122nd ASEE Annual Conference & Exposition
June 14 - 17, 2015
Seattle, WA
Making Value for Society
Paper ID #12246

Understanding a New Paradigm for Engineering Science Education Using Knowledge about Student Learning

Dr. Donald E. Richards, Rose-Hulman Institute of Technology

Dr. Richards is Professor of Mechanical Engineering at Rose-Hulman Institute of Technology and teaches in the area of thermal-fluid sciences. He earned his mechanical engineering degrees at Kansas State University (BS), Iowa State University (MS), and The Ohio State University (PhD). Prior to joining Rose-Hulman in 1988, he was on the faculty at The Ohio State University. In 1998, he joined Kenneth Wark as co-author of Thermodynamics (6th Ed) published by McGraw-Hill. Since 1995 he has taught in Rose-Hulman's innovative, integrated Sophomore Engineering Curriculum, and his textbook, Basic Engineering Science–A Systems, Accounting, and Modeling Approach, is used in this curriculum. In addition to teaching, he also served two years as the Director of the Center for the Practice and Scholarship of Education at Rose-Hulman.

Dr. Michael A. Collura, University of New Haven

Michael A. Collura, professor of chemical engineering at the University of New Haven, received his B.S. in chemical engineering from Lafayette College and M.S. and Ph.D. degrees in chemical engineering from Lehigh University. After several years in industry, he moved to the academic world, where he has taught engineering for over 30 years. He is currently the Buckman Professor of Chemical Engineering in the Tagliatela College of Engineering. His professional interests include the application of computers to process modeling and control (particularly for energy conversion processes), engineering education research (student self-assessment, developing conceptual understanding, multidisciplinary learning models), and reform of engineering education.

Understanding a New Paradigm for Engineering Science Education Using Knowledge about Student Learning

Abstract

Over the last thirty years much attention has been given to improving engineering education; however, much of this effort has been devoted to understanding and improving the classroom environment while the courses in a typical curriculum have remained unchanged. This paper examines a unique curricular change, a new paradigm, for organizing and teaching engineering science courses at two different institutions. This approach has been used successfully for many years at these institutions (10 years and 20 years, respectively) to organize curricula for sophomore engineering students from a range of disciplines. Many of the key ideas in this framework are singled out as core ideas in the new K-12 Science Education Framework and could also have application to designing first-year courses and curricula. The foundational sophomore course in each of these curricula is the focus of this paper. Each course is part of a larger integrated engineering science curriculum that emphasizes fundamental principles and de-emphasizes traditional course boxes. Stressing a common framework for presenting and applying the fundamental principles, the foundational course emphasizes the construction of problem-specific solutions not just "plug and chug" procedures using memorized formulas. The paper discusses the features of these sophomore courses, the underlying curriculum paradigm and how they are consistent with current knowledge about student learning. Through this discussion, the authors also hope to encourage others to consider this and other new approaches to organizing engineering courses and curricula.

INTRODUCTION

The content and structure of first- and second-year curricula are critical in setting our students on the path to success. Typically first-year curricula involves mathematics, physics, chemistry plus some engineering topics. As a student moves into the second year, the amount of engineering content increases. New national K-12 science education standards[1] propose a framework for student learning in the sciences that should influence how we organize and teach this material in college. It only makes sense to build on what our students know coming out of high school to increase their chances for success in college.

The road to becoming an effective engineer involves acquisition of both knowledge and skills, but most importantly it requires the development of a particular mindset. Engineers should approach problems with creativity and an understanding of the underlying concepts. Current computer tools are very effective at performing the detailed calculations needed to model even very complex systems, but the engineers using them need to have a clear understanding of the physical systems they are modeling in order to properly set up the computer model and, most importantly, to perform a reality check on the software results. In most cases, the systems that engineers deal with have become complex and involve phenomena from multiple disciplinary domains. For example, digital logic, electric-circuit behavior, and heat transfer all play a role in designing computer chips. Does our engineering curriculum prepare our graduates to deal with such complexity?

The authors suggest that the current approach to the engineering curriculum is out of step with the current practice of engineering. A modification to the early engineering science courses, and possibly the first-year science and mathematics courses, would serve to change the students' approach toward problem solving and better prepare them to apply what they learn to solve realistic problems. Curriculum change is difficult. Traditional science and engineering science courses have been in place for decades supported by an infrastructure of classic textbooks and growing web resources. Why change? The nature of the practice of engineering has drastically changed[2] as has our understanding of how students learn[3].

In this paper, we first discuss what we feel are problems with the traditional approach to teaching engineering science fundamentals and then introduce an alternate approach that we feel addresses these concerns. Next we discuss how this approach was implemented at two different institutions and present assessment data. Finally, we discuss features of this new approach that we believe should promote learning based on our current knowledge about student learning.

TRADITIONAL APPROACH TO ENGINEERING FUNDAMENTALS

A traditional engineering curriculum is very effective at developing high-level competence in the analysis of a narrow range of systems. The traditional curriculum includes a set of fundamental engineering courses, usually at the sophomore level, that differ for each discipline. A typical mechanical or civil engineering program would begin with a course in mechanics, e.g. statics, as the first "difficult" engineering-analysis course. For electrical engineers, it would be circuit analysis, while chemical engineers would begin with mass balances. Each discipline seems to have a foundational course intended to immerse students in discipline-specific, engineering-analysis methods. Students and faculty often view this course as a "gate keeper" or "weed out" course. This reputation is earned because of the demands on students to fundamentally change their approach to problem solving and even to modify their learning strategies. Typically these courses emphasize the documentation process in addition to correct computational procedures.

There are three fundamental issues that arise from the traditional presentation of engineering fundamentals:

- Emphasis on procedural competence at the expense of conceptual understanding
- Compartmentalization of knowledge
- Difficulty applying common methods across disciplines

Concepts vs Procedures

As students strive to solve a problem, it is common for students to focus on surface details and specific solution methods but miss the bigger picture or underlying concept. To draw an example from math, students are taught in high school algebra to multiply a pair of binomials, e.g. $(a+b)(c+d)$, using the "FOIL" method – First, Outer, Inner, Last. Most students fail to realize that this is a specific application of the distributive property of mathematics, and when faced with a small variation, e.g. $(a+b)(c+d+e)$, they are lost. In an engineering setting, a student may be very adept at applying mesh analysis to find the currents in a branched resistive network, but that same student will often be unable to identify by inspection which currents should differ in a simple network. The problem is that they focus on the method of solution (get an answer) and do not master, and may not even recognize, the underlying concepts. A course built around a single disciplinary area, e.g., statics or mass balances, allows students to become proficient at the solution methods without necessarily requiring a deep understanding of the underlying concepts. To be fair, many, if not most, instructors try very hard to get students to focus on concepts, as evidenced by the recent interest in concept inventories. However, students have become very adept at optimizing their time to achieve good grades by focusing on learning solution methods. In doing so, they limit their understanding to the set of examples they have seen or the solved problems they can find on-line.

