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A NEW UNDERGRADUATE COURSE: "PROBLEMS IN NUCLEAR ENGINEERING"

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ABSTRACT

During the past five years, a new third-year undergraduate nuclear engineering course has been developed and taught at the University of Michigan. The course was created to correct certain deficiencies in the undergraduate nuclear engineering curriculum. Here we discuss the origins of the new course and our experience with it.

Key Words: nuclear engineering, undergraduate curriculum, mathematical methods, numerical simulation

1. INTRODUCTION – BACKGROUND

About 15 years ago (roughly in 1996), several of the faculty in the Department of Nuclear Engineering and Radiological Sciences (NERS) at the University of Michigan (UM) began to realize that in some respects, the undergraduate NERS curriculum was not fulfilling all the students' needs. Discussions concerning undergraduate students' comments to faculty and staff illuminated the following issues:

- First and second-year engineering students at UM took standard freshman and sophomore computing and mathematics (calculus, differential equations) courses. These courses were taught by faculty outside the NERS department; for example, the calculus and differential equations courses were taught by staff in the UM Department of Mathematics. The lecturers of these courses never discussed how the course topics could be applied to technical problems in nuclear engineering.
- During their third (junior) year, NERS students took nuclear physics and basic engineering courses, but no courses that deal with specific problems in nuclear engineering. Also, during the summer between their junior and senior years, NERS students often interned at a nuclear utility or national laboratory. Going into their internships, these students often complained that they "didn't know any nuclear engineering" and were "only pretending to be nuclear engineers."
- To the professors who taught the major undergraduate fourth-year nuclear engineering courses, it seemed that many of the senior NERS students had forgotten much of what they were taught in their freshman and sophomore courses in calculus, differential equations, and scientific computing.

To summarize, during their first three undergraduate years, NERS students took basic computing, mathematics, physics, and engineering courses. These prepared the students for their major senior-level nuclear engineering courses, but they contained no in-depth presentations of technical topics in nuclear engineering. At the end of their junior year, NERS students had only a superficial understanding of what nuclear engineering is, or how the coursework taken during their first three years applied to it. This information was "revealed" to NERS students only in their fourth-year courses.

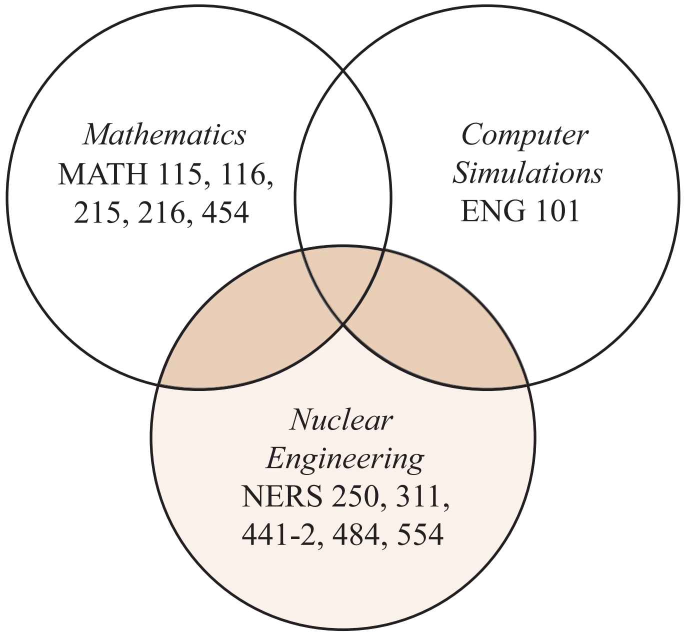
In the undergraduate NERS program at UM, students choose one of two *tracks*: (i) fission systems, and (ii) health physics. The main difference between these is that during the second semester of their senior year, students in different tracks choose different engineering design courses; fission systems students take NERS 442 (Nuclear Power Reactors), while health physics students take NERS 554 (Radiation Shielding Design). Any curriculum changes meant to correct the described deficiencies would need to account for this dichotomy in the student population.

2. THE PROPOSED NEW COURSE (1996)

The basic situation during the mid-1990's is described above. Certain deficiencies in the undergraduate NERS curriculum had become apparant, but it was not evident how to easily correct them. (It was not even clear that the deficiencies *should* be corrected – the NERS undergraduate curriculum had operated in the same mode for years, students had been completing their coursework and going on to successful careers, and it was not obviously necessary to try to fix a system that did not seem to be seriously broken.)

