Topic Order in Introductory Physics and its Impact on the STEM Curricular Ladder

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Abstract—Introductory physics courses are an important rung on the curricular ladder in STEM. These courses help to strengthen students critical thinking and problem solving skills while simultaneously introducing them to many topics they will explore in more detail in later courses in physics and engineering. For these reasons, introductory physics is a required element on the curricular ladder. Most often, introductory physics is offered as a two-semester sequence with basic mechanics being taught in the first semester and electricity and magnetism in the second. In fact, this curricular sequence has not been altered in decades. Is there a reason for this? There are many other enduring questions that arise pertaining to these foundation courses in physics. These questions include: *Does taking the introductory course sequence "out of order" have an impact on student learning in physics? What topics should be taught? When should these topics be taught? What topics could be left out?* The list of questions is essentially endless. This paper will address some of these questions in part, through a brief discussion on student learning in a second-semester algebra-based physics course. Connections will also be made to the broader curricular ladder in STEM. To this end, an illustration that makes connections to an engineering statics course will be presented. This discussion will conclude by presenting some broader implications for the larger STEM communities.

Keywords—Assessment, curricular content in STEM, introductory physics, student learning in STEM, physics in the major, physics for non-majors, topic order in physics.

1 Introduction

The amount of material presented in the typical introductory physics sequence is literally enormous. In fact, many introductory textbooks used in the introductory physics sequence contain well over 1000 pages of interesting and relevant material. The sheer size and volume of many current introductory physics textbooks has continued to grow over the past several decades. Because of the immense amount of content included in a typical introductory physics textbook it is almost impossible to cover every topic presented, yet alone cover every topic equally well. Often, there is a significant amount of pressure on instructors of physics to cover everything as it is well-known that these introductory courses form the foundation of the curricular ladder in STEM.

Many questions often surface each time a department is faced with the decision of changing the textbook used in their introductory physics sequence. These questions include: What topics should be covered in the introductory sequence of university physics? Which topics might be left out or covered in less detail? If one topic is taught in less depth so that another could be covered in more detail what impact could this have on student learning? And, what if a topic is left out altogether in favor of the "less is more" idea pertaining to learning in general? Is less really more when it comes to physics teaching? Moreover, is the order in which the topics are presented important? Questions such as these might be considered "age-old" questions, but truly there is not a categorical standard or definitive answer to them. Thus, physics faculty must often make these tough choices. With the physics and engineering curricula being so tightly packed with courses at most universities, the introductory physics sequence is most often taught over a two-semester period of time.

The next section provides a look at the traditional topic order used in most introductory sequences. This order seems to have remained unquestioned for several decades. Perhaps this longstanding order is important and should not be messed with. On the other hand, perhaps the time has come to revisit some of these venerable questions.

2 Traditional Topic Order in the Introductory Physics Sequence

The topics that are commonly addressed in the two-semester sequence of physics courses are, and have remained, largely within the classical domain. The first-semester course usually covers topics in basic mechanics. These topics typically include:

- Introduction to Systems of Measurement,
- Coordinate systems, Vectors, and Vector Algebra
- Kinematics
- Newton's Laws
- Work, Energy, and Momentum
- Rotational Motion
- Newton's Universal Law of Gravity
- Fluid Mechanics
- Thermodynamics

Topics typical to the second-semester course commonly include:

- Oscillations
- Waves and Optics
- Electricity and Magnetism
  - Electric Charge and Forces
  - The Electric Field
  - The Electric Potential
  - Gauss's Law
  - Electric Circuits
  - The Magnetic Field
  - Electromagnetic Induction
  - AC Circuits

The above lists don't aim to address every topic in detail: rather, they are intended as a general overview of common topics in most introductory physics courses. Often the decision of what to teach rests upon a small committee of faculty, or in some departments, on an individual faculty member. This decision is often made with other curricular issues, such as time constraints, in mind.

