AN INTERDISCILINARY SIMULATION-BASED LABORATORY FOR UNDERGRADUATE WIRELESS COMMUNICATIONS EDUCATION

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ABSTRACT

In this paper, we offer information concerning a state-of-the-art Radio Frequency Computational Laboratory (RFCL) that has been implemented within the Systems Engineering Department (SED) of the Donaghey College of Information Science and Systems Engineering (Cyber College) at the University of Arkansas at Little Rock (UALR). We present our experience in delivering a pedagogical approach conducted for the past three years using commercial Computer-Aided Design (CAD), simulation, and visualization tools to deliver fundamental background, link theory to real world applications, and improve skills in three interrelated disciplines: Electromagnetic (EM) waves and fields, antennas, and RF components design. Many students find these materials in a traditional course environment abstract and dry. The RFCL makes them seem more concrete, providing a high-level technical expertise, reinforce physical principles and mathematical analysis offered in the class, foster students motivation and enthusiasm, and stimulates undergraduate students participation in research. The implementation of the proposed curriculum approaches proved to be highly motivational and educational. The majority of the students appear more motivated to tackle the difficult theoretical and physical principles in the courses as they become more aware of their relevance in engineering application.

1. INTRODUCTION

Contemporary communications systems encompass integrative components-to-systems challenges, merging a diverse range of interrelated software and hardware disciplines to which most undergraduate systems engineering students have little exposure: communication theory, Digital Signal Processing (DSP), RF, Very Large Scale Integration (VLSI), battery technology, EM waves and fields, antennas, and propagation [1]. Considering the breadth of advanced technical background level required, special strategies and tools are needed to impart knowledge in a hands-on fashion. Textbooks provide well-established theoretical treatment and fundamental principles using simple canonical problems, but CAD tools offer unique pathways to introduce students, while they are still in the classroom setting, to current industrial approaches for learning design that otherwise can only be obtained through painstaking and time-consuming experimental iterations.

The fundamental importance of EM waves and fields problems can hardly be in doubt; they arise in diverse areas such as electrical machines and apparatus, super conducting techniques, radar systems, antennas, MMIC, RFIC, PCB, Bluetooth transceiver, mobile phones, and optical communication systems. Furthermore, as clock frequencies increase and pulse rise times drop below a nanosecond, the inclusion of high-frequency physical attributes based on rigorous understanding of EM wave phenomena in the design process of modern digital components become mandatory to achieve reliable systems with low cross-talk and pulse degradation.

High-density, wideband electronic packaging cannot be treated as lumped elements; transmission-line, inductance, and stray capacitance phenomena, which are the dominant factor limiting top speed, need to be taken into account.

It is generally acknowledged that "fields" in any discipline are one of the most abstract and conceptually difficult subjects where most students have difficulty comprehending [1]-[3]. The exposure of our undergraduate students to EM waves and antennas is limited to a one-semester core course, SYEN 4356: *Electromagnetic Waves and Antennas* and a technical elective SYEN 4357: *Advanced Antennas for Wireless Communication*. The high level of mathematical agility, abstract concepts, and vector operations on 3-D spatially and temporally varying field quantities tend to frustrate a student who has been dealing mostly with scalar quantities.

A heavy reliance on mathematical analysis often obscures intuitive understanding of basic concepts and requires a long learning cycle to conceptualize the underlying physical concepts. Additionally, closed-form analytical solutions are only available for highly symmetric, oversimplified geometries. Very often, even simple problems are analytically intractable, and hand-based calculations cannot be used. This poses challenges to the educator seeking to provide a broad and deep background to students enrolled in these courses.

From an industrial point of view, computer-based modeling reduce the cost of developing new ideas and allow users to quickly test new products without costly prototyping and experimentation. For these reasons, we have developed an interactive teaching and learning paradigm for introducing students to EM waves and antennas, which involved a switch from the conventional lecture-based approach to team-based project-driven venture using CAD tools in integrated laboratory/classroom environments to enhance the student educational experience and help them gain a more thorough appreciation of the physics upon which high-frequency principles are based.

In light of the current industrial trend towards utilizing CAD for the analysis, design, optimization, management, and deployment of wireless communications systems, it is imperative that academia respond to these technological advances and make appropriate changes in research and teaching missions with a great deal of emphasis on system design issues. We seek to equip students with the fundamental knowledge required to build productive careers spanning several technological generations and to cope with today's environment that calls for immediate on-the-job productivity and the ability to work in quickly changing themes.

