A Unified Framework for Engineering Science: Principles and Sample Curricula

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Abstract

Engineering sciences were first formalized in the Grinter Report [1,2] and have been a foundation of engineering education for the past fifty years. Traditionally, engineering sciences have been taught in separate courses with each course focused on one of the engineering sciences: statics, dynamics, circuits, thermodynamics, and fluid mechanics. A different approach, teaching the engineering sciences within a unified framework, was pioneered at Texas A&M University and has since been adopted not only there, but also at Rose-Hulman Institute of Technology. The unified framework provides a common framework for understanding basic physical laws, e.g., conservation of mass, momentum, energy, and charge, and the Second Law of Thermodynamics, and applying these laws to development of mathematical models of engineering systems. The framework is built upon four concepts: 1) system, boundary and surroundings, 2) property, 3) conserved property, and 4) accounting for the exchange of properties across the boundary of a system. After presenting the concepts for the framework, the paper explores three different curricula that have been developed in which students study engineering science using the framework. Assessment results are presented for two of the three sample curricula.

I. Introduction

When students complete their required physics, chemistry, and mathematics, they bring a large quantity of fragmented information and skills into their engineering courses. Unfortunately, their abilities to integrate various concepts, to use these concepts to analyze novel physical situations, or to justify the applicability of the solutions they "know" are less developed than desired for engineering design and analysis. The following examples are intended to illustrate the information that students bring and some of the challenges that they face in integrating their knowledge.

Example: Person Supporting a Barbell

Imagine a person holding a barbell above his head. Is the person doing work? Answers to the question often challenge students in physics because intuition and experience (they have held weights for a sustained period of time and they get tired) suggest that the answer is yes, but the traditional answer in a physics class is no. However, the answer depends on the choice of the system to be considered. If the system is the barbell, which is not moving, then the work, which is force through distance, being done on the barbell is zero and the traditional answer in a physics class is correct. However a different answer is obtained if the system is chosen to be one of the muscle cells in the arm of the person holding the barbell. In this case, the muscle cell is stretching and contracting to maintain the barbell in its static position. Since force is exerted through a distance, the muscle cell is doing work. This answer confirms the experience of any person holding a barbell over his/her head for an extended period of time. This type of example stresses the importance of choosing a system before answering the question of whether or not energy is being transferred either in or out of the system.

Example: Ice Skater

Imagine an ice skater on the edge of an Olympic-size rink. She pushes off the wall and glides toward the center of the ice. Here are two questions that often cause confusion for first-year and sophomore students.

- Does the skater gain energy by pushing off the wall?
- Is the linear momentum of the skater changed by pushing off the wall?

Students often indicate that the skater gains energy because they notice that the kinetic energy of the skater in motion is greater than when at rest. However, when students are asked to describe the mechanism through which energy is transferred from the surroundings to the skater, they pause. After prodding, they admit that the skater does not gain energy by pushing off the wall because the force of the wall on the skater is exerted through zero distance. After realizing that there is no mechanism through which the skater gains energy from the surroundings, they conclude that potential energy stored in the muscles of the skater was transformed to kinetic energy. However, the force of the wall on the skater does change the magnitude and direction of the linear momentum vector so that it now points to the center of the ice. Distinguishing linear momentum from energy, understanding that one is a scalar quantity and that the other is a vector quantity, and understanding how linear momentum and energy may be transferred across the boundaries of a system and applying the knowledge of the transfer mechanisms are all areas coursework in the engineering sciences is designed to improve.

Example: Swimming Pool

Imagine that you have (or had) a summer job at a swimming pool. In preparation for the summer sun worshipers, you are asked to fill up the pool. To schedule the opening day, your boss wants to know how long it will take. Without any formal engineering background, most people would inquire about the size of the pumps, say 100 gpm (gallons per minute) and the capacity of the pool, say 150,000 gallons. Given this information, a quick calculation indicates that the pool will fill in 1,500 minutes. But why does this work out and more importantly what can you show me that will support your answer?

This is the question we consistently ask engineering students as they progress through their education. What happens when there is no answer in the back of the book? What's the basis for your belief that your analysis is correct? What's the physical law(s) that governs the your answer?

Taking a more fundamental approach to this apparently simple problem, the experienced problem solver recognizes that the underlying physical law is the *conservation of mass* (not the conservation of volume as often applied by many students). As developed in most fluid mechanics classes, students would first identify a *control* *volume*, say the volume of the water inside the pool at any time *t*, and apply the conservation of mass equation:

$$\frac{dm_{\text{cv}}}{dt} = \sum_{\text{inlets}} \dot{m}_{\text{in}} - \sum_{\text{outlets}} \dot{m}_{\text{out}}$$

where the left-hand side represents the rate of change of the mass inside the control volume and the right-hand side represents the net mass flow rate of water into the control volume. Now by a suitable set of assumptions this equation can be simplified as follows:

- Water is incompressible, therefore density is uniform in space and constant with time, thus $m_{\text{cv}} = r\mathcal{V}$ and $\dot{m} = r\dot{\mathcal{V}}$
- There is only one mass flow rate into the system, $\dot{m}_{\text{pump}}$.

Thus the conservation mass equation can be simplified as follows:

$$\frac{dm_{\text{sys}}}{dt} = \dot{m}_{\text{pump}} \quad \rightarrow \quad \frac{d}{dt}\left(r\mathcal{V}_{\text{sys}}\right) = r\dot{\mathcal{V}}_{\text{pump}} \quad \rightarrow \quad \cancel{r}\,\frac{d}{dt}\left(\mathcal{V}_{\text{sys}}\right) = \cancel{r}\,\dot{\mathcal{V}}_{\text{pump}}$$

$$\frac{d\mathcal{V}_{\text{sys}}}{dt} = \dot{\mathcal{V}}_{\text{pump}}$$

Thus for this particular problem, the rate of change of the volume of the system equals the volumetric flow rate of water into the system. Integrating both sides of the equation and assuming that the pump flow rate is a constant gives the following result:

$$\int_0^{\mathcal{V}_{\text{final}}} d\mathcal{V} = \int_{t_1}^{t_2} \dot{\mathcal{V}}_{\text{pump}}\,dt \quad \rightarrow \quad \mathcal{V}_{\text{final}} = \dot{\mathcal{V}}_{\text{pump}}\Delta t \quad \rightarrow \quad \Delta t = \frac{\mathcal{V}_{\text{final}}}{\dot{\mathcal{V}}_{\text{pump}}}$$

$$\Delta t = \frac{\mathcal{V}_{\text{final}}}{\dot{\mathcal{V}}_{\text{pump}}} = \frac{150{,}000\ \cancel{\text{gallons}}}{100\dfrac{\cancel{\text{gallons}}}{\text{minute}}} = 1{,}500 \text{ minutes}$$

This kind of methodical solution to a problem is a goal of engineering science education.

Typically engineering science, sometimes referred to as applied science, has worked to build student understanding, integration and application of concepts from first-year science courses through a set of engineering science courses. In the courses, usually dynamics, thermodynamics, fluid mechanics and circuits, students improve their students problem solving skills in these specific disciplines. This does in fact improve their ability to solve problems within these individual areas; however, it does very little to help students begin to see the larger picture that many of us first understood in graduate school. To this end we believe that a unified framework, henceforth referred to as the Conservation and Accounting Framework, provides several benefits:

- It provides a common framework for developing/stating/understanding the basic physical laws of nature—conservation of mass, momentum, energy, and charge, and entropy accounting (the Second Law of Thermodynamics).