Traditional foundational courses require students to cover a significant range of concepts and applications. Skim through the table of contents of a popular statics textbook and you will find a dozen or more chapters each of which includes dozens of formulaic solutions corresponding to different situations. Students who are taking a typical engineering course load do not feel that they have the time nor do they see the need to develop a solid understanding of the various quantities, e.g., mass, force, or momentum, and the relationships among these quantities. Instead they tend to focus on developing proficiency in solving problems like those presented in the book. Hence they find it prudent to trade deep understanding of a few basic concepts for a potentially false sense of proficiency in solving a wide variety of problems. The irony is that time spent understanding the basic ideas would actually allow them to handle a wider range of problems than what they can muster by cramming for the chapter quizzes or midterms and final exam. Despite the best intentions of the instructor to help them develop conceptual understanding, expediency demands that students rely on the tried-and-true learning method of memorizing procedures for each expected situation.

Disciplinary Silos

The nature of the traditional curriculum fosters the development of mental walls that compartmentalize knowledge and solution methods. Current practice requires that engineers have a broad understanding of science and technology along with depth in their chosen discipline. In most cases, real problems will be addressed by multi-disciplinary teams that include engineers from several disciplines and other specialists. One of the recommendations of the NAE Engineer of 2020 study is that engineering schools introduce multi-disciplinary learning[4]. The usual approach to achieve this goal is to require that students take introductory courses in a discipline other than their own. However, the foundational course in another discipline will typically have a narrow focus on the knowledge and procedures relevant to that discipline. Unless the ideas from this course are reinforced in subsequent courses, the experience will likely be a brief and forgotten excursion into another discipline. The opportunity to connect concepts across disciplines will most likely be missed as the instructor for this course focuses on preparing students in her discipline. Most importantly, this approach does not expose students to the nature of realistic problems that require understanding of concepts from different disciplinary domains. We generally wait until the senior design course to present this reality to our students.

Common Ideas and Mathematical Structures

In a discussion of conceptual knowledge in engineering science, Streveler and co-authors[5] list several previously identified misconceptions in the areas of mechanics, thermal-fluids and DC circuits. A common theme across these knowledge domains is the difficulty of understanding basic physical quantities, e.g. momentum, force, heat, temperature, current, voltage. Another recurring theme is the difficulty students have in properly developing useful abstract diagrams for the phenomena involved in a specific problem, e.g. free-body diagrams, process flow diagrams, circuit schematics. Solving these difficulties requires a level of abstraction that does not come easily to most students and is rarely emphasized in the traditional foundational courses. The fact that there are common, although abstract, links across these domains could present an opportunity to influence students' approach to learning if time was available to address the more abstract thought processes. However, as pointed out above, instructors of traditional foundational courses are under significant pressure to cover the required chapters as preparation for subsequent study in the discipline.

A number of other common themes exist across these knowledge domains, although many are masked by the unique terminology used by each discipline. A partial list of common themes include:

- Need to develop a diagram (abstraction) to focus on specific parts of a system
- Similar mathematical representations for the interaction of system properties
- Ideas of equilibrium, steady-state vs. transient behavior, open vs. closed systems
- Need to define a system and its boundary (system vs. surroundings)

There are also common procedural methods, usually resulting from the underlying mathematical models and accompanying assumptions. One example is combining parts of a system in such a way that the interior need not be examined. This common methodology goes by different names in each discipline:

- Overall mass balances - when considering mass flows in streams for a multi-unit system
- Super node - when applying nodal analysis to a branched resistive dc circuit
- Method of sections - when examining internal forces in a truss structure

In all cases, the fundamental idea is similar: internal interactions will cancel out when the system boundary is selected to include multiple sub-systems.

SYSTEMS, ACCOUNTING, AND MODELING (SAM) APPROACH

While the Systems, Accounting, and Modeling (SAM) approach is not entirely new, the use of this approach within the first sophomore-level analysis course is a more recent development. The SAM approach, although not referred to by that name, was the basis for the Texas A&M / NSF Engineering Core Curriculum[6] introduced in 1990. This included a set of four interdisciplinary courses organized around what they called the conservation and accounting principle. It was subsequently adopted by members of the Foundation Coalition as part of a comprehensive set of educational reforms. Glover, Lundsford, and Fleming later published an introductory textbook[7] for the first course in this curriculum which provides a unified introduction to topics in several engineering science subjects. Holtzapple and Reece[8] have also included this approach within a