To effectively teach the topics listed presents many challenges. A primary challenge is that there are simply so many topics to teach! How does one orient the syllabus in order to assign an appropriate amount of class time to each topic? Congruent with that challenge is the fact that these introductory courses form the foundation for many other courses within the physics, engineering, and broader STEM curricular areas. So, if one topic is left out or not covered in as much detail as another, what impact will that have on student learning … not only in the course itself but also in terms of future courses the students will need to take within their respective disciplines? This is particularly important within the engineering curriculum as courses are often taken in a building-block format. Namely, each course builds upon the foundation laid in the previous course. The introductory physics sequence is very important within the broad domains of engineering and is often used as the foundational rung on the curricular ladder for other courses such as statics, dynamics, and electric circuits, to name just a few.

Ultimately, the question is what do we teach and when in our introductory physics courses? While this is a question educators have wrestled with for a very long time, it recently resurfaced in spring 2016 in a second-semester introductory algebra-based physics course. Following a synopsis of the research literature, an overview of this second-semester introductory course will be presented. One aim of the discussion presented in this paper is simply to provide a catalyst for further conversations within the physics, engineering, and broader STEM education communities.

3 Background Literature

As has been established, the questions posed in this paper are not necessarily new. For many decades, discussions about what topics to cover and when to teach these topics in introductory physics have taken place around the globe. However, the answers to these questions seem to be somewhat elusive and hence, worthy of further discussion. It is truly amazing that over the course of the past 100 years or so, there has been little change in the curricular content of the two-course sequence in introductory physics.

In his seminal work written approximately 100 years ago, Mach [1] treated the topic of mechanics as a branch of the physical sciences. In a very real sense, there mechanics has stayed. Mach described the mechanics of various physical phenomena and in his introduction describes it as: "That branch of physics which is at once the oldest and the simplest and which is therefore treated as introductory to other departments of this science, is concerned with the motions and equilibrium of masses. It bears the name of mechanics. The history of the development of mechanics, is quite indispensable to a full comprehension of science in its present condition. It also affords a simple and instructive example of the processes by which natural science is generally developed" (p. 1). Surprisingly, or perhaps unsurprisingly, little has changed in terms of the content in introductory physics since Mach wrote this description of basic mechanics.

In the decades that followed, numerous discussions took place regarding what the content should be in a first-year course in physics [2 – 4]. Later decades saw a shift from merely talking about content to how the content should be taught [5 - 7]. French [8] suggested that the introductory physics courses taken by prospective engineers and scientists had fallen into an appallingly predictable pattern. In fact, French posited that in some respects, physics as traditionally taught in these introductory courses appears to be a success. However, he raised the question "but can we honestly say that these courses are providing our students with what we, as physics teachers, might hope they would carry away with them: a real enjoyment of physics? A sense of wonder? An appreciation of how physicists try to grapple with the unknown, so that the students too, can look at the word with heightened awareness, curiosity, and analytical power?" (p. 110). It is questions such as these that provided the fertilizer for the development of physics education as an important field of research. These questions still drive much of the research being conducted today.

Over time many questions arose related to content versus process within the physics education community regarding student conceptions (or misconceptions). As is generally well-known, students in traditional classrooms often acquire most of their knowledge through passive classroom lectures, textbook reading, and the internet. Passive learning routinely results in students merely trying to learn and regurgitate what the teacher and textbook are telling them. A discouraging fact is, after instruction, students have often emerged from our classes with significant misconceptions [9 - 15]. Additionally, Beatty and Gerace have argued that traditional exams are not the most effective tools for understanding the structure and knowledge of students' knowledge of physics [16].

In the latter part of the 20th century, many innovative methods of teaching and assessing students in introductory physics classes were developed. Many of these methods involved different approaches to teaching physics and have been implemented to try and address some of the students' misconceptions. These approaches have also served to help the physics and engineering education research communities better understand how students learn physics, what topics often cause difficulties, and which strategies work better than others [17 – 30]. Many strides have been made in determining new curricular tools and strategies to help students combat their misconceptions.

Paramount to the learning strategies that were developed is the type of methods that can be used to assess student learning. In recent times, numerous research-based normalized tests and surveys such as the Force Concept Inventory (FCI), the Force-Motion Concept Evaluation (FMCE) the Mechanics Baseline Test (MBT), the Newtonian Gravity Concept Inventory (NGCI), and many others have been developed [31 – 35]. These inventories are typically given in pre- and post-test format and often focus on a specific subset of physics content routinely covered in introductory courses.