In the traditional pedagogical process of delivering a typical EM and/or antenna course, lecture is the main mode of instruction. Traditionally, the presentations are top-down, from the abstract to the empirical. Emphasis is primarily on solving the types of problems found at the end of the chapters in textbooks that are appropriate for the chalkboard. For most students this is a passive learning experience that cultivates the belief that finding the right formula is the key to solving a problem. It should be noted that many of simulation software vendors provide free student versions while the full version are readily available to educational institutes for little to no cost.

The RFCL creates opportunities for undergraduate student teams to work on less procedural, discovery-based, open-ended problems with direct relevance to real-life experience to acquire the modeling expertise necessary to simulate the design and testing of new ideas in a virtual laboratory environment, produce professional-quality reports and presentations, and develop lifetime learning practices. This research environment can play a role to bridge the gap between teaching and learning.

Students analyzing the transient EM fields of a device, circuit, or antenna produced by an impulse-like excitation can observe its characteristics over a broad range of frequencies via a discrete Fourier transformation using a single time-domain analysis. Students can test many configurations in order to compare their merits and to evaluate the influence of different parameters on the phenomena. The simulation tools combine the functionality of a network analyzer, a spectrum analyzer, and a digital signal processor. Students contribute their elements to the simulated model and can investigate how the performance of their subsystem impacts the overall performance criteria.

The focus of this paper is to improve the learning experience in two courses: SYEN 4356 and SYEN 4357, each of which is offered once a year. These courses are offered simultaneously at the undergraduate and graduate level. This dual offering is accomplished using stratified assignments, whereby graduate students are required to perform at a higher level than the undergraduates in the same course. Lecture and laboratory work are combined into a single three-credit-hour course, with the same instructor handling both facets to provide tighter coordination. Classes are presented as two 50-minute lectures a week; the remainder time is allocated to laboratory work. The lectures are carefully sequenced to remain in step with the laboratory/demonstration sessions throughout the semester to enrich the students' understanding. To allow time for relatively sophisticated design projects while keeping a reasonable workload on students, we do not give traditional assignments. Instead, students are required to complete three projects over the semester in topics of current interest in the wireless industry.

3. GOALS AND OBJECTIVES

An engineering educational experience combines a theoretical inquiry of a topic with an experiment, which illustrates the concept. The difficulty of orchestrating this combination is more pronounced in EM waves and antennas, owing to their abstract character. Students registered in SYEN 4356/5356 and 4357/5357 are subjected to rigorous analyses and design techniques. However, due to time constraints and the need to cover a wide range of topics in the curriculum, little time exists for building an intuitive feeling for the subject. In addition, hardware-based laboratories for experiments in EM and antennas or those requiring RF, microwave, and millimeter components and test equipment are often prohibitively expensive to acquire and maintain. It must be emphasized that such hardware resources are currently unavailable in our institution.

Due to their inherent fascination, visualization and simulation tools are widely used for objects that cannot be seen because they are too fast, too small, too large, and too complex or because they exist only as theories or data sets. Simulation is the method of choice where the acquisition of skills in real-world situations would be dangerous, unethical, logistically difficult, time-consuming, or excessively costly. Interactive learning is placed under the control of students, allowing a safe environment where students can learn from their mistakes without penalty. Perhaps more importantly, modeling tools enhance the students' abilities to work well in teams, communicate effectively in written and oral forms, and solve open-ended problems. Abstract mathematics need no longer be the sole approach of analysis. Students whose strengths might lie instead in numerical and computational analysis, algorithm development, and programming can become productive contributors as well.

An instructor's multimedia presentation during a lecture is considered to be a passive use of technology. In contrast, a student who can control a simulation environment is making an active use of such technology. The difference between passive and active use of technology is similar to the difference between watching a laboratory demonstration and performing an experiment. Aside from making the learning experience more interesting, a well-designed experiment can challenge the student and encourage creativity. We are planning far beyond textbook delivery and homework assignments. The emphasis is to influence and favorably change the students' intellectual, analytical, innovative, and integrative abilities. Our methodology essentially combines the pervasive presence of PCs and commercial CAD and simulation tools to develop a project-driven curriculum that offers truly hands-on laboratory experiences at a reasonable cost.

