Concept Maps Afford Connections From Mathematics and Physics to Electrical Engineering Courses

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Abstract*—*Contribution: **Visual maps that illustrate how mathematics, physics, and electrical engineering classes are connected to each other during the first two years of the electrical engineering curriculum were developed. Key terminology and differences in presentation between fields are discussed.**

Background: **Experience has shown that engineering students struggle when they need to use an approach from their mathematics or physics courses in their first- or second-year engineering courses. In particular, students have difficulty making connections between what they learned in mathematics and physics and how it applies to engineering problems. Improving students' ability to identify the connections between fields could increase student resilience in their engineering coursework.**

Research Questions: **1) Can visual representations of topic connections between fields across the entry-level engineering curriculum increase student's motivation for learning topics in physics and mathematics and improve their problem solving ability? 2) Are there language barriers or other differences between fields that hinder student learning?**

Methodology: **A multidisciplinary team of faculty members from mathematics, physics, and electrical engineering developed visual representations of the links between the core electrical engineering, physics, and mathematics concepts required to solve problems that students will see in their early electrical engineering coursework. Inconsistencies in terminology or notation were explored and documented.**

Findings: **The developed visual aids, coined systematic approach to problem solving (SAPS) maps, describe a mechanism for linking concepts and skills across the technical courses in the first two years of the electrical engineering curriculum.**

***Index Terms*—Concept map, knowledge map, learning styles, mind map, student learning.**

I. Introduction

IN THIS article, the authors propose a novel teaching and learning resource that will ideally improve students' skills in their engineering courses by enabling them to make the necessary connections between their entry-level mathematics, physics, and engineering courses. The authors created visual representations that link the concepts together. The creation of such a tool (referred to as a systematic approach to problem solving (SAPS) map) enables faculty members to easily show students connections to topics within their chosen major. Furthermore, this helps the students develop an appreciation for the relevance of the topics covered in class as they related to their courses. This may lead to increased motivation and success in all courses. Another advantage is that SAPS maps provide a bird's eye view to both faculty and students of where concepts appear in other courses in the curriculum. The authors hypothesize that making these connections is critical during the first two years of the engineering curriculum. Ideally, if students can make a mental model of how the introductory topics in their curriculum build upon each other, they will have a solid foundation on which to develop mastery of later material. The SAPS maps provide a view of the bigger picture for how course concepts are connected and demonstrate how these concepts tie to concrete examples. There are several unique opportunities in this approach including the following.

1) *Mathematics instructors* may not be familiar with where electrical engineering students encounter concepts in future courses. These aids, that is, the SAPS maps, provide a useful tool for making those connections and allow instructors to introduce practical examples in their courses.
2) *Engineering and physics instructors* become more familiar with what their students have learned and can modify their expectations and learning objectives accordingly.
3) *Students* can use visual representations of course and concept connections as they matriculate through the curriculum. These SAPS maps illustrate the relationship between certain topics, and thus motivate students to master the mathematics and physics topics.

Two variations of the SAPS maps are presented in this article for a sample first-year voltage/power/energy problem. Both maps describe the mathematics and physics concepts required to solve the problem, but the two maps present the material through different lenses. The intent is that different presentations of the connections between course topics will help the SAPS maps have a broader reach among students and faculty members alike. Through building the SAPS maps, the authors discovered several language differences between fields that can contribute to miscommunication and a failure of the students to link topics from course to course. These terms are

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discussed in detail in Section III so that others can be aware of the linguistic differences that students must navigate. Future work will cover dissemination of the maps and assessment of their efficacy in supporting student learning during the first two years of the electrical engineering curriculum.

II. Background

A literature search was performed to identify patterns, themes, trends, and opportunities in this multidisciplinary approach to the creation of concept maps across the entry level electrical engineering curriculum. The search focused on how concept maps are used to enhance student learning and support teaching in engineering, mathematics, and physics education. Although there was much published work on the use of student-generated or faculty-generated concept (topic) maps to assess learning in a singular course, there was limited literature on the holistic approach of using concept maps to facilitate learning across multiple courses or disciplines. However, there were multiple papers about the learning advances from students creating mind maps and concept maps in single courses (see [1], [2], [3]).