A primary goal of many of these instruments is to assess students' content knowledge of introductory physics. In a standard application students are given the assessment before and after a particular topic or content area has been covered in class. In this way, one measure of student learning gains can be made. These inventories can provide some insight into the question of which topics to cover and in what depth.

Conceptual inventories can be very useful as one data point pertaining to student learning. For example, if the results of a pre-test given to assess students' prior knowledge of force and motion concepts show that most students already have a reasonable grasp of the material, an instructor could decide that these topics might be covered in slightly less detail to make room for more in-depth coverage of other topics. Decisions made regarding depth and breadth of coverage may correspondingly have broader implications for many engineering and STEM-related disciplines.

Because introductory physics is taken by both STEM- and non-STEM majors, it is of interest to look at topic order in both types of introductory courses. While the level of mathematics used in introductory physics courses varies depending on whether or not they are taken by majors or non-majors, the order of the topics presented remains largely the same in all introductory courses. The next section will explore some of the questions raised in this paper using a second-level introductory course for non-majors as the backdrop.

4 Light, Sound, Action!

A second-level introductory physics course for non-majors entitled Light, Sound, Action (LSA) serves as the catalyst for the questions framed in this paper. LSA is a new name given to a recently "retooled" second-level introductory course for non-majors. The course is designed in a workshop/studio format as research has shown that this is an effective way to teach introductory physics [36].

Figures 1 and 2 provides an illustration of students working in the workshop/studio format. Note that a significant emphasis is placed on hands-on interactive learning throughout all facets of the LSA course.

Fig. 1. Students explore sound waves in a workshop/studio style.

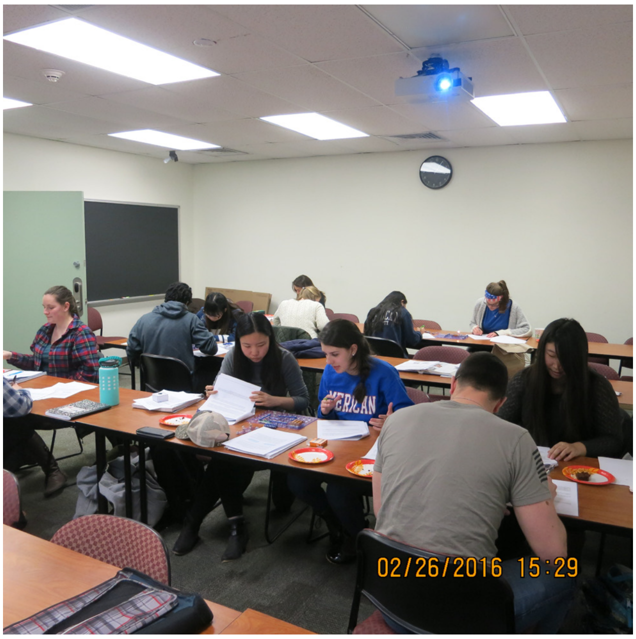

Fig. 2. Students explore electric circuits in a workshop/studio style.

The LSA course serves as one that satisfies the university's general education requirements towards graduation. As part of the retooling of the course, the prerequisite that students must first take a first-level introductory physics course was dropped. As a result, a number of students (roughly one-third of the 15 students) that chose to enroll in LSA during the spring 2016 semester had not previously taken a first-level physics course.

Following the retooling of the course, there were no significant changes made to the topics covered nor the order in which they were presented in the LSA course. The topics covered are typical for a second-semester course and involve most of the topics listed in the previous section. A number of workshop-style interactive learning activities were, however, enhanced. For example, in spring 2016, the entire set of hands-on electric circuits activities were completely rewritten to allow for the use of some new equipment.

As a second-level course, the traditional topics pertaining to electricity & magnetism and waves & optics were covered in their usual order. Because about one-third of the class had not had the first-level introductory course as preparation for LSA, questions pertaining to topic order in the introductory sequence were logically raised. Just how important is it that students take the first-level course before they take the second-level course?

A preliminary answer to this question based on the grades students received in the course might be that topic order is not all that important. The students who had not taken a first-semester course prior to taking LSA performed comparably to those that had.