- It provides a common framework for approaching the development of mathematical models of engineering systems.
- It highlights the similarities between many physical processes.
- It underscores the differences between and the role of physical laws, constitutive relations, definitions, and physical constraints.
- It highlights the importance and impact of making assumptions in modeling systems.
- It negates the need for "through" and "across" variables commonly stressed in systems engineering.
- It helps students recognize the interconnectedness of the world and how systems interact.

Overview of the Paper

Section II will describe the conservation and accounting framework. Then, we will describe three different curriculum structures through which students have learned and applied the conservation and accounting framework. Section III will describe the four-course engineering science core curriculum that was taught at Texas A&M from 1989 until 1995. Section IV will describe the five-course engineering science curriculum that is required for all engineering majors at Texas A&M. Section V will describe the sophomore engineering curriculum that has been taught at Rose-Hulman Institute of Technology since 1995. Section VI will present some example problems to give a sense of the type of problems that students tackle in these curricula and the approaches that students take based on the conservation and accounting framework. Section VII will present student performance data that provide a partial picture of the impact of these curricula on student learning.

II. Conservation and Accounting Framework

The conservation and accounting framework for engineering science structures engineering science topics around several common concepts to help students grasp relationships between apparently disparate ideas and develop powerful problem-solving methodologies for a wide range of physical situations.

Basic Concepts

Review of the common concepts will lay the foundation for discussion of the conservation and accounting framework. Although these terms are familiar, it is instructive to explicitly state our definitions to avoid confusion in the following discussion.

System — A **system** is any region in space or quantity of matter set aside for analysis. Everything not inside the system is in the **surroundings**. The system **boundary** is an infinitesimally thin surface, real or imagined, that separates the system from its surroundings. It has no mass and merely serves as a delineator of the extent of the system. Any system can be further subdivided into **subsystems**.

For modeling purposes, it is useful to classify systems according to the behavior of their boundaries. Using this approach we define three types of systems: closed, open, and isolated systems. The first two classifications specify whether a system can exchange mass with the surroundings. A **closed system** is a system whose boundary prevents mass transfer; thus a closed system has a fixed and unchanging mass. An **open system** is a system whose boundary allows mass transfer with the surroundings. (Traditionally, the closed system has been referred to as a control mass or sometimes just a system, and the open system has been referred to as a control volume.) The third classification applies to all interactions between a system and its surroundings. An **isolated system** is a system whose boundaries prevent *any* and *all* interactions with the surroundings. Thus, an isolated system exchanges nothing with its surroundings.

Property — A **property** is any characteristic of a system that can be given a numerical value without regard to the history of the system. Properties are classified as either intensive or extensive. An **intensive property** has a value at a point and its value is independent of the extent or size of the system. (To talk about a value at a point, we assume that we are dealing with a continuum where a "point" is physically small enough to have a single value and large enough to contain sufficient particles that the value has statistical significance. This concept is described in most fluid mechanics' textbooks.) The value of an intensive property is typically a function of both its position within the system and time. An **extensive property** does not have a value at a point and its value depends on the extent or size of the system. The amount of an extensive property for a system can be determined by summing the amount of extensive property for each subsystem that comprises the system. The value of an extensive property for a system only depends upon time. Table 1 illustrates typical extensive properties and the related intensive property.

TABLE 1 – Examples of Extensive and Intensive Properties

Extensive Property			Intensive Property		
Symbol	Name	Units	Symbol	Name	Units
m	Mass	kg			
q	Charge	C			
$\not{V}$	Volume	m^3	u	Specific Volume	m^3/kg
E	Energy	kJ	e	Specific Energy	kJ/kg
E_k	Kinetic Energy	kJ	$e_k = V^2/2$	Specific Kinetic Energy	kJ/kg
$\mathbf{P}$	Linear Momentum	kg·m/s	$\mathbf{p} = \mathbf{V}$	Velocity (Specific Linear Momentum)	m/s
S	Entropy	kJ/K	s	Specific Entropy	kJ/(K·kg)
			P	Pressure*	kPa
			T	Temperature*	K

*Specific intensive properties

An intensive property that has an extensive counterpart is called a **specific intensive property,** e.g. specific volume and volume. Temperature and pressure are two of the most familiar specific intensive properties.

Conserved Property — Empirical evidence as codified by science has identified a class of extensive properties that can neither be created nor destroyed. An extensive property that satisfies this requirement is called a **conserved property**. The following five statements are equivalent and all characterize a conserved property.

- The amount of the extensive property in the universe is constant.
- The extensive property can be neither generated nor consumed within any system.
- The extensive property can be neither created nor destroyed.
- The amount of the extensive property in an isolated system is constant.
- The amount of the extensive property in a system plus the amount of the extensive property in the surroundings is constant.

Based on results of numerous experiments there are three conserved quantities: charge, linear momentum, and angular momentum. Conditions under which two other extensive properties: mass and energy, are more restricted, but widely applicable. In the absence of nuclear reactions, at speeds significantly less than the speed of light, and over time intervals that are long compared with intervals common in quantum mechanics, mass and energy are conserved as separate extensive properties. However, under more unusual conditions mass and/or energy are no longer conserved. First, if nuclear reactions are allowed, then a single extensive property that could be referred to as mass/energy is conserved. For nuclear reactions, Einstein showed that mass could be transformed to energy or vice versa via the $E = mc^2$ relationship. Second, in the regime of quantum mechanics, Heisenberg's uncertainty principle, $\Delta E \cdot \Delta t \leq (h/2p)$, asserts that the uncertainty in energy times the uncertainty in time must be less than Planck's constant divided by 2p. If the uncertainty in time is very small, the uncertainty in energy could be very large. Thus, conservation of energy could be violated for very small time intervals. Third, at speeds near the velocity of light, mass/energy must be redefined in order to be conserved. Despite the restrictions, five quantities: charge, linear momentum, angular momentum, mass and energy are conserved in a large number of situations. Conservation of these five quantities can be very useful in developing mathematical models for analysis of engineering artifacts.

It should be noted that the use of the concept of conservation in the conservation and accounting framework is slightly different that the use of conservation in physics. Traditionally in physics, the idea of conservation has been used as a modeling assumption for a specific problem. As used here, a conserved property is a statement about the way the world behaves in general. Conservation is never used as a modeling assumption. A property is either conserved or not.

In addition to conserved properties, there are other extensive properties for which we know limits on the generation/consumption terms. The classic example of this is the Second Law of Thermodynamics and its associated property entropy. Written as an accounting equation, we know that entropy can only be produced within a system. Furthermore in the limit of an internally reversible process, the entropy production rate reduces to zero.

State — The **state of a system** is a complete description of a system in terms of its properties. Strictly speaking this requires knowledge of *all* the properties of a system at an instant in time; however, it turns out that we will often only need to know information about a few of the properties of a system to describe the behavior of a system. For some properties, we will discover that only a few need to be specified to uniquely determine the rest, e.g. the state postulate and the thermodynamic properties of a system. In other cases, we will discover that the problem at hand only requires knowledge of a limited number of properties, e.g., velocity of a falling object in a gravitational field with negligible air resistance.