For example, Ellis et al. [4] examined how students creating concept maps enhanced their understanding in engineering education. The concepts maps helped the students see the big picture and connect concepts to real world projects. Jackson et al. [5] performed an extensive systematic literature review on using concepts maps as an assessment tool in engineering education. The majority of the uses included student-generated concept maps evaluated by the instructor. Jackson et al. concluded that concept mapping in engineering should focus on specific topics, such as emphasizing the interdisciplinary nature of topics like the entrepreneurial mindset.

Daugherty et al. [6] evaluated the use of concept maps to facilitate and assess learning in secondary-level engineering education. They concluded that there were several factors that impacted organizing knowledge with concept maps. For example, to be valuable, engineering concepts must be situated in a larger social, cultural, or discipline-specific context. Concepts presented within this context enabled the learner to grasp the depth and complexity of the ideas. The SAPS maps help make these associations across courses and disciplines to create a base for faculty members and students to create this context.

Castles and Lohani [7] explored how to use a comprehensive concept map to model student knowledge in a large first-year mechatronics course. They conjectured that this work could be scaled across an entire course or degree program to represent student knowledge gains. Furthermore, they emphasized that concepts maps were not just applicable to academic research and knowledge modeling but also for facilitating student learning. It is this last point that the SAPS maps attempt to address. The SAPS maps would not only bolster student learning but also serve as an aid for faculty members as they share knowledge and a holistic view of the engineering curriculum.

Morsi et al. [8] presented work on using concept maps for the validation of curricula development and of program outcomes for certain engineering disciplines. They proposed that concept maps were better than curriculum flow charts to help students see the big picture in the context of main concepts and their relationships. Students indicated using a curriculum concept map helped them understand how courses tied together. Students could then create a relationship between their current courses and their future courses. Morsi et al. recommended creating concept maps for each course that connected with the curriculum flowchart. This would enable students to build mental models of the topics. The key distinction between this work and the SAPS map approach was that the concept maps in [8] show no linkages between courses in the same or different disciplines and provide no sample problems for the students to refer to in that linked concepts.

Tokdemir and Cagiltay [9] took a holistic approach for introducing the computer engineering course curriculum to first-year students. Their goal was to provide structure in the computer engineering program and make connections among the courses in the curriculum. Once again, there are some similarities between their efforts and the SAPS maps but their approach is not as broad or detailed. They also proposed that a curriculum concept map allowed the department to reflect on how well the curriculum met the program mission. The SAPS maps will provide a global perspective to allow faculty members to identify gaps in the curriculum.

The literature search reinforced the idea that concept maps are a valuable tool for representing student knowledge, assessing student achievement, and encouraging student understanding. However, there was a dearth of literature on interdisciplinary and multidisciplinary concept maps in engineering education. The lack of interdisciplinary concept maps to assist course instruction and student learning is the deficiency that the SAPS approach attempts to address. The authors hypothesize that the SAPS would provide a multidisciplinary approach to connect the lower level electrical engineering, mathematics, and physics curriculum in the context of sample problems that students will encounter. SAPS maps would also aid faculty with teaching the relevance of these topics.

III. Nomenclature

When collaborating on this project, the authors discovered inconsistencies in terminology and techniques among the fields of mathematics, physics, and electrical engineering. For instance, one source of discussion centered around the various uses of the letter i as a variable. Mathematics classes always use i to denote $\sqrt{-1}$ whereas engineering classes use j. This is necessary because i is the variable for current in electric circuits, but $\hat{\mathbf{j}}$ is the unit vector along the y-axis in physics and mathematics.

