The role of computational physics in the liberal arts curriculum

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Abstract. The role of computational physics education varies dramatically from department to department. We will discuss a new computational physics course at Randolph-Macon College and our attempt to identify where it fits (or should fit) into the larger liberal arts curriculum and why. In doing so, we will describe the goals of the course, and how the liberal arts curriculum conditions the exploration of computational physics.

1. Introduction
Institutions of higher education in the United States have been under scrutiny in recent years. Popular books and articles have questioned the stability and effectiveness of colleges as well as the value of getting a college degree, where the increasingly high cost of tuition may not be worth the uncertain returns [1–3]. Among this general crisis of higher education, there is a sub-crisis among schools that characterize themselves as liberal arts colleges, prompting defenses of liberal education [4].

The humanities and fine arts sometimes take center stage in discussions of the value of the liberal arts, but the natural sciences, particularly physics, are clearly integral to the liberal arts, properly understood. The humanities stand out partly because to understand human beings and the human condition is one of the most important kinds of knowledge, but also because the humanities often seem the most in need of justification. In the eyes of a society concerned with practical outcomes, the sciences are much easier to justify. Yet, ironically, within an institution devoted to the liberal arts, scientists do not always have the vocabulary to fully connect their work with the institution’s mission.

Liberal arts colleges have the weighty task of responding to changing student populations, developing job markets, and perceptions of the value of higher education, while holding true to their core values. As courses and curricula evolve in response to student and college needs, tensions inevitably arise as to how limited resources can best serve students. For faculty, these factors suggest a need to reflect on the goals of a liberal arts curriculum and examine how individual courses support this curriculum.

At Randolph-Macon College (where the authors teach), college relevance and the value of a liberal arts education are frequent topics of discussion. Our identity as a 'small liberal arts
college’ drives this discussion. Our introductory physics classes are capped at 24 students and upper division physics courses are capped at 12 (though a typical upper division course has half this number.) Randolph-Macon has around 1400 students total, all of whom are undergraduates. In contrast, Boston University (a research university, the host institution to this conference, and the alma mater of one of the authors) has about 15,000 undergraduates, not including graduate students [5]. Randolph-Macon has three full time physics faculty members, while Boston University has about 40 [6]. These statistics support the image that Randolph-Macon fosters close-knit and personal learning communities in contrast to larger institutions.

More generally, liberal arts institutions tend to market themselves as providing a formative, student-centered experience, whereas research institutions advertise an opportunity to experience the creation of new knowledge. Liberal arts institutions tend to devote more required courses to general education requirements, emphasizing breadth across curricula over depth within the major. Depending on how they are fulfilled, the general education requirements at Randolph-Macon may occupy as much as 70% of a student’s four year course of study. This number is roughly 40% in the College of Arts and Sciences at Boston University [7]. (These percentages can be mitigated by factors such as placement credit from high school, and taking courses that count for multiple requirements.) In this paper, we explore how a computational physics class can uniquely contribute to the goals of a liberal arts curriculum.

2. Liberal education

The proper form and content of liberal education has been a subject of debate for centuries, and today the answer is often ambiguous even within a single institution. The term ‘liberal education’ describes an education that is related to liberty, or freedom, in some way; but there are several ways to understand both the kind of freedom involved and the way the process of education is related to it.

First, an education may be liberal in the sense that it is pursued freely. This could mean simply that the student is free to pursue his or her interests, and many faculty today will emphasize this; but traditionally liberal education refers to an education pursued for its own sake, rather than to meet some external need, such as the need to find a job. For Aristotle the defining feature of a liberal education is that it prepares the student for activities that are pursued for their own sake because they are good in themselves [8]. The traditional liberal arts disciplines fit this description straightforwardly: the humanities and natural and social sciences are traditionally understood to pursue knowledge for its own sake, while the fine arts particularly pursue beauty. Liberal activities, in this sense, are distinguished from those that are merely useful or necessary for some other purpose, and in particular from paid labor.

Second, an education may be liberal in the sense that it liberates, or makes the student free. As J.S. Mill discusses, one kind of intellectual freedom comes from acquiring the skills and foundational principles that allow the student to draw freely and intelligently on the full range of human knowledge, as she may need to do in many ways throughout her life [9,10]. This requires a fluency in all the major kinds of knowledge, a sense of how various disciplines contribute to our understanding, and also the ability to integrate knowledge from across disciplines. Ultimately the world is an integrated whole that transcends disciplinary boundaries, as are most of the challenges with which it confronts us. Liberal education, in this sense, is comprehensive and holistic.

Another aspect of intellectual freedom is the ability to think for oneself, and form sound judgments of one’s own—‘critical thinking’ in today’s vocabulary. Enlightenment thinkers such as Kant emphasize relying on one’s own reason and being freed from reliance on the authority of others [11]. As human knowledge expands, increasing reliance on others for their expertise becomes unavoidable, but the ability to choose sources wisely, discern legitimate expertise, and
assess its limits is all the more essential. Such qualities of intellectual independence have a special value for citizens of a self-governing society, which led Thomas Jefferson to found a university.

