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Education in Electrification for Societal Sustainability: History and philosophy

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Education in Electrification for Societal Sustainability – History and Philosophy

Marcelo Godoy Simões, Paulo F. Ribeiro

1. Introduction

We all depend on electricity, and as such, we define a mapping of Electrification onto Education because we all need a provision of life sustained by infrastructure that is powered by electricity. Electrification began at the end of the 19th century, becoming global, but is not yet complete. It is evolving, and in the last few decades, electrical power systems have undergone a re-enchantment, a paradigm-shift associated with renewable energy sources, energy storage systems, power electronics, and modernization of communication and automation of infrastructures. This paper starts with several concepts and boundaries that have transformed electrical energy from a somewhat simple technology to the recent acceleration of the development process. We also look at how current and future pedagogical perspectives for the 21st-century Electrical Engineer – will help us to become a sustainable society.

History, Philosophy, Reflections, and a Vision is the approach taken by the authors in connecting Education for Electrification, inasmuch as considering undergraduate programs focusing on renewable energy, environmental science, and advanced communications, with capabilities to advance and sustain developments for energy conversion and power transfer. In addition, further graduate studies will provide in-depth knowledge and research opportunities in areas like energy management, electrical engineering modeling, and integration of renewable energy and storage. This paper also touches on the history and philosophy of technology, data analytics, IoT, AI, systems engineering, engineering systems, practicum experiences, and the capacity of students to work on regulatory and policy landscape to significantly impact electrification projects.

Looking at the development of the electrotechnology field and how it evolved in the past 100+ years, regarding electromagnetism and circuits, from Faraday and Heaviside time, the invention of transformers and electrical generators performed by Tesla and others, the AC electrical power distribution became a reality, and the birth of electronics with vacuum tubes, then solid-state transistors made possible further many other great inventions and discoveries during the 20th century.

From the 1950's to now, our world has become totally immersed in electronics and information, software implemented on silicon-based microprocessors and microcontrollers, and industries automatized with mechatronics-based solutions.Any segment of our economy was transformed by advanced machinery, computers, data communications, and the Internet. The first two decades of the 21st century ushered in distributed computing, cloud-based services, ultrafast real-time execution of control with digital twins, the incorporation of highly sophisticated mathematical models, and the maturity of artificial intelligence.

A pillar motivating the engagement of universities and industries is building a workforce that can meet the future demand in the electrification sector, focused on the required scientific, engineering, and technological changes. It is necessary to train many more electrical engineers and electrification-literate educators in an all-encompassing way. When scientific and academic education is replaced by only technicians' urgent needs of the industry, the process in educating professionals becomes distorted and vulnerable because it compromises the creative development process necessary for sustainable development. The authors advocate for all of us to see the signals and data holistically, and not be concerned just with the number of graduates. Adjustments might be necessary to adequately encourage new generations of engineers who see the profession as a calling, and who are aware of the technical, social, economic, and environmental challenges.

Resources are not everlasting, and electrification has also become a social process of empowering individuals. In the circular economy approach, which keeps materials and products in circulation for as long as possible) industry and society must be effective in renewable generation technologies, in order to supply a complex network, ever-evolving dynamic demand, and life-sustaining infrastructure.

In order to motivate individuals, a philosophical path is making students choose something that aligns with their strengths and passions. Then, a well-rounded education should be multidisciplinary in order to give breadth and allow for in-depth discoveries. Teaching should be fun and, at the same time, serious, letting pupils immediately value their learning and ringing bells for further inquiries. A well-made curriculum of theories and practices should be assembled to focus on incremental improvements, which should be SMART (Specific, Measurable, Achievable, Relevant, and Timely). The authors of this paper have an optimistic expectation to motivate the current young generation of future leaders who will need to be confronted with problems and develop the solutions to make our planet sustainable, fair, and just, and use our energy resources in an optimum way.

2. Early Foundations

Practices in engineering education have significantly developed in the last decades with new technological dimensions. There has been a transformation from the early 70s, in the field of electrical engineering. The evolution of induction machines is a good example: invented by Nikola Tesla and manufactured by Westinghouse. So are the first AC transmission lines, the current high-tech microgrids, electric cars, and industry automation. Electrical Engineering was initially focused on physics, and the first fifty years in the 20th century could be defined as the Age of Electrotechnology. After the invention of the bipolar junction and field-effect transistors, the Age of Electronics started, and with the invention of the thyristor Power Electronics. Silicon Valley made chips, microprocessors, and ever-increasing innovations in hardware and software possible. Computer technology and information systems shaped education and related industries, control systems developed in mature applied mathematical analysis and real-time control applications, artificial intelligence evolved from Cybernetics, Connectionism, Intelligent Control and Smart-Grid systems, computer systems paradigms, and Deep Learning. From the early 1960’s mainframes, towards the 1970s and ’80s, desktop computers, interactive operating systems of advanced Digital Signal Processors, Systems-on-Chip, FPGAs, and RISC based architectures(those are microelectronics implementations for silicon computation) for real-time implementation and parallel computation. The establishing of analog into digital control, from hardwired circuits to embedded microelectronics, from electromagnetism for radio and television to WI-FI, wireless applications, space and satellites, the foundations of electrical engineering, physics, electromagnetism, and control theory, all of those intertwined areas of expertise are depicted in Figure 1, which shows typical Electrical Engineering Education as we have now.

Analysis and techniques for electrical circuits developed exponentially. For example, modeling and simulation for induction machines (IMs), initially carried out by manual solution of differential equations, were enhanced with equivalent circuits in three-phase ABC plus stationary d-q and rotating d-q references, the development of vector control and the introduction of DSPs made possible modern adjustable induction motor drives to become available towards the end of 1980’s. Power electronics was born in the 1960s when GE released the SCRs, so in such a historical past, the first thyristor-based induction motor drive was implemented with analog op-amp based control, where the variable frequency could be implemented with a voltage-oscillator control. Also, a proportional open-loop configuration would control and keep the voltage at a constant ratio of (Volts/Hz).