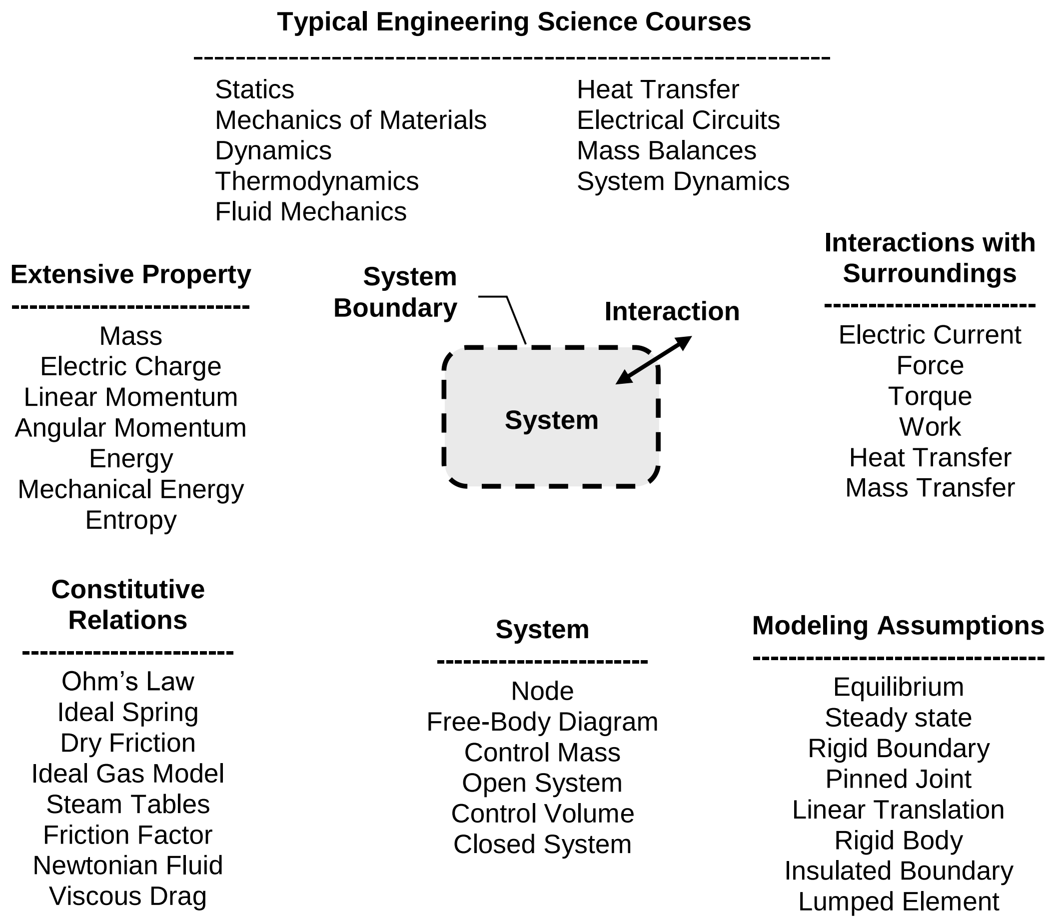

Figure 1 -- Common Concepts in Core Engineering Science Courses

freshman engineering textbook. Saterbak, McIntire, and San[9] have used this approach for an introductory bioengineering textbook. A number of physics educators have also advocated for a similar approach to teaching introductory physics, as exemplified by the work of Burkhardt on System Physics[10], Fuchs on the Continuum Physics Paradigm[11], and Simon and Fuchs on using a Systems Dynamics methodology to teach physics[12]. A detailed description of the SAM approach as used by the authors is presented in papers by Richards and Rogers[13], Richards[14,15], and Collura, Daniels, and Nocito-Gobel[16] and only an overview of the key aspects will be presented here.

As shown in Figure 1, the core set of engineering science courses have a number of common features that can be organized around common concepts. Typically, when an engineer faces a problem, he or she will need to work through a series of steps in creating a solution. A broad summary of the steps would include:

- Examine the situation to determine what phenomena are involved (e.g. is this a mechanics problem or a thermodynamics problem) and to define the nature of the problem
- Isolate a part of the physical world and identify the **system** and its **surroundings**
- Identify the important **properties** or parameters that describe the state of the system

- Identify the **processes** that change the state of the system and the **interactions** the system has with its surroundings during these processes
- Obtain or create a mathematical **model** to predict the effect of changing parameters on the state of the system, making reasonable assumptions about the properties involved
- Use the model to try out some solutions
- Iterate as needed (including modification of the selected properties, model, etc.)

The model development step generally involves the application of fundamental principles or laws, e.g. Newton's laws, the first and second laws of thermodynamics, conservation of charge, conservation of mass, etc. These are bedrock **accounting principles** used to keep track of important **extensive properties**, e.g. mass, charge, energy, linear momentum, angular momentum, and entropy. Five of these are **conserved properties** and the sixth one, entropy, can only be generated. In addition, the model will require **modeling assumptions** to capture the essential features of the problem and selection of **constitutive relationships** to supplement the fundamental laws. With this information collected, it is now possible to analyze the situation and ultimately solve the problem

The underlying organizing principle for the SAM approach is what we will refer to as the accounting principle. Holtzapple and co-authors[17] point out that "engineering accounting" is a unifying framework that applies to all engineering disciplines and underlies much of the analysis taught in engineering science courses. The key ideas are that every system has associated with it numerous extensive properties and that the behavior of the system can be determined by monitoring how these properties change. For a finite-time interval, the accounting principle for a generic extensive property *B* can be written as follows:

$$\begin{bmatrix} B\text{ inside} \\ \text{the system} \\ \text{at the} \\ \text{end of the} \\ \text{time period} \end{bmatrix} - \begin{bmatrix} B\text{ inside} \\ \text{the system} \\ \text{at the} \\ \text{start of the} \\ \text{time period} \end{bmatrix} = \begin{bmatrix} B\text{ transported} \\ \text{into the} \\ \text{system} \\ \text{during the} \\ \text{time period} \end{bmatrix} - \begin{bmatrix} B\text{ transported} \\ \text{out of the} \\ \text{system} \\ \text{during the} \\ \text{time period} \end{bmatrix} + \begin{bmatrix} B\text{ generated} \\ \text{inside the} \\ \text{system} \\ \text{during the} \\ \text{time period} \end{bmatrix} - \begin{bmatrix} B\text{ consumed} \\ \text{inside the} \\ \text{system} \\ \text{during the} \\ \text{time period} \end{bmatrix}$$

Any change in the amount of an extensive property within the system can be accounted for by considering the amount *transported* across the system boundary and the amount *generated* or *consumed* inside the system. (An interesting historical discussion of the development of this principle for open systems or control volumes is presented by W. G. Vincenti in his fascinating book *What Engineers Know and How They Know It*[18].)

Using the accounting principle as a common framework, it is possible to introduce each of the fundamental principles of engineering science through a process of answering four questions: (1) What is the extensive property, (2) How can it be stored within and quantified (expressed using variables) for a system, (3) How can it be transported across the system boundary, and (4) How can it be generated or consumed inside the system? Using this process stresses the underlying structure that is common to all the principles and helps students understand these equations in a broader way. The result of this process is the general rate form of the accounting principle that leads to five conservation equations—mass, charge, linear momentum, angular momentum, and energy—and one accounting equation for entropy as shown in Figure 2.

Generic Property B	$\frac{d}{dt}\left(B_{sys}\right)=\left[\sum \dot{B}_{transport,in}-\sum \dot{B}_{transport,out}\right]+\left[\dot{B}_{generation}-\dot{B}_{consumption}\right]$
Mass	$\frac{d}{dt}\left(m_{sys}\right)=\sum_{in}\dot{m}_i-\sum_{out}\dot{m}_e$ (Total mass) $\frac{d}{dt}\left(m_{j,sys}\right)=\sum_{in}\dot{m}_{j,i}-\sum_{out}\dot{m}_{j,e}+\left[\dot{m}_{j,generation}-\dot{m}_{j,consumption}\right]$ (Mass species j) $\frac{d}{dt}\left(n_{j,sys}\right)=\sum_{in}\dot{n}_{j,i}-\sum_{out}\dot{n}_{j,e}+\left[\dot{n}_{j,generation}-\dot{n}_{j,consumption}\right]$ (Moles species j)
Net Charge	$\frac{d}{dt}\left(q_{sys}\right)=\sum_{in}i_j-\sum_{out}i_j$ reduces to Kirchhof's Current Law for a node which cannot store charge
Linear Momentum	$\frac{d}{dt}\left(\mathbf{P}_{\text{sys}}\right)=\sum_{\text{external}}\mathbf{F}_j+\sum_{\text{in}}\dot{m}_i\mathbf{V}_i-\sum_{\text{out}}\dot{m}_e\mathbf{V}_e$
Angular Momentum	$\frac{d}{dt}\left(\mathbf{L}_{o,\text{sys}}\right)=\sum_{\text{external}}\mathbf{M}_{o,j}+\sum_{\text{in}}\dot{m}_i\left(\mathbf{r}_o\times\mathbf{V}\right)_i-\sum_{\text{out}}\dot{m}_e\left(\mathbf{r}_o\times\mathbf{V}\right)_e$
Energy	$\frac{d}{dt}\left(E_{\text{sys}}\right)=\dot{Q}_{\text{net,in}}+\dot{W}_{\text{net,in}}+\sum_{\text{in}}\dot{m}_i\left(h+\frac{V^2}{2}+gz\right)_i-\sum_{\text{out}}\dot{m}_e\left(h+\frac{V^2}{2}+gz\right)_e$
Entropy	$\frac{d}{dt}\left(S_{\text{sys}}\right)=\sum_j\frac{\dot{Q}_j}{T_j}+\sum_{\text{in}}\dot{m}_is_i-\sum_{\text{out}}\dot{m}_es_e+\dot{S}_{\text{gen}}$ with $\dot{S}_{\text{gen}}\geq 0$