Nonetheless, discussions among the NERS faculty led to a potential solution: a proposed new course that would be taught during the winter semester of the junior year. This course would have the following features:

- It would be structured around half a dozen or so different physical problems in nuclear engineering. For each problem, the underlying mathematical equations would first be developed; after this, solution methods – both numerical and analytic – would be developed, and assignments would involve both analytic and numerical approaches.
- The necessary mathematical and numerical techniques would be presented using concepts that the students had already been taught in their freshman and sophomore calculus, differential equations, and scientific computing courses.
- The physical problems around which the course would be structured would be basic, fundamental, and relevant to *all* NERS students, whether their coursework focused on fission systems or health physics.
- At the conclusion of the course, NERS students would have (i) been introduced to a range of basic physical problems in nuclear engineering and radiological sciences, (ii) used mathematical and simulation methods taught in previous courses to solve these problems, and (iii) gained a better understanding of what nuclear engineering is and the relevance of their coursework during their first three undergraduate years to nuclear engineering. The intention was that NERS students should more confidently enter summer internships between their junior and senior years, and should be significantly better prepared for their senior-level nuclear engineering courses.



(The courses listed above are standard undergraduate mathematics, computer science, and nuclear engineering courses taken by NERS students at the University of Michigan. Courses taken during the first three years *do not* cover topics in the darkly shaded area – overlapping mathematics and nuclear engineering; and computer simulations and nuclear engineering. The subject areas of the proposed new course would lie within this darkly-shaded area.)

The difficulty with this proposed solution was that it required a new course; thus, it required someone to teach it, and for this, extra resources had to be found. Unfortunately, during the decade of the 1990's, student enrollments in nuclear engineering programs across the U.S. had declined, to such an extent that many nuclear engineering departments had been merged with other engineering departments, or were terminated. More pressing issues had to be dealt with, stemming from declining student enrollments, that could lead to the demise of the department. This was not an auspicious time to devote new resources to upgrade the undergraduate NERS curricula. For this reason, the idea of the new course was temporarily shelved.

3. IMPLEMENTATION OF THE COURSE (2006)

Ten years later, in 2006, the circumstances at UM – and in many of the surviving nuclear engineering departments across the U.S. – had improved. Undergraduate enrollments had significantly increased, and the climate for nuclear engineering was more positive than it had been in many years. During the planning for NERS courses to be taught during the 2005-06 academic year, I was asked to develop and teach the proposed new course to the junior-level NERS students, during their winter 2007 semester.

The course was first offered in the winter 2007 semester, with a class size of 33 students. The student response was positive, so the course has been taught each subsequent winter semester – each time with substantive changes meant to improve the quality of the lectures, the written notes, and the weekly homework assignments.

No suitable textbook existed for the course, so all the lectures and class notes had to be developed from the basic outline developed in the original faculty discussions. In the first year, the lecture notes were handwritten, and then scanned and emailed to the students. During the second year (1998), the notes were thoroughly rewritten and typed (in Latex) by a teaching assistant. Each year since then, the typed notes have been corrected, revised, and expanded into what is now a reasonably self-contained set of about 240 pages. These notes are meant to be (i) a "textbook" for the course, (ii) an introduction to several senior-year NERS courses, and (iii) a reference for basic problems and solution methods in nuclear engineering.

The topics covered in the course adhere to the principle that they should be relevant to all NERS undergraduate students. The one topic that all these students work with, whether they are oriented toward reactor physics or health physics, is *radiation*. Therefore, the course is structured around six different topics that concern the modeling of radiation in reactor and health physics problems encountered in required NERS senior-level courses. The six topics are:

1. *Radioactive Decay.* The mathematical aspects of this topic involve coupled systems of first-order ordinary equations. Methods for analytically and numerically (deterministic and Monte Carlo) solving these equations are developed in the lectures.

   A main theme of the course is that many different types of physical phenomena in nuclear engineering can be described by coupled systems of first-order ordinary differential equations. Even though NERS students are already familiar with the physical process of radioactive decay, extra time is spent on solution methods for these problems because the methods are relevant for other problems discussed later in the course.
2. *Simplified Rate Problems.* This refers to simplified problems in which a time- and space-dependent process involving radiation is crudely modeled by a coupled system of first-order ordinary differential equations involving only time, t. (For instance, a source of radioactive nuclei could leak into a tank of water, and to eliminate the spatial variable, the radioactive nuclei is assumed to instantly mix with the water.) Problems of this type are relevant in health physics, and the equations that have to be developed are often similar to those in radioactive decay problems. This topic encourages students to think about problems involving radiation in structured ways that can quickly lead to approximate, but useful, quantitative solutions.
3. *Basics of Radiation Transport and Shielding.* The fundamental concepts underlying neutron and photon transport are described, and students are asked to write and run analog Monte Carlo programs to perform simulations for basic shielding-type problems. Analog Monte Carlo methods for neutron transport are based directly on the underlying neutron physics, so by writing and running these codes, students should simultaneously (i) polish their programming skills, and (ii) gain a better understanding of the underlying radiation transport process.
4. *Point Kinetics.* The Point Kinetics equations are derived phenomenonogically, using the approach developed for Simplified Rate Problems. The result is the familiar coupled system of first-order ordinary differential (Point Kinetics) equations. A numerical method for these equations is developed, and students write and run computer codes to solve some basic problems.
5. *Neutron Diffusion.* This topic is the only one in the course that leads to a second-order differential (diffusion) equation. Basic analytic and numerical solution methods for these equations are developed.