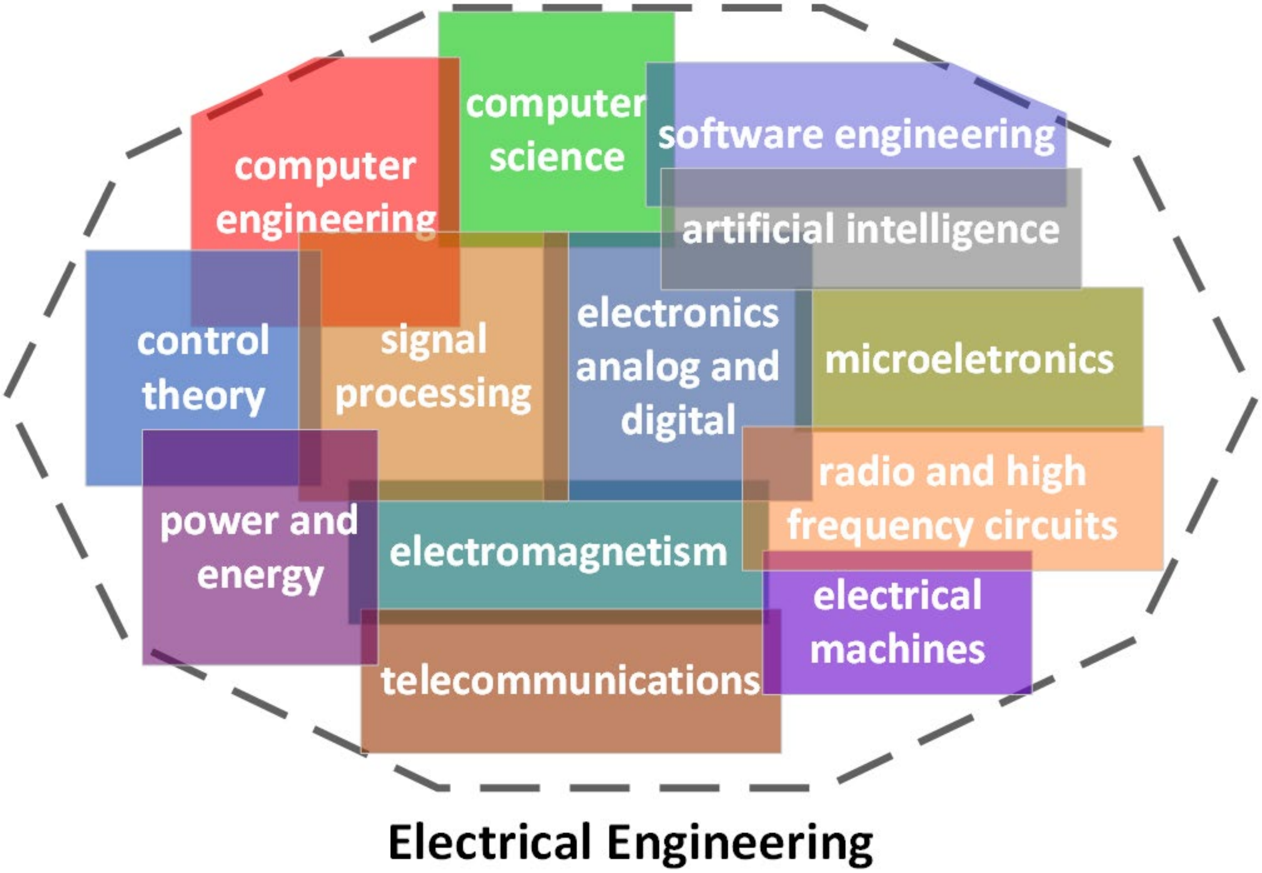

Figure 1 Electrical engineering evolved along electronics, information, computer technology, and artificial intelligence in the past 100+ years

3. From Transistorized Radios, Inverters, and Microcontrollers to DSP Based Control

With the advent of transistor-based inverters with bipolar-junction-transistors and Synchronized Pulse-Width Modulation (SPWM) it was then possible to implement scalar control of induction motors to achieve a suitable torque speed with impressed slip, since the slip frequency (angular speed of the machine flux subtracted by the equivalent shaft speed in the machine flux rotating reference frame) is proportional to torque. Those were the slip controllers, still Scalar Control, but with a better and enhanced torque calculation. Since the IM is described by differential equations, the model accounts for both steady state and transient dynamics of the IM.

Field-oriented control developed in the 1960s and 1970s became possible in the 1980s with the introduction of DSP – digital signal processors for a mathematical implementation of the induction motor where the flux aligned to the d axis of the reference frame, d component of the stator current represents the flux and q component of the stator current represents the torque. Then, the control of IM is reduced to a simple control scheme, where torque and flux components are decoupled in the adopted reference frame. Field-oriented control is dependent on having good machine parameter characterization, in addition to excellent sensor monitoring and feedback of the required machine variables, plus a very capable microcontroller, or DSP-based processor, for very fast real-time computation with PWM methodology, good protection against over-currents or over-voltages, making possible that an inverter controlling the induction machine impresses current-control capabilities in a closed loop control.

During the last 50 years, a great deal has happened due to the revolution of microelectronics, computer technology, and advancements in hardware, software, digital implementations, and mathematics and physics-based computer simulation environments. In the past 25 years, everything that was Analog became Digital, and everything that was designed based on relationships of input/output connectionist analysis of algebraic and differential equations became overly influenced by simulation-based design and re-used models developed by academics, industrialists, and technology-savvy entrepreneurs

The advances in physics, applied math, and modern analysis and design in electrical engineering utterly transformed our understanding of what Electrification means and the revolution in computing power and Energy. The scientific quest, the trial and error inherent in testing any theory against facts by experimenting and corroborating with theory, is what has defined our profession. We could evaluate how the Physics of Semiconductors is current, whether stalled or progressing, how silicon and the new wide-band-gap materials will make the new transistors for the future, as well as how Quantum Computing and Quantum Engineering will become our new computational capabilities. We stand on the crossover of another technological revolution in which artificial intelligence will transform how we live and work, and yet not have the informed civil discourse with innovators that could help to make wise policy decisions regarding its regulation. Therefore, there is no 21st-century Electrical Engineering without considering:

- AI, Deep Learning, and Neural Networks require a broader perspective - the past knowledge, for example, functional analysis, FFT, SVD, Bayes Theorem, Time-Series, Machine Learning, are all centered on Data Science. Currently, data-driven modeling is an important topic, given the fact that most engineering product units are protected on intellectual property. It seems that only access to data is still a possibility for further developments. Maybe Data Architecture will become an associated domain in Electrical Engineering, as Computer Engineering and Computer Science exacerbate the need for scientific computing and the preparation of engineers to become fully matured in this area early in their careers.
- Our society has a pervasive utilization of handheld devices for any personal connection, interaction, an communication. The recent hype of ChatGPT, or language-based-natural processing (Zadeh used to call this “computing with words”) makes all people become users, and the need for developers and makers based on their tools of everyday use. Online education, demand education, and just-in-time expertise focused experiences may change the landscape of our future professional careers.
- Hardware -in-the-Loop, co-simulation of CPU and FPGA, RT Control, and Multi-Domain Modeling entirely change the education landscape. Previously, universities required hardware testbeds. Nowadays, it is simple to set up RT simulation plus control hardware-in-the-loop, sometimes with solutions provided by vendors that cover the whole design process. What was once difficult to accomplish in the past can now be achieved within minutes, thanks to computer simulations available in numerous technological and even humanities courses, providing students with hands-on experience. There are already massive data analytics on cloud-based computing and data is overflowing, with barriers of handling such data and having the right tools for making possible data-driven modeling in lieu of physics driven modeling.

- Another approach that must be incorporated in such a transition on the research and education based on scientific, engineering, and technological electrification regarding *Societal Sustainability*, is to develop a marshal program to have many more electrical engineers and electrification-literate educators and a workforce that also understands Circular Economy for the future demand in the electrification sector. In this way, our whole society will encompass the understanding of energy sustainability and willingness to have the right Philosophy of Technology, and Appropriate Design Criteria to guarantee societal sustainability.

4. Education in Electrical Engineering Until the Birth of the Thyristor

By reflecting on earlier work in the electrical engineering education area, we understand what skills electrification engineering graduates need, and become aware of repercussions on curriculum design and delivery. Therefore, with a mindset, from the beginning till the day after tomorrow, the authors decided initially to observe the growth in our profession, which has been captured by data analysis of previous papers and reports, as well as organizing a relational structure-aware knowledge graph representation, based on surveys taken by electrical engineering in our professional community. It was great to get such valuable data from inquisitive minds and specialists in our area of expertise. Figure 2 shows a timeline of the establishment of electricity from the 19th century towards the electrification, electronics, and computer early developments, till the transformation made by silicon devices.

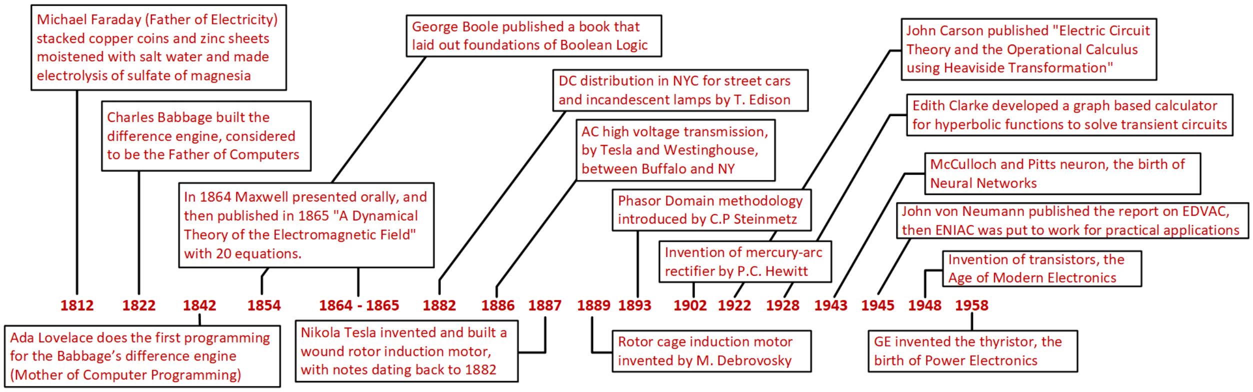

Figure 2 Timeline since the establishment of electricity towards the age of silicon: Electronics, Power Electronics, initial phases of electrical engineering

The emerging electrical industry of the decade 1875- 1885 created a need for educational programs that would prepare people for careers in a new field of activity. Massachusetts Institute of Technology (MIT) established the first electrical engineering educational program in 1882 in the USA. In their Physics Department, the 1882-1883 catalog, there was a description of "an alternative course in physics for the benefit of students wishing to enter upon any of the branches of electrical engineering." In 1884, this course of study was renamed Electrical Engineering; in 1902, separate departments of Electrical Engineering were established at MIT, Cornell University, University of Missouri, and the University of Wisconsin quickly followed suit, while at Stanford University, students interested in electrical engineering would enroll in mechanical engineering, with a functioning very small electrical engineering unit. The electrical content of the early electrical engineering curricula was minimal, the engineering knowledge about electrical phenomena was limited, with very few textbooks, most of the time only notes made by teachers, and laboratory facilities were mostly Physics-oriented. There was an absence of electives with a considerable number of required courses in the humanities and social sciences. Towards the end of World War I, the general pattern of electrical engineering curricula was emphasizing dc and ac circuits, the characteristics of motors, generators, transformers, distribution systems, and the measurement of electrical quantities. A few courses were commonly available as professional electives dealing with topics such as communication systems, batteries, electrical railways, and illumination. This was the beginning of the Electrotechnology Age.

Electricity was discovered by Michael Faraday. His many inventions granted him the title Father of Electricity. -In 1812, he made the first voltaic pile with stacked coins and zinc sheets moistened with salt water and made electrolysis of sulfate of magnesia - for many years, he enhanced the newly born electricity and electromagnetism. Having found the principles of mutual inductance, James Clerk Maxell was motivated to write about field theory. He invented the first electric motor and dynamo and experimented with the first electric current from a magnetic field. Fast forward to the turn of the 20th century, there have been many important discoveries and theories with practical developments. Electricity was even becoming an accepted knowledge that there was an energetic flow in wires, with fields transmitting waves, and electrons were not even a reality until 1897 when Thomson discovered the electron. The adopted idea nowadays as electricity being a “flow of electrons” is a pedagogical tool. Thomson proposed a model for the structure of the atom, and the British engineer John Ambrose Fleming was curious about how electrons could be free inside a thermionic valve, and he made the first vacuum tube in 1904, starting the Age of Electronics.

