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The Role of Commercial Simulators and Multidisciplinary Training in Graduate-Level Electromagnetics Education

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This article provides a summary of a panel discussion at the 2016 IEEE International Symposium on Antennas and Propagation/U.S. National Committee for the International Union for Radio Science (USNC-URSI) National Radio Science Meeting on the role of commercial simulators and multiphysics (or, more generally, multidisciplinary) training in graduate-level electromagnetics education. Several general-consensus points are conveyed to stimulate further discussion and reflection in the community on best practices for present and future graduate-level curriculum design and instruction in engineering electromagnetics (EM).

BACKGROUND

The use of commercial computational EM (CEM) simulation codes in EM research and education is ubiquitous. This is a relatively recent phenomenon, and the availability and utility of simulation tools have fundamentally changed how research and graduate education is accomplished at many universities. The widespread adoption of these tools has many benefits for students. Commercial CEM tools can serve as a virtual lab bench for scientific inquiry or a rapid optimization tool for engineering design problems—all of which has relevance to graduate-level course work and research. The vast majority of graduate students pursuing EM-related Ph.D. degrees will likely rely at some point in their future career on CEM tools; thus, educators have a responsibility to ensure that their graduates have some degree of familiarity with such indispensable tools.

However, as with most things, there is the possibility of misuse or overreliance. Commercial software tools give nearly instant answers but not necessarily instant insight. Writing one's own code is no longer a necessity to conduct CEM simulations, and graduate students often prefer to use simulation tools than to wrestle with analytical models. Everyone, from students to research supervisors, would like results today rather than six months from now. These tensions lead to a number of questions about the appropriate role of commercial simulators in graduate-level EM education. To what extent should graduate students be expected to develop their own simulation codes and understand the theory of CEM algorithms? To what extent should these students develop underlying quantitative models? How much analytical work should they be expected to perform in the course of their graduate education? Does the advent of commercial simulators lessen the need to train graduate students to analytically or numerically solve Maxwell's equations themselves (via, e.g., Green's functions and integral equations, complex-plane analysis, home-grown CEM codes, and so on)? To what extent should all graduate students understand CEM algorithms? Modeling and simulation that used to take months or years of work can now be done within hours; to what extent should we focus on the answer, and to what extent should we focus on the path to the answer?

In addition, an increasing array of EM research problems involves multidisciplinary aspects. For example, material complexity and an emphasis on miniaturization increase the need to understand material physics, nontrivial EM-material

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interactions, and quantum mechanics. Increasingly exotic materials (natural or artificial/meta) as well as the use of traditional materials in higher- (previously unexplored) frequency regimes are gaining interest, and the material response, often arising from semiclassical or quantum transport equations, becomes paramount. Students need to know a fair bit of solid-state physics and quantum mechanics to understand the dynamic processes in these materials. Two-dimensional materials for flexible electronics and photonic topological insulators are prominent examples wherein the traditionally trained EM graduate student is ill-equipped. Moreover, the trend in wave-matter interaction is also going toward extreme scenarios. This may involve 1) extreme dimensions such as zero-dimensional (e.g., quantum dots), one-dimensional (e.g., quantum wires and carbon nanotube), and two-dimensional (2-D) (e.g., graphene, molybdenum disulfide, and so on) structures; 2) extreme sizes such as nanoscale (e.g., nanoparticles and nanomaterials); 3) extreme duration, such as ultrashort pulses (e.g., attosecond pulses); and 4) extreme energy such as ultrahigh power (e.g., terawatt) and ultralow energy (e.g., attojoule). At these extreme paradigms, certainly the knowledge of non-EM topics, such as quantum phenomena, nanoelectronics, solid-state physics, and nanomechanical platforms, is necessary. Other non-EM physics domains (heat transfer, acoustics, and so on) emerge in a host of other EM research applications. Take, for example, the multiphysics medical imaging technology known as *microwave-induced thermoacoustic imaging*. Here, microwaves interact with biological tissue and EM power is absorbed, leading to heating, thermal expansion, and acoustic wave generation and propagation.

Thus, we find that Maxwell's equations often need to be linked to other equations across multiple scientific disciplines. Examples include (but are not limited to) the Schrödinger equation, Boltzmann transport equation, heat equation, and acoustic wave equation. Not all commercial CEM tools offer multiscience capabilities, and even for those that do, the user needs to understand the underlying principles and, often, the mathematical models. Additionally, mathematical domains, such as statistics, are playing an even more important role in tackling EM research problems. Consequently, it seems that designing a cohesive graduate-level EM curriculum is not a straightforward endeavor these days. How much math, computer science, physics, and other physical and biological sciences are needed for the completion of a degree where course work is not the sole or even primary emphasis?