Figure 2 -- Fundamental Conservation & Accounting Equations

One of the advantages of using the accounting framework is that it lends itself to a common problem-solving approach regardless of the problem. When a student tackles a problem, he or she has a consistent set of questions to ask about the problem as they construct a model. These are illustrated in Figure 3. Notice how the questions are framed in a manner that is independent of the specific problem. Because students are asked to construct their solutions beginning with the basics, they must now focus on how the modeling assumptions simplify the general equations instead of looking for the already simplified equation in the text.

By asking and answering these questions, the student develops a problem-specific model which will typically be a single equation or a set of algebraic and/or differential equations that contain most of the important variables and parameters for the system. Additional constitutive equations, e.g. ideal gas equation, Ohm's law, etc., may be needed to augment the ones obtained from the accounting equations. These "laws" can be recalled from earlier work in science courses or provided as needed, but many will reappear in later engineering classes within the student's discipline.

Written Format
• Known
• Find
• Given
• Analysis
-- Strategy
-- Constructing Model
-- Symbolic Solution
-- Numerical Solution
• Comments

Typical Questions
• What's the system?
• What properties should we count?
• What's the time interval?
• What are the important interactions?
• What are the important constitutive relations?
• How do the basic equations simplify?
• What are the unknowns?
• How many equations do I need?

Figure 3 – Problem-Solving Format and Questions

Engineering faculty will recognize the accounting principle as a fundamental relationship in upper-level disciplinary courses. It is unusual, however, to see it used as a scaffolding framework to help students understand concepts that appear in different engineering science subjects at the sophomore level. Note also that the problem-solving process described above is similar to what a working engineer should do when faced with a new problem, and thus it should be taught in the foundational engineering courses. However, students often take a shortcut that may be summarized with the following steps:

- Read the problem.
- Note the chapter that is being covered in the lecture this week.
- Find a similar problem in the chapter and use it as a pattern to solve the given problem – plugging in the new numbers in place of the ones in the example.
- If no similar problem can be found, select one of the equations from the chapter that has the variables shown in the problem and improvise.

The best way to avoid this common student behavior is to require that students develop the specific form of the equations needed by applying general concepts which is the essence of the SAM approach. And a key pedagogical feature of the SAM approach is its use as a mechanism to learn abstraction, modeling, problem-solving, and critical thinking.

IMPLEMENTATION OF THE SAM APPROACH

Rose-Hulman Institute of Technology (RHIT)

In 1993, RHIT joined with six other schools to form the Foundation Coalition, an NSF-funded Engineering Education Coalition. Building on the work done at Texas A&M, another member of the Foundation Coalition, we developed the Rose-Hulman Sophomore Engineering Curriculum (SEC), an eight-course sequence for a quarter system that was completed during the sophomore year and replaced traditional courses in dynamics, fluid mechanics, thermodynamics, electrical circuits, system dynamics, differential equations, matrix algebra, and statistics[13].

Beginning in fall of 1995, the SEC was required for all electrical and computer engineering majors at Rose-Hulman. Later they were joined by mechanical engineering and biomedical engineering majors. Over the years the SEC has evolved and the tight integration of its early days has loosened as SEC ideas have infiltrated and been incorporated into standard courses. For example, the original SEC mathematics courses were stand-alone and different from the standard mathematics courses; however, many of the SEC ideas for content were incorporated into the standard sequence so the SEC math courses disappeared. Today the SEC is only required for mechanical engineering and biomedical engineering majors.

While much has changed within the SEC, the one constant has been the introductory course ES201 Conservation & Accounting Principles, a four-credit course taken during the first quarter of the sophomore year, which introduces the SAM approach and sets the tone for the rest of the engineering science courses. ES201, called ConApps by the students, is a rigorous introduction to the conservation principles for mass, linear momentum, angular momentum, and energy and to the accounting principle for entropy. (Although conservation of charge was originally included in this course, the current version does not cover this material.) Based on a 10-week quarter with four class periods per week, the class periods devoted to each topic are shown in Figure 4.

From the beginning, the emphasis in ConApps has been on avoiding "tricks" and developing (and documenting) a mathematical model starting with first principles that will produce and support a student's answer to a specific problem. Examples of using a trick would be to start a problem with *F=ma* or to apply Kirchhoff's Current Law without stating how these useful and possi-

Classes	Fundamental Principle
2	Introduction & Basic Concepts
6	Conservation of Mass Substance models for density (Ideal gas and incompressible substance)
8	Conservation of Linear Momentum
5	Conservation of Angular Momentum Tipping problems (one-dimensional, translational motion)
11	Conservation of Energy Substance models for specific internal energy, enthalpy, and volume. Mechanical Energy Balance (replaces the Work-Energy Principle) Thermodynamic Cycles and Measures of Performance
4	Entropy Accounting Reversible process Substance models for specific entropy Best performance for a thermodynamic cycle
3	Mid-term Exams (Final Exam is not included in course contact hours)
40	Total 50- minute Class Periods

Figure 4 – Material Coverage in ES201

bly correct ideas flow from the general principle, e.g. $F=ma$ is always true for a *closed system* which emphasizes the need to clearly identify your system. Because of this, ConApps is often a challenge for many students who are used to looking for “the equation” and then just plugging in numbers.

The pattern is the same throughout the course for introducing each new conservation or accounting principle and is organized around answering the four questions listed earlier: (1) What is the extensive property, (2) How can it be stored within and quantified for a system, (3) How can it be transported across the system boundary, and (4) How can it be generated or consumed inside the system? Once these questions are investigated and answered, the complete form of the governing equation (See Figure 2) is constructed and this equation becomes the starting point for all applications of the principle.