When electrons were still being discovered in 1897, around the same time Nikola Tesla filed his own radio patent applications, granted in 1900. Marconi's patent application was filed in the USA in 1900, but it was turned down because it too closely resembled Tesla’s work. Surprisingly, in 1904, the US court abruptly reversed its decision. It is now known that there were political maneuverings behind the scenes, regarding the politics in Europe. Marconi Wireless Telegraph Company was established in America, with powerful financial backing for Marconi in the United States because banks and financial conglomerates wanted to continue to pursue new markets with Marconi, which was considered to be a safer choice. Marconi even won the Nobel Prize for inventing radio in 1911. Tesla was emotionally destroyed, particularly with so many other disruptions caused by Thomas Edison. After his death, the U.S. Supreme Court decided that the radio patent should belong to Tesla — and the justices used his St. Louis lecture as evidence to invalidate Marconi’s claims. In the first two decades of the 20th century, some schools offered at least one course in wireless telegraphy, then the radio became integrated into the curriculum, and the invention of vacuum tubes made clear that Electrical Engineering with the advent of the Age of Electronics would define the 20th century.

The Second World War disrupted life, education, industries, and commerce. Figure 3 shows data that was aggregated and collated from several sources. The beginning of the data series (1926 until 1947) is unreliable, but it is visualized in the graph as supporting a panorama of the overall growth of master and doctoral students. After WWII, there were many academic and program developments in the USA, but those are not possible to describe in this paper due to lack of space. There was a theoretical pragmatism in making electrical engineering a science by itself, with a sequential and congruent curriculum that pretty much was adopted all over the world, particularly with the publication of books, handbooks, and the emergence of some conferences where people could network, mingle, and interact. The invention of the thyristors (SCRs) by General Electric marked the birth of Power Electronics.

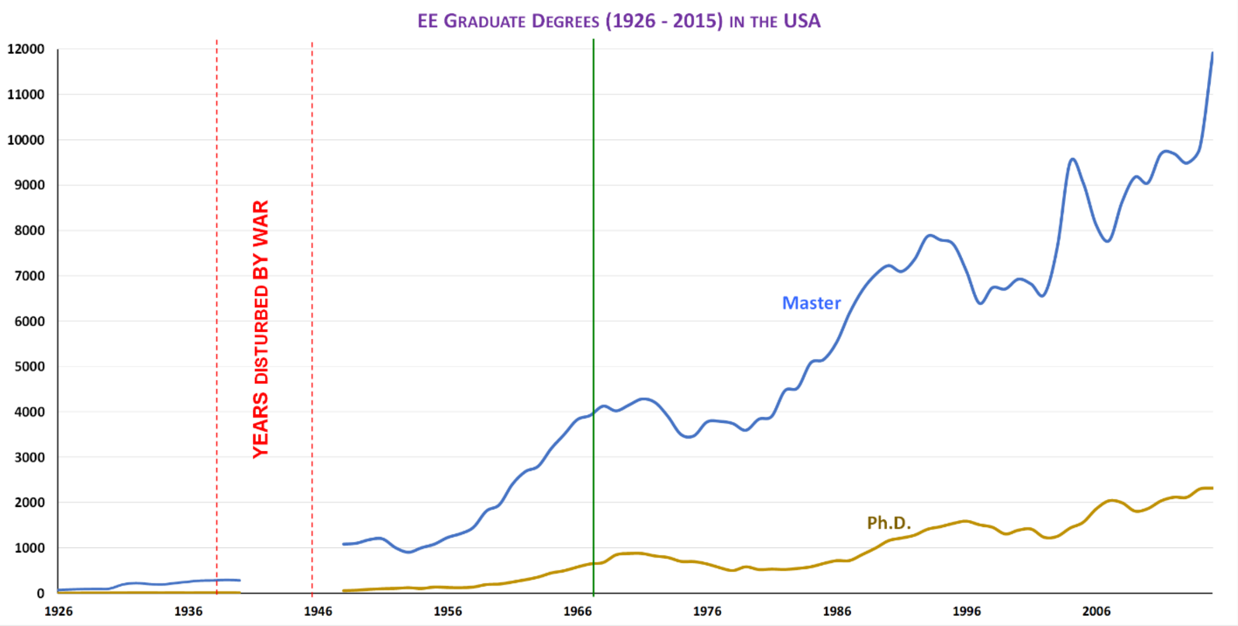

Figure 3 Graduate degrees (MSc and PhD) in Electrical Engineering conferred by US institutions.

For many years, since the inception of electrical engineering courses in the USA, the approach of education in electrification has been to understand the "mathematics" and "physics" integrated in an approach that makes electrical and electronics engineering a science in their core. A prevailing view of a dynamical system from the 1960s to the end of the 1990s was to define it as an input/output frequency-domain based. Transfer functions were believed to be the way to characterize a system.

5. From 1960s to Now

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Heaviside's operational calculus allowed to have a differential operator, or a delay, as a formal operator to solve circuits in an algebraic approach. Then electrical engineering educators squeezed through the mathematical rigor of Laplace transforms, using complex functions, with domains of convergence and other cumbersome, most of them mathematical elucubrations. However, Laplace Transforms, in alignment with Fourier Transforms and Z Transforms, have been the ultimate theory to support the foundations and baseline of electrical engineering until now. The view of a system as a frequency transformation has been so heavily emphasized, instead of time-domain descriptions, that a whole generation, or maybe two generations of engineers and professors were trained to think, model, and design systems on the frequency domain, the use of complex numbers and phasor analysis started to be considered a frequency domain, without any frequency information, just steady-state representations of an electrical circuit. Information theory started from a different set of principles. Computers were initially taken only as machines or calculating devices. However, very early, it was found that computers could be used as decision-making machines, with communication devices, that became part of futuristic books, movies, and TV shows. The black-box approach, with transfer functions, applied mostly to continuous-time single-input/single-output systems, became the mathematical language of control, where a differential equation as p(d/dt)y and q(d/dt)u, with p and q real polynomials, was immediately transformed to a transfer function. It has been fundamental for any electrical engineer to understand the framework of classic and modern control, PID, Nyquist criterion, lead/lag compensation and gain and phase margins, graphical techniques like Bode plots, Nyquist diagrams, Nichols charts, and root-locus graphs. Ernst Guillemin was the main driver of electrical engineering as a *science approach*, instead of a *technician approach* (which would certainly be favored by industries) in the first half of the 20th century. Norbert Wiener had a strong unifying perception of circuits, control, communication, and information theory. In 1948, he published Cybernetics, or Control and Communication in the Animal and the Machine, a book in which he described a theory of everything based on systems, inputs, outputs, information flow, noise, stability, and feedback, The Kalman filter built upon the Wiener filter, for advanced problems with model-reference and parameter estimation became a de-facto influencer for generations of faculty and students towards the end of the 20th century, and still has strong usage until now.