Process — When a system undergoes a change in state, we say that the system has undergone a **process**. It is frequently the goal of engineering analysis to predict the behavior of a system, i.e., the path of states that result, when it undergoes a specified process. Processes can be classified in three ways based on the time interval involved: finite-time, transient, and steady-state processes. A **finite-time process** involves a change in state over an explicitly or implicitly defined time interval of finite duration. Problems that talk of initial and final states typically fall in this category. Mathematically, the analysis of a finite-time process often involves solving a definite integral to determine the change in a property of the system. A **transient process** involves a finite, yet changing time interval. Problems that consider how the state of a system evolves or changes with time fall in this category. Mathematically, the analysis of a transient process often involves the solution of an ordinary differential equation to determine the variation of a system property with time. A **steady-state process** is a special type of transient process in which the intensive properties of the system are independent of time; thus, time is no longer a variable in the analysis. Typically, the analysis of a system undergoing a steady-state process involves the solution of a set of algebraic equations. If the properties of a system undergo steady-periodic variations, it is frequently assumed that the system undergoes a steady-state process on a time-averaged basis.

Accounting Principle — Now that we have defined the basic concepts, we can discuss the accounting principle. Experience has taught us that the extensive properties of a system, i.e. the amount of an extensive property within a system, may change with time. Based on our observations, we postulate that this change can only occur by two mechanisms: (1) transport of the extensive property across the system boundary and (2) generation (production) or consumption (destruction) of the extensive property inside the system. Thus, we can relate the change of an extensive property within a system to the amount of the extensive property transported across the boundary and the amount of the extensive property generated (or consumed) within the system. This simple balance is referred to as the **accounting principle for an extensive property**. Although this principle can be applied to a system for any extensive property, it will be especially useful for those properties that are conserved.

Two forms of the accounting statement

There are two forms of the conservation/accounting statements: the accumulation form and the rate form.

In the accumulation form, the time period used in the analysis is finite. When accounting for the input and output, you compute the total amount that enters in the time period and subtract the total amount that exits in the same time. The accounting statement is total amount that came in - total amount that went out + total amount generated - total amount consumed = amount inside at the final time - amount inside at the beginning.

The advantages of using an accumulation form of the conservation or accounting laws is that you will end up with either algebra or integral equations. The disadvantages of the accumulation form of the law is that it is not always possible to determine the amount of stuff entering or exiting from the system.

In the rate form you add the rate that stuff enters subtract the rate that stuff leaves add the rate that it is generated subtract the rate that it is consumed and set this equal to the rate that it changes inside the boundary. The advantage of the rate form of the law is that the laws of physics generally make it easy to find the rates that things are happening. The disadvantage of the rate form is that it generates differential equations. To apply the rate form of the law, you should choose an infinitesimally small time period.

When applied to a system over a finite-time interval, the **finite-time (or accumulation) form of the accounting principle** says that for any extensive property the

$$\begin{bmatrix} \textit{Final} \\ \textit{amount} \\ \text{inside} \\ \text{the system} \end{bmatrix} - \begin{bmatrix} \textit{Initial} \\ \textit{amount} \\ \text{inside} \\ \text{the system} \end{bmatrix} = \begin{bmatrix} \textit{Amount} \\ \textit{transported} \\ \textit{into} \\ \text{the system} \end{bmatrix} - \begin{bmatrix} \textit{Amount} \\ \textit{transported} \\ \textit{out of} \\ \text{the system} \end{bmatrix} + \begin{bmatrix} \textit{Amount} \\ \textit{generated} \\ \text{inside} \\ \text{the system} \end{bmatrix} - \begin{bmatrix} \textit{Amount} \\ \textit{consumed} \\ \text{inside} \\ \text{the system} \end{bmatrix} \tag{1.1}$$

or the

$$\begin{bmatrix} \textit{Amount accumulated} \\ \text{inside the system} \end{bmatrix} = \begin{bmatrix} \textit{Net amount transported} \\ \text{into the system} \end{bmatrix} + \begin{bmatrix} \textit{Net amount generated} \\ \text{inside the system} \end{bmatrix} \tag{1.2}$$

For a generic extensive property B, Eq. (1.1) can be written symbolically as

$$\boxed{B_{\text{sys,final}} - B_{\text{sys,initial}} = \left[B_{\text{transport,in}} - B_{\text{transport,out}}\right] + \left[B_{\text{generate}} - B_{\text{consume}}\right]} \tag{1.3}$$

where B_{sys} is the amount of property B inside the system, $B_{\text{transport}}$ is the amount of property B that crosses the system boundary, and $B_{\text{generate/consume}}$ is the amount of property B generated/consumed.

When applied to a system for an infinitesimal time interval the accounting principle is written in terms of rates (**rate-form of the accounting principle**) and says that for any extensive property the

$$\begin{bmatrix} \textit{Rate of change} \\ \text{inside} \\ \text{the system} \\ \text{at time } t \end{bmatrix} = \begin{bmatrix} \textit{Transport rate} \\ \textit{into} \\ \text{the system} \\ \text{at time } t. \end{bmatrix} - \begin{bmatrix} \textit{Transport rate} \\ \textit{out of} \\ \text{the system} \\ \text{at time } t. \end{bmatrix} + \begin{bmatrix} \textit{Generation rate} \\ \text{inside} \\ \text{the system} \\ \text{at time } t. \end{bmatrix} - \begin{bmatrix} \textit{Consumption rate} \\ \text{inside} \\ \text{the system} \\ \text{at time } t \end{bmatrix} \tag{1.4}$$

or the

$$\begin{bmatrix} \textit{Rate of change} \\ \text{inside} \\ \text{the system} \\ \text{at time } t \end{bmatrix} = \begin{bmatrix} \textit{Net transport rate} \\ \text{into} \\ \text{the system} \\ \text{at time } t. \end{bmatrix} + \begin{bmatrix} \textit{Net generation rate} \\ \text{inside} \\ \text{the system} \\ \text{at time } t. \end{bmatrix} \tag{1.5}$$

For a generic extensive property B, Eq. (1.4) can be written mathematically as

$$\boxed{\frac{dB_{\text{sys}}}{dt} = \left[\dot{B}_{\text{transport,in}} - \dot{B}_{\text{transport,out}}\right] + \left[\dot{B}_{\text{generate}} - \dot{B}_{\text{consume}}\right]} \tag{1.6}$$

The mathematical relationship between the finite-time form and the rate form can easily be developed by dividing the finite-time form through by the time interval Δt and taking the limit as $\Delta t \to 0$.