Using this approach in ConApps provides an answer to the frustratingly common question that faculty often get as to which form of “the equation” a student should use, e.g. “Which form of the energy equation should I use, the one from physics, the one from chemistry, the one from dynamics, the one from fluid mechanics, or the one from thermodynamics?” Our consistent answer to this question — apply the problem-solving format presented in Figure 3. Using this, students are guided to construct their own solution starting with the problem statement and building a model from fundamental principles using explicit assumptions and application of problem specific information. Thus, the answer produced by the student is supported by an explicit chain of logic that can be examined by everyone.

University of New Haven (UNH)

In 2004 Tagliatela College of Engineering at UNH introduced a set of common engineering fundamentals courses for all engineering programs. The set of courses, collectively referred to as the Multidisciplinary Engineering Foundation Spiral Curriculum (MEFSC)[19,20], spanned the freshman and sophomore levels. First-year courses include project-based courses to introduce the engineering design process, project planning, and the use of spreadsheets with Visual Basic programming for analysis of engineering problems. In the sophomore year, the course EASC2211 Introduction to Modeling of Engineering Systems[16] is taken by students in all engineering programs. For some programs, EASC2211 is used simply to provide exposure to engineering topics outside the main discipline (Computer and Electrical Engineering), while other programs require EASC2211as a prerequisite for subsequent courses in mass balances, thermodynamics or mechanics (Chemical, Civil, Fire Protection, General, Mechanical, and System Engineering).

The learning outcomes for EASC2211 state that at the conclusion of this course, students should be able to do the following:

- Apply the balance principle in the solution of simple engineering problems.
- Develop models by applying the balance principle and selecting the appropriate empirical relationships.
- Given a set of problems from different areas, explain the similarities and differences in solution methods and underlying concepts
- Apply the modeling process in the solution of engineering problems

- Model engineering systems using fundamental principles:
  - Mass balances applied to systems with changes in composition and quantity
  - KVL and KCL applied to circuits including resistance and capacitance.
  - Linear and angular momentum and force balances applied to static and dynamic systems of solids and fluids
  - Energy balances applied to systems with changes in thermodynamic and other relevant properties

A list of topics in a recent offering of EASC2211 is shown in Figure 5.

In order to emphasize that realistic problems involve multiple phenomena, topics and examples are selected to provide an interface between traditional areas of study. For example, when moving from mass balances to electric charge balances the study of systems with electrochemical reactions (batteries and fuel cells) provides a bridge between the traditional areas of study. This helps students appreciate the need for lowering the mental barriers between areas of study when addressing realistic problems.

Originally, EASC2211 was seen as an opportunity to help students integrate concepts and methods from science and math classes to analyze engineering situations. It was also intended as a step along a spiral curriculum approach for the development of engineering fundamentals. In teaching the class over the past 10 years, several additional features have emerged that we feel

General Topic	Specific Topic	Weeks
Introduction	course introduction, review of engineering calculations,	0.5
Problem Solving	problem-solving strategy, the conservation and accounting principles	1.0
Mass Balances	integral & differential mass balances on single & multi-component systems, concentration variables, mixing, multi-unit systems, mass balances with reactions, batteries and electrochemical reactions, transient mass balances	3.0
Charge Balances	analysis of resistive circuits using KVL/KCL, power, independent/sources models for real sources, capacitance, RC circuits (first order circuits)	3.0
Energy Balances	forms of energy, heat and work, conservation equations, closed and open systems, mechanical & thermal energy equations, analysis of the energy changes in solid, liquid and gas systems undergoing changes, transient systems	3.0
Force and Momentum Balances	conservation of linear momentum, stress, strain, conservation of angular momentum , rigid body statics, distributed loads, analysis of simple trusses, pressure due to static fluid, force on submerged objects, transient systems	2.5
	Midterm and final exams	1.5

Figure 5 -- Topics in EASC2211

provide significant value to the students. By its nature, EASC2211 forces students to wrestle with the idea of applying a general method to specific problems. This is an application of critical thinking, which is at the heart of good engineering practice but is foreign to most students at the sophomore level. Some students get rather indignant when the instructor refuses to tell them how to solve a particular problem by giving them a simplified equation for plug-and-chug. Students may need frequent reminders that engineers are expected to solve new and unique problems, not simply plug numbers into well-published formulas. Early in the semester they may not appreciate the instructor's attempts to guide them toward developing their own equation, as they see getting the answer as the only goal. By the end of the course, many have begun their journey toward independent thinking.

EASC2211 is not expected to develop the same level of depth in any particular engineering science domain as would be expected from a course devoted solely to that area. This provides a level of freedom to place greater emphasis on the fundamental concepts rather than needing to cover the full range of methods that will be needed for use in upper-level disciplinary courses. This situation makes it possible to directly address some common misconceptions, particularly those that involve cross-disciplinary ideas. One such example involves topics from charge balance (electric circuits) and mass balances. The belief that a battery is a source of constant current has been identified by McDermott and Shaffer[21] as a source of considerable difficulty for students of DC circuits. The brief encounter with the internal workings of a simple battery mentioned above provides insight into how a battery is able to generate a potential difference. When presented with a circuit diagram showing an ideal source, students can recall the complexity of the processes inside the black box, now shown as a "constant voltage source" or a "constant current source". Instructors can refer back to the earlier mass balance view, cite the inherent mass transfer rate limitations, and thus set the stage to discuss more realistic source models. This also helps students begin to understand that models of systems are inexact representations of much more complex behavior. The idea that a piece of the model need only be as accurate as necessary for the purpose at hand is illustrated when the circuit problem is solved using a model for the battery that captures the essential behavior (e.g., a constant voltage source in series with a fixed resistance), but which is devoid of any representation of the underlying chemistry and physics.

ASSESSMENT OF THE SAM APPROACH

Given the length of time that this approach has been used, the reader is undoubtedly expecting to see assessment data supporting the effectiveness of the SAM approach. Unfortunately, there is little data currently available. At both institutions, the SAM approach was implemented for all of the students in the targeted programs, thus eliminating the possibility of a formal comparison study between the SAM approach and the more traditional curriculum. In addition, adoption was accompanied by other curricular and pedagogical changes. The available studies primarily focused on how well the students have mastered certain content. Other expected benefits of the SAM approach, such as improved transfer of knowledge across domains and improved problem-solving skills, are more difficult to assess but should be part of any future, comprehensive study.