The students in the LSA course completed regular homework assignments that involved both written conceptual questions as well as algebra-based questions that involved a good deal of problem solving. The students also took periodic exams and quizzes. Unique to the course is a conference paper activity in which the students write a research paper. To that end, this activity requires that students experience all stages of writing a professional conference paper. These stages include:

- responding to a call for papers through submission of an abstract,
- submitting a first draft for instructor review,
- submitting a second draft for peer review, and
- submitting a final camera-ready copy for publication in the conference proceedings.

The students also present their papers at an end-of-semester course conference. In addition, students conduct a peer review of the oral presentations. The conference paper activity takes the place of the final exam. Students are restricted in terms of the topics they can select for their papers. The topics must correspond in some direct way to one or more of the topics discussed in class.

Throughout the spring 2016 semester, the instructor was repeatedly reminded of how much the second-level course builds upon the first level course. The students, however, seemed unaware of and impervious to this fact. For example, topics such as Newton's Laws and conservation of energy are particularly important to topics covered in electricity and magnetism. In addition, a knowledge of the basic mathematics required to deal with vector quantities is also demanded in the second-level course. There were several times over the course of the spring semester that the instructor went back and reviewed these topics. Perhaps this review was helpful to all students and not just those who had not taken the first-level physics course.

Interestingly, the students who had not taken the first-level course did not appear to feel discouraged by their choice to take the introductory courses out of sequence. In fact, some of these students may not ever take the first-level course. As a reminder, most of the students enrolled in the course did so to satisfy the university's general education requirement in the natural sciences.

In the next section the questions posed will be explored in a bit more detail using some preliminary data from the spring 2016 LSA class. This data is not intended to provide firm answers to the questions posed. Rather, it's presentation is intended to further exemplify the need to ask the questions.

5 Preliminary Data

To address the question of the importance of topic order in an introductory physics course for non-majors, a comparison of student performance over the past three years was made. Table 1 illustrates the grading schema used in all courses in the university.

Throughout the course, there were many ways for students to earn points towards their overall course grades. The various assessment elements for the course are highlighted in Table 2.

While the students did take two hour exams and three quizzes over the course of the semester, these assessment measures were collectively worth about one-third of the students' overall course grades. Naturally, the conference paper activity comprised a significant portion of the overall course grade. Collectively the conference paper activities counted for approximately one-third of the students' course grades. In fact, the conference paper activity served to replace a final exam which is common in most courses.

Because the conference paper was an activity in which student learning was assessed at various milestone points (first draft, second draft, peer review, etc.) giving this activity considerable weight in the overall course grade is very appropriate. In addition to the traditional quizzes and exams and the more non-traditional conference paper activity, students also received points for completing numerous in-class, collaborative, hands-on activities. A sampling of these activities was shared in the previous section.

While the topics in the second-level introductory Light, Sound, Action course were presented in a traditional order, some of the students enrolled had not taken the first-level course. The spring 2016 class was the first class allowed by the university to take the course without first taking the first-level introductory physics course. Because of this fact, the question of topic order was naturally raised.

It is appropriate to explore the question of topic order as it relates to overall student performance in the course. To that end, a comparison of course grades was conducted for a three-year time period. These results of this comparison are presented in Table 3.

Table 1. Grading System

Grade	Quality Points
A (Excellent)	4.00
A-	3.67
B+	3.33
B (Good)	3.00
B-	2.67
C+	2.33
C (Satisfactory)	2.00
C-	1.67
D (Poor)	1.00
F (Academic Fail)	0.00

Table 2. Point Distribution for Course Grades

Activity	Points Allotted	Percentage of Course Grade (%)
Hour Exams	200	21.1
Quizzes	75	7.9
Homework	175	18.4
Hands-on Collaborative Activities	175	18.4
Conference Paper	200	21.1
Conference Paper Peer Review	50	5.3
Conference Presentation	75	7.9
Total Points	950	

Table 3. Course Grade Comparison

Semester	Traditional Sequence	Non-Traditional Sequence
Spring 2014	3.24	N/A
Spring 2015	3.41	N/A
Spring 2016	3.45	3.13

