Seattle
Making Value for Society
122nd ASEE Annual
Conference & Exposition
June 14 - 17, 2015
Seattle, WA

Paper ID #11316

Scientific Foundations of Engineering: A New Curricular Model for Engineering Education

Prof. Stephen W. McKnight, Northeastern University

Stephen W. McKnight received a B. A. in Physics from Oberlin College in 1969 and a Ph. D. in Solid State Physics from U. Maryland-College Park in 1977. After completing a National Research Council Fellowship at the Naval Research Lab, he joined the faculty in the Physics Department at Northeastern University in 1980. In 1985, he took an appointment in the Center for Electromagnetics Research, an NSF-sponsored Industry/University Collaborative Research Center. In 1987 he was appointed Associate Professor in the Department of Electrical and Computer Engineering at Northeastern and in 2001 was promoted to Full Professor. Since 2000 he has been the Education Thrust Leader for the Center for Subsurface Sensing and Imaging Systems, an NSF Engineering Research Center headquartered at Northeastern, and since 2010 he has served the same role for the Department of Homeland Security ALERT research center at Northeastern. He has published over 40 refereed journal publications on microwave, far-infrared, and optical materials and devices, served five terms on the Northeastern University Faculty Senate Agenda Committee including two terms as the elected Secretary of the Faculty Senate, and wrote the department's self-study report and coordinated the site visit preparations for the Electrical and Computer Engineering ABET accreditation in 2001. In 2004-2005 Prof. McKnight served as Interim Chair of the Electrical and Computer Engineering Department.

Prof. Christos Zahopoulos, Northeastern University

Christos Zahopoulos is Associate Professor at Northeastern University, with a joint appointment in the College of Engineering and the Department of Education. He also is the Founder and Executive Director of Northeastern University's Center for STEM Education (www.stem.neu.edu). For more than 20 years, Professor Christos Zahopoulos has been actively involved in STEM Education at the local, state and national levels, playing a key role in initiating and implementing numerous STEM Education programs and partnerships, which have received close to $30 million in grants and gifts. He serves in numerous STEM Education Boards, including the Governor's STEM Advisory Council. Professor Zahopoulos received his Ph.D. degree in Physics from Northeastern University and was a Postdoctoral Research Fellow in the Division of Applied Sciences at Harvard University.

Scientific Foundations of Engineering:
A New Curricular Model for Engineering Education

Introduction

Traditional physics undergraduate education has used a "spiral curriculum" method[1]: mechanics, waves, statistical and thermal physics, electromagnetics, and quantum physics are introduced in a freshman-level survey course; each of these subjects is covered again at a higher level in sophomore and junior level courses; and selected topics are revisited in senior-level "special topic" or advanced study courses. This model allows for deepening understanding of each topic and the application of more sophisticated mathematical methods – such as complex analysis, differential equations, integral transforms, matrix methods, and linear algebra – as the students' mathematics preparation progresses. In addition, the connections between each subfield of physics become apparent from the early survey courses and from the application of similar advanced mathematical techniques at each level of coverage.

In contrast, most engineering students take all of their basic physics and chemistry during freshman year in survey courses, which are commonly perceived to be unpopular hurdles into the study of engineering. After this early cursory exposure to the science, engineering students spend the rest of their undergraduate education focusing on the details of electrical, mechanical, civil, or chemical engineering in which applications take precedence over scientific foundations to the extent that electrical engineers, for example, typically assume that Kirchhoff's voltage law is always true despite its obvious violation of Faraday's law of induced EMF. The danger of this premature specialization of engineering education becomes apparent when engineers from one discipline work in teams with engineers from other disciplines and find they have no common understanding of problems outside of their own engineering discipline. [2]

The authors have collaborated in teaching an advanced survey course on the physical science foundations of engineering to graduate engineering students in an engineering leadership program. The elevator speech on why such a course is needed goes as follows: 1) most engineering students take all of their basic science courses during their Freshman year, 2) most of them don't like those freshman courses very much, and 3) they forget the material as quickly as they can and concentrate on the specifics of electrical engineering, or mechanical engineering, or other engineering discipline where their interests and enthusiasm lies.

This summary may be unfair to some engineering students, but most engineers (and their professors) at least grudgingly admit that it isn't terribly far off. And, in general, this approach serves the students well through their undergraduate education process and in their industrial careers – as long as they remain specialized in their specific engineering discipline.