Institution	Course Used for Comparison	Performance of SAM Group vs. non-SAM Group	References
Texas A&M	Chemical Engineering	Better	Holtzapple et al. [17]
RHIT	Engineering Dynamics	Equal or Better	Cornwall and Fine [22]
UNH	Chemical Engineering	Equal or Better	Collura and Harding [23]
UNH	Mechanical & Civil Engineering	Equal or Better	Nocito-Gobel et al. [24]

Figure 6 -- Summary of Assessments – Mastery of Content

Where the SAM approach has been implemented, it has been important to establish that students met faculty expectations and are not less well-prepared for subsequent courses. Some data is available in that context and is summarized in Figure 6. Holtzapple et al.[17] report that the use of this approach at Texas A&M has persisted only in the chemical engineering program, with other disciplines reverting to more traditional approaches. This provided an unexpected opportunity to assess the SAM approach by tracking the performance of students in the subsequent chemical engineering class and comparing students who transferred into the chemical engineering program to those who had participated in the SAM approach. Significant improvements in course grade and a reduction in "retakes" were observed for the SAM students. In an earlier paper, Cornwell and Fine[22] tracked the performance of students in dynamics at Rose-Hulman and compared the SAM approach to traditional courses. Selected final exam questions used in the new SAM curriculum were similar to those from the traditional courses. Comparison of student performance showed that SAM students performed as well as or better than traditional students in both multiple choice and work-out problems in the area of dynamics. A similar study, but with a small sample size, was conducted at the University of New Haven in the chemical engineering program[23]. The original sequence of two sophomore courses (Fundamentals of Chemical Engineering I and II) focused on material and energy balance applications using a traditional approach. The new curriculum included a SAM course discussed earlier followed by a course that provided more depth in material and energy balances. Student performance on the final exam of the second course was compared, as well as course grades in two junior-level chemical engineering courses. Slight improvements were observed in all cases, although the number of students rendered the differences statistically insignificant. Again at the University of New Haven during the early years of the SAM approach, students entering a first disciplinary course in mechanical and civil engineering were examined while there were still students in the pipeline from the traditional curriculum[24]. Slight improvements were observed, but the small numbers allow only the observation that the students in the SAM course did at least as well as traditional students in a follow-up disciplinary course.

One interesting student perspective came from a recent graduate at the University of New Haven who majored in Computer and Electrical Engineering. At a faculty retreat prior to the start of the Fall 2012 semester, the dean of engineering invited several recent graduates to address the faculty about how well they felt prepared by their education. This particular student was selected because he had been quite successful in his first few years after graduation. He specifically mentioned EASC2211 (the SAM course) as being very valuable in preparing him for the kind of problems he faced in his work. It is particularly interesting that his program does not use the course as a prerequisite for subsequent courses.

INSIGHTS USING CURRENT KNOWLEDGE ABOUT STUDENT LEARNING

Fourteen years ago, Richards[14] listed four aspects of the SAM approach that he thought were advantageous to both students and faculty:

- … It provides a conceptual framework that supports all engineering science courses.
- … It provides a unified format, uniquely suited to engineering applications, for presenting and understanding the basic laws taught in physics and chemistry.
- … It enables a common, consistent problem-solving approach for all courses.
- … It helps students (and faculty) see connections among what are often perceived as unrelated topics by reinforcing the similarities underlying the basic principles.

Today our collective (and the authors') knowledge of how students learn allows a more detailed discussion of the advantages of the SAM approach in light of this knowledge. We organize this discussion around the significant characteristics of the SAM approach and then discuss how these features support student learning. Because the authors are practicing engineering educators and do not claim to be learning scientists or engineering education experts, we have chosen to base most of our discussion on what we have learned from two secondary sources, one by Svinicki[25] and one by Ambrose and colleagues[26]. These books should be on the bookshelf of every engineering educator because they provide an exceptional synthesis of the primary literature with practical recommendations to improve student learning. We have also tried to use boldfaced type to indicate the concepts and terminology that comes from the cognitive and learning sciences.

Use of Common Concepts in Engineering Science

The use of common concepts and its associated vocabulary represents two unique aspects of the SAM approach that support student learning. First is the explicit **use of analogy** and the second is providing and reinforcing an **explicit organizational structure for knowledge**.

One of the recommended ways to connect with students' prior knowledge and everyday experience is the **use of analogy**[27]. **Analogical reasoning** has also been shown as a way to promote transfer of knowledge to new situations. At the heart of the SAM approach are two analogies that work together. The first analogy is the system-container analogy that asks students to idealize any object or device as a system — a region in space or a quantity of matter — that acts like a container that can change shape, size, and contents. The second analogy encourages students to think of extensive properties—mass, charge, momentum, energy, and entropy—as substance-like quantities that can flow across boundaries of this container, can be accumulated within the container, and can be produced or consumed inside the container. Although some authors have warned of the dangers of using analogies because students often carry them too far or employ a hidden analogy that the instructor is unaware of, it has been our experience that the explicit use of these two analogies helps students in visualizing and understanding material.

Knowledge organization has repeatedly been shown to have a significant effect on student ability to learn new content (encode information into long-term memory), to recall the content (activate the appropriate network in the brain), to understand the content (increase the number and the complexity of connections within the knowledge organization), and finally to transfer and apply it in new situations (see abstract patterns that can be applied to new situations). Using the common concepts and vocabulary begins helping students gain an overview of what they are studying which then becomes a structure for organizing and placing new knowledge as it is acquired during the course.

Accounting Principle Framework for Fundamental Equations

The SAM approach was specifically developed using the system-container and substance-like quantity analogies as the basis for the accounting principle framework which applies to all the fundamental conservation and accounting principles of engineering science. Using this again expands the structure for **knowledge organization** and clearly indicates what's important. The accounting principle framework is usually introduced at the beginning of the course and then used repeatedly throughout the course to help students construct and discover the features of each new fundamental principle. In addition to providing a conceptual framework, it also provides the common mathematical structure that students use in applying the fundamental principles as they solve problems.

Another benefit of this framework is that it helps students **make their own analogies and connections**. For example, what are the similarities between the following three tasks: (1) finding your checkbook balance; (2) calculating the rate of change of water level in a tank, and (3) calculating the steady-state temperature of a laundry iron left unattended? When the SAM approach is used, the concepts of storage, interactions, and conservation can be used to identify similarities.

Consider the two equations shown below:

$$\overbrace{\underbrace{\frac{d}{dt}\left(m_{sys}\right)}_{\substack{\text{Rate of change}\\ \text{of mass}\\ \text{inside the system}\\ \text{at time t}}} = \underbrace{\sum_{in}\dot{m}_i - \sum_{out}\dot{m}_e}_{\substack{\text{Net transport rate}\\ \text{of mass}\\ \text{across the boundary}\\ \text{into the system at time t}}}}^{\text{Conservation of Mass}} \qquad \overbrace{\underbrace{\frac{d}{dt}\left(\vec{\mathrm{P}}\right)}_{\substack{\text{Rate of change}\\ \text{of linear momentum}\\ \text{inside the system}\\ \text{at time t}}} = \underbrace{\sum_{external}\vec{F}_j}_{\substack{\text{Net transport rate}\\ \text{of linear momentum}\\ \text{across the boundary}\\ \text{into the system at time t}}}}^{\text{Conservation of Linear Momentum}}$$

By examination, students would observe that system mass and system linear momentum play similar roles in these equations as do the net mass flow rate into the system and the net force acting on the system. From this a student might begin to see a connection between the height of water in a tank as a measure of system mass and the magnitude of the velocity of a system as a measure of its momentum and that force can be thought of as a transport rate of linear momentum. These are connections that typically do not happen nor are they encouraged when fundamental principles are taught in silo courses. Unfortunately students are often frustrated and confused by implicit assumptions that are made to develop the "general" equations in discipline-specific courses. This typically plays itself out in students asking, "Which equation should I use—the one from fluid mechanics, the one from dynamics, or the one from physics?" Students fail to recognize that all three are just special cases of one general principle because they were originally taught to students and then applied without suitable discussion of the underlying restrictions, e.g. $F = ma$ is only applicable to a closed system, a system with constant mass.