Misunderstandings as to what exactly is taught in prerequisite classes were also observed. A few examples of this are highlighted in this section to bring attention to additional challenges that students and instructors face throughout the curriculum. Such small inconsistencies may present a road block for a student exposed to this material for the first time.

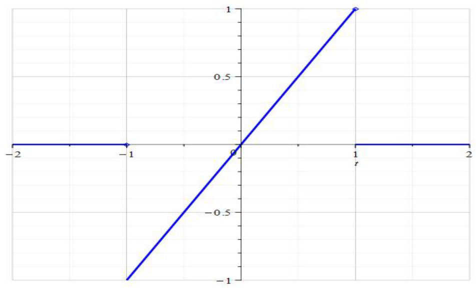

Fig. 1. Sample discontinuity graph from a mathematics course.

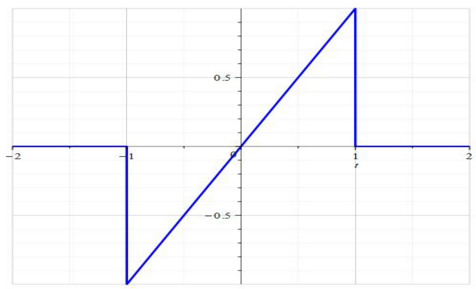

Fig. 2. Sample graph of corresponding ramp function.

A. Discontinuous Functions

Representation of discontinuous functions was one discrepancy noticed among the fields. In mathematics, it is stressed that for a relation to be a well-defined function, every input (value of independent variable in the domain of definition) will have exactly one output (value of the dependent variable). That is, given the graph of a relation, if there is a vertical line that intersects the graph at more than one point, then the graph does not represent a function. Discontinuous functions are visually presented as having a gap (for a jump discontinuity; see Fig. 1), a hole (for a removable discontinuity), or a curve going off to infinity (for an infinite discontinuity).

However, in engineering, the term "function" is not presented so strictly. For example, in electrical engineering courses, the step function and ramp function are typically shown with a vertical line in lectures, just as it is represented on a function generator, oscilloscope, or in MATLAB. These functions represent position, velocity, or a switch opening or closing on a circuit.

An example of the difference in these representations is shown in Fig. 2. Since the students in mathematics courses are never shown graphs of functions with vertical lines, students do not know how to physically interpret what graphs containing vertical lines are describing when the discontinuity is not explicitly shown. Students should be reminded in all their classes that a vertical line in a graph formally means that the function is not well defined, but in applications this most likely means there was a jump in the function and this is how the oscilloscope or function generator displayed the results.

B. Phasors

Different universities introduce complex numbers (particularly Euler's formula regarding polar form of a complex number) at different points in their curriculum. Typically, electrical engineering students are expected to use the polar form of complex numbers in their courses before polar form is introduced in the mathematics curriculum. While Euler's formula is most likely covered in one required mathematics class, phasors are probably not. A phasor is a vector that represents a complex number with a magnitude and direction (phase angle). When referring to Euler's formula

$$re^{i\theta} = r\cos(\theta) + ir\sin(\theta) \tag{1}$$

mathematicians will almost exclusively use radians. However, engineers will represent a phase shifted cosine as

$$A\angle\theta^\circ = A\cos\big(\omega t + \theta^\circ\big) \tag{2}$$

where A is the amplitude, ω is in radians/seconds, the angle θ may often be in degrees, and t is in seconds.

Second, mathematicians use polar form, $re^{i\theta}$, for multiplication, division, and powers of complex numbers but standard form, $a + ib$, for addition, subtraction, and (usually) solving systems of linear equations. Therefore, many students tend to be unfamiliar with solving a system of linear equations that involves phasors. Most likely, students previously solved a system of linear equations by equating the real and imaginary parts on both sides of each of the n equations, resulting in $2n$ linear equations.