These traditional approaches to liberal education continue to be valuable and relevant in the 21st century; but they are also under pressure. The breadth of a comprehensive approach to knowledge comes into competition with the depth of specialization needed to master any one area. Meanwhile, with the explosive growth of knowledge and information, a comprehensive education may seem more of an aspiration than a real possibility.

Today, college and university professors may think of their jobs mainly in terms of the discovery of new knowledge. This goal can compete with the goal of passing on knowledge to the next generation, as teaching comes to seem a mere distraction from research. Both learning what has already been discovered, and discovering new knowledge, are paradigmatically liberal activities, but we sometimes struggle to reconcile the two at a practical level.

Perhaps most urgently, with higher education no longer merely a privilege for the elite, the idea that education should be pursued primarily for its own sake becomes difficult to sustain. With college becoming a standard expectation for the middle class, most students can only afford an education if it will bring economic rewards. There is great pressure for a vocational approach to higher education.

Traditional conceptions of liberal education need a certain amount of rethinking in this context. Fortunately, this is a healthy part of any good tradition. One point to reconsider is the traditional opposition between liberal activities and paid work. The idea that paid employment is necessarily without intrinsic value is an oversimplification that seems out of place in our democratic and industrious culture. Some labor is merely useful, but many activities and achievements have great intrinsic value, whether they are paid or not.

This adjustment leads to a third conception of liberal education: an education may be liberal by preparing students for a self-directed life of action and accomplishment. Today’s college-bound students have an enormous range of possible choices; their education should prepare them to choose their path well and succeed in it. For this aim, intellectual skills and the ability to learn new things are at least as important as any knowledge acquired in school.

The traditional liberal arts disciplines, approached in the right way, can be an excellent preparation in this sense as well, however. Skills such as written and oral communication, problem-solving, research, and creative application of prior knowledge to new situations are essential to a wide range of activities both in and outside the workplace in an advanced economy. One may learn other knowledge and technical skills, distinctive to one’s chosen path, either in school or afterward. Liberal education should enable one to meet one’s material needs through a career whose value goes beyond money.

3. Computational physics course

Turning to a more specific consideration of the place of computational physics in liberal arts education, we discuss here a course taught at Randolph-Macon. The course uses computational math techniques to solve sometimes advanced physics problems, where content is complementary to the core physics content of the major. A primary goal of any stand-alone computational physics course ought to be to teach content unique to the interdisciplinary field of computational physics. This may include methods such as numerical calculus, methods of solving differential equations, and Monte Carlo methods. However, computational physics generally can be used within the physics curriculum in a variety of ways.

On one end of the spectrum is a black box approach, where computers use software (such as Mathematica [12]) as tools to do calculations or solve differential equations. With this approach, there is often minimal effort to teach the students how the tool is doing the computation. Many physics departments use some kind of black box approach in traditional theoretical classes as a problem solving tool. On the other end of the spectrum is a comprehensive approach to teaching
computational physics, essentially integrating computational physics (including math, physics, and computer science) throughout the physics curriculum [13]. This approach may result in a separate computational physics degree, or concentration, distinct from the traditional physics degree. For example Oregon State and Illinois State [14, 15] (both large, public universities) have separate majors in computational physics including several computational physics courses integrated throughout the four year program. Requiring a considerable amount of resources, this ‘all in’ approach is not currently within the scope of the capabilities of Randolph-Macon (and probably most small, liberal arts institutions.) The course described below is somewhere in the middle of this spectrum.

3.1. Course logistics
The course is three credit hours (though the next time the course is taught it will be a three credit lecture plus a three hour laboratory). The time is used for a variety of activities, including lecture, tutorial, and student-led seminars. Despite the low number of students enrolled in this class (four to five in a semester, which is a typical number for advanced physics courses at Randolph-Macon), a large number of majors have been represented including physics, engineering physics, mathematics, computer science, chemistry, and environmental science. The prerequisites include only introductory physics and calculus, allowing sophomores through seniors to take the course. Therefore, the students come to the course with varied skill sets and backgrounds. Opening advanced courses to a diverse group of students is encouraged at Randolph-Macon to boost enrollments and allow students to explore new topics. The course fulfills a general education requirement for a natural science as well as a computing requirement.

3.2. Course structure and content
The coursework begins with tutorial-type exercises, where students learn basic programming skills. The homework consists of physics content-driven project-style problems. The capstone of the course is a final independent project. Most of this work comes from the text, “Computer Simulation Methods” by Harvey Gould, Jan Tobachnik, and Wolfgang Christian [16]. The current version of the book uses Java and the Open Source Physics library, (though there is now an Easy Java Simulations (EJS) version of the text [17].) This library contains code that allows students to create graphical user interfaces (GUIs), plots and animations. Though the students do not have to write this code, they must learn to implement existing code. This approach allows the course to focus more on physics content than on computer science content.

