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Transfer of Learning from Mathematics, Science, and Physics Courses to Upper-Level Engineering Courses in Biological Systems Engineering

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Abstract

Almost all undergraduate engineering programs require fundamental courses in mathematics, physics, and science. These often include calculus, chemistry, physics, differential equations, statistics, and many others. While some students begin to take these courses in high school, many engineering students spend the majority of their first and second years fulfilling these requirements. The learning from these courses is critical since many engineering topics build upon the concepts covered. This paper focuses on how students apply learning from mathematics, science, and physics courses to engineering courses using the lens of learning transfer. Learning transfer refers to the application of learning from one context in a new context. For example, it may be important for students to apply concepts from their differential equations coursework to new concepts in their signal and system analysis course. Alternatively, students may need to transfer their physics knowledge to their power systems design course. Though fundamental for success in engineering, very little research has investigated the transfer of learning between basic math, science, and physics courses and the rest of the engineering curriculum, specifically through the eyes of students. As a result, little literature is available for helping instructors assist students in transitioning into these courses. In addition, there is little guidance for students seeking to learn best practices for transferring their learning. This paper presents findings from interviews with current biological systems engineering students regarding their perceptions of transfer between fundamental coursework and more advanced engineering courses. The potential implications of this paper include providing valuable insights into the effectiveness of current educational approaches in facilitating the transfer of learning from fundamental coursework to advanced engineering courses, thereby informing strategies to enhance the learning experience for biological systems engineering students.

Introduction

Transfer, or the application of knowledge from one environment to another, is a critical element of engineering education, as engineers must effectively recall and apply requisite knowledge to solve problems in higher-level courses and their future careers [1]. Undergraduate engineering programs are structured to facilitate this process, as they train students in math and science, then in problem-solving and more complex engineering concepts using this foundation. Transfer allows individuals to use the knowledge acquired in their undergraduate years in a variety of situations, whether in graduate school, the workforce, or any other environment.

The exact courses that make up the requisite knowledge for an engineering program vary by discipline. One such discipline is Biological Systems Engineering (BSE), which emphasizes applying engineering principles to living systems. BSE is known to necessitate a diverse background in science and math, providing substantial opportunities for transfer to occur. Much of the relevant literature discusses transfer using student performance as a metric and is meant to determine methods that encourage transfer or present barriers to transfer; however, there is little focused on the perceptions of students regarding the transfer process and the factors by which it is shaped.

This study seeks to understand how undergraduates in a BSE program perceive the transfer of their learning between foundational courses to more involved upper-level courses. Foundational courses, for the purpose of this study, are the pure science and mathematics courses taken largely in the first two years of the program, such as physics and calculus. We define upper-level courses as courses that require students to synthesize multiple foundational courses at the same time, such as thermodynamics.

Literature Review

The transfer of learning is a crucial element of engineering education across disciplines. Courses must be organized to encourage effective transfer, focusing on developing a foundation in mathematics and science before training complex problem-solving using this foundation. There are many types of transfer that describe transfer with more nuance, several of which are listed in Table 1. Far transfer in undergraduate coursework is of particular interest. This occurs when students use their foundational skills in other contexts (in this case, courses) that do not immediately appear connected. In near transfer, the connection is more apparent. Basile [2] notes that far transfer is generally harder for students to demonstrate but is a behavior indicative of higher order thinking. Dixon and Brown [3] came to similar conclusions, stating that far transfer requires students to intentionally identify aspects of their knowledge that are applicable to a problem. In engineering problem-solving, a solution is rarely immediately obvious and often requires a creative approach. Because of this, far transfer has implications of benefiting the problem-solving process that is central to engineering.

Table 1 – Types of transfer

Type of Transfer	Description
Near Transfer	Transfer between similar environments
Far Transfer	Transfer between dissimilar environments
High-road Transfer	Transfer occurs from a deliberate effort
Low-road Transfer	Transfer occurs easily, possibly automatically

Another facet of transfer is the context in which knowledge is both learned and transferred. This is well-documented to impact the success of transfer. Günay and Kilinc [4] found that students struggled to effectively transfer their knowledge in environments that were vastly different from the context in which they were taught. Students in this study found it challenging to transfer their theoretical knowledge learned in the classroom to tasks in clinical practice. Rebello et al. [5] found that the direction of transfer is important as well. This study had students take both an algebra and a physics course, with some of the students taking algebra first and some taking physics first. They found that students who took algebra first were better able to transfer their skills to the physics class [5].