Due to the fact that the spring 2016 class was the first to be allowed to take the second-level course without having taken the first-level course, no data is available for the non-traditional sequence for the spring 2014 and spring 2015 classes. The column representing the traditional sequence provides the overall course grades for students in each class that had first taken the first-level introductory physics course. The second column shows the breakdown of course grades for students in the spring 2016 class who had not taken the first-level course before enrolling in Light, Sound, Action. As can be seen, the overall grades for students not having taken the first-level course was about 0.3 points lower than for students that had. This piece of preliminary data might suggest that taking the more traditional path and experiencing the introductory physics topics in the traditional order is, in fact, important. Because the class size was relatively small, additional data collection is warranted and is planned for the spring 2017 class.

As evidenced by their written homework and their performance on exams and quizzes, however, there was literally no reason to think that taking these courses out of order had a significant impact on these students. Many of these students scored just as well, and in some cases even outperformed, those who had taken the first-level course in a previous semester. In addition, there was no obvious evidence based on the scores of the students' written conference papers those who had not taken the first-level course had been at a disadvantage. It was this fact that provided some motivation for revisiting the question of the importance of topic order in the introductory physics sequence.

At this point, we return to the question of just how important is the issue of what to teach and when in introductory physics. This issue has helped to provide the framework for over a century of research and work in physics education. In the current section, the question was addressed by looking at preliminary data for an introductory second-level course for non-majors.

There are, however, broader issues and implications within the larger engineering and STEM communities in terms of the impact that topic order in the introductory sequence may have. These communities often use the introductory physics courses as a foundation for their upper-level courses. To illustrate, the next section will discuss some of these implications using an engineering statics course as one example.

6 Broader Implications in STEM

The use of concept inventories within the broader disciplines of engineering and STEM has also helped to bring to bear a better understanding of student difficulties with basic concepts, such as mechanics. An excellent example is Steif's work to quantify student conceptual understanding in an engineering statics course [37 – 39]. Because engineering statics often comes immediately after a first-semester introductory physics course, this work is particularly relevant.

Steif and Dantzler used a 27-item instrument called the Statics Concept Inventory (SCI) to address student understanding of topics basic to engineering statics [40]. Their study involved 245 students in a statics course at Carnegie Mellon University and the psychometric results obtained provided evidence of the reliability and validity of the instrument. One inference made based on this study was that the results of the inventory provided general evidence of the concepts in statics that students had the most difficulty with.

Steif and Hansen explored the value of web-based administration of concept inventories such as the SCI that make it easy and convenient to compare the results with other measures of performance such as classroom exams [41]. Streveler, et. al. addressed the issue of the importance of conceptual knowledge in engineering science as an essential element of the development of competence and expertise in engineering [42]. Their research drew heavily on that of cognitive psychologists and science educators to address issues and methods of assessing conceptual knowledge. Streveler, et. al. found that some of the most common difficulties with conceptual understanding could be found in three basic domains. These domains were: mechanics, thermal science, and direct current electricity. Interestingly, these are also topics commonly covered in introductory physics classes.

Since students typically take at least the first-semester introductory physics course prior to taking engineering statics, the issue of topic order in physics and depth and breadth of topic treatment certainly resurfaces. Perhaps some issues related to student conceptual difficulties in both of these classes could be linked to students' inability to see the connections between their basic mathematics and science courses and their engineering courses. This inability to see these important connections has given rise to the idea of integrated curricula within engineering education. Froyd and Ohland, for example, have looked at efforts to build links between distinct disciplines [43]. These researchers found that perhaps the most noteworthy long-term outcome of integrative programs may be in terms of the faculty development component. To design and develop a successful integrative program requires significant faculty collaboration across disciplines and learning communities.

In terms of what educational research teaches us, Redish and Smith have suggested that science and engineering instructors know that "… a knowledge of facts, equations, and even concepts is only the beginning. [44]" Redish and Smith have also posited that students in an introductory physics class may learn that memorizing equations is important – but that learning the derivation of the equation or the conditions under which those equations are invalid is not as important. This is certainly not the message instructors wish to convey, but is an unfortunate outcome of many physics classes. Outlining a framework involving the neural, cognitive, and behavioral sciences, Redish and Smith further considered some of the theoretical underpinnings for some best-practice instructional methods related to the specific skill of using mathematics in modeling physical situations. To this end, building student's modeling skills and diversifying skills in a more traditional course (such as physics) may have many implications for instruction as well as curriculum design.