The goals of the RFCL are to expose students to class rhythm and activities that will create an atmosphere of self discovery and experimentation; to break the passivity of traditional lecture formats; to foster creative thinking; to highlight the relevance of high-frequency effects for modern telecommunications applications by integrating modeling and simulation in subjects that cut across three interdisciplinary areas: EM fields and waves, antennas, and RF circuits and systems; to integrate high-frequency, physics-based EM simulations, modeling, and optimization into a seamless environment for circuits, devices, and systems analysis; to advance the students' understandings of the concepts by introducing fundamentals with the context of applications; to make learning more enjoyable and challenging; and to give students a sense of accomplishment. Also, there are distinct advantages in having a teaching aid that can double as a research tool.

The RFCL enhances the infrastructure for undergraduate research, a strong component of our program, providing an easy bridge between learning and doing, and integrate research activities into the teaching of several graduate courses in the Cyber College's Applied Science Department. This provides an environment in which undergraduate students, graduate students, and professors speak a common language. It should be noted that mathematical analysis cannot be dispensed with entirely, but our objective is to make the subjects under consideration accessible to students from a wider range of abilities and inclinations.

The RFCL is currently equipped with CST's Microwave Studio and Design Studio (MWS) and the Ansoft's software packages: Maxwell 2-D, Maxwell 3-D, Ansoft Designer, High Frequency System Simulator (HFSS), ePhysics, and Optimetrics. HFSS and MWS yield detailed analysis of EM fields associated with a specific component, structure, circuit, or subsystem. They are employed for (i) developing accurate models for coaxial, waveguide, and microstrip transmission line discontinuities, (ii) developing designs incorporating the effects of spurious EM mutual couplings in microwave and millimeter-wave circuits, (iii) analyzing and designing antenna structures and integrated-circuit antenna modules, and for (iv) analyzing the radar scattering cross sections of objects exposed to EM radiation.

4. THE TEACHING SCENARIO

HFSS and MWS are easy to use for both students and instructors, and require little familiarity with numerical methods. Students are introduced to the simulation tools through a series of structured assignments. Initial problems are simple and designed to get the students over the "computer phobia" hurdle. Subsequent assignments involve simple 3-D real-life design issues.

The applications should not replace the presentation of theory. Instead, applications are used to explain fundamental theoretical concepts. In the early stages of their studies, students can see the utility of simulations for analyzing complex problems and the role of basic theory in practice. This allows the students to experience EM waves and antennas as they are encountered in practice and requires that they deal with real-world ambiguities and limitations.

Students are given control of the 3-D environment to set up experiments and view results in an attempt to tie together a number of important skills and concepts. The simulation tools are not only interactive but also informative in real time. Students work in small cooperative groups and share their findings more widely with other members of the class. The simulations allow the students to explore how the design performance will be affected if the value of a design parameter were to be altered either intentionally or because of the unavoidable tolerances in the components' values or in the fabrication process. It has been our experience that there is a tendency for a number of the very best students to be stimulated by the use of HFSS and MWS that they choose to do their senior design courses using these tools.

HFSS and MWS are used extensively to give students experience in dealing with problems that reflect much of the complexity of the real world, characterize realistic project scenarios and devices, make changes in shapes and materials, optimize and parametrically investigate existing designs, and experiment with new designs. Simulation results are compared to those available from analytical/experimental results, or both when available. Conclusions are drawn regarding the solvers' accuracy with respect to experimental/analytical values.

A laboratory manual detailing each experiment has been developed to serve as the laboratory text. A step-by-step description of each experiment is provided along with an input file for the simulation procedure, which allows full interactivity.

These experiments are fundamentally different from regular hardware-based experiments, which are intended to verify theory. The two sets of experiments are not mutually exclusive, simulation-based experiments should also be used for verification purposes to close the feedback loop of learning. Students are required to solve realistic problems. Ordinarily, this would be a time-consuming task, so we provide the students with the tools necessary to make these tasks manageable.