However, consider the case where an electrical engineer is leading a multidisciplinary project. One day a mechanical engineer who reports to her walks into her office and says, “Boss, this isn’t going to work – we can’t get the heat out!” A conventionally trained electrical engineer isn’t likely to be able to frame a single substantive question about the problem. She hasn’t studied heat transport or thermodynamics since the freshman year (if at all!), and certainly has forgotten anything she ever knew about the subject. The ability to frame questions which put fundamental boundaries on the problem, “What is the power load? How hot will the device get? How much blackbody emission is there at that temperature? What is the thermal conductivity of the substrate?”, will not only enable an engineering leader to quickly frame the gravity of the problem, but will undoubtedly earn her a reputation as someone with whom you want to have done your homework carefully before making rash statements about engineering limits!

Among the topics that the typical quick pass through scientific fundamentals causes to be neglected or skipped in most engineering educations is the entire field of quantum science. Despite the critical and growing importance of nanoscale quantum science on nearly every electronic device we use or carry on us, we suspect that most engineering professors would be surprised by how few engineering students or professional engineers can give even a rudimentary description of the source of semiconductor band gaps, the distinction between metals and insulators and semiconductors, or how a p-n junction or micro-mechanical device works!

Finally, if the process of engineering can be thought of as designing under constraints, where some of the important constraints are the laws of science which span different disciplines, shouldn’t all engineers have adequate understanding of these laws?

Scientific Foundations of Engineering

This lack of depth of understanding of fundamental scientific principles and lack of any formal instruction in the science of quantum systems is what we intended the “Scientific Foundations of Engineering” course in the Gordon Engineering Leadership Program at Northeastern University to address. The Gordon Engineering Leadership Program, the recipient this year of the National Academy of Engineering Gordon Prize for innovation in engineering education, has the goal of fostering the development of engineers who have the rare and highly-prized ability to lead an engineering project all the way from concept to a marketable product.

Our model for the “Scientific Foundations of Engineering” course seeks to increase the confidence with which a well-trained engineer can approach an unfamiliar problem and quickly recognize the fundamental principles and use them to make “back-of-the-envelope” calculations about how large an effect each may have. Even a little bit of this ability to understand the basic physical laws underlying a phenomenon, to place a problem in context, and to estimate the size of various influences on a system can give an engineering leader the ability to direct a project through proof-of-principle experiments and make-or-break decision points to a marketable product. An important goal of the Gordon Engineering Leadership program is to develop engineers with gravitas, to whom no area of engineering is outside of their sphere of understanding in the “here be dragons” area of the unknown. Developing the knowledge of scientific fundamentals in the “Scientific Foundations” course is essential to achieve this goal.

In looking for a book to teach the “Scientific Foundations” course, however, the authors found only freshman survey texts that did not make use of advanced mathematics and were intended for readers who were new to the study of science and engineering or highly theoretical books for professional physicists, which lacked examples meaningful to engineers, but no book suitable for the intended audience. Since available physics texts are not well-designed for the target audience of advanced engineering students, the authors have written a draft text *Scientific Foundations of Engineering* which has been accepted for publication by Cambridge University Press and will become available in July 2015. This book combines a unified treatment of classical and quantum physics with a wealth of worked examples with an engineering flavor. Each chapter typically begins with a question about physical phenomena that engineers may know and have wondered about. This approach helps put the treatment of the physics in a context of what the implications of the theory are and why anyone would want to know about it.

Advanced engineering students have often used sophisticated mathematical techniques in their disciplinary training to treat phenomena such as harmonic oscillator resonances in mechanical systems and electromagnetic response of materials. In our course, and in our pending book, such similar phenomena that cross disciplines are treated in a unified manner, showing the conceptual connection between them. Both the class and the text have been informed by our experience that engineers respond well to theory illustrated by examples – particularly examples with an engineering flavor. In a feedback survey administered to the students who are presently taking the class, 79% of them indicated that these solved problems helped them understand the concepts in the text, despite the fact that 75% of them found the concepts difficult or very difficult.

A Model Curriculum for an Advanced “Scientific Foundations of Engineering” Course

The curriculum for the “Scientific Foundations of Engineering” course that we have been teaching, and in the book, is outlined below.

1. Kinematics and Dynamics

We begin the course by addressing kinematics in the broadest framework to understand the limits of reaching for the “d-equals-one-half-a-t-squared” solution, and how this low-order solution can be used iteratively to find solutions even outside the limits of constant acceleration problems.