Several studies have identified barriers to the transfer of learning relating to how relevant information is presented. One such barrier is extraneous processing, where unnecessary information distracts students from learning the desired material [6]. Mayer [6] determined that students better demonstrated transfer when information was organized to minimize extraneous processing. Nakakoji and Wilson [7] found that students struggled to demonstrate transfer between courses that appeared to have few obvious similarities They found this problem is less prevalent when considering transfer between math, physics, and engineering courses and specifically noticed an absence of opportunities for transfer when biological sciences were introduced [7]. Given the disciplinary emphasis biological systems engineering has on life sciences, this barrier may be more prevalent in BSE than in other disciplines. There is little information available about transfer in BSE specifically, and as a result, this is an area that needs exploration.

BSE, like any other engineering discipline, standardizes what undergraduate students must be trained in. Kaleita and Raman [8] documented the degree requirements for BSE programs at several universities across the United States. While they noted many differences between the requirements of individual institutions, courses in calculus, physics, statics, and thermodynamics were almost universally required [8]. These areas of study are crucial to the success of a biological systems engineer after graduation, making it even more important that transfer of learning successfully occurs between them.

Most of these studies quantified the occurrence of transfer by assessing students' performance against a desired outcome. This analysis of curriculum presents a "paper view" of transfer, potentially limiting conclusions that can be drawn about student experiences. There has been little focus on the students' perspectives of their own transfer, or how they perceive certain fundamental classes to directly apply to later courses in curriculum. Investigating this could reveal best practices to encourage student success.

Understanding student perceptions is a key step to better support engineering students through their undergraduate education and encourage their success. Kirn and Benson [9] studied engineering students' perceptions of problem-solving and found that these perceptions reflected their aspirations for the future. Students who perceived a problem as being relevant to their goals were more motivated to pursue a solution. Korte and Smith [10] found that students interested in and capable of studying engineering may still leave their program if the learning environment does not suit them. This implies that a student's personal experience can be just as important to their success as academic performance. As such, this study highlights student perceptions in the context of learning transfer.

Purpose

The purpose of this study is to explore student perceptions of transfer in BSE between calculus and physics to upper-level courses. The following research question was addressed:

1) *What learning do biological systems engineering students describe as transferring between foundational and advanced coursework?*

Students were asked about their experiences in foundational courses and the later advanced courses that build off them. These advanced courses have a reputation of being challenging for undergraduates, and we seek to understand if a lack of transfer contributes to this difficulty [11].

Theoretical Framework

This study uses actor-oriented transfer as a theoretical lens. Actor-oriented transfer is a learning theory emphasizing the role of the learner as an active agent in transferring knowledge and skills from one context to another. This theory acknowledges that learners are not passive recipients of information but rather active participants who engage in the process of learning and applying knowledge in various situations [13]. This perspective emphasizes the learner as the center of the experience, which is conducive to examining the relationship between individual perceptions and the success of transfer. Overall, actor-oriented transfer emphasizes the active role of the learner in the transfer process and was chosen as the theoretical lens for this paper as it promotes a deeper, more flexible understanding of knowledge and skills as compared to more traditional theories of transfer.

Methods

We conducted a thematic analysis of interview data from five participants. Though we acknowledge the limited size of this sample, it is not our intention to make any generalizable conclusions from this data – instead, we present the findings of this study as a catalyst for starting further conversations and research in the transfer space.

All participants were fourth-year biological systems engineering students from a large R1 university in the Midwest United States. After completing appropriate screening material, each participant completed a semi-structured interview with the research team. Interviews took place either over Zoom or in person according to the participant's preference and were recorded and transcribed for thematic analysis.

In their interviews, students were asked about their experiences in relevant coursework. Specifically, they were asked about their time in foundational engineering courses, what they felt they took from these courses, and how that applied to their experiences in later courses. A question in this section would resemble "What went well with your experience in physics?" They were also asked about their motivations in the course, whether they wanted to understand the material for the sake of learning or for the sake of receiving a particular grade, and about any barriers to transfer they encountered. Questions in this portion would be similar to "Did anything make it difficult for you to transfer your learning between physics and dynamics?"

Results

Four themes emerged from the data, including (1) class structure, (2) expected value, (3) metacognition, and (4) identical elements.