Figure 4 shows remarkable events since the 1960s, making the 20th century the maturity period of electronics, power electronics, power systems, controls, information, computer systems, hardware, and software, the foundation for the current electrical engineering and electrification of today. Solid-state electronics with transistor technology started when the first germanium-based point-contact transistor was invented by John Bardeen and Walter Houser Brattain at Bell Labs in 1947. They were very bulky and difficult to manufacture. Bell Labs physicist William Shockley made documented annotations in a lab notebook supporting the fact that on January 23, 1948, he conceived a distinctly different transistor based on the p-n junction. Shockley disagreed with Bardeen's explanation of how their transistor worked, claiming that positively charged holes could also penetrate through the bulk germanium material, with a basis for "minority carrier injection" crucial to the operation of his junction transistor. On February 16, 1948, John Shive achieved transistor action in a sliver of germanium with point contacts on opposite sides, demonstrating that holes were indeed flowing through the germanium. Shockley applied for a patent on the junction transistor that June and published his detailed theory of its operation in 1949; it was born such a three-layer sandwich of n-type and p-type semiconductors separated by p-n junctions, today called "bipolar" junction transistors. Following suit, a silicon-based MOSFET (metal-oxide-semiconductor field-effect transistor, or MOS transistor), was invented by Mohamed M. Atalla and Dawon Kahng at Bell Labs in 1959. It was a compact transistor that was easy to miniaturize and mass-produce for a wide range of uses, leading to the silicon revolution. Figure 4 shows a time starting from when solid-state devices started becoming prevalent from the 1960s with a transition from vacuum tubes to semiconductor diodes, transistors, integrated circuit (IC) chips, MOSFETs, microprocessors, and light-emitting diode (LED) technology.

After GE introduced the thyristors, making them available for industrial applications, the nascent area of power electronics had several developments in the 60s and 70s, initially with the complicated forced-commutation (McMurray topologies) of SCR's with capacitors to impose the commutation conditions for thyristors used those early induction motors drives, as well as the initial circuits for soft-starting control. It was possible from the 1960s to the middle of the 1980's to have controllable torque by the rotor winding (for slip-rings machines with rotor connection).

Transistor-based dc/dc converters, flybacks, and dc power supplies were implemented with BJTs for TV sets, computer power supplies, and space missions. The transistor-based inverters for dc/ac control of electrical machines and initial UPS (uninterruptible power supplies) were based on analog control and BJTs during the 1970's and early 1980's.

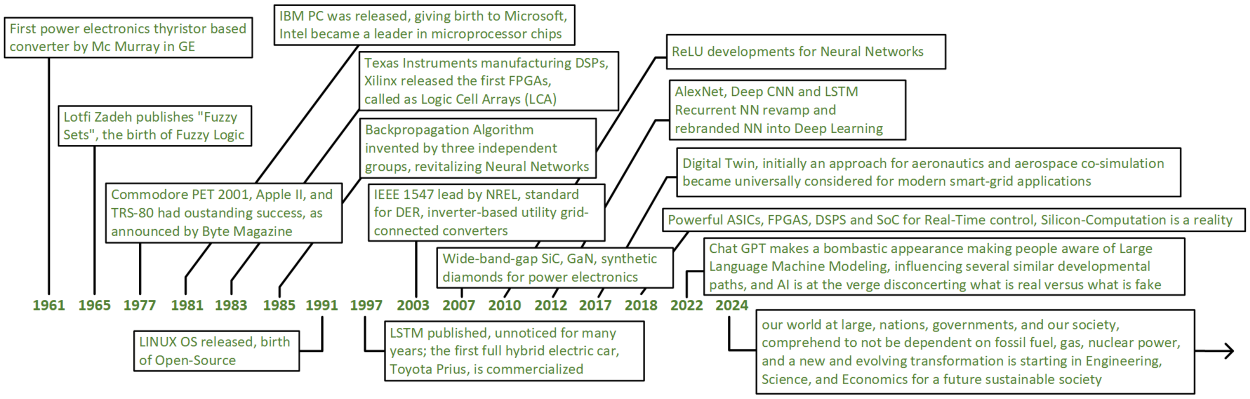

Figure 4 Remarkable events defining the 20th until now.

The invention of computers was initially based on vacuum tubes and then transistors. There happened further invention of semiconductor-based diodes, transistors, and thyristors. Moreover, the understanding of electromagnetics design, the emergence of control systems theory, the alignment of applied mathematics, and then the invention of integrated circuits, made possible all nascent ideas and thoughts that influence, the educational approaches for about 70 years ahead. With computer technology, operating systems, and digital electronics, the Age of Computers was established in parallel with the Age of Electronics. The area of Power Electronics displaced a little the heavy influence of the early electrotechnology curriculum.

Around 1960, the basic model for studying dynamics in control shifted from Single Input Single Output (SISO) to Multiple Input Multiple Output (MIMO) state-space modern systems, and multivariable systems could then be covered. Also, nonlinearities and parameter time-variation became more evident. There was a strong push for non-linear theory, and control systems professors became mathematicians disguised as electrical engineers. Finite state machines and automata were introduced, accompanied by a slow but surely always coming of neural networks and the birth of fuzzy logic. Control as a research field in electrical engineering opened up new possibilities that were intangible before. Optimal control was picked up enthusiastically in the USA and UK. The results were astonishing. For most of the Western European countries, the shift to state space models did not happen until the second half of the 1970's decade.

There was resistance to the mathematization, perceived as irrelevant and alienating engineers, *de´ja` vu encore*, fuzzy logic became developed in Japan, neural networks as a field had its first death, and research in neural networks was rebranded as self-organizing maps, or cerebellar articulation modeling control, or as optical cortex mimicry signal processing because Minsky and Papert's book successfully bomb-shelled Rosenblatt's perceptron with insurmountable limitations, killed neural network research entirely. But research continued, quietly and in at least three different and geographically dispersed academic environments. The backpropagation algorithm was independently discovered by different people, and neural networks suddenly came to their re-birth in 1985.