Dynamics are considered next on the basis of Newton's equations, where we untangle the maze of definitions and empirical observations contained in Newton's laws of motion based on the treatment of Weinstock[3]. For example, Newton's First Law – an object at rest remains at rest and an object in motion remains in motion in a straight line at a constant speed – can best be considered as a definition of an inertial reference frame, which is only approximated by horizontal motion in a classroom on the earth's surface (as demonstrated by the Coriolis "force"). Given an inertial reference frame, the Second Law combines the definition of a (net) force – a push or pull that creates an acceleration – with an empirical assertion: individual forces applied at the same time to an object add like *vectors*. Similarly, the Third Law combines a definition of inertial mass (the ratio of the acceleration or force on two interacting objects) with an empirical assertion that the accelerations are oppositely directed. This leads directly to conservation of momentum – an even more fundamental law than conservation of mechanical energy which is, of course, violated whenever heat is generated.

In these chapters and throughout the book, with few exceptions, we consider examples only in Cartesian x-y-z space. While many real problems are best addressed in cylindrical or spherical coordinates, the concepts are fundamentally the same and we have opted for conceptual clarity over computational completeness.

2. Rotational Motion

Next we discuss rotational motion and use the generalization of the scalar mass in linear motion into a moment of inertia tensor in rotational motion as a way to introduce the concept of tensor quantities. The linear motion concepts of force, momentum, and energy are similarly generalized into torque, angular momentum, and rotational kinetic energy with the fundamental principles of conservation of momentum (always!) and conservation of mechanical energy (in ideal systems that do not generate heat) reinforced. We introduce rotation matrices to deal with cases where tensor quantities are not aligned with the principal axes. Rotation matrices can be used to transform any tensor quantity or response function into relevant system axes. As an example, the generalization of an isotropic mass into an effective mass tensor for electrons in anisotropic materials is considered.

3. Elasticity

With the fundamental mechanical laws established, the role of materials is introduced in the fundamental property of elasticity. Shear and compressive stress and strain are shown to be elements of the 3x3 second-order stress and strain tensors, making elasticity that links stress and strain a fourth-order elastic tensor, which can be reduced by symmetries to a 6x6 symmetric tensor with 21 independent material parameters. This is further reduced in isotropic materials to an elastic tensor with three independent parameters: the Young’s modulus, the shear modulus, and the Poisson ratio.

4. Simple Harmonic Motion

Simple harmonic motion of a system with a linear restoring force and a velocity-dependent loss mechanism is discussed with and without a harmonic driving force. The use of Euler’s relation to describe oscillatory motion with amplitude and phase by a complex exponential is introduced, allowing the inclusion of a small imaginary part to model the loss mechanisms. The identical form and solution of an LCR electrical circuit with the spring-mass system is shown, with complex exponentials representing the charge and current leading to the electrical engineering method of complex impedance.

5. Waves

Next, harmonic motion in time is extended to systems with spatial coupling, creating the phenomenon of waves in mechanical systems: one-dimensional waves in strings and three-dimensional sound waves in fluids. By continuing the complex exponential notation for the wave oscillation, lossy media, interference in films or from multiple sources, and diffraction phenomena can be modeled with a complex exponential wave form with a complex wave vector. The nature of boundary conditions in mechanical systems and how they lead to reflection and transmission coefficients is presented with examples in sonic reflection from surfaces and layers.

6. Quantum Science

With the use of complex exponentials for waves introduced, we provide an introduction to quantum physics and chemistry. We begin by discussing the historical origins of quantum theory, why it was such a radical departure from classical physics, why it became necessary to accept such a totally different approach to understand the world, and why the “quantum picture” continues to be anti-intuitive and difficult to accept. Next, we examine the postulates of quantum mechanics and how we can “shut up and calculate” everything that is determinable for quantum systems, including tunneling, and low-dimensional quantum systems, such as 1D and 2D quantum wells. We then extend the quantum analysis to real systems from quantum dots to the hydrogen atom and touch on the chemistry of the “s-p-d-f” quantum states and hybridized outer orbitals. Finally, we look at electrons in extended lattices with band states with both direct and indirect band gaps, and how these are necessary to understand the electronic properties of metals, insulators, and semiconductors, and optical interactions such as in light-emitting diodes.