Class Structure

We define class structure as the teaching practices and/or course setup that help students transfer their learning from previous courses. A common practice in this theme includes engaging example problems as a teaching tool:

"I think [the professor] tried to like make us excited about the subject. ***He would usually try to bring in those, like, real-world examples, or try to make like jokes or like something that would try to help you remember and make those things like stick in terms of like, what they are and why they were important.****"*

As this excerpt illustrates, students often found concepts more memorable when the instructor used an engaging style of teaching (in this case, the use of humor) paired with real-world examples. In fact, the benefit of making connections between course content and real-world applications was echoed by other participants as well, such as in the following excerpt:

"And then the whole class was more or less graded on the big project...And ***actually thinking through a somewhat real-world example****, even though it's, it probably wasn't a super great solution that many people came up with. But* ***it definitely helped****."*

In sum, the use of engaging, practical, example-based material encouraged students to delve into the material and led to a more memorable understanding of course content. Practices such as this better prepare students to transfer their learning and allow for stronger connections to be made between new material and existing knowledge.

Expected Value

We define expected value as students' perception of the potential usefulness of the material they are learning, which in many cases affected their willingness to learn and transfer course content. In some instances, students did not perceive an immediate benefit to their learning, which affected their willingness to learn and retain the content:

"I understand why you need to use them sometimes. But like, overall, a lot of what we learned in college can like, it can be done by like computer programs, or like, once you know how to do it, you don't ever, ***you really never have to do it by hand again****, because there are things that you can make do it for you."*

This student cited the prevalence of automated problem-solving tools as a detractor to learning course's content. Another student expressed similar apprehension about the usefulness of a course, but because they were taking it late in their degree program and had not struggled without it:

"But as of right now, I wouldn't say that any of my classes have been very useful for this class. Nor do I think that this class will be helpful for my last semester here, because it's not a prerequisite for anything. And ***I'm only taking it because it is required by my degree****."*

On the other hand, some students were driven by perceived future value:

"I know there some people look at classes that they're in and the content that they're learning and say, well, why do we need to memorize this stuff? If I'm going to have an equation sheet in the real world, or I can just look stuff up on Google. And it's like, well, yes and no. That that you will have those things. But if you haven't, at least, memorized them a little bit at the beginning of when you're starting to learn them, or when you're first tested on them, when you're taking the class, then ***it's harder for you to form those connections in your brain that set you up so that you know how to solve or where to potentially start solving a problem later****. But also, memorization can definitely make solving problems a little quicker. Because if you have to constantly look everything up, that's, that introduces a lot of latency."*

The above excerpts demonstrate the relationship between students' perceptions of course value and learning – those unable to understand the importance of the content were less likely to put in the time to learn the material. It follows, then, that transfer is then unlikely to occur if students do not buy into the value of the course content in the first place. Overall, this underscores the importance of explicitly helping students see the value of all material incorporated into the classroom.

Metacognition

Several participants highlighted the transfer of metacognitive skills, meaning that they were able to transfer some of their learning strategies from one course to another. Most held the belief that their problem-solving skills formed the basis of this transferred learning:

*"One thing I've noticed that's kind of been nice...**as I go into some higher level courses, the problem-solving method that, like, I was more taught in high school, but then really had to learn how to use well in my freshman and sophomore years, has been super helpful for learning how to approach and break down problems**. So, like when I see a physics problem, breaking it down into, you know, what I'm trying to find, what I'm given, what my assumptions are, like, **just having a framework that I've had to rehearse a lot in those early years has been a huge time saver**."*

This problem-solving framework was often cited by students as a positive example of transfer. Others benefitted from taking the lead in their learning and reflecting on the material. These students found what worked for them in terms of transfer:

*"**What I figured out about myself is I learn best through, like, evidence learning and example learning** where I go through and essentially like, will diagram out problems of being like, okay, now solve this, or this is how the book solved it. How did we get to each line? What...what principle is this applying? What equations am I using? Why do we move on to each step? And I will, like, do that for different systems until I understand the overall ideas of why."*

This theme draws attention to the importance of transferring all types of learning, not just technical content. Findings like this reinforce the importance of actor-oriented transfer, as student performance metrics (such as grades) alone would likely not have uncovered the transfer of critical metacognitive strategies.

Identical Elements

A common theme amongst all participants was the discussion of identical elements between learning contexts. Students perceived that transfer was more likely to take place if there were common elements between courses of interest. This helped them recognize that new material was asking them to apply knowledge they had previously acquired.