Engineering subjects have their origin, in one way or another, in the physical world, trying to make sense of circuit variables response, or maybe multi-domain with mechanical velocity, motion, and position, but maybe with patterns, signals, or geometric features such as volume, integral and shape, symmetry, rotation. If a closed system is an interconnection of two systems, these two systems will be open. Therefore, basic laws in physics can address open systems, Newton's second law, Maxwell's equations, gas law, and the first and second laws of thermodynamics. It is very typical in electrical engineering to have a causal modeling, where dynamics of differential equations will lead to block diagrams, which will lead to a flow of energy or information from input towards output, facing parameters (which may have variation or sensitivity issues), and external disturbances.

The decade of the 1980s was heavily influenced by the educational approach for the past 70 years of the 20th century. The paradigm started to shift in the middle of the 1990s, morphing into what became a very accelerated transition towards the beginning of the 21st century. The current generation of senior professors were students then, and their coursework was a learning mechanism for a bachelor's degree in electrical engineering. Professors used blackboards, chalk, or colored pens on a whiteboard, plus plastic overhead transparencies on a light bulb projector, which were the main instruction methods. There was heavy homework, lists of exercises, possibly using scientific calculators, written on paper notebooks, with absurdly difficult exams. By the end of the 1980s, it was still possible for anyone having a B.Sc. in electrical engineering to be ready and well prepared to work for industries, even for teaching foundation courses, or very specialized ones, in technical colleges, high schools, and lyceums.

As depicted in Figure 3, the post-graduate programs, such as Master's or Ph.D. were typically only meant for the ones who could imagine themselves working in academia (an MBA was the dream of anyone seeking a quick way to ascend in the management path), conducting research in national laboratories, maybe doing government or science-based programs, or partaking in social-economics policy jobs in international non-governmental agencies. PhD programs still have very substantial coursework, but doing novel research, and publishing the findings in conference records or scientific and engineering transactions and journals were fundamental for the neophyte scholar. Figure 3 shows an increasing positive derivative trend on the growth of Master's and PhD graduates in electrical engineering. From 1996 to 2006, there was a plateau because many of those students decided to pursue careers in computer science, computer engineering, or mechatronics.

Towards the end of the 1980s till the turn of the 21st century, typically, university courses would range from electrical and electronics engineering to applied math, computers, and computation. Most doctoral students would devote a lot of time to controls, linear and nonlinear systems, system identification, optimal and process control, stochastic control with time series, and signal processing. Many would study electrical power systems because the opportunities to work for the utilities and electrical power companies were abundant. Some would try to understand electrical machines, how to use transistors to control those electromechanical devices, and how to use control systems in the emergent area of microelectronics for real-time systems. The aerospace industry allowed the emergence of dc/dc converters and switching regulators during the 1970s and 1980s. One advantage in the past few years is the further integration of electrical energy flow, with flow of information, in a unified implementation allowed by computer-based technology, i.e., making a reality of the very idea that Wiener proposed about pulling communication and control together, many decades ago.

6. Surveys with our Professional Community to Support our State of Art and Vision

The authors of this paper conducted three surveys (data files are available upon request). One survey regarding the understanding of relationships of subjects and their intertwining in a curriculum peaked with almost one hundred inputs on answers. The aging profile of professionals who identify themselves with the area of Electrification is portrayed in Figure 5. It is interesting to note that this area of expertise is aged, with an average of 48 years old, and the peak of professionals is from 30 to 40 years old. They are probably motivated to go on managerial ladders and administrative or business-oriented jobs, but there is a steady profile of people who might love their technical duties, staying active from 50 to 80 years of their age. It is clear that we must modernize education to recruit younger students, increasing as marked in the figure for a great amount in the ages of 20 to 30, which should be the peak.

Our educational institutions must thrive to help them professionally mature faster, in addition to working with the industry sector to maintain their lifelong learning interests to retain them, also increasing the age window from 40 to 50 years old people, making it possible that an enhanced Aging Profile in the Electrification area will make possible the Energy Transition and Energy Transformation required for the sustainability of our worldwide society for the next hundreds of years.

Today, we design based on action and reaction; the environment acts by imposing certain variables, the inputs, on the system, and the system reacts by imposing certain variables, the outputs, on the environment. In most current engineering applications, there are terminals with real physical entities, and there are many physical variables associated with one and the same terminal, for example, forces and torques acting on a mechanical structure and displacements and accelerations of some featured points. It can also be currents and voltages, mass flows and pressures, and heat flows and temperatures.

Electrical engineers will continue to use block diagrams, signal flow graphs, or electrical circuits, the paradigm of computer simulation-based design, with graphical block diagram-oriented frameworks (such as Matlab/Simscape/Simulink, ALTAIR, Amesim) or similar ones that have been enhanced with hardware-in-the-loop, with customized processors (INTEL or ARM), with RISC based processors (FPGAs). The interaction pathways are often considered the essence of interconnections following system theory ideas. The same approach is often used in other engineering domains, such as thermal interconnections, and hydraulics. Therefore, the Input/Output thinking is completely at odds with physical interconnections.