7. Thermal Physics

Next, we look at thermal physics from the perspective of random equipartition of particles into energy states, extending into thermal transport, thermal equilibrium, heat capacity, and thermodynamics, including entropy and Helmholtz and Gibbs free energies. As an extension of classical thermodynamics, we consider how equipartition is modified by the quantization of the available energy states. We follow by studying thermal effects through the mathematics of quantum statistics: Maxwell-Boltzmann statistics for classical distinguishable particles, Fermi-Dirac statistics for quantum indistinguishable particles that obey Pauli's Exclusion Principle ("fermions"), and Bose-Einstein statistics for quantum particles, such as photons, that do not have any restrictions on the occupancy of a single quantum state ("bosons"). The differences in the occupation of states for the three different statistical models is demonstrated though a simple "thought experiment," and the different statistical models are developed in the examples of blackbody radiation (photon/boson statistics) and semiconductor occupancy and p-n junctions (electron/fermion statistics).

8. Electromagnetic Properties and Materials

Next, we look at electromagnetic theory, effects, and materials. First, we develop Maxwell's equations in the mathematics of vector calculus ("div, grad, curl"), using Gauss's and Stokes' theorem integral relations to move from the four Maxwell's equations and the electromagnetic Lorentz force equation to understand a wide variety of electromagnetic effects: Faraday effect, electrical generation, eddy currents, transformers, and electromagnetic motors. Starting from the four Maxwell's equations in differential form, we then develop the electromagnetic wave equation and apply it to examine wave propagation in uniform, lossy, and anisotropic materials. The electromagnetic boundary conditions are derived and applied to plane-wave reflection at surfaces at both normal and non-normal incidence, and to interference effects in thin films. Next, electromagnetic wave propagation in materials is studied from the viewpoint of the constitutive relations and the material-dependent tensor permittivity, conductivity, and permeability. Physical models are used to develop examples including the plasma edge in gases, semiconductors and metals, Lorentzian oscillators in the infrared properties in polar crystals, in quantum absorption in transparent gases, and ferromagnetic resonance in magnetic materials.

9. Fluids

Finally, we provide an introduction to the physics of fluids, using mechanical concepts for static fluid effects, such as buoyancy, and vector calculus from electromagnetics to develop the continuity equation, Euler equation, Bernoulli equation, and Navier-Stokes equation for moving fluids. The transition from laminar to turbulent flow with increasing Reynolds number, still one of the most important unsolved scientific problems, is presented.

Throughout, we have emphasized the connections between concepts and phenomena in different fields and the similarity of the mathematics used to describe them: how a spring-mass Lorentzian harmonic oscillator described by a complex exponential leads to familiar expressions in AC electrical circuits, in infrared properties in crystals with optical phonons, and in quantum-energy-level absorption lines in gases and transparent solids. Or how anisotropic materials effects in elasticity, electrical permittivity, or magnetic resonance can be described by tensor properties similar to a general description of rotational motion with a tensor moment of inertia. The ability of a scientist or engineer to apply models and concepts from their area of specialization to new phenomena in different limits can serve to demystify unfamiliar technologies and allow them to apply their knowledge to novel systems.

We have, with regret, left out the topic of relativity since it seems theoretical and divorced from most engineering practice, despite its relevance in GPS satellite systems. We also have no discussion of subatomic physics. We have taught most of the material above in two semesters of a 2 SH graduate course. It could also be taught as a one-semester 3 or 4 SH junior- or senior-level elective in an electrical or mechanical engineering program, although the instructor would be well-advised to pick and choose among what topics to include. The introduction of Maxwell’s equations in differential form and the derivation of the electromagnetic wave equation and optical properties of materials could be particularly useful for any engineer in a world suffused by microwave and optical technology.

Student Response to the “Scientific Foundations” Text

The current class of the Engineering Leadership program has had access to the final draft of the “Scientific Foundations of Engineering” text during this academic year. We surveyed the current class about the level of the material and the difficulty of the quantitative and conceptual problems contained in the book. Results compiled from 24 responses out of a class of 30 are show in Figures 1-3.

In general, the students find the course to be quite challenging. The Engineering Leadership program mixes together students who have studied in all engineering disciplines. Our observation is that students with a background in electrical or mechanical engineering have an easier time with the course than those with a background in civil or industrial engineering, with chemical engineers somewhere in the middle. It is notable that, as shown in Figure 1, the students find the conceptual material from the course more difficult than the mathematics. This supports our assumption that engineering graduates from their disciplinary training are able to take advantage of mathematical concepts such as linear algebra, differential equations, and complex numbers that are not typically used in their overview freshman physics classes. It is also apparent that the students find the conceptual foundations challenging.