6. *Neutron Slowing Down.* This topic starts with an integral equation in neutron energy, but quickly is approximated by another first-order differential equation, via the age approximation. Problems are solved analytically, deterministically, and by Monte Carlo.

The first three of these topics are directly relevant to all undergraduate NERS students, for obvious reasons. Topics 2 and 3 are most relevant to health physics problems covered in NERS 484 (Radiological Health Engineering Fundamentals) and NERS 554 (Radiation Shielding Design), while topics 4-6 are most relevant to reactor physics problems covered in NERS 441 (Nuclear Reactor Theory I) and NERS 442 (Nuclear Power Reactors). All senior NERS students are required to take three of these four courses; they must take NERS 441 and 484, and they must choose between the two design courses NERS 442 and 554.

During the first two years that the course was offered, and before the objectives of the course began to be more fully understood, NERS faculty often referred to the course as "Ed's math class." I strongly objected to this oversimplification. The course does rely on a considerable use of mathematics and *could*, conceivably, be categorized as an applied math class. However, the goal of the course is not to teach new mathematics. *The principle goal is to use previously-taught mathematics (and simulation methods) to solve nuclear engineering problems.* When asked what name the course should have, I struggled to find a simple name that communicated the right information, but that did not contain the word "mathematics" – because it was evident that people would erroneously think of the course as a mathematics course. The first chosen name was "Problems and Solution Techniques in Nuclear Engineering," which unfortunately is not simple. The current course name is "Problems in Nuclear Engineering and Radiological Sciences." I would prefer the simpler name "Problems in Nuclear Engineering," but the official name contains the full name of this department at UM.

During the second year that the course was taught, several students asked if the course could be used to count toward a minor in mathematics. At the end of the semester, I sent the freshly-typed lecture notes to the appropriate committee in the UM Department of Mathematics and asked this question. After deliberation, the committee replied with the answer "No." The reason: to count toward a minor in Mathematics, the course would need to be cross-listed between NERS and Mathematics; and to do this, the Math Department would need to expect that occasionally, one of their faculty would teach the course. However, since the strong focus of the course material is on physical problems in nuclear engineering, the committee believed that this would be unlikely to happen. This decision was unfortunate from the students' perspective, but it probably helped to end the misnomer "Ed's math class."

With two exceptions, the contents of the new course adhere to the principle that the mathematical and numerical methods in the course should be ones that the students have basically already seen – or should be very easily recognizable from material taught in freshman and sophomore courses. One exception is the topic of Monte Carlo methods, which is introduced in the lectures on Radioactive Decay and used in several subsequent chapters. This simulation method is unfamiliar, but student feedback on it has been – almost without exception – positive. NERS students respond favorably to the intuitiveness of this method and the relative ease with which Monte Carlo programs can be written. The second exception is the delta function, which is used in several of the six different physical problems discussed in the course. One full lecture in the course is devoted to this topic.

4. CURRENT STATUS OF THE COURSE

During the next winter semester (2011), the course will be offered for the fifth time. By now, the lecture notes have become fairly stable, but sections continue to be revised in an effort to improve clarity. Also, the problems listed at the end of each chapter consist of all old homework problems, together with problems from all the old midterm and final exams; these sections of the notes are expanded each year. (The students definitely like this aspect of the notes.)

Graduating NERS seniors have been asked their opinion about the course – in hindsight, having taken it in their junior year and then taken the required nuclear engineering courses in the following year. Not all NERS students responded to these surveys; students with higher grade point averages (GPAs) were more likely to respond than those with lower GPAs. However, the great majority of the responses were positive.

Several NERS seniors that took the course have come to my office to volunteer that they used topics from the course for work during summer internships, or for senior research projects. (Two such projects – one involving the analysis of traffic patterns, the other involving the diffusion of cancer cells – made use of Monte Carlo methods.)

I have often been if there are plans to have the typed lecture notes published as a book; my response has always been "Perhaps, but not yet." The main reason for hesitancy is that the lecture notes are not sufficiently stable; meaningful revisions are made to them each year. Also, it has recently become apparent that other topics could replace some of the current chapters. For instance, a chapter based on applications of probability and statistics to reactor safety problems could replace one of the current chapters. Also, a chapter based on applying the diffusion equation to study the diffusion of metal atoms at a material interface could be included. A chapter involving a simple plasma physics problem could also possibly be added. My current viewpoint is that perhaps not *all* the topics covered in the course need to be seen again by *all* NERS students in their senior courses. NERS students will benefit by seeing how freshman and sophomore mathematics and computing can be applied to a wider range of nuclear engineering problems – even if some of these problems will not be seen by some of the students in their senior year. Thus, new chapters to the notes could (and will likely) be added, covering a wider range of problems and topics; and future teachers of the course could select the topics that work best for them.

Because the course is viewed as successful, the NERS curriculum committee recently recommended that it be made required for NERS undergraduates. Shortly after, the NERS faculty voted to approve the committee's recommendation. Thus, the course will continue to be taught, and it will continue to evolve in ways intended to increase its benefit to the students.

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