4.1 SYEN 4356: Electromagnetic Waves and Antennas

Basic concepts in calculus, analytic geometry, linear algebra, physics, and electric circuits and systems are prerequisites. Basic EM is also taught in physics courses in the first two years, encompassing electricity and magnetism and introduction to wave propagation and optics. The first three lectures are devoted to the physical interpretation of the vector operations: gradient, divergence, curl, and ending with Helmholtz theorem for vector fields. The concept of field is defined at first, in terms of its measurable effect; electric and magnetic forces.

Students are introduced to EM through electrostatics including dielectrics, continuity equations and steady currents and magnetostatics including magnetic forces and media. In contrast to classical EM courses, only 20% of the total course hours are allocated to electrostatics and magnetostatics. This is followed by Faraday's law, Maxwell's equations, and the Poynting vector. The topics discussed next are: transmission line theory, Smith chart, plane wave propagation in conducting and dielectric media, coaxial cables, waveguides, cavity resonators, and finally elementary radiation and antenna theory including antenna radiation characteristics and radiation by currents flowing in wires such as short dipoles and dipoles of arbitrary length. At present, we use the text *Fundamentals of Applied Electromagnetics*, by Fawwaz T. Ulaby, Prentice Hall, 2004 Media Edition.

Due to space limitations, only a brief description of a single laboratory demonstration is provided. In the first part of each demonstration, the following features are explained in detail: structure definition with the GUI; mesh generation; implementation of sources; port definition for scattering parameters; simulation set-up and control; post-processing; field animation; and optimization of critical parameters to achieve an objective function.

A typical application that brings research into the classroom includes a microwave-heating problem using loads of different electrical properties [4]. Figure 1 depicts the cavity under consideration. It consists of a section of a 3.175-mm thick WR 975 waveguide (24.765 cm × 12.3825 cm) terminated by an adjustable short-circuit plunger at one end and a conducting plate containing a circular iris at the center of the transverse wall on the other end. Microwave energy is injected into the cavity via an adjustable coupling iris.

When positioned properly, the tuning plunger ensures that the cavity is tuned at a resonant frequency of 915 MHz. Samples are introduced via a 25.4-cm long, cylindrical choke tube of 6.985-cm inner diameter, which

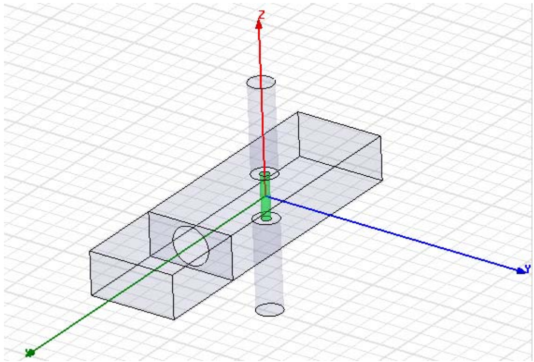


Figure1. Geometry of the TE_{103} resonant cavity

mitigates leakage of microwave energy, passing through the broad wall center near the region of maximum electric field strength.

Every design process involves a number of approximations. For examples, in arriving at the initial design, we normally assume the waveguide to be lossless and ignore the effects introduced by the coupling aperture to make the design process tractable. However, we know that in real life these waveguides have finite

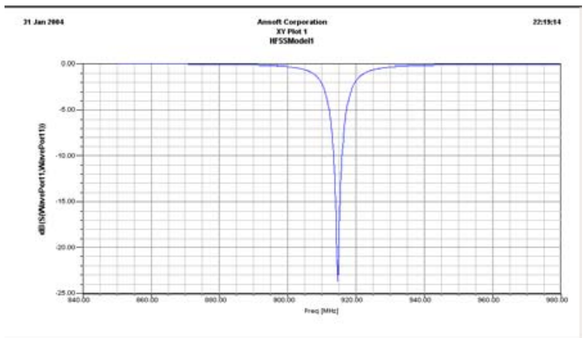


Figure 2. S_{11} versus frequency, the load has a dielectric constant of 4.5-j0.45

conductivities and that the coupling mechanism affects the resonant frequency and the quality factor. Losses due to the aluminum cavity walls and the feed to the cavity are next investigated by employing surface-impedance boundary conditions. Students computed the loaded Q-factor, optimum iris size to achieve critical coupling, and shift in resonant frequency caused by the introduction of the processed materials.

