet of things, and quantum information systems provide promising directions for ECE — and embracing them provides a path to a bright future.

The Present Situation

In many ways, ECE is a victim of its own successes. Advances such as computer-aided design tools reduce the number of designers needed. The increased integration reflected in Moore's law means that more functionality can be integrated into a single integrated circuit (IC), replacing the need for engineering to integrate multiple components in custom designs. After many years of research and development, some technologies have become "good enough" and commoditized, giving industry and funding agencies fewer incentives to invest. In some industries, success and economies of scale have led to global consolidation, and in some cases, moving manufacturing overseas — both of which reduce job opportunities for students seeking employment in the US. For many years, industrial research and development in ECE flourished in research centers such as Bell Labs, Motorola Labs, and IBM. But these same trends have led to dramatic changes in that landscape as well.

The successes of ECE have led to the discipline becoming less visible. For example, the evolution of the modern smartphone includes many significant advances, thanks to ECE. This includes technologies used for communication, geo-location, imaging, computing, and storage; however, many people take these devices for granted with little thought given to the technology that makes them possible. Modern design and integration reinforce this, making many details of this technology invisible to end users. Long gone are the days when a hobbyist could take apart a device and understand how it works. While this is a triumph of technology and design, it raises

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[2] Depending on the school, ECE may be a separate department or one or more units in a large EECS department, or even spread over multiple departments. Here, for simplicity we refer to these all as "ECE departments."

challenges for attracting undergraduates who may have little idea as to what an electrical or computer engineer does.

Another issue for ECE is simply the breadth of this field. Over time, ECE has expanded into a dizzying array of subfields. For instance, the IEEE, the main professional body for ECE, has 39 distinct societies. The discipline is continuing to expand, now encompassing topics such as the application of information theory to bioinformatics problems, to exploring brain-computer interfaces, to quantum networking. Students and faculty specializing in one of these subfields often have little in common with those working in another. This makes it hard to find a common culture within a department, or to provide a clear picture of the discipline to prospective students.

One of the unifying themes in ECE undergraduate curriculum at most universities has been electronics and circuit analysis. Electronics are a key enabler of many of the key technologies of interest today, such as autonomous vehicles, machine learning, cyber security, or the emerging Internet of Things (IoT). However, as technologies have developed, many of the interesting (and visible) problems are occurring at many layers of abstraction above that at which electronics operate. Work on these problems often requires minimal understanding of the underlying hardware and stronger background in higher layer issues implemented in software. Often, there is a strong multi-disciplinary component. As such, other disciplines often have as much claim to these as ECE. This can create the impression (albeit not one I subscribe to) among prospective students that ECE is about the "low-level" details, while the "bigger" questions are taken up in other majors.

The Past as a Springboard for the Future:

ECE as a discipline has had an enormously successful history. We look at two examples.

First, we consider the list of the 20 greatest engineering achievements of the 20th century initiated by the National Academy of Engineering (NAE) [1]. Of those, eight are in primary ECE fields: electrification (1), electronics (5), radio and television (6), computers (8), telephone (9), Internet (13), imaging (14), and lasers and fiber optics (18). Many of the other achievements selected also have strong ECE components to them such as spacecrafts (12), health technologies (16), and household appliances (15).

A second example is the NAE's Charles Stark Draper Prize, one of the preeminent awards for engineering achievement, given annually to "honor an engineer whose accomplishment has significantly impacted society." The first award in 1989 went to Jack Kilby and Robert Noyce for their independent development of the monolithic integrated circuit, a milestone for ECE. In the last 10 years alone, nearly every winner has been for work related to ECE. This includes the development of the Viterbi Algorithm (Viterbi, 2016), the invention and commercialization of LEDs (Akasaki, Craford, Dupuis, Holonyak, and Nakamura, 2015), development of the first cellular telephone (Cooper, Engel, Frenkiel, Huag, and Okumura, 2013), the invention of DRAM (Dennard 2009), and the development of the Kalman filter (Kalman, 2008).