The independent project is essential to the goals of the course. The student must extend a practice problem from the text with an original line of inquiry and develop a simulation to investigate a physical problem. The student must then design an investigation to study the problem by collecting, analyzing, and visualizing data, as well as presenting preliminary and final results in an informal classroom and a formal presentation setting. The projects completed in this class spanned a wide range of topics, including the Magnus force of a soccer ball, irregular quantum wells, environmental physics, critical systems, general relativity, complex networks, and thermal systems.

3.3. Liberal arts skills
A computational physics course can be quite valuable for advancing a number of skills connected to the goals of a liberal arts curriculum. Some of these skills are associated more directly to the content of computational physics than others. For example, clearly there are a number of technical skills required to perform the tasks of the course, such as basic computer skills, programming skills, and the collection and analysis of data using a variety of software tools. All of these skills are certainly assets to attaining a technical or scientific vocation. Such a course also introduces students to computation as a unique and legitimate problem solving technique.
However, problem solving in a computational course, such as the one described here, may provide a unique opportunity to focus on the development of higher level thinking skills, another important goal of a liberal education. A robust approach to problem solving encourages students to think critically about scientific investigation and the relationship of knowledge to inquiry. Investigatory activities in any science context can promote this goal [18], and reforms are underway to remove constraints such as cookbook laboratory protocols that hinder this goal [19].

However, there are always necessary constraints to creative inquiry in physics courses. Theoretical problems are often based on limited information and student mathematical abilities, while measurement tools and physical limitations restrict laboratory activities. Indeed, such constraints are an important part of the creative process in science, and specific constraints promote certain skills and limit the development of others.

Problem solving using computational physics techniques has inherent restrictions as well, including computational limitations, but many other physical and mathematical constraints are lifted. The relative ease with which students may adjust physical parameters (one cannot change the gravitational constant in a lab!), and analyze simulated measurements makes the computational investigatory process a unique environment for students to creatively explore new questions. In particular, students have control over, and think critically about, the investigatory process.

It was evident in the student led seminars of the Randolph-Macon course that students were thinking creatively and critically about their investigations. The evidence came through verbal explanations, questions, reasoning, and thoughtful interactions. This unique skill of oral communication as part of the investigation process within a learning community was practiced in a semi-formal way (something beyond struggling to get homework done in the middle of the night with friends). This practice of science is especially valuable in small college settings, where it is unlikely that students will be members of sizable research groups. The Randolph-Macon course also stressed more formal modes of scientific communication, including written laboratory reports and formal research talks as part of a college-wide research day.

3.4. Connection to the liberal arts curriculum
Intellectual freedom requires a broad command of human knowledge and an understanding of the relationships between disciplines. Computational physics is itself interdisciplinary, integrating knowledge and techniques from mathematics, computer science, and physics. The study of computational physics underscores that science itself is comprehensive, emphasizing that theory, modeling, mathematical algorithms, and empirical data have a place in building scientific knowledge.

The open-ended investigations in the course described above provide opportunities for students to freely explore content of their own interests within the relatively broad bounds accessible to computational investigation. They develop their investigations with supervision from the instructor and collaboration with their classmates. This free exploration of content and method increases the relevance of the course to liberal education and provides motivation to students. It encourages students to take responsibility for their own learning by investing time and effort in their educational pursuits.

Such investment is necessary for students to achieve intellectual freedom through scientific independence. This course provides an opportunity for students to develop investigative autonomy with manageable-sized projects at the undergraduate level. Such independence can empower students to achieve their goals, especially in scientific fields, preparing them for a life of self directed action and accomplishments. More directly, the nature of computational physics realistically models the complex tools used by scientists, providing valuable preparation for more substantial research projects in the future. Ruben Panoff expresses the need for this type of background: “The substantial role of computational approaches to physics research is
not currently reflected proportionately in how we prepare future physicists” [20].

In essence, a computational physics course can teach students to think like scientists. Scientific thinking as discussed here not only aids students in achieving their goals, but helps to develop free individuals more generally, which is a good in itself. Scientifically literate individuals with a robust appreciation for the development of scientific knowledge thrive in a democratic society and enable such a society to thrive.

4. Conclusions
A computational physics course can contribute to the goals of a liberal arts curriculum in a substantial and unique way. Indeed, a liberal arts environment conditions the exploration of computational physics, setting parameters for prioritizing class and work time. Such a course is quite ambitious, and pursuing the goals set forth in this paper in a meaningful way necessarily requires sacrifices in content. However, the course described contributes to the full development of a free individual, and their ability to pursue knowledge both for its own sake and with a sense of its place and purpose in community.

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