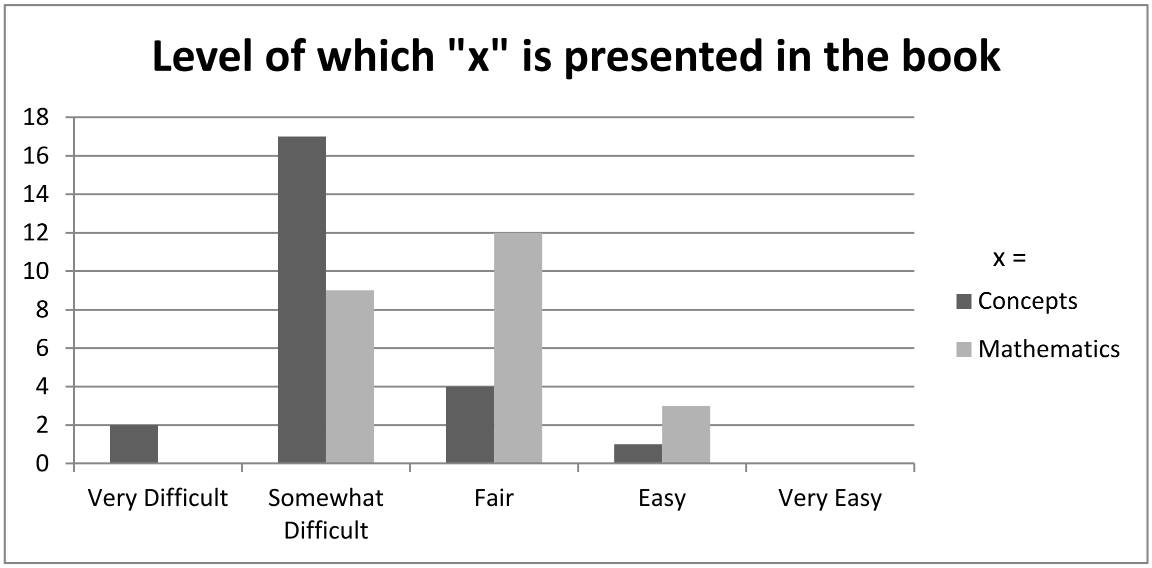

Figure 1 Response from Engineering Leadership students on level of difficulty of conceptual and mathematical material in book draft.

The students also found the problems from the draft text, both quantitative and conceptual, challenging, but useful in understanding the material as shown in Figure 2 and 3. The usefulness of quantitative problems (and particularly numerical worked examples which 79% found helped them learn, as noted previously) in understanding material is characteristic of engineering students in our experience. The importance of examples and applications of theory for engineering students was one of our guiding principles in writing the book to feature concrete applications and phenomena that arise from the scientific principles.