Although the accounting principle can be applied for any extensive property, it is most useful when the transport and generation/consumption terms have physical significance. The most useful applications of this principle occur when something is known *a priori* about the generation/consumption term. For conserved extensive properties the equations that apply the accounting principle are significantly simpler. In the finite-time form the equations become [need Don's help to convert the MathType stuff, I need to drop the net generation term.]

$$\begin{bmatrix} \textit{Amount accumulated} \\ \text{inside the system} \end{bmatrix} = \begin{bmatrix} \textit{Net amount transported} \\ \text{into the system} \end{bmatrix} + \begin{bmatrix} \textit{Net amount generated} \\ \text{inside the system} \end{bmatrix} \tag{1.7}$$

Equation (1.1) can be expressed symbolically for a generic extensive property B as [need Don's help to convert the MathType stuff, I need to drop the generation and consumption terms.]

$$\boxed{B_{\text{sys,final}} - B_{\text{sys,initial}} = \left[B_{\text{transport,in}} - B_{\text{transport,out}}\right] + \left[B_{\text{generate}} - B_{\text{consume}}\right]} \tag{1.8}$$

[I need Don's help to insert the rate form of the accounting principle for conserved extensive properties.]

Formulating the Physical Laws in the Conservation and Accounting Framework

To help students begin to see the common features of the basic laws of physics and to provide a framework for problem solving it is useful to restate all of the basic laws in terms of the CAF. Answering four questions for each extensive property of interest provides the form of the physical law in the CAF:

(1) What is it?

(2) How can it be *stored* inside the system?

(3) How can it be *transported* across the system boundary? Students need to understand and apply the mechanisms through which an extensive property can cross the boundary. For example if you are counting something like energy, you will need to know all of the ways that energy can cross a boundary and determine which, if any, are applicable to the situation at hand.

(4) How can it be *generated* or *consumed* inside the system? In addition to transport mechanisms, students need to understand and apply knowledge about when and how an extensive property can be created or consumed. For example if you are counting positive charge, then you need to know that positive charge can be created by ionization processes or consumed by recombination processes. When a quantity can neither be created nor consumed we say that quantity is conserved. Again, this definition is different from the definition used in many textbooks on physics and engineering science.

Once students have answered these four questions, then they can adapt the accounting principle for each extensive property and demonstrate the underlying similarities between the fundamental principles of physics. Consider the extensive properties mass and linear momentum. Table 2 provides answers to each of these questions for mass, and Table 3 provides answers for linear momentum.

Table 2: Accounting Principle for Mass

Question	Answer
What is it?	The mass of an object is a measure of the amount of matter in the object.
How can it be *stored* inside the system?	If there is any matter inside the system, then the system has mass. Given a system of volume V and information about the density r of the matter in the system, then the system mass m_{sys} can be calculated from the integral over the system volume $m_{\text{sys}} = \int_{V_{\text{sys}}} r \, dV$ where r is the mass density of the substance.
How can it be *transported* across the system boundary?	Mass can only be transported across a system boundary when atoms or molecules physically move across the system boundary between the system and the surroundings. In general, this transport occurs due to

	either gross fluid motion or through molecular diffusion. In either case, we can define the **mass flow rate** to be the rate at which mass crosses a boundary per unit time. The symbol adopted for the mass flow rate will be a dotted lower-case "m", $\dot{m}$.
How can mass be *generated* or *consumed* within the system?	Empirical evidence has repeated demonstrated that for the conditions of most engineering applications, mass cannot be created or destroyed within the boundaries of a system. Thus **mass is conserved**!
Accounting Equation for Mass (Conservation Equation)	
Rate form of Conservation of Mass	$\frac{dm_{\text{sys}}}{dt} = \sum_{\text{inlets}} \dot{m}_i - \sum_{\text{outlets}} \dot{m}_e$ where $\dot{m}$ is the mass flow rate and the summations are over all the inlets and outlets.
Finite-time form of Conservation of Mass	$\Delta m_{\text{sys}} = \sum_{\text{inlets}} m_i - \sum_{\text{outlets}} m_e$ where $m = \int_{t_1}^{t_2} \dot{m}\, dt$, the amount of mass that flows across the boundary in the time interval.

This author's prejudice is to focus on the rate-form of the equations because it is an easy matter to go from the rate-form to the finite-time form by integrating both sides with respect to time.

Table 3: Accounting Principle for Linear Momentum

Question	Answer
What is linear momentum?	Linear momentum of a particle is the product of mass and velocity: $\mathbf{P} = m\mathbf{V}$
How can linear momentum be *stored* inside the system?	If there is any matter inside the system and that mass has velocity, then the system has linear momentum. For a system of *n* discrete particles, then the linear momentum of the system of particles is $\mathbf{P}_{\text{sys}} = \sum_{i=1}^{n} m_i \mathbf{V}_i$ For a continuous system of volume $\cancel{V}$ with density r and velocity $\mathbf{V}$, both functions of position and time, the system linear momentum can be calculated from the integral over the system volume $\mathbf{P}_{\text{sys}} = \int_{\cancel{V}_{\text{sys}}} \mathbf{V} r \, d\cancel{V}$

How can linear momentum be *transported* across the system boundary?	Linear momentum can be transported by two mechanisms: forces and mass-transport of linear momentum. For a system, the transport rate of linear momentum by an *external force* is $\mathbf{F}_{\text{external}}$. External forces can be classified as either *body* forces, like weight, or *surface* (or *contact*) forces. For an open system, every mass that crosses the system boundary carries with it linear momentum due to its velocity. The mass transport rate of linear momentum is the product of the mass flow rate and the velocity, $\dot{m}\mathbf{V}$.
How can linear momentum be *generated* or *consumed* within the system?	Empirical evidence has repeatedly demonstrated that linear momentum cannot be created or destroyed within the boundaries of a system. Thus **linear momentum is conserved**!
Accounting Equation for Linear Momentum (Conservation Equation)	
Rate form of Conservation of Linear Momentum	$\frac{d\mathbf{P}_{\text{sys}}}{dt} = \sum \mathbf{F}_{\text{ext}} + \sum_{\text{inlets}} \dot{\mathbf{P}}_i - \sum_{\text{outlets}} \dot{\mathbf{P}}_e$ where $\mathbf{P}_i = \dot{m}_i \mathbf{V}_i$ and $\mathbf{P}_e = \dot{m}_e \mathbf{V}_e$ are the mass-transport rates of linear momentum at the boundary and the summations are over all the inlets and outlets.
Finite-time form of Conservation of Linear Momentum	$\Delta\mathbf{P}_{\text{sys}} = \sum \int_{t_i}^{t_f} \mathbf{F}_{\text{ext}}\, dt + \sum_{\text{inlets}} \mathbf{P}_i - \sum_{\text{outlets}} \mathbf{P}_e$ where $\mathbf{P}_{i/e} = \int_{t_1}^{t_2} \left(\dot{m}\mathbf{V}\right)_{i/e} dt$, the amount of mass that flows across the boundary in the time interval.