As a field, ECE has continually reinvented itself. For example, ECE departments[3] at the start of the 20th century often focused on the generation and transmission of electric power (the first achievement in the NAE list). The rise of commercial broadcasting (achievement 6), telephony (achievement 9), and vacuum tube-based electronics (achievement 5) led to communications

[3] At this point these were simply EE departments as computing had not yet entered the picture.

and electronics becoming a new part of ECE [3]. Eventually, the areas focused on using electromagnetic waves to transmit and process information rather than deliver power became the main focus of the major. By the end of the century, at many schools, including Northwestern's McCormick School of Engineering, electric power courses were no longer taught. This was not because electric power became less important to society, but rather that those problems were viewed as "solved" (echoing some of the concerns raised today about other areas). Notably, in recent years, interest in electric power has re-emerged with a focus on the smart-grid, especially where it involves integrating power grids with communications and information processing made possible by advances in other areas of ECE.

The dramatic successes during World War II in areas such as radar, microwaves, and control systems spurred more changes. After the war, this continued with developments such as the transistor, magnetic recording, early computers (achievement 8), and lasers (achievement 18). As pointed out in [3], many of these advances, though in core ECE areas, were due to mathematicians and physicists, not engineers. This led to EE adding significantly more rigor in physics and math to their curricula to be better positioned to lead future advances. The payoff from this change is evident in the list of Drapper prize winners, many of this new breed of electrical or computer engineer who often worked on problems well ahead of their time. For example, the Viterbi algorithm was considered "hopelessly complex" when it was published in 1965; but now it is implemented on a "fraction of a chip" and widely used for applications beyond the original use. [4]

Additionally, the so-called "digital revolution" has roots in the research emerging from World War II. This led to the rise of digital electronics, integrated circuits, and ultimately, digital computers and the Internet (achievements 5, 8, 13 and the first Draper prize). Again, this also required a radical rethinking of curricula that were largely analog based, and eventually led ECE departments to include topics such as digital logic, digital signal processing, digital communications, digital control, computing and networking. As computing increased in importance, this led eventually to new degrees in computer engineering or computer science. The impacts of this digital revolution are still being felt today.

A Bright Future

Despite these challenges, this is a time of great opportunity for ECE to reinvent itself. The Internet of Things, data science and machine learning, and quantum information systems provide promising avenues for this, and all are areas in which Northwestern has established footholds. The increasing importance of computing and Northwestern's effort at expanding computer science provide another opportunity. Seizing these opportunities will require defining a new vision as to what the discipline is about as well as developing a plan to make this vision a reality. We elaborate on a few of these areas next.

The growing area of IoT involves connecting a wide range of devices in the everyday world to the Internet and is viewed as a way of enabling "intelligence" in a wide variety of domains such as smart-cities, smart homes, or smart manufacturing. Many IoT solutions challenge traditional design paradigms (for example, by focusing on low power over communication bandwidth) and are tightly integrated with application domains. As such, they often require new customized hardware and software solutions driven by specific application needs. This includes embedded devices (an area of recent hiring in computer engineering), wireless communications (an area of strength in electrical engineering), and a variety of application domains such as transportation and manufacturing (also areas of strength at Northwestern). Seizing this opportunity will in part require building strong collaborations across these areas.

ECE has much to offer in the areas of data science and machine learning. Recent advances tie to core ECE disciplines, such as signal processing and information theory. ECE researchers are also contributing to improvements of the underlying hardware used by these algorithms. ECE researchers — including some at Northwestern — actively contribute to these areas. Northwestern's broader data science initiatives, as well as pushes in this direction by the industrial engineering and management sciences and computer science departments, provide opportunities to partner and strengthen these efforts.

Many ECE departments have launched initiatives such as concentrations in these areas, something to be considered at Northwestern. Techniques from these areas and the growing access to data sets are also impacting work in other areas of ECE as they become more focused on data-driven research. Fully embracing this trend requires traditional ECE curricula to adapt and integrate more data science techniques. For example, a traditional ECE degree requires a probability course focused more on probability and modeling and less on statistics and dealing with data. Adding data-focused content is needed.