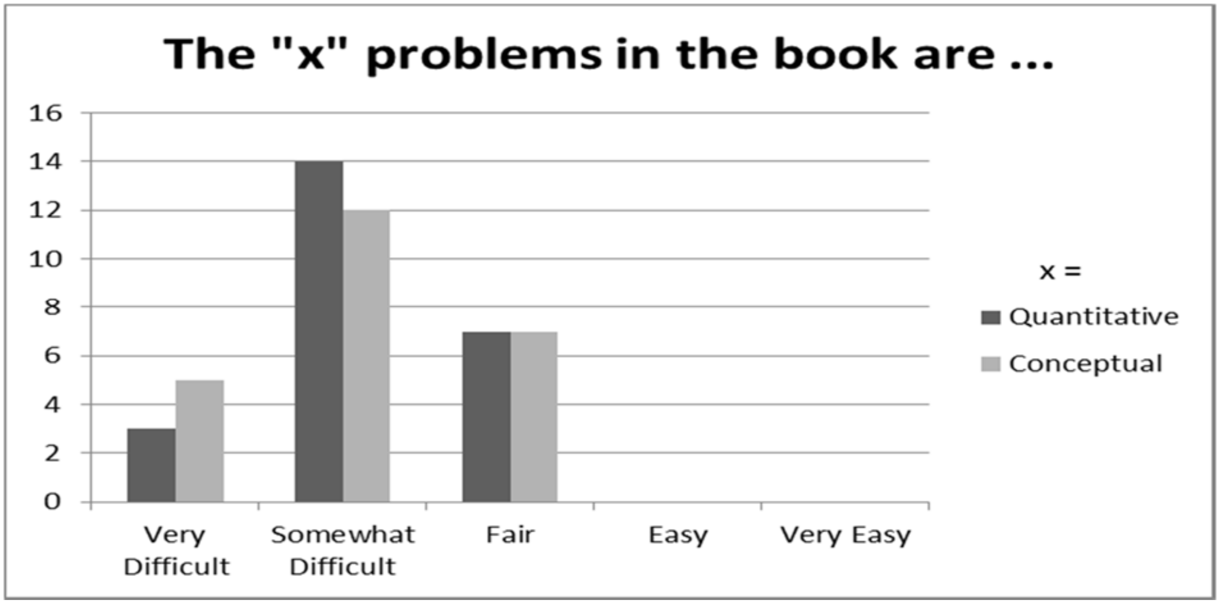

Figure 2 Response of Engineering Leadership students on difficulty of problems based from draft text.

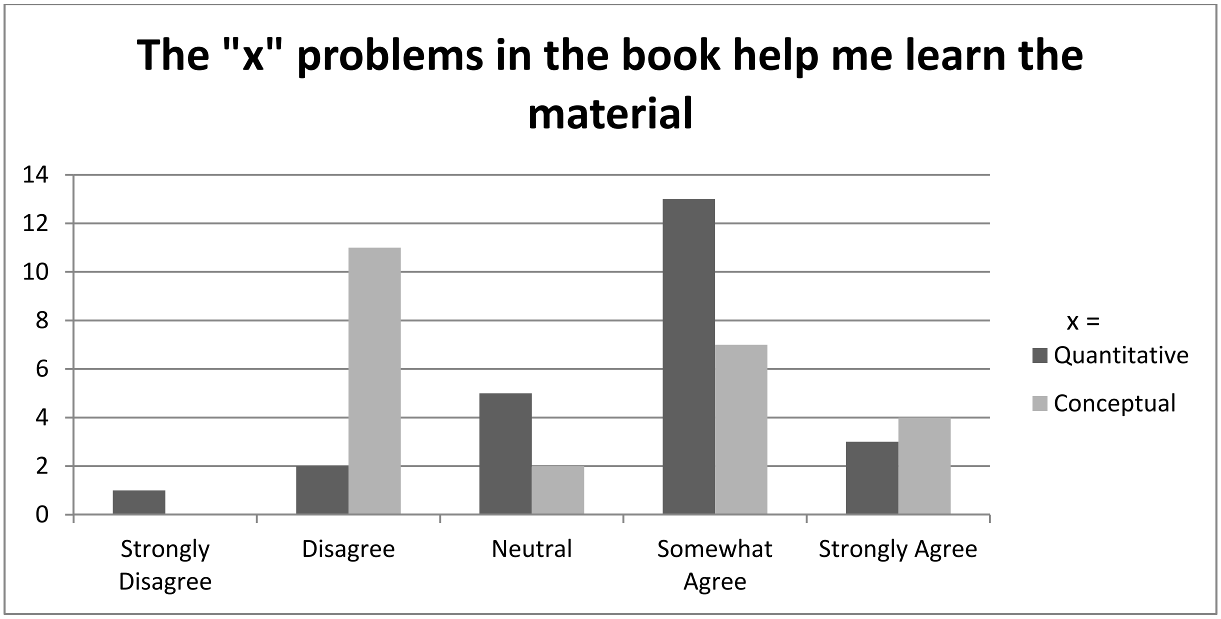

Figure 3 Student response on usefulness of quantitative and conceptual questions in learning.