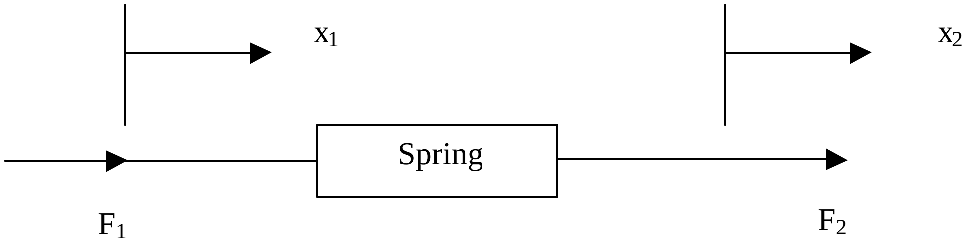
Table 4 summarizes the rate-form of the accounting principle for six extensive properties that are commonly used in engineering analysis. As students attempt to solve engineering problems, they are often confronted with relating changes within a system to things that happen to the system. The accounting equation provides an explicit way to relate these things. It in fact is the only mechanism for relating system interactions that are spatially separated on the boundary of a system. For example, if I consider a compressed spring, how are the forces acting on the ends of the spring related? If we take the stationary spring as the system and apply conservation of linear momentum, we see that the linear momentum of the system is constant (in fact it is zero) and the forces acting on the system boundary must be equal in magnitude and opposite in direction.

Table 4 - Rate-form of the Basic Laws

Mass (Conserved)	$\frac{dm_{\text{sys}}}{dt} = \sum_{\text{inlets}} \dot{m}_i - \sum_{\text{outlets}} \dot{m}_e$
	The rate at which mass is accumulated within the system is equal to the difference between the rate at which mass enters the system and the rate at which mass leaves the system. The symbol $\dot{m}_i$ is a conventional symbol for mass rate into a system. The symbol $\dot{m}_e$ is a conventional symbol for mass rate exiting a system.
Charge (Conserved)	$\frac{dq_{\text{sys}}}{dt} = \sum_{\text{inlets}} \dot{q}_i - \sum_{\text{outlets}} \dot{q}_e$
	The rate at which charge is accumulated within the system is equal to the difference between the rate at which change enters the system and the rate at which charge leaves the system.
Linear Momentum (Conserved)	$\frac{d\mathbf{P}_{\text{sys}}}{dt} = \sum \mathbf{F}_{\text{ext}} + \sum_{\text{inlets}} \dot{m}_i \mathbf{V}_i - \sum_{\text{outlets}} \dot{m}_e \mathbf{V}_e$
	The rate at which linear momentum is accumulated within the system is equal to the sum of the external forces acting upon the system plus the rate at which mass entering the system adds linear momentum minus the rate at which mass leaving the system subtracts linear momentum. For a closed system, i.e., a system that does not exchange mass with its surroundings, the rate law simplifies to a statement of Newton's second law.
Angular Momentum (Conserved)	$\frac{d\mathbf{L}_{\text{sys}}}{dt} = \sum \mathbf{M}_{\text{ext}} + \sum_{\text{inlets}} \dot{m}_i \left(\mathbf{r}_i \times \mathbf{V}_i\right) - \sum_{\text{outlets}} \dot{m}_e \left(\mathbf{r}_e \times \mathbf{V}_e\right)$
	The rate at which angular momentum is accumulated within the system is equal to the sum of the external moments (or torques) acting upon the system plus the rate at which mass entering the system adds angular momentum minus the rate at which mass leaving the system subtracts angular momentum. For a closed system, i.e., a system that does not exchange mass with its surroundings, the rate law simplifies to a statement that the rate at which angular moment accumulates within a system is equal to the sum of external moments (or torques) acting on the system.
Energy (Conserved)	$\frac{dE_{\text{sys}}}{dt} = \dot{Q}_{\text{net,in}} + \dot{W}_{\text{net,in}} + \sum_{\text{inlets}} \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_{\text{outlets}} \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)$

	The rate at which energy is accumulated within the system is equal to the net rate of heat flow into the system plus the net work done on the system plus the rate at which mass entering the system adds energy (through either potential, kinetic or internal energy{?}) minus the rate at which mass leaving the system subtracts energy. {Do we need comments about sign conventions?}
Entropy	$$\frac{dS_{\text{sys}}}{dt} = \sum_{\text{surfaces}} \frac{\dot{Q}_j}{T_{\text{b},j}} + \sum_{\text{inlets}} \dot{m}_i s_i - \sum_{\text{outlets}} \dot{m}_e s_e + \dot{S}_{\text{gen}}$$
	I’m not going to attempt this one yet.

Another approach to understanding the CAF is to compare it to the discipline of system dynamics. In the later discipline, much emphasis is placed on energy storage and transfer by identifying "through" variables and "across" variables. How are the "through" and "across" variables related to the six intensive properties in Table 4? To facilitate the comparison, consider a simple, linear, ideal spring as a closed system. Application of the conservation of linear momentum ~~and~~ shows that the forces at the two ends of the spring



are opposite direction and differ in magnitude by the rate at which linear momentum is accumulated in the spring. If the spring is stationary or the spring mass is negligible, the forces (transport rates of momentum) are equal and opposite in direction. Application of the conservation of energy shows that the rate at which energy accumulates in the system is given by

$$\frac{dE_{sys}}{dt} = \vec{F}_1 \cdot \frac{d\vec{x}_1}{dt} + \vec{F}_2 \cdot \frac{d\vec{x}_2}{dt}$$

If the force F_2 is rewritten as the difference between the rate at which linear momentum is accumulating and the force F_1, then the conservation of energy equation may be rewritten.

$$\frac{dE_{sys}}{dt} = \vec{F}_1 \cdot \left(\frac{d\vec{x}_1}{dt} - \frac{d\vec{x}_2}{dt}\right) + \frac{d\vec{P}_{sys}}{dt} \cdot \frac{d\vec{x}_2}{dt}$$

If the rate at which linear momentum accumulates is zero, e.g., if the spring is stationary or massless, then the rate at which energy accumulates is equal to the force applied to the spring dotted with the difference in the velocities between the two ends of the spring. In a systems dynamics framework,~~,~~ the force is the "through" variable for energy transfer. The through variable exists if and only if the spring does not accumulate linear momentum. Also, in a systems dynamics framework, the velocity difference between the two ends of the spring is the "across" variable and is related to the rate at which energy accumulates in the spring. Typically, the "across" variable is really just the difference between the values of an intensive property measured at two points on the system boundary. So the "through" and "across" variables in a systems dynamics framework can be obtained from the accounting equations for the intensive properties in Table 4..

Problem Solving using the Conservation and Accounting Framework

Now that the basic concepts of the conservation and accounting framework have been formulated, we can suggest a problem solving approach that is based on a set of generic questions. As students approach a new physical situation focusing on a recurring set of questions helps students focus on the important issues involved in formulating models of the physics situation and finding the desired quantities.

What is the system? **Choose the boundary**

This is almost always the starting point for the analysis of every physical situation. In each engineering science, the question of choosing the system is often phrased differently and the focus is on a node, a free-body diagram, a closed system, or a control volume. In fluid mechanics and thermodynamics this is usually accomplished when students are usually asked to sketch the control volume and in dynamics when students are asked to sketch the free-body diagram. It is important for the students to learn that more than one system may be required for the solution of a particular problem. Although terminology differs, the goal is always the same — a clear description of exactly what you intend to analyze. Implicit in this question is the need to clearly identify the boundary and the surroundings. The conservation and accounting framework recognizes the interconnectedness of everything. To avoid becoming overwhelmed by the knowledge that almost everything is impacted by almost everything else, answering the first question forces the students to define the system, recognize the surroundings and consider the interactions between the two.