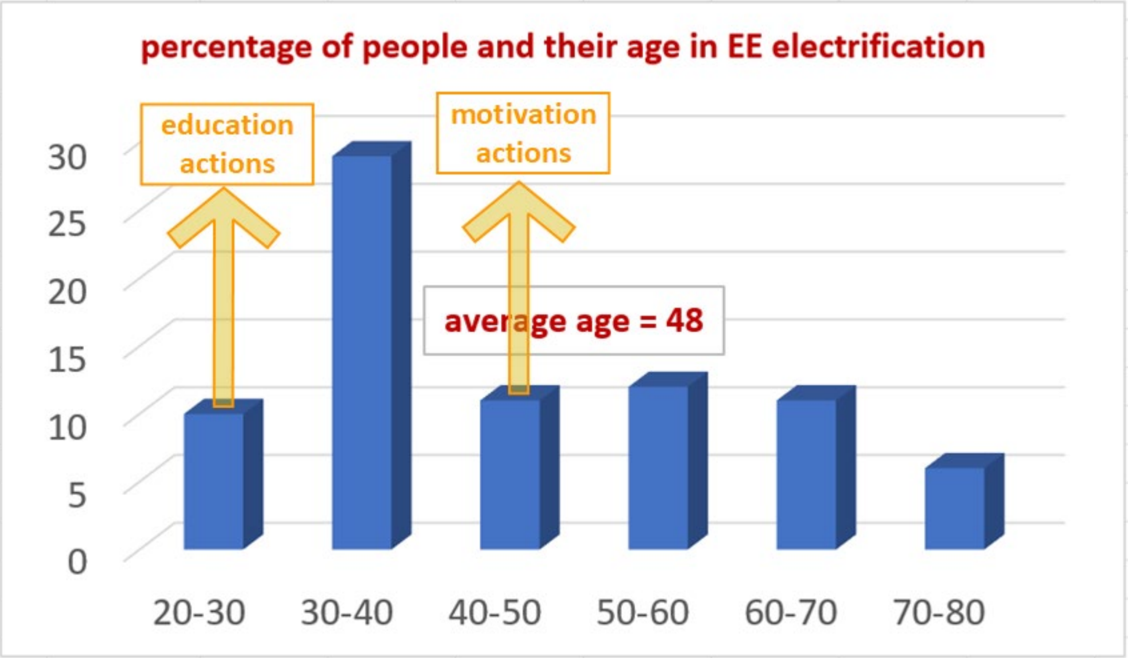

Figure 5 Age distribution of electrical engineering professions in Electrification

Behavior and understanding Physics in Electrical Engineering requires equivalence of models, representations of models, properties of models, approximation of models, and symmetries, all referring to the behavior. Dynamic modeling and system identification aim to come up with a specification of the behavior. Control is how to either restrict the behavior or conduct the input to make the system follow a trajectory of the required behavior. Then a system is controllable if any two trajectories in the behavior are patchable, that is, if for any two trajectories in the behavior, there is a third trajectory in the behavior that has the past of the first one as its past, and the future of the second one as its near future. There are real-life situations in our world that do not follow this approach, such as dampers for vibration attenuation, heat fins, strips, grooves to control turbulence, insulation equipment for heat or noise, stabilizers on ships, power-flow management based on droop control or modern synchrophasors, they do not function through sensing and actuation, energy resources and their conversion from origin to end user do not have sensing and actuation.

If a new paradigm of electrification education in the 21st century can be implemented based on casual modeling, where devices or subsystems have their laws of interconnection given by their physical modeling, and a multi-domain. The open systems approach combined with interconnection, fits modern technological developments, which have been enhanced with microcontrollers, digital signal processing, and cloud-based, internet-based applications to align with signal processing, communication, and optimization. However, the coherence of the overall education in electrification has weakened because the beauty of implementation on a highly complex computer-based system has taken priority over understanding how decision-making can be modeled, analyzed, and implemented for closed systems, instead of interconnected open ones.

We are have been ocusing on the feedback of trajectories of differential equations, but we have to start focusing on the balanced system performance of a casual multi-domain and multi-expertise enhanced global environment.

7. Invariants in EE Education vis-à-vis Enhancements and Trends

Depending on who you ask, you may have a different definition of electrical engineering, but most would agree that it is a branch of engineering that deals with the technology of electricity, with so many more layers on top of it. As depicted in both timelines of Figures 2 and 4, there are remarkable achievements just to pinpoint how the discipline of electrical engineering, less than 200 years old, and at the fundamental level, came through the first 100 years as a combination of physics, mathematics, electricity, electromagnetism, electronics, and how information could be processed either in analog or in digital ways. In order to define the future, the present must be accessed. One methodology could be to anticipate skills and projects that students would be working on in the future and how we might prepare them for this and indeed motivate students to engage.

When the authors started collaborating and writing the initial drafts of this paper, it was important to define what our methodology should be in validating what invariants and what foundations and core programs are, and then come up with recommendations for our educators. It is important that we let students choose what they want, yet many schools would not have resources to make possible a very open-ended umbrella program. In the first two decades of the 21st century, it became clear that our humankind is bound to finite resources. Most of institutions, associations, and non-governmental organizations are aware that energy sustainability and access to information via the Internet with data and working cloud-based solutions is vital for the development (in addition, of course, to the basic resources that every human needs, as defined by the United Nations). We may have discussions at conferences, TED talks, and streaming vlogs and blogs, but is there a roadmap for what invariants are in education and where we need enhancements, and how to deploy, sustain, train, and make possible the new electrical engineering, the new electrification of the near future? The authors discussed a survey methodology, at least to support our philosophical and pragmatic thoughts.

It was assumed in this paper that the case studies are based on the technique of a Relational Structure Aware Knowledge Graph, i.e., how to construct a qualitative framework. The case study is a revamped EE curriculum based on knowledge graphs. Given an “entity,” let us say a subject of an EE curriculum, we could make a family relationship to other subjects (other entities). Some topics will go further and further, and some topics may give a large breadth and depth of family-like relationships, while other topics will be some islands with other islands. Figure 4 also shows the basic relations, exploited in questions addressed in Surveys, based on two "entities." Let us say two topics, two courses, or two fields; respondents may try to find some basic representations such as (i) symmetry, (ii) anti-symmetry, (iii) inversion, and (iv) composition. Typically, curriculums are based on prerequisites, so admins and faculty find composition as a way to chain knowledge. Instead of regular research questions, we have how elements of a course are connected to the next, how they depend on the previous ones, how important one or more courses are towards a pedagogical goal, and how important in the future such preparation makes the professional successful.

The feedback on such surveys helps to understand "reachability", i.e., how far a topic propagates. For example, Linear Algebra may be of very little reachability for someone who works towards a degree in antennas and high-frequency circuits (whereas Physics III would be of deep reachability), while Linear Algebra has a very deep reachability for people who study Data Science and even a professional important skill to work for many years in AI-based fields. Reachability is the reach of something as a prerequisite, not only for courses, but also for work, comprehension, and analysis in a given field. The survey has been done on these nodes and their interactions, and how much information was available to describe elements to participants, their locations, their causations, and providing a structured representation.