The Ansoft optimization module, Optimetrics, is used to infer the optimum iris diameter to achieve maximum electric field strength within the processed material. According to the graph shown in Figure 2, minimum reflection occurs at an iris radius of 5.3cm. The loaded Q factor is found as 275.11. Power deposition patterns, a typical example of which is shown in Figure 3 are essential in evaluating the temporal and spatial temperature profiles--a problem that is the subject of much current research interest in microwave material processing.

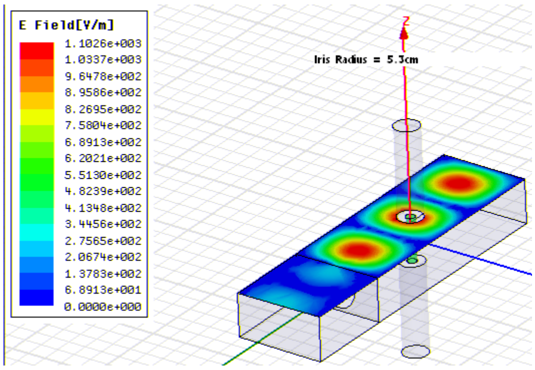


Figure 3. Electric field distribution for the optimum iris size

4.2. SYEN 4357: Advanced Antennas for Wireless Communications

Introduces advanced concepts in antenna theory and design techniques applicable to new generations of compact internal antennas for wireless communication devices. In addition, the course develops appreciation for research issues in antennas and propagation for mobile wireless systems. It provides the current state of antenna array research and describes how an antenna array may be used to help meet the ever-growing demand of increased channel capacity and coverage area for mobile communications services. The course uses *Antenna Theory and Design* by Stutzman and Thiele, New York, Wiley, 1998 and covers EM theorems before treating wire antennas, array, planar, and microstrip antennas. We have also used manuals, recent journal publications, and the author's own notes. Lectures provide the theoretical framework of EM, and simulation laboratories involving computer explorations with realistic devices back up the theory.

The following simulation example, performed using HFSS is intended to analyze a horn antenna. Horn Antennas are extremely popular in the microwave region. In this tutorial, our objective is to analyze a horn antenna resonating at a frequency of 11.3 GHz. The dimensions of the problem, shown in Figure 4, are: air box: 6 in × 4 in × 3 in, horn top: 1.944 in × 2.65 in, distance from the horn top plane to the bottom is 5.475 in and from the horn top plane to the base of the horn is 5.16 in.

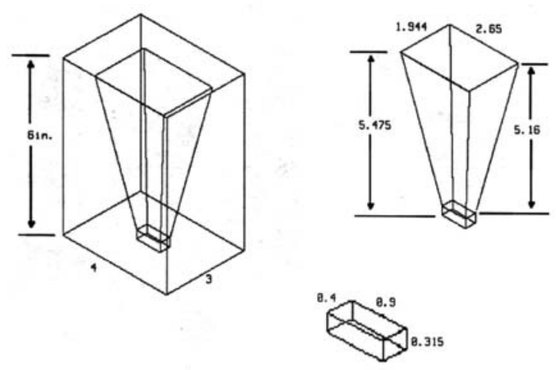


Figure 4. Geometry of the horn antenna

Figure 5 depicts the frequency spectrum of S_{11}

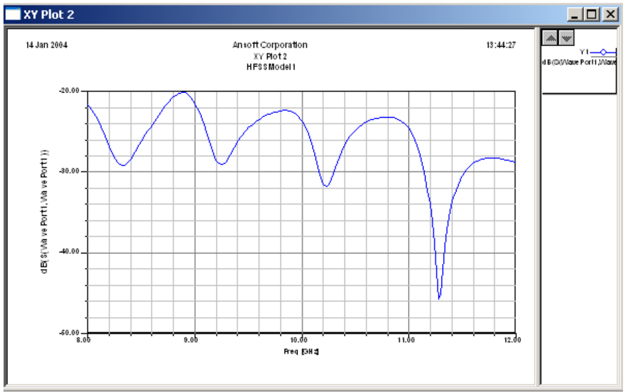


Figure 5. S_{11} versus frequency

5. RESEARCH PROJECTS

Students are involved in various research projects that will allow them to better grasp the significance of Maxwell's equations and gain physical insight into what could otherwise be a sea of mathematical manipulations. Two students may collaborate on the project if it is of sufficient scope, and the contributions of each student are clearly delineated.