During the process students are required to clearly define a system and its boundary. Then, they can apply the accounting principle by watching the boundary for things entering and leaving. They can also watch the interior of the boundary to determine what changes inside. The boundary can be something physical like a rigid container, or it can be something imaginary. A useful example for introducing concepts about the conservation and accounting frame is a checking account at a bank where the boundary is an imaginary boundary. The bank does not have small areas where they keep money. An account is simply a convenient way to think about your money. A safe deposit box is a physical boundary in a bank and you could use it to apply conservation principles to money you put inside. The method requires students to carefully identify boundaries and interactions between the system and its surroundings.

What should we count? **Choose what to count**

Next, in order to apply the accounting principle students should determine what to count. There are five quantities that are commonly counted in engineering problems. These quantities are mass, momentum, angular momentum, energy, and entropy. An advantage of the framework is it focuses attention on physical properties and helps students to think about physical processes in terms of these properties. Further, the question focuses attention on what is actually happening in the problem in terms of the extensive properties. Which of the extensive properties — mass, charge, linear momentum, angular momentum, energy, or entropy — should we be interested in? Which of these properties are changing?

What is the time interval of interest?

This question focuses student attention on the process. What type of process has occurred or will be occurring? This question is basically asking the students to identify whether the rate form of the basic principles or the finite time form is most appropriate.

What are the important interactions?

This question is intimately related to the previous question. For example if linear momentum is to be counted then the student should be on the look out for interactions that transport momentum: external forces and mass flow. Or if a student believes that forces acting on a system are important, then linear and possibly angular momentum must be counted. Although the mechanisms and names vary from property to property, the underlying idea of an exchange of something with the surroundings is a common feature of any engineering system.

Know how to count

The last thing that you need to be able to do is determine how much of a quantity is inside your boundary. For example, if you are counting energy to solve a problem then you will have to determine the amount of energy inside your boundary. The majority of the time spent in the class deals with this concept therefore it is impossible to enumerate all the intricacies here. Essentially these concepts involve relating temperature to internal energy, speed to kinetic energy and vertical height to gravity potential.

Tools for Insight in Analysis

Two additional concepts that are sometimes useful in the analysis and design of a system are the degrees of freedom (dof) and order.

Order is the number of independent storage elements inside the system boundary. The easiest operational definition for independent storage is one that is not dependent on another. Two storage elements are dependent if knowing the quantity stored in one implies the storage in the other is also known. For example, a mass moving in a single direction has the ability to store kinetic energy and linear momentum. If the linear momentum is known, the velocity of the mass is known, once the velocity is known, the kinetic energy is also known therefore the mass has one order. If the mass can move in two directions, the order is two since knowing kinetic energy will not completely specify the two momentums but knowing energy and one momentum will fix the other momentum. Students often find the exercise of determining order helpful in identifying what conservation equations to write, knowing how many equations to expect when they are finished, and for helping to define a proper set of variables to use in the formulation.

Determining the Degree of Freedom (dof) is an exercise in identifying different types of variables. One type of variable is a flow or motion. For example, velocity and current are motion variables. The dof is the minimum number of independent motion variables required for describing the conservation equations. By determining the dof, students are forced to think about the problem formulation before they begin to write equations. In addition, the dof will indicate when extra constraint equations are required. For example, suppose a mass moves in a plane such that it remains a constant distance from a point of rotation. The mass has one dof because a single angle and its derivatives are sufficient to express all the motion related quantities in the conservation equations. If the conservation equations are expressed in terms of two variables (say horizontal and vertical positions) then the conservation equations will have more variables than can be uniquely determined. What is required is a kinematic constraint equation that relates the motion variables together. By counting the dof and the number of motion variables in the conservation equations, a student can determine if constraint equations are required.

III. Curriculum Structure: Texas A&M four-course structure

Now that the conservation and accounting framework has been described, this section and the following two sections will describe three different curricular structures which have been developed to help students learn engineering science via the conservation and accounting framework. The first two structures were developed at Texas A&M University and the third structure was developed at Rose-Hulman Institute of Technology. The three diverse structures will hopefully help readers to envision the different ways in which students may study engineering science with the conservation and accounting framework.

The original program, begun as a pilot project in September 1988 and supported by a Course and Curriculum Development grant from the National Science Foundation, had the following goals [2]:

1. To develop a stronger, principle-oriented engineering core program,
2. To develop a program that would be applicable to all or most engineering disciplines.
3. To strengthen undergraduate design education.
4. To give students a better ability to transfer concepts across disciplinary lines.
5. To relieve pressure on 4-year curricula.
6. To foster a greater degree of creativity among students.

The original program developed four sophomore level courses each with their own textbook. All the courses were based on the unifying theme of conservation. The first course, ENGR201, in the original series was titled “Conservation Principles in Engineering” [4,5] and presents the unifying structure applied to macroscopic systems in a variety of “traditional” areas. The second course, ENGR202, was titled “Properties of Matter” [6,7] and presented a method for understanding material behavior in light of the conservation framework. The third course, ENGR203, was titled “Understanding Engineering Systems Via Conservation” [8,9] and applies the conservation framework to complex interdisciplinary problems. The fourth and final course, ENGR204, was titled “Conservation Principles for Continuous Media” [10,11] which essentially emulated the first course with application to infinitesimally sized systems. Together, the four-course sequence was referred to as "ENGR 20x."

The original program laid the groundwork to achieve all six goals; however, they were not all achieved by the end of the first development. In particular, the courses from the first project, which officially ended in 1993, were not widely accepted at TAMU. Some of the more important advantages and disadvantages of the first project include the following [12]:

+ Four courses and four textbooks were developed and taught for several years.

+ Twenty faculty members from seven departments became involved in the program.

+ Dissemination workshops were presented to faculty members from more than twelve universities. Some of these universities (University of Virginia, University of Alabama-Tuscaloosa, Rose Hulman Institute of Technology, Texas A&M University-Kingsville, and Arizona State University) have implemented similar courses. Others are considering adoption.

+ The courses were adopted by the Industrial, Electrical, Petroleum, and Civil engineering departments at Texas A&M.

+ “Traditional” knowledge was enhanced in the new curriculum. Based on exams similar to the Fundamentals in Engineering exam, the mean core student scored 55% ±5% while a comparable (in GPR and SAT) group from the “traditional” curriculum scored 49% ±5%.

+ The main difference between the “control” group of students and the experimental group is the control students had completed several junior courses whereas the experimental group had only completed the sophomore courses. More detailed testing demonstrated that the experimental group performed worse in statics (65% ±6% to 78% ±6%), better in dynamics (51% ±8% to 35% ±8%), and statistically the same in thermodynamics (66% ±7% to 66% ±7%).

+ Student reported performance in advanced courses was satisfactory. Most students felt confident and said they believed they understood material much better than other students did.

+ The burden of teaching the courses was left on the shoulders of very few faculty members. This was in part due to the radical departure from “traditional” single discipline courses.

IV. Curriculum Structure: Texas A&M Five-Course Structure

While the new integrated course sequence appeared to satisfy the objectives listed above, it soon became apparent that changes in the course structure were needed for the following reasons:

- Too much material had been placed in the four course sequence,
- The four course sequence was too integrated and too optimistic as to how much material could be covered,
- To make the courses more palatable for both students and instructors, and
- A general need to reduce the total credit hours in most engineering programs.