C. Systems of Equations

At the authors' school, electrical engineering students need to be able to solve a system of linear equations for real numbers by the end of their first year and for complex numbers by their second year. Using a matrix to solve a system of linear equations, via reduced row echelon form, will not be covered in the mathematics curriculum until linear algebra courses in the second year of study or later. Engineering faculty members need to be aware of when systems of equations are taught in their curriculum and be prepared to adjust their expectations accordingly.

D. Solution Forms

When considering a homogeneous differential equation whose characteristic polynomial has complex roots (and therefore has a periodic oscillating solution), the general solution will be represented as

$$c_1\sin(bt) + c_2\cos(bt) \tag{3}$$

in an introduction to differential equations class. Engineering instructors use trigonometric properties to show students that (3) is equivalent to $c\cos(bt + a)$.

E. Work Versus Energy

Work and energy are two terms that are used slightly differently between physics and electrical circuits courses. For example, the variable w represents energy in electrical engineering but represents work in physics. In a physics setting, one definition of work is *a change in energy*. Furthermore, both work and energy have the units Joule, J. When circuits are covered in physics courses, the emphasis is on electric potential, particularly the change in electric potential across components. Since electric potential is related to potential energy, a change in electric potential is related back to work. The use of "work" instead of "energy" in electrical engineering classes is a natural evolution of language, creating a field-specific "technical slang" that can cause confusion.

F. Passive Versus Active Sign Convention

Electrical engineering and physics faculty members at the authors' school, identify nodes and use Kirchhoff's current law to solve for unknown voltages and currents in a circuit in different ways. Many physics texts use the active sign convention to highlight changes in electric potential across circuit elements. In electrical engineering, the passive sign convention is used. Transitioning between the two sign conventions sometimes created confusion as students attempted to identify voltage rises, voltage drops, and whether power was delivered or absorbed.

These examples provide additional justification for the creation of the SAPS maps as these maps give a way for faculty and students to share in a common language and description. The need for clarification in each of the mentioned topics supports research question 2, that yes, there are language barriers that hinder communication between fields.

IV. Formation of the SAPS Maps

The use of the terms concept map, road map, knowledge map, and topic map is widely varied across the literature. Therefore, to eliminate confusion and inconsistency in the definitions, the authors coined the term SAPS map to describe their graphical representation of connections between the mathematics, physics, and electrical engineering fields. The authors created 20 sample problems relevant to first- and second-year electrical engineering curriculum. Then, two varieties of SAPS maps were created for each problem. Due to spacing constraints, the SAPS maps for only one problem is presented in this article. The *SAPS-T* map, where T stands for "Topic" to indicate the focus of this representation of a problem, has a flowchart feel and emphasizes which topics from the mathematics and physics curriculum resurface during the process of solving a specified electrical engineering problem. The *SAPS-C* map, where C stands for "Concept," has a concept-map feel and precisely illustrates the relationship between mathematics and physics courses to the main electrical engineering concepts used to solve the sample problem.

As course content and names vary across universities, the authors necessarily consolidated course names into an overarching theme. The primary courses used to create the maps are in the first-and second-year of the curriculum as summarized in Table I.

The authors identified sample homework problems in first- and second-year physics and electrical engineering courses and created the solution steps. Each step was annotated to indicate which mathematics and physics courses and corresponding concepts were necessary. This was followed by discussion on

TABLE I
Courses Considered When Designing SAPS Maps

Discipline	Course
Mathematics	Calculus Sequence
Mathematics	Differential Equations
Physics	Mechanics
Physics	Electricity and Magnetism (E&M)
Electrical Engineering	Circuits
Electrical Engineering	Signals & Systems
Electrical Engineering	Control Systems

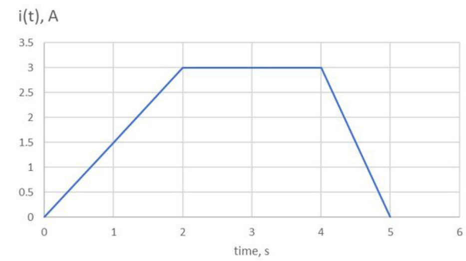

Fig. 3. Current flowing through a 5H inductor over time.

the inconsistencies in terminology and notation between fields and the creation of the two varieties of SAPS maps.