Response of Gordon Engineering Leadership Program Alumni to the Scientific Foundations Course

We have also surveyed recent graduates of the Gordon Engineering Leadership program about the usefulness of the "Scientific Foundations" course in their personal, technical, and leadership development. From a survey sent out to 139 graduates of the program, we received 45 responses. The results reinforced our premise that this material is new and challenging to most graduate engineers. As shown in Figure 4, most of our Gordon program alumni had found over 40% or more of the material in the "Scientific Foundations" course to be new to them. Perhaps

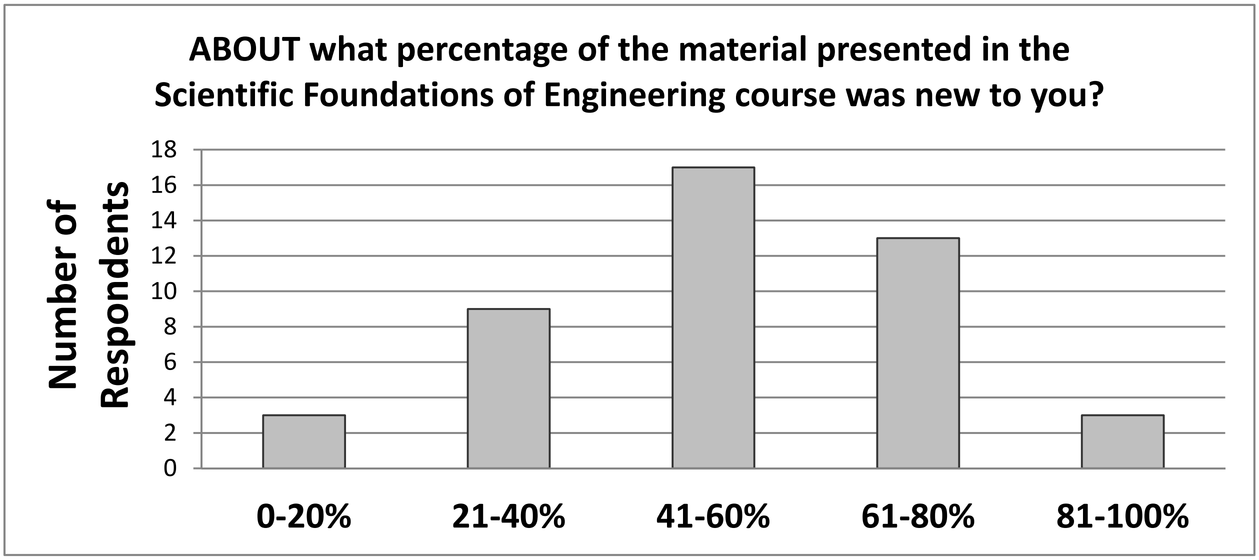

Figure 4. Gordon Engineering Leadership Program alumni response on course material.

as a consequence, 49% found the material "very difficult" and an additional 36% found it "somewhat difficult." Nevertheless, 73% reported that they learned "very much" or "a lot." Moreover, as shown in Figures 5, fully 60% of the students reported that what they had learned in this class had helped them in their professional career. Additionally, 84% of the alumni respondents agreed that such a course should be part of the Gordon Engineering Leadership Program, with 2% disagreeing and 14% not sure.

Some comments from the alumni in their responses capture this well. One reported: "Even with a solid foundation in engineering, physics, and chemistry, this course challenged me to learn beyond the basic understanding. The ability to fully understand a physical phenomenon is something I now possess that my peers in industry do not." Another comment from one of the alumni reinforced our premise that the greater familiarity with the scientific fundamentals helps in approaching new engineering problems: "The course gave a very good overview of many important topics in engineering. I didn't become an expert in any of the fields, but I feel that I now have a good foundation and will know where to begin looking or asking questions if problems arise in my projects."