Table 5 – Evolution of the Sophomore Engineering Science Sequence at TAMU

Sophomore Engineering Core Course Changes

Traditional Sequence (before 1990)		FC, Conservation-Based, Integrated Sequence (1990-96)		Principles of Engineering Sequence (current)	
	Credits		Credits		Credits
Statics (MEEN 212)	3 (3-0)	ENGR 201 - Conservation Principles in Engineering	4 (3-2)	ENGR 211 - Conservation Principles in Engineering Mechanics (mass flow, statics & dynamics for macroscopic systems)	3 (2-2)
Dynamics (MEEN 213)	3 (3-0)	ENGR 202 - Properties of Matter	4 (3-2)	ENGR 212 - Conservation Principles in Thermodynamics	3 (2-2)
Materials Science	3 (3-0)	ENGR 203 - Modeling and Behavior of Engineering Systems	4 (3-2)	ENGR 213 - Title ?????? (materials science)	3 (2-2)
Strength of Materials (CVEN 205)	3 (3-0)	ENGR 204 - Conservation Principles for Continuous Media	4 (3-2)	ENGR 214 - Conservation Principles in Continuum Mechanics (continuous media, conservation principles, heat transfer, strength of materials applications)	3 (2-2)
Thermo-dynamics	3 (3-0)			ENGR 215 - Title ???????????? (electrical circuits)	3 (2-2)

Electrical Circuits (ELEN 306)	4 (3-3)	Electrical Circuits (ELEN 306)	4 (3-3)		
Total Credits	19		20		15

Consequently, in 1995, changes were begun to restructure the courses by:

- Regrouping some course topics along more traditional lines but retaining the conservation framework (for example, "statics" and "dynamics" brought into one course, ENGR 211; thermodynamics brought into one course, ENGR 212),
- Dropping conservation of charge, developing conservation principles only in Cartesian and polar coordinates, and [stuff here]
- Reducing credit hours from 4 (3 lecture - 2 recitation) to 3 (2-2),
- Incorporating the electrical circuits course, ELEN 306 (4-0) into the ENGR sequence as ENGR 215 (2-2),
- Adding cohorted sections for ENGR 211-212 and ENGR 213-214 which provided common student teams for the cohorted sections,
- Added team design projects, and
- Added an administrative structure with a faculty coordinator and oversight committee for each course and overall supervision by the Associate Dean of Engineering.

The new Principles of Engineering course sequence still retains the conservation framework as the fundamental basis for all courses. Course titles and broad topic areas are listed in Table 5. ENGR 211 and 212 are taken during the first semester of the sophomore year while ENGR 213, 214 and 215 are taken the second semester of the sophomore year. While ENGR 212 (thermodynamics), ENGR 213 (materials science) and ENGR 215 (electrical circuits) are most like their traditional counterparts, ENGR 211 and 214 are unique. ENGR 211 provides the conservation for macroscopic systems (with application to statics and dynamics of rigid systems) while ENGR 214 addresses conservation principles for continuous media (with application to mass flow, heat transfer, stress, strain, torsion and beam bending). Both ENGR 211 and 214 are vector based. ENGR 211 and 212 require registration in Calculus III (MATH 251/253), while ENGR 214 and 215 requires registration in the differential equations course (MATH 308)

Initially, ENGR 211-214 was taught using the textbooks developed earlier for ENGR 201-204. This proved to be unacceptable since topics for ENGR 211 were spread between the textbooks for ENGR 201 and 203. In addition, portions of the ENGR 20x textbooks were no longer being covered. Consequently, a new textbook was written for ENGR 214 and web-based notes were written for ENGR 211 (a formal textbook is currently being written). Traditional textbooks for ENGR 212 and 213 are currently being utilized but are supplemented with instructor and web-based notes to incorporate desired conservation framework elements.

At Texas A&M, all of the ENGR 21x courses have been taught with relatively large section sizes (80-90 students) typically meeting twice a week for two hours per class meeting. Most faculty have found that artificial separation of the four contact hours per week into lecture and recitation is not desirable and each will typically allocate the two hour block as needed to lecture and recitation. In order to accommodate the large section size and the interactive nature of the classroom, a TA is always present to assist the instructor. We have found that in ENGR 211 and 214, which contain a wide diversity of topics and requires considerable interaction between students and TA, the TA must be chosen carefully and must receive sufficient instruction in pedagogical issues related to teams, collaborative learning, etc., and the TA obviously must have good communication skills. Likewise, the faculty teaching these courses must have some training in collaborative learning, team dynamics, use of technology in the classroom, etc. Instructors generally require significant start-up times because of the non-traditional format for the courses.

V. Curriculum Structure: Rose-Hulman Institute of Technology Sophomore Engineering Curriculum

At Rose-Hulman the engineering science material usually covered in Dynamics, Thermodynamics I, Circuits I and Fluid Mechanics has been repackaged into a new sequence of courses called the Sophomore Engineering Curriculum (SEC) where the concepts of conservation and accounting permeate the courses and are used to tie the subjects together. This curriculum has its pedagogical roots in a sophomore curriculum at Texas A&M University [4] and there is at least one textbook that utilizes this methodology [5]. This curriculum is required for all mechanical and electrical engineering students.

A comparison between the old and new curriculum at Rose-Hulman is illustrated in

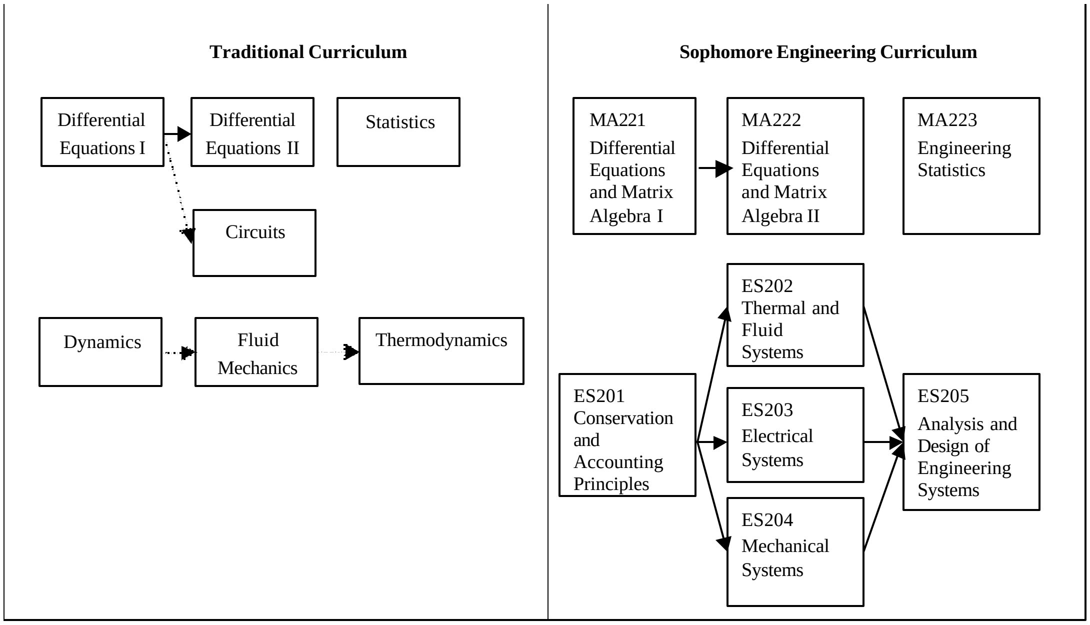


Figure 1 - Comparison of the traditional and the new sophomore curriculum at Rose-Hulman. A sequence of three courses can be used since Rose-Hulman is on the quarter system.