At the beginning of the course, the instructor defines the objectives of the projects and offers initial guidance and procedures. The students organize themselves into one or more teams as necessary, and decide how the work to be allocated. Each project illustrates a concept and encourages the students to examine the concept in depth. These projects should improve the students' understanding of the concepts and make learning more enjoyable and challenging.

The project is a problem-based design assignment. The aim is learning by doing and by searching for the knowledge needed for the project assignment. The objective of the project is for students to digest a wider range of emerging topics and design techniques that are not covered in the class. The project has a time-plan with milestones, oral presentations, and written reports. This has a pedagogical motivation in that application-oriented projects are more effective than simplified problems in generating student interest. The author readily involved undergraduate systems engineering students in research-oriented special projects. As an example, two of our seniors were involved in integrating a Planar Inverted F antenna (PIFA) on a mobile handset, as shown in Figure 6. The DCS 1800 GSM handset, operating over the frequency band 1.71 to 1.88 GHz, is modeled as 80 mm × 40 mm × 10 mm plastic box. The horizontal element of an inverted F antenna is transformed from a wire to a plate. For a further reduction in size, a capacitive load is added. PIFAs, as internal antennas, have the desired features of compactness, moderate bandwidth, higher gain in principal planes for both polarizations and less prone to breakage as compared to external antennas.

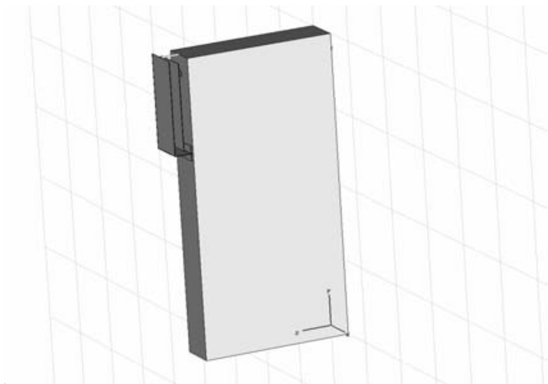
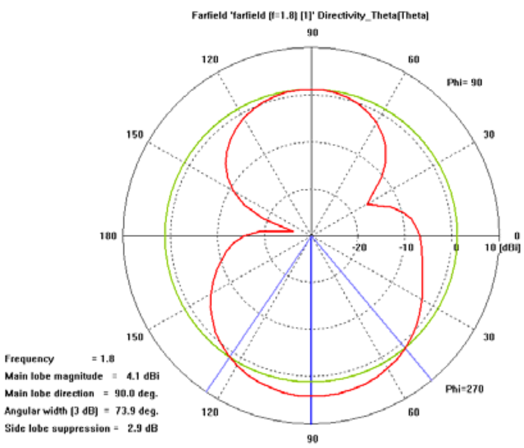


Figure 6. Geometry of a PIFA mounted on a handset

The E_ϕ and E_θ radiation patterns of the mounted antenna are shown in Figure 7.



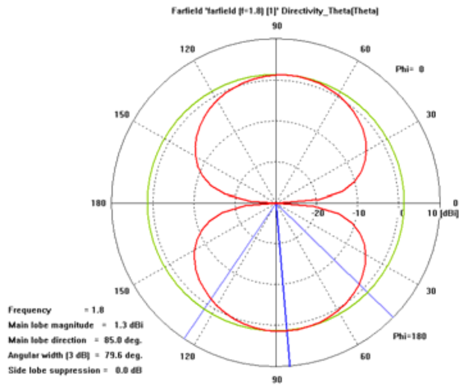


Figure 7. E_ϕ and E_θ radiation patterns of the PIFA mounted antenna

6. CONCLUSIONS

In this paper, we presented and overview of an innovative laboratory/classroom learning paradigm that incorporates state-of-the-art CAD and simulation tools to perform and verify RF design, parametric analysis, and optimization in realistic world situations. The distinguishing feature is the integration of breakthrough technology as a bridge between classical theory and industrial practice to reinforce knowledge about solving complex open-ended problems not possible in traditional lecture environments and to foster integration of research and teaching in the courses. It is imperative that our students be trained to use these tools and acquire hands-on learning and research activities early in their careers, thereby gaining the experience necessary to tackle real-world challenges and developing sufficient skills and confidence to conduct a comprehensive senior research project.

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