Since each pair of SAPS maps is unique to a given sample problem, example SAPS maps are defined here in the context of an AC circuits problem (see Fig. 3).

> Fig. 3 shows the current flowing through a 5H inductor. Assume that the inductor is initially uncharged, $i(0) = 0A$. Find the voltage, $v(t)$, power, $p(t)$, and energy, $w(t)$.

The SAPS-C maps are designed to emphasize the relationship between courses, topics covered in courses, and topics needed to understand other topics. Various styles of arrows highlight these relationships. The formatting for the SAPS-C maps is as follows.

1) Course name Courses that introduce necessary problem-solving concepts are designated with an oval around the course name.
2) $\boxed{\text{Concept title}}$ Topics essential for solving the given problem are designated by a rounded box.
3) $\longrightarrow$ A solid line with a single arrow is connected either to a topic covered in a course or connects topics that are necessary for another topic.

The SAPS-C map for the AC circuits problem is given in Fig. 4 and details the concept flow for the problem of determining, among other things, energy when given a plot of current through an inductor. The topic of functions is reviewed at the beginning of the calculus sequence. An understanding of functions is necessary for calculating derivatives which are prerequisites for integration. Electrical engineering students will use integration of polynomials to calculate energy. The concept of energy for passive circuit elements is also covered in the physics course that emphasizes electricity and magnetism (E&M), hence the solid line with single arrow from the oval containing E&M to the energy box.

SAPS-T maps are twofold in design. The first is to outline the general steps a student must follow in order to complete a

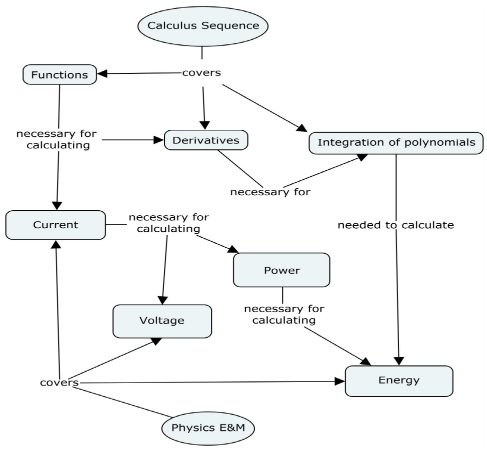

Fig. 4. SAPS-C map for sample AC circuits problem.

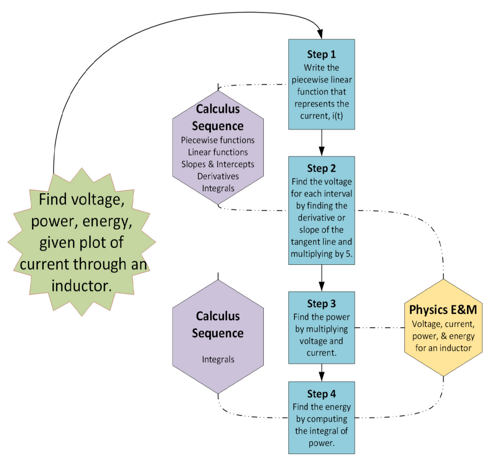

Fig. 5. SAPS-T map for sample AC circuits problem.

problem. The second is to indicate which courses and topics covered within said course are relevant to a given step. The formatting for an SAPS-T map is a modified flow chart. The 16-sided star contains the problem statement which is connected with a solid line arrow to the first step needed for the solution. Subsequent steps, and detailed instructions for solving the steps, are labeled and are connected with a solid line arrow. Mathematics and physics courses along with the concepts introduced in those courses are notated with hexagons. These courses are connected with dotted–dashed lines to the problem-solving steps to indicate where these concepts are needed within the steps.