The common concepts discussed above are tied closely to **threshold concepts** for engineering science. The idea of threshold concepts was developed by Jan Meyer and Ray Land[28] for their field of economics; however, there has seen increasing use in other fields to understand what causes student problems and how to organize courses and curricula[29]. In the words of Meyer and Land: "A *threshold concept* can be considered as akin to a portal, opening up a new and previously inaccessible way of thinking about something. It represents a transformed way of understanding, or interpreting, or viewing something without which the learner cannot progress." They further say that threshold concepts are *transformative*, in that they produce a significant shift in understanding, are *irreversible*, in that once understood it is difficult to forget or go back, and are *integrative*, in that it exposes new connections. Thus, encountering a threshold concept is like standing on the threshold of a door and understanding the concept is akin to walking through the door and seeing everything anew. (Anyone who has watched the original Wizard of Oz movie has experienced something similar when Dorothy moves from black-and-white Kansas to a colorful Land of Oz. One of the author's has had students report midcourse that they start seeing "dashed-line systems" around everyday objects much to the joy of the instructor.) If one were to look for threshold concepts in engineering science, many of them would be found within the common SAM framework. Thus, it would seem that the constant repetition and reference back to the SAM framework should help focus a student's attention on key and possibly troublesome ideas.

Using a Common Problem-Solving Approach and Starting from the Basics

Although the use of a common problem-solving approach clearly helps support knowledge organization, the main benefit is its use as **scaffolding** for the problem-solving process. As discussed earlier, the problem-solving approach consists of two parts: 1) a series of prompts to organize the information and outline a process, and 2) a series of questions to guide the process (see Figure 3). This set of common questions provide a problem-solving heuristic that helps students tackle problems both familiar and new.

When faced with any problem, the student is expected to explore the given information, decide on exactly what he or she is being asked to find, and then begin an analysis process to construct a problem-specific model from fundamental principles. Students are repeatedly reminded that all of the fundamental principles govern the action of any physical system but not all of them are helpful in answering a given question. Thus, they must look for cues that help them discern what is important. The list of questions is designed to help them begin this process, and they are encouraged to expand the list of questions and make their own list of heuristics. For example, if information is given about forces in a problem, then conservation of linear and angular momentum may be important. To proceed, a student must select a system and begin the process of identifying how the system interacts with the surroundings and finally how the two conservation principles for linear and angular momentum can be simplified using the given information or applicable assumptions.

By requiring that students always start with the general form of a fundamental principle, students are required to explicitly document their reasoning process which exposes how they are thinking about the problem. It is through the repeated application of the fundamental laws in the form of accounting principles and application of this problem-solving process that students **develop mastery** of the material and the ability to transfer this knowledge to new situations.

Surprisingly, using the problem-solving process and starting with the basics has also been shown in our classes to **encourage student creativity.** When they start with the most general form of the accounting principle, students often explore alternate solution paths and build different models than what the instructor was thinking and frequently it exploits a new way of thinking about a problem. The classic example of this is a simple impact problem: a moving train car traveling to the right strikes and is coupled to an initially stationary train car; after the impact, the two train cars move together to the right with a common speed. As taught in physics and even in most engineering dynamics classes the "correct" approach is to consider both cars as a two-particle system of fixed mass with horizontal linear momentum "conserved" meaning horizontal linear momentum is constant. This is the typical solution when your only tool is the equation $F = ma$. Using the SAM approach to this problem and similarly treating the two cars as a closed system, we would never *assume* that horizontal linear momentum is conserved. Instead, we would demonstrate that the horizontal linear momentum of a closed system is a constant because no forces act in the horizontal direction. Because the concept of conservation is built into our fundamental principles about how the world works, it is never a problem-specific assumption. Now if you start with the general conservation of linear momentum equation, which allows for linear momentum entering the system via forces as well as with mass flow, many students take an entirely different and non-traditional approach. They now begin to think creatively about an open system where the momentum of the moving car flows in and then the momentum of the coupled cars flows out of the system. This gives a novel and correct solution that would never appear in a traditional dynamics course because textbooks typically link specific, simplified equations to specific types of problems. Because the SAM approach always starts with the general equations, students are encouraged to not waste time looking for *the* system or equation, but to pick *a* system and construct the solution. As they do this, they learn that when they follow the process and correctly execute the steps, they can adjust and change their model as difficulties arise and the *best* solution is usually the easiest one.

Conceptual Framework for K-12 Science Education and the SAM Approach

Recently the authors came across work on the K-12 science education standards[1], and we were pleasantly surprised to see how many of the ideas and concepts in SAM were addressed in the proposed framework. The three dimensions of the framework are Scientific and Engineering Practices, Crosscutting Concepts, and Disciplinary Core Ideas. Using the words from the report, we can identify a subset of the stated outcomes that particularly resonate with the SAM concepts discussed above:

Scientific and Engineering Practices — defining problems, developing and using models and using mathematics and computational thinking

Crosscutting Concepts — patterns, systems and system models, energy and matter: flows, cycles, and conservation, and stability and change

Disciplinary Core Ideas for Physical Sciences — matter and its interactions, motion and stability: forces and interactions, and energy

The authors are encouraged to see that these over-arching ideas are finding their way into K-12 education in the United States. Interested readers are encouraged to examine a high-school level curriculum developed in Germany that is based on these ideas, The Karlsruhe Physics Course[30], and three innovative, undergraduate physics textbooks developed in the United States that make use of these ideas: *Principles and Practices of Physics* by Mazur[31], *Six Ideas that Shaped Physics* by Moore[32] and *Matter & Interactions* by Chabay and Sherwood[33].

CONCLUSIONS

The Systems, Accounting, and Modeling (SAM) approach for teaching and organizing an engineering science curriculum is significantly different than the traditional discipline-based engineering science curriculum where individual courses are usually offered to support specific majors. Although the traditional approach to engineering science courses provides significant depth in important areas, it does this at the expense of promoting an understanding of the common principles and concepts that undergird all engineering sciences. An alternative is to provide all students with a common foundation using the SAM approach and then spiral back in subsequent courses adding the extra emphasis and specialized problem-solving techniques needed for each discipline. By building an engineering education on a common foundation, we believe that we are helping our students learn a vocabulary and common understandings that will support multidisciplinary projects in the future. In addition, as we have tried to demonstrate in this paper, the features of the SAM approach are consistent with good pedagogy and are supported by what we now know about how to improve student learning.