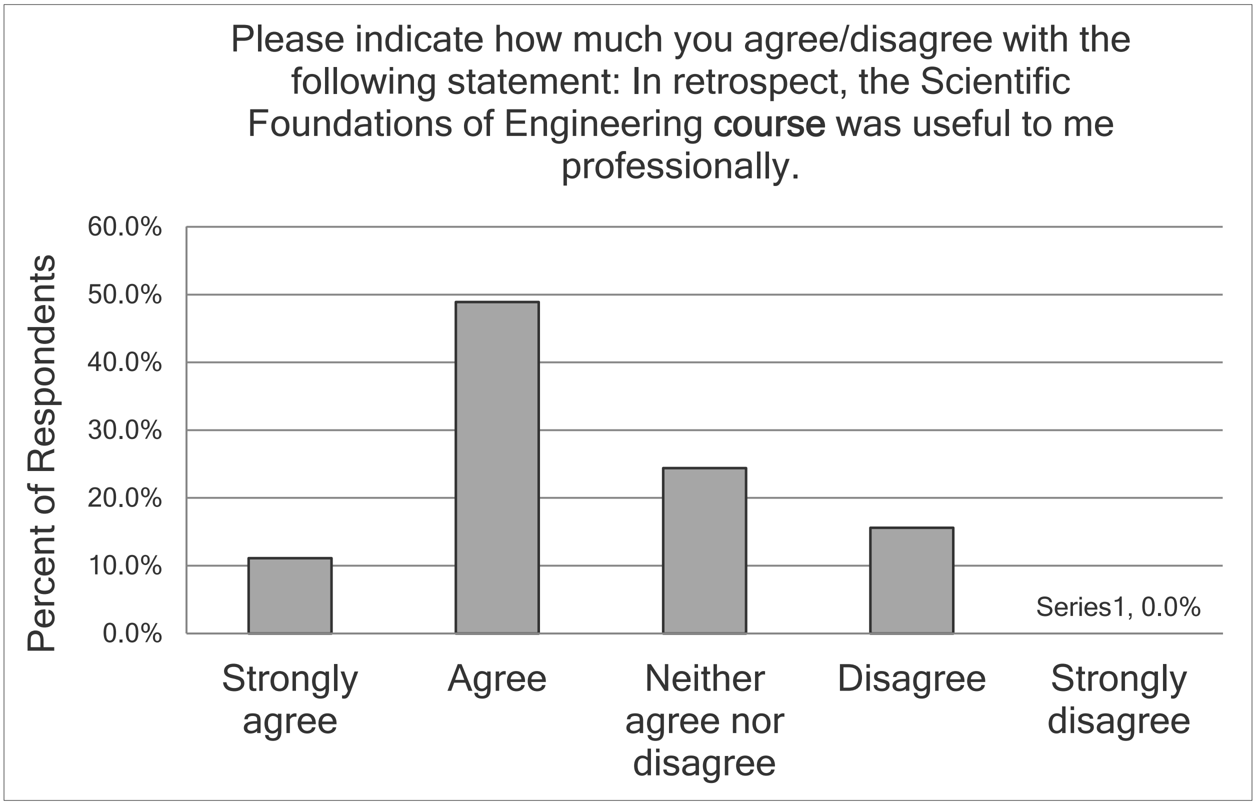

Figure 5 Response of Gordon Leadership Program alumni on their use of course material in their professional career.

Other comments indicated that the course contributes to scientific and engineering self-confidence in being able to attack difficult or unfamiliar problems: "It really stretched me beyond what I thought my engineering capabilities were," and "The best thing I learned was that I am capable of understanding any physics or engineering topic at the fundamental level."

Conclusions

We have designed and taught a course in "Scientific Foundations of Engineering" as a part of a graduate Gordon Engineering Leadership program. The course provides an opportunity for engineering students to revisit the fundamental physical principles that they have, in most cases, last studied as a coherent unit in their first-year beginning physics course. The course provides an opportunity for students, in the model of a spiral curriculum, to review the fundamental physical science underlying all engineering at a more sophisticated mathematical level than introductory freshman physics that emphasizes the connections between the physical phenomena in different disciplines.

The course, and a book by the authors currently in press, present the fundamental physical principles of mechanics, rotational and harmonic motion, waves, thermal and statistical phenomena, electromagnetics, and fluids, emphasizing the conceptual and mathematical connections between different areas. In consideration of the applications-focused learning style of engineering students, applications and numerical examples are featured throughout. A unit on quantum science – generally missing from engineering education despite being the basis of the semiconductor electronics revolution – is included. The course is useful for engineers who find themselves in a leadership role in cross-disciplinary projects, but could also be appropriate as a junior or senior-year elective in an engineering curricula.

The authors would like to express their gratitude to the classes of students from the Gordon Engineering Leadership Program who, with their questions and comments, have helped move this project from a set of cryptic notes to a text, which we trust will be comprehensible and useful to engineering and science students and professionals.

---

[1] Bruner, Jerome. *The Process of Education*. Cambridge, MA: Harvard Univ. Press (1960).

[2] Lohani, Vinod K., *et al.* "Work in Progress - Spiral Curriculum Approach to Reformulate Engineering Curriculum," 35th ASEE/IEEE Frontiers in Education Conference, Indianapolis, IN, pp. F1D1 (2005).

[3] Weinstock, Robert, "Laws of Classical Motion: What's F? What's m? What's a?", American Journal of Physics 29(10), pp. 698 (1961).