The corresponding SAPS-T map given in Fig. 5 details the four general steps need to determine equations for voltage, power, and energy when provided the graph of current flowing through an inductor. Since the topics of voltage, current, power, and energy are covered in E&M, the E&M hexagon is linked to Steps 2–4. The topics of linear functions, slopes, intercepts, and derivatives are covered in a first-term calculus course. Therefore, a calculus hexagon is linked to Steps 1 and 2, since these topics are necessary for finding the voltage of an inductor. Integration techniques covered in a subsequent calculus course are used in determining the energy of the inductor, and so another calculus hexagon is linked to Step 4.

The SAPS-C and SAPS-T maps provide different views of the concepts needed to solve a sample problem from a first- or second-year electrical engineering course. The SAPS-C maps presents the students with a detailed view of the topics within mathematics and/or physics courses that are necessary to successfully solve a sample problem. On the other hand, the SAPS-T maps spotlight the general steps needed to solve a problem while highlighting the courses that cover the material that is needed in each step. The students should have a clear understanding of how concepts relate to the sample problems when they view both SAPS maps with the given problem.

V. Diversity, Equity, Inclusion, and Justice

Schroeder et al. [10] found that concept maps coupled with other learning and teaching strategies were effective for student learning. The verbal and visual approach of coding information assists with long-term memory and information retrieval. Student generated concepts maps may also distribute the cognitive load and consolidate audio and sequential concepts at a single point. Chiou et al. [11] concluded that students with different types of learning styles may have different levels of achievement based upon the concept mapping technique used. Wang et al. [12] evaluated a question prompt-based technique for creating concept maps versus conventional concept map making and found that students using the question-based approach performed better in terms of learning achievement, learning attitudes, reflective style versus active style and with the 5C competencies, including communication, critical thinking, complex problem solving, collaboration, and creativity.

SAPS maps provide various visual presentations of linkages between topics to assist students, with diverse learning preferences and prerequisite skills, in understanding the material. The implementation of SAPS maps into an introductory electrical engineering curriculum could address equity, diversity, inclusion, and justice through universal design, providing the same information in varied presentations to better support learners from different backgrounds. For example, whether global or sequential, intuitive or reflective, the concept map provides the learner with the ability to see concepts in the context of their course or the curriculum. SAPS maps are a tool that faculty members with diverse teaching styles can use when presenting theory to students. These maps help faculty members establish context for concepts and provide the students with relevant examples to help students connect abstract concepts.

VI. Conclusion and Future Work

In this article, the authors described their preliminary work creating concept maps (SAPS maps) to link topics in mathematics, physics, and electrical engineering. The primary goal was to create concrete examples connecting the disciplines. The motivation was to assist faculty members and students in viewing the curriculum with a holistic perspective. This perspective will provide context and relevant engineering examples to abstract concepts in mathematics and physics.

Providing this context may increase student motivation to master these concepts.

The next steps in this work include refining the SAPS-C and SAPS-T maps for the remaining sample homework problems. The maps and problem statements will then be converted to an easily accessible electronic, interactive online media format. In order to evaluate the usefulness of the SAPS maps to meet the aforementioned goals and to answer the research questions, they will be distributed to faculty members and students in several courses. The assessment will involve evaluating usefulness for developing curriculum, archiving knowledge, and scaffolding learning. Based upon the results, the SAPS maps may be made available as a free-to-access resource to support other higher education communities with a similar need.

In summary, SAPS maps were developed. The goal was for the two variations of the SAPS maps to assist faculty members and students in the formation of connections among electrical engineering topics and the relevant concepts from mathematics and physics courses. To demonstrate the application of the SAPS-T (topic-focused) and SAPS-C (course-focused) variations of the SAPS maps, an example of each type of map was given with respect to a single example problem. Beyond providing a visual representation of how concepts link across fields, the multiple presentations aim to assist EDI efforts by supporting learners with different backgrounds, experiences, and learning preferences.

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