Bibliography

1 National Research Council, A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas, Washington, D.C.: The National Academies Press, 2012.

2 National Academy of Engineering, The Engineer of 2020: Visons of Engineering in the New Century, Washington, D.C.: The National Academies Press, 2004.

3 National Research Council, How People Learn: Brain, Mind, experience, and School, J. D. Bransford, A. L. Brown and R. R. Cocking, Eds., Washington DC: National Academy Press, 1999.

4 National Academy of Engineering, Educating the Engineer of 2020: Adapting Engineering Education to the New Century, Washington, D.C.: The National Academies Press, 2005.

5 R. A. Streveler, T. A. Litzinger, R. L. Miller and P. S. Steir, "Learning Conceptual Knowledge in the Engineering Sciences: Overview and Future Research Directions," *Journal of Engineering Education*, vol. 97, no. 3, pp. 279-294, July 2008.

6 C. J. Glover and C. A. Erdman, "Overview of the TAMU/NSF Engineering Core Curriculum Development," in *ASEE/IEEE Frontiers in Education Conference*, Nashville, 1992.

7 C. J. Glover, K. M. Lunsford and J. A. Fleming, Conservation Principles and the Structure of Engineering, 5th ed., New York: McGraw-Hill, 1996.

8 M. T. Holtzapple and W. D. Reece, Foundations of Engineering, 2 ed., New York, NY: McGraw-Hill Higher Education, 2003.

9 A. Saterbak, K.-Y. San and L. V. McIntire, Bioengineering Fundamentals, Upper Saddle River, N.J.: Pearson Prentice-Hall, 2007.

10 H. Burkhardt, "Systems Physics: A uniform approach to the branches of classical physics," *American Journal of Physics,* vol. 55, pp. 344-350, 1987.

11 H. U. Fuchs, "The Continuum Physics Paradigm in Physics Instruction. II. System dynamics modeling of physical processes.," Department of Physics and Mathematics, Winterthur University of Applied Sciences, Winterthur, Switzerland, 1997.

12 M. Simon and H. U. Fuchs, "System Dynamics in Engineering Education," in *Proceedings of the Systems Dynamics Conference*, Tokyo, 1995.

13 D. E. Richards and G. M. Rogers, "A New Sophomore Engineering Curriculum - The First Year Experience.," in *Frontiers in Education 26th Annual Conference*, Washington, DC, 1996.

14 D. E. Richards, "Integrating the Mechanical Engineering Core," in *Proceedings of the 2001 ASEE Annual Conference,* Albuquerque, 2001.

15 D. E. Richards, Basic Engineering Science — A Systems, Accounting, and Modeling Approach, Terre Haute, IN: Rose-Hulman Institute of Technology, 2001.

16 M. A. Collura, S. B. Daniels and J. Nocito-Gobel, "A Multi Disciplinary Modeling Course As A Foundation For Study Of An Engineering Discipline," in *Proceedings of the 2006 ASEE Annual Conference and Exposition*, Chicago, 2006.

17 M. Holtzapple, K. Toback and C. Holtzapple, "Foundation Coalition: Impact on Chemical Engineering Education at Texas A&M University 20 Years Later," in *6th First Year Engineering Experience (FYEE) Conference*, College Station, TX, 2014.

18 W. G. Vincenti, What Engineers Know and How They Know it: Analytical Studies from Aeronautical History, Baltimore: Johns Hopkins Press, 1990, pp. 112-136.

19 M. A. Collura, B. Aliane, S. B. Daniels and J. Nocito-Gobel, "Development of a Multidisciplinary Engineering Foundation Spiral," in *Proceedings of the ASEE 2004 Annual Conference*, Salt Lake City, 2004.

20 M. A. Collura, S. B. Daniels, W. D. Harding and J. Nocito-Gobel, "The Current Generation Of Integrated Engineering Curriculum," in *Proceedings of the 2007 ASEE Annual Conference and Exposition*, Honolulu, 2007.

21 L. C. McDermott and P. S. Shaffer, "Research as a Guide for Curriculum Development: An Example from Introductory Electricity. Part 1: Investigation of Student Understanding," *American Journal of Physics,* vol. 60, no. 11, pp. 994-1003, 1992.

22 P. J. Cornwall and J. T. Fine, "Mechanics in the Rose-Hulman Foundation Coalition Sophomore Curriculum," *International Journal of Engineering Education,* vol. 16, no. 5, pp. 441-446, 2000.

23 M. A. Collura and W. D. Harding, "Material and Energy Balances Taught in a Multidisciplinary Course," in *American Society for Engineering Education 2012 Annual Meeting*, San Antonio, TX, 2012.

24 J. Nocito-Gobel, S. Daniels, G. Broderick, M. A. Collura and R. Stanley, "Civil and Mechanical Engineering Students Learning Mechanics in a Multidisciplinary Engineering Foundation Spiral," in *American Society for Engineering Education 2007 Annual Conference & Exposition*, Honolulu, HI, 2007.

25 M. D. Svinicki, Learning and Motivation in the Postsecondary Classroom, Bolton, MA: Anker Publishing Co, Inc., 2004.

26 S. A. Ambrose, M. W. Bridges, M. DiPietro, M. C. Lovett and M. K. Norman, How Learning Works: Seven Research-Based Principles for Smart Teaching, San Francisco: Jossey-Bass, 2010.

27 H. U. Fuchs, "From Image Schemas to Dynamical Models in Fluids, Electricity, Heat, and Motion: An Essay on Physics Education Research," 2007. [Online]. Available: https://home.zhaw.ch/fuh/LITERATURE/Literature.html.

28 J. H. F. Meyer and R. Land, "Threshold concepts and troublesome knowledge: linkages to ways of thinking and practising within the disciplines," in *Improving Student Learning -- Ten Years On*, C. Rust, Ed., UK, OCSLD, 2003.

29 S. A. Male and C. A. Baillie, "Engineering threshold concepts," in *Proceedings of SEFI Annual Conference*, Lisbon, 2011.

30 F. Herrmann, "The Karlsruhe Physics Course," *European Journal of Physics 21(2000), S. 49-58,* vol. 21, no. S, pp. 49-58, 2000.

31 E. Mazur, Principles & Practices of Physics, Pearson Higher Education, 2014.

32 T. A. Moore, Six Ideas that Shaped Physics, New York: McGraw-Hill, 2002.

33 R. Chabay and B. Sherwood, Matter and Interactions, 4 ed., New York: Wiley, 2015.