Advances in many ECE application areas have been driven by leveraging the steady rate of improvement in IC capability, known as Moore's law. However, it is increasingly clear that after 50 years, this rate of improvement is reaching an end. This has led to growing interests in exploring paradigms for scaling computing in a "post-Moore's law" world. One such technology is quantum computing and quantum networks, which exploit quantum mechanical properties such as superposition and entanglement. Again, ECE is well positioned to lead such efforts. At Northwestern Engineering, a number of ECE faculty have worked at the forefront of photonics and quantum communication. Work in this area also overlaps strengths in physics, materials science, and chemistry.

In many areas, the increasing role of software and computing is undeniable. This is also true in many traditional areas. For example, in communication systems, new protocols can be tested by writing code for software-defined radios instead of through hardware implementations, and even the communication infrastructure itself is moving away from custom hardware implementations to programable "software defined networks." To stay relevant, ECE majors in these areas need to have a strong background in computing. CE degrees by their nature already do this. EE degrees have some exposure to programming and computer architecture, but these trends suggest that more is needed, at least for students concentrating in subfields that are experiencing these trends. Northwestern's investment in computer science will benefit efforts in doing this.

Given the multidisciplinary nature of many of these problems, ECE needs to continue to build stronger collaborative links with other majors, such as working with industrial engineering and computer science on data science problems, computer science and mechanical engineering on robotics, civil engineering on smart-city problems, physics on approaches to quantum computing and networking, materials science on future materials for electronics, and biomedical engineering and neuroscience on human-brain interfaces.

The examples can already be found at Northwestern and other universities of ECE faculty reinventing themselves to move in new directions. Indeed, many top researchers re-invent themselves several times during their careers. Fully seizing these opportunities will require more faculty to do this. Organizing faculty workshops and workgroups on new opportunities, providing "seed funding," and bringing in visitors who have moved in these directions encourages this.

Building on strong collaborations outside of Northwestern is also important. There are opportunities to collaborate and share ideas with groups at peer institutions or within academic societies that are struggling with similar issues. Northwestern is well positioned to better leverage collaboration with labs such as Argonne National Laboratory or Fermilab. Both are “in our backyard” and both have efforts related to the areas discussed above. Also, we can leverage opportunities abroad by working with Global McCormick, building on strong international collaborations already present within the department.

The challenges facing ECE departments at the undergraduate level deserve a special mention. These manifest themselves in lower than desired undergraduate enrollments at many universities including Northwestern.[4] Here, change is slower. Researchers can be much more nimble than undergrad programs (and public perception of a field). This is not simply a problem of being slow to integrate new research areas into undergrad curricula–many cutting-edge areas are simply not mature enough for undergraduates to have job opportunities working in these areas without pursuing a graduate degree. However, areas such as data science and the Internet of Things are mature enough to warrant increased emphasis in an undergrad program; others like quantum networking are more forward looking. Clearly, there is a benefit of exposing undergrads inclined to pursue graduate studies to such areas, but that group of students is not representative of the study body at Northwestern (or at most other schools).

Additionally, the growing “maker movement,” which encourages people of all ages to “tinker” and build projects from scratch, is an opportunity to increase undergrad enrollment. Already, this movement has reached high schools and even grade schools, making ECE more visible to prospective students. Re-thinking introductory courses to better leverage this movement is a promising opportunity.

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[4] Enrollment trends depend in part on how admission is done. In some universities, students are admitted directly into departments and switching majors is more difficult, so enrollments are more controlled (none of these options would be desirable at Northwestern). In these cases, some of the challenges we discuss may manifest themselves instead as lower selectivity or lower student quality. Enrollment trends also appear to depend on Computer Science (CS) enrollment policies; in schools where CS limits enrollment or is in a different college, ECE may benefit as an option to students that cannot get into CS or want to pursue a CS-related degree within the engineering school.

Works Cited

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