A panel was convened at the 2016 IEEE International Symposium on Antennas and Propagation/USNC-URSI National Radio Science Meeting, held 26 June–1 July in Fajardo, Puerto Rico, to address these questions. We authors served as panelists and presented opening statements and engaged in dialogue with audience participants. The panel topic and points raised are documented in this summary.

HISTORICAL PERSPECTIVE AND CURRENT TRENDS IN GRADUATE EM EDUCATION

As a brief historical perspective, let us recall that, although the study of electric and magnetic phenomena can be traced back to ancient Greek society, the laws of EM were developed primary in the 1800s [1], culminating in Maxwell's synthesis of the known electric and magnetic field equations in the 1860s and Hertz's partial verification in 1888. Toward the end of the 1800s, Heaviside put Maxwell's equations in their modern form, and by the start of the 20th century, researchers began to solve Maxwell's equations for a variety of problems.

To summarize the historical evolution of EM education, we can divide the 20th century into two 50-year periods, give or take ten years. From 1900 to 1950, virtually all EM calculations were done using simplified models that described the interaction of EM energy with canonical geometrical objects: planes, cylinders, and spheroids. Many extremely important solutions to EM problems were developed during this time period. (The list of examples is quite rich: Sommerfeld's solution for a source over a half-space, Mie's solution for scattering from a sphere, solutions to various diffraction problems, and more.) Graduate education focused on the analytical solutions of Maxwell's equations for these EM wave interaction scenarios involving geometrically simple objects and classical descriptions of material properties.

From 1950 to 2000, with the advent and emerging widespread use of computers, many numerical methods [integral equation, finite-difference time-domain (FDTD), finite-element method, and others] were developed and applied to model increasingly realistic geometries. The capability to model more complicated materials increased, and EM interactions with plasmas (motivated by the space race in the 1960s) and semiconductors (due to the development of integrated circuits) were increasingly considered as we approached the latter part of the 20th century. Graduate education would have included these topics, often in an ad hoc manner as dictated by the needs of a given project. Mostly, researchers and graduate students needed to develop their own codes for each problem.

From 2000 and on, and especially in the last five to ten years, full-wave commercial simulators have become very widely available and affordable for academics. It has become rarer for graduate students to need to create their own codes to perform simulations. At the same time, the shift in focus from simple material descriptions (i.e., good conductors versus lossy dielectrics) to more accurate, detailed descriptions of material properties has become paramount. For example, in the area of antenna engineering, researchers are tackling the design of deformable antennas/flexible antennas for body-area networks, optical antennas for which the metal does not behave as perfect electrical conducting plasmonic structures, and antennas on 2-D materials such as graphene. Engineering EM is now not only about interactions with structures (planes, cylinders, and spheres at the simplest level) but increasingly with complex materials where non-EM phenomena arise and cannot be ignored.

In summary, during 1900–1950, EM researchers needed to be familiar with analytical techniques for solving

Maxwell's equations, and from 1950 to 2000, researchers needed to be familiar with both analytical and semianalytical techniques, as well as numerical methods. The extra training usually required in EM education was more mathematics (advanced calculus such as convergence of series, functional analysis for completeness of eigenfunction expansions, numerical methods, and so on). Today, however, we find more often than not that our students need to augment their EM training with a knowledge base in other sciences.

In addition, the education systems in some countries have recently experienced a push toward shortening the duration of Ph.D. studies (to typically three to four years, with regional disparities). In parallel, explicit requirements for graduation, e.g., in terms of a predefined number of publications, have become commonplace. This clearly puts pressure on graduate students and their supervisors to focus on deliverables. At the same time, a growing emphasis in graduate education is placed on job readiness, with prospects of immediate productivity outside academia, i.e., industrial or government research and development labs.

It is clear that the demand for shorter studies aiming at employment readiness do impact the boundary conditions of Ph.D. education. Furthermore, in EM research, this recent evolution has coincided with profound changes in the discipline, caused by a dramatic progression in the availability of both computing power and sophisticated simulation tools. In this context, it is not surprising to observe a decline of the traditional model of EM graduate education, where doctoral candidates would first independently develop the necessary analytical and numerical tools before tackling a practical problem. In contrast, application-driven research projects using readily available simulators have in the meantime become prevalent. Such projects with tangible practical outcomes might even be explicitly encouraged by potential future employers, universities, and even funding bodies.