How to best represent temporal changes in the narrative network and how to evaluate the narrative of the proposed curriculum, and to assess whether a set of events is a good one to achieve some prescribed goals? How many links are necessary for building up a sequence of courses, or a parallel of paths to consider the narrative complete, or well done? There is the scaling question, related to how many possible differences are allowed from one curriculum implementation to another one to achieve the same goals. Lastly, there is the question of relevant input resources to use to build the narrative. Using generic knowledge graphs can be a starting point. Sometimes, domain-specific knowledge graphs are more suited. Nevertheless, it is possible to improve the methodology presented in this paper for other decision-making-based scenarios. One aspect of the collected data was about teaching modes. We addressed colleagues, professional networking, e.g., LinkedIn, perhaps some interested undergraduate and postgraduate students, as well as researchers. The educational delivery methods have been reported as indicated in Figure 5, enlightening how respondents see the preparation of incoming new professionals, particularly focusing on what they feel is important for the future 21st-century electrical engineer. And the task of the contemporary educator is not to cut down jungles but to irrigate deserts.

The life of academic learning at university does not have much to do with a well-organized curriculum of pre-cooked, filtered, and purged subjects collected by an academic committee. Otherwise, we will be limiting our students to our present knowledge and pet topics.

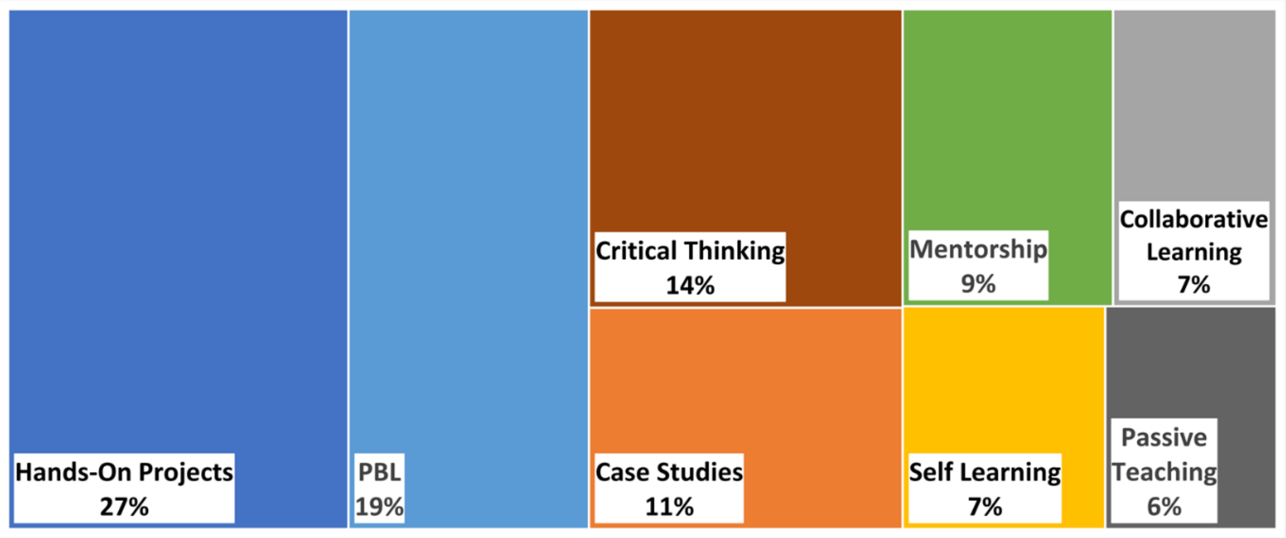

Figure 6 Survey data results supporting the methodologies that would best fit modern education in electrical engineering.

8. Integration of Multidisciplinary Context

The Energy Transformation of the 21st century requires challenges related to power generation, conversion, and distribution, to be dramatically enhanced and improved with a focus on high-performance power electronics converters, associated with sophisticated control strategies, optimization methods, energy management systems, energy storage systems, and power quality issues. In addition to technological and technical issues, we have to address educational needs. For topics that are weakly coupled with each other, learning is fast, and self-learning is an option, although Figure 6 shows Self Learning and a few others (Collaborative Learning and Mentorship with a fraction of overall importance in the modern paradigm, modules that people can study on their own time, probably based on streaming platforms, is still a possibility. It is clear that Passive Teaching, with 6%, is the least choice of methodology for a modern curriculum. An unabridged Education, a curriculum to be delivered with accreditation, has to focus on strongly coupled topics that require layers and layers of foundations. For example, to understand ac motor drives, a student is required to know control, power electronics, and machines. To know machines, knowledge of electromagnetics is required, for which calculus is necessary. To know control well, mathematics, including calculus, Fourier transform, and Laplace transform, all need to be mastered. In a sense, the original setup of EE curriculum that has been evolving in the past few decades is ok as a baseline, but shared governance in universities should adopt incremental changes, which should be applied to suit the current world, such as data analytics skills. Computer simulation/animation or visualization platforms will greatly facilitate learning.

One initiative that could help the learning process is the integration of design in a multidisciplinary context. In "Our English Syllabus," published in 1939, C.S. Lewis from Oxford University, discussed the emphasis on letting students have a sense of ownership of the education process is very important. Another methodology would be to provide a foundation and core program and allow students to choose what they want, but many schools would not have the resources to make possible a very open-ended umbrella program. It encourages the student to be proactive and not expect from the instructor to have a detailed menu of the subjects he or she should read and learn from. “With these limitations, then, we hand you over our tract of reality. Do not be deceived by talk about the narrowness of the specialist. The opposite of the specialist is the student enslaved to someone else's selection. In the great rough countryside, which we throw open to you, you can choose your own path. Here's your gun, your spade, your fishing-tackle; go and get yourself a dinner. Do not tell me that you would sooner have a nice composite menu of dishes from half the world drawn up for you. You are too old for that. It is time you learned to wrestle with nature for yourself. And whom will you trust to draw up the menu? How do you know that in that very river which I would exclude as poisonous the fish you especially want, the undiscovered fish, is waiting? And you would never find it if you let us select. Our selection would be an effort to bind the future within our present knowledge and taste: nothing more could come out than we had put in. It would be worse; it would be a kind of propaganda, concealed, unconscious, and omnipotent. Is it really true that you would prefer that to the run of your teeth over the whole country? Have you no incredulity, no skepticism, left?" {Our English Syllabus, C.S. Lewis, Oxford University, 1939].

BIOS

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