Figure 1. Parallel to the engineering science course are three math courses Applied Math I (linear algebra and some linear ordinary differential equations), Applied Math II (statistics) and Applied Math II (systems of differential equations). In Fig. 1, the dashed lines are intended to illustrate a weak coupling between courses and a solid line is a strong coupling between courses.

One purpose of the Sophomore Engineering Curriculum is to enhance the students' abilities in solving problems in engineering analysis. We believe that the incoming students have some misconceptions about the problem solving process that need to be corrected before they can progress to the more difficult problems that they will face later in their undergraduate careers. These misconceptions include the ideas that, "solving problems means finding a formula to evaluate," and "I can demonstrate my cleverness by solving problems while showing as little of the actual work as possible." To cause the students to change some of their notions of problem solving, we require a far more formalized and complete approach to problem solving than they have yet experienced.

In the first course, ES201 Conservation and Accounting Principles, students are taught a problem solving methodology and format that is used in all subsequent courses. Next, students take three courses that build on the first course. These courses are and “ES202 Fluid and Thermal Systems” “ES203 Electrical Systems”, “ES204 Mechanical Systems”. In these courses more detailed applications of the conservation principles within more specialized problem areas are discussed as well as some of the additional topics required to solve problems such as Kirchhoff’s voltage law and active devices in “Electrical Systems”, properties in “Fluid and Thermal Systems”, and kinematics in “Mechanical Systems.” Finally, the material is brought back into a single course “ES205 Analysis and Design of Engineering Systems” where multi-disciplinary problems are tackled.

Brief Descriptions of the courses

ES201 Conservation and Accounting -- [Don, could you polish the description of ES201?] In ES201, students are introduced to the elements of the conservation and accounting framework that was describe above and to the problem-solving approach based on the framework. In this class, students develop models for systems by accounting for extensive properties that are conserved such as mass, charge, linear momentum, angular momentum and energy and also entropy. Initially, students work on problems that focus their attention on one extensive problem, but as the course progresses students may need to consider more than one extensive property. For example, a problem may require conservation of mass, conservation of energy, and conservation of linear momentum.

ES202 Fluid and Thermal Systems -- [Don, could you polish the short description of ES202?] Students apply the conservation and accounting framework to the specific area of fluid and thermal systems. They both refine the framework to focus on assumptions and extensive properties common to these disciplines. They apply conservation of energy, conservation of momentum, and entropy accounting to thermal and fluid systems. In addition, they work with constituent properties related to fluid and thermal systems, such as fluid and thermodynamic properties of pure substances. Students work with both open and closed systems. They consider special cases such as fluid statics, fluid dynamics, mechanical energy balance and pipe flow, and lift and drag.

ES203 Electrical Systems -- [Don, could you polish the short description of ES203?] Students apply the conservation and accounting framework to the specific area of electrical systems. They explore the assumptions necessary to obtain Kirchoff's Laws from the conservation and accounting framework [11] Starting with Kirchoff's Laws, students work with basic circuit elements: sources, resistors, inductors, capacitors, and operational amplifiers. They study traditional circuit topics such as voltage and current dividers. They study transient behavior, especially the cases of first and second order circuits. Finally, they student sinusoidal steady-state behavior, AC circuits and power.

ES204 Mechanical Systems -- In the Mechanical Systems course (ES204) taken in the winter quarter, students learn the kinematics necessary to apply the conservation principles to more difficult problems. A traditional dynamics textbook is used in the course and the relationship between how the principles are presented in the dynamics book and how they were introduced the previous quarter is shown. Maple is used extensively in the course and the dynamic simulation program Working Model is used as a visualization tool [6]. The students also perform three labs as a part of this course. The first lab involves using Working Model, the second, angular momentum and the third general plane motion.

In dynamics the primary kinetics principles used to solve problems are usually presented as 1) direct application of Newton's Second Law, 2) work-energy methods, and 3) impulse-momentum methods. In this curriculum these are presented as conservation of linear and angular momentum (rate and finite time forms) and conservation of energy (finite time form). A comparison of the terminology is shown in Figure 2 that is given to the students at the beginning of the course to help them relate the material in the text to the material learned in the previous course.

Principle	ES201 Name	Dynamics Name	Comments
$\frac{d\vec{P}_{sys}}{dt} = \sum \vec{F}$ $\frac{d\vec{L}_{sys_0}}{dt} = \sum \vec{M}_o$	Rate form for conservation of linear and angular momentum for a closed system.	Direct application of Newton's Laws	When to use: • want to find forces and/or accelerations • want to find velocities and/or distance traveled (which can be found by separating variables and integrating the basic kinematical relationships) Other: • Be careful! These are vector equations. • The book uses H_0 for angular momentum instead of L_0.
$\Delta\vec{P}_{sys} = \int_{t_1}^{t_2} \vec{F}dt$, $\Delta\vec{L}_{sys_0} = \int_{t_1}^{t_2} \vec{M}_0 dt$	Finite time form of conservation of linear and angular	Impulse-momentum methods	When to use: • have an impact or impulsive forces • the system consists of several objects

$\Delta \vec{L}_{sys_0} = \int_{t_1}^{t_2} \vec{M}_0 \, dt$ or if there are impulsive loads acting on the system $\Delta \vec{P}_{sys} = \sum \vec{F}_i \Delta t$, $\Delta \vec{L}_{sys_0} = \sum (\vec{M}_0)_i \Delta t$ where F_i and M_i are the external impulsive forces and moments acting on the system.	angular momentum for a closed system.		• given a force as a function of time • want to find velocities, times, or forces (especially impulsive forces) Other: • Be careful! These are vector equations. • The book uses H_0 for angular momentum instead of L_0.
$\Delta E_{sys} = W$	Finite time form of conservation of energy for an adiabatic closed system.	Work-energy methods.	When to use: • have two locations in space • given a force as a function of position • want to find velocities, distances, or forces (sometimes) Other: • This is a scalar equation

Figure 2 - A comparison between the nomenclature used in Dynamics and the one used in Mechanical Systems

One advantage of this approach is that as the kinematics is taught, it can immediately be applied to kinetics problems thereby motivating the kinematics and reinforcing the kinetics. For example, when normal and tangential coordinates are introduced for particles, problems involving kinetics can be solved. These problems may involve conservation of energy and/or direct application of Newton's Second Law, that is, the rate form of conservation of linear momentum in our framework.

Another advantage of this approach is that students are required to apply the principles "out-of-context". Typically in dynamics students know what principle to apply based on the topic currently being discussed in class. With this arrangement of the material, students need to decide which conservation principle is most applicable. Similarly, after the kinematics associated with fixed axis rotation is introduced