This seems to naturally split EM graduate education into two broad streams: application-driven research and more basic research. Even if these streams have some overlap, they have generally different aims and require various sets of competencies. It is then appropriate to consider how much mathematical, computational, scientific, and practical skills are desirable for graduates in either direction.

THE ROLE OF COMMERCIAL SIMULATORS IN GRADUATE EDUCATION

The extent to which graduate students need to understand the underlying CEM theory behind commercial simulation tools depends on what they are preparing to do in their graduate research and beyond. A small fraction of students will be interested in research in CEM (defined here broadly to include full-wave techniques and high-frequency asymptotics). In this case, they will be working on advances in CEM theory and algorithms that ultimately further the state of the art in CEM tools. Their knowledge in numerical analysis, computer science, and applied mathematics is of critical importance—arguably just as important as their knowledge of EM. These are the students for whom constructing their own codes is central to their research progress.

Much research, even at the Ph.D. level, however, is application driven and relies on available computer modeling tools, especially commercial EM simulators. In this case, students are conducting research with the aid of CEM tools (in contrast to research in CEM itself). A deep expertise in the application-specific technology is required first and foremost, but experience would suggest that intelligent use of the research-supporting commercial software tools requires a basic familiarity with the fundamentals of CEM. This knowledge enables an informed choice among solvers; the correct usage of solvers to obtain accurate, converged results; and critical interpretation of computed results. Additionally, basic training in some of the most widespread computational methods can build the basis of a solid EM education, whereby the concepts applied in numerical methods often reinforce theoretical aspects, e.g., by providing an intimate knowledge of the coupling between magnetic and electric fields (e.g., FDTD) or of the mechanisms of radiation (e.g., Green's functions).

The potential pitfall we collectively face, given significant pressures on deliverables, especially for industry projects, is the overreliance on commercial CEM simulators without a deeper theoretical understanding of the problem. The advent of significant computing power and sophisticated software tools makes it possible to churn through countless simulations to get the job done without taking time to learn from the simulations, gain insight, and develop critical intuition, Obviously, there is a balance to be struck between the timeliness of completing projects and rigorous graduate education. We view this balance as one of the key responsibilities of the graduate research advisor.

THE ROLE OF MULTIDISCIPLINARY TRAINING IN GRADUATE EDUCATION

The emergence of powerful commercial software has offloaded the burden of carrying out complicated, lengthy calculations involving complex geometries. This presents new opportunities for students to expand their knowledge in other directions, especially in the area of basic sciences. Given the increasingly interdisciplinary nature of research, it is often in the student's best interest to develop at least a basic understanding of a wider range of basic sciences and mathematics. Depending on the research area, this may take on a diversity of forms: quantum mechanics, cell biology, thermodynamics, and so on.

The mastery of fundamentals in these non-EM areas allows students to build bridges and effectively contribute to multidisciplinary research problems. A contemporary graduate EM curriculum should be flexible enough to allow for the development of an understanding of the fundamentals in the appropriate complimentary fields. Research problems of interest in our community and of significance for society span quite a broad spectrum; thus, a one-size-fits-all prescription of what these complimentary fields of study is not advised.

Part of this multidisciplinary education is related to CEM, in the development of numerical methods for emerging problems. This is particularly relevant in research dealing with nonstandard cross-disciplinary problems, including multiple scales, multiphysics, or new exotic materials. Clearly, the level of sophistication of computational research currently leaves little space to address the practical applications of newly developed methods in the timeframe of a Ph.D. candidature. Nevertheless, beyond academia, graduates in this area will gather competences in high demand. This places them ideally not only for employment in scientific software development but also for design and engineering work. Indeed, a background in numerical methods builds the strongest basis for the most effective use of software tools.

CONCLUSIONS

First, it is clear that some level of fundamental understanding of CEM is necessary in this age in which the use of commercial CEM simulation tools is ubiquitous but the intelligent use of such tools is not. Early in a student's graduate studies is arguably the best time to acquire this knowledge, as it can serve as a foundation for the usage of various CEM tools throughout one's Ph.D. research pursuits and beyond. Second, multidisciplinary training in non-EM sciences is becoming more essential. As most Ph.D. programs require the completion of course work in a secondary area of minor subject, EM students should work closely with their research advisors to select a set of complementary courses that round out a multidisciplinary foundation appropriate for his/her specific research area. New textbooks integrating traditional EM with multiphysics or multiscience knowledge would be useful. Third, as a community, we may want to encourage more collaboration on multiphysics CEM by creating public websites and/or online forums for sharing codes and algorithms for problems that commercial simulators cannot accommodate.

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