*"It's just recognizing, like, **linking those physics and like calculus concepts to the like work you're doing in...like, the upperclassmen classes**. I feel like sometimes it's easier, like with calculus, because if you see an integral or a derivative, you're like, ah, yes, that is calculus. I see why I needed to learn this."*

In some cases, obvious signals like calculus notation encouraged the transfer of learning. In other cases, especially where this is not possible, pattern recognition proved to be an asset to this process and provided students with another signal to transfer.

"I think either, like, pattern recognition of like, I don't know, especially with kinematics or like, I'm trying to remember, like, exact things are especially like, with like polar coordinates and how you do like that stuff. Like in dynamics. I feel like I was like, yes, this is math. Especially, like centripetal acceleration. ***If I had, like, recognized the like, I don't know, either like patterns or like the corresponding like variables, it would have been easier to recognize****."*

Recognizing any link between learning contexts can help students in novel situations. Even so, this recognition of identical elements does not necessarily always lead students directly to success:

"And I didn't understand how to apply that knowledge to a new setting outside of the practice examples because I felt like ***the examples he gave were usually pretty straightforward*** *and that it contained a lot of the steps or help would, like, guide you along with what you need to do next, and definitely* ***the final was a lot more of like, here's a paragraph worth of information, now figure out what you have to do with it****"*

Excerpts such as this one illustrate the importance of identical elements but highlight one critical importance: though students may recognize connections between learning contexts due to identical elements present in both environments, this recognition does not mean that students are automatically able to *apply* the learning in a new context.

Discussion

The results of this study condensed into four themes: (1) class structure, (2) expected value, (3) metacognition, and (4) identical elements. The variety of the outlined themes provides many opportunities to better understand the student perspective of transfer. This study took care to pay attention to the student perspective and work within the framework of actor-oriented transfer. We let students tell us what learning they thought was transferring in their own experience and why this was the case. This differs from many other transfer studies that "pre-prescribe" what learning should transfer and focus only on the researchers' perceptions of transferable content [13]. The actor-oriented perspective allowed us to maintain a more holistic view of transfer, allowing for the discovery of less obvious skills that transfer between courses, such as metacognitive strategies [13].

Very little evidence of low road and near transfer was found. Participants reported exerting deliberate effort in the transfer of learning between dissimilar environments. The occurrence of transfer between dissimilar situations is an example of far transfer as described by Dixon and Brown [3]. These findings are also indicative of high road transfer as described by Hajian due to the deliberate effort reported [12]. The complex nature of advanced engineering coursework in BSE requires students to draw conclusions and make connections that are not immediately obvious. These results indicate that it may take deliberate effort on the part of instructors to help students make connections between content from other courses that may not be immediately clear. Because far and high road transfer do not happen automatically or easily, prompting students to make these connections may facilitate better learning transfer in BSE courses.

Along these lines, participants reported that transfer occurred more easily and often when they noticed identical elements between contexts. In particular, they felt more confident in their abilities when they were presented with course content that resembled their previous coursework. As such, this finding aligns with the theory of identical elements and serves to expand the understanding of how this relates to the transfer of learning [14]. It should also be noted that participants reported a heavy emphasis on transferring problem-solving skills and methodologies as opposed to minute details of course content. In other words, instead of transferring specific technical details, most students discussed the successful transfer of larger metacognitive and problem-solving strategies. This may have connections to the general principles theory of transfer, which places emphasis on the transfer of broad concepts and principles as opposed to specific details [15]. As a result, future studies on transfer should consider multiple theories when designing their studies. Theories such as the identical elements model and general principles model may not be mutually exclusive, but instead may be smaller pieces of a larger picture that describe the transfer of learning.

While we recognize the limitations of a small study like this, we are hopeful that this sparks further conversation and provides a jumping-off point for other analyses of transfer. In the future, exploring these ideas in the context of other engineering disciplines could provide discipline-specific approaches that encourage transfer and provide the foundation for student success.

Conclusion

Transfer of learning is a vital part of engineering education because applying previous knowledge is a foundational aspect of the engineering problem-solving process. This study specifically sought to explore BSE students' perceptions of what they transfer in courses and what affects the process. We categorized these ideas into themes consisting of class structure, expected value, metacognition, and identical elements. Understanding these themes and students' perceptions about transfer can be useful in the future to help students transfer their learning between foundational to advanced coursework, better preparing them for the challenges of engineering work.

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