Erdil, et. al. noted that such things as curriculum crowding and time restraints are reasons that the issue of content and coverage in introductory physics courses is often raised [45]. Simply put, the engineering curriculum is already overcrowded and physics classes have been examined by some as areas where certain content may be reduced or left out altogether. As a result of a survey of engineering faculty, Erdil, et al. discovered that topics in classical physics are important to engineering curricula, but topics in modern physics are not. However, topics in some engineering disciplines that involve such things as electronics, mechatronics, nano-technology and advanced materials demand a better knowledge and greater competency in areas related to quantum physics. Typically, modern physics is not a topic area that is covered in the introductory physics sequence. It is quite possible then, as these educators suggest that more physics is needed (at least by some engineering disciplines) than is provided in the typical introductory physics sequence.

Lindenfeld addressed the issue of format and content in introductory physics classes by suggesting that the content of these courses has become rigid and inflexible [46]. But perhaps there is merit in this rigidity and inflexibility. One might in fact argue that the topics typically covered in the introductory physics sequence are appropriate and are doing what they are intended to do; namely, preparing students for additional coursework in physics and engineering. Furthermore, one might argue that if these introductory courses are doing what they are intended to do, then their content should remain essentially unchanged. In light of the fact that engineering itself largely falls within the classical domain, one could also argue that the traditional topic order in introductory physics should be preserved.

7 Summary and Future Research

Not much has changed over the past century or so in terms of the topical content of introductory physics courses, and perhaps rightly so. The basic topics in these courses are vital to the foundation of the education of the engineer. Possibly it is because engineering itself is chiefly a classical discipline that the topics covered in introductory physics (which rely heavily on classical physics) remain so firmly and rigidly fixed.

So, is topic order important in introductory physics? And, how do we know what topics could be treated in less depth and what topics could be treated in more depth? The answers to these questions might plausibly be “it depends.” In other words, there is perhaps no single answer to the questions posed. Topic order might not be so important for a course taken by non-majors. However, the topic order might be extremely important in a course subscribed to by physics and engineering majors.

Over time, physics courses have become more and more technique-driven, rather than concept driven. Given this fact, perhaps it is time to once again pause to address the notion of what concepts truly are important in the introductory physics sequence.

One might contend that the basic skillset that is developed through physics problem solving is most important in terms of preparing students for additional courses in physics, engineering, and other STEM-related disciplines. If that is the case, then perhaps introductory physics is doing a pretty good job. On the other hand, if the main goal of introductory physics classes is to develop and enhance the conceptual knowledge base of our students, then as the research suggests, conceivably more needs to be done. With the expanded knowledge base, tools, conceptual instruments, etc. that the research in physics and engineering education has provided, perhaps the time has come for additional discussions and efforts that specifically target the issues related to content.

An interesting future study might include tracking students who take introductory physics and then go on to take a course such as engineering statics. An assessment of student conceptual understanding through an instrument such as the FCI given in the introductory physics course could then be followed up with the SCI in the statics course. It would be noteworthy to see what correlations might be made between key topics in mechanics covered in both courses. In addition, it might be interesting to see if students who had difficulty with a topic in basic mechanics as determined through pre-and post FCI scores might be comparable to the same topic covered later in the statics course and then assessed through students' SCI scores.

As the recent experience in the second-level LSA course (where approximately one-third of the students had not taken a first-level physics course) revealed, it is certainly possible for non-majors to be successful when taking introductory physics courses out of order. Perhaps a follow-up study that focused on teaching the physics content in a course for majors somewhat "out of order" would reveal some additional useful results. The fact that taking the introductory courses out of order did not seem to have a significant impact on the success of non-majors may have reopened the door to question the order of topics as they relate to the overall curricular ladder. This fact also links the questions raised here to perhaps rekindling the need for a revitalized discussion pertaining to the importance of both the depth and breadth of topics covered in the traditionally-oriented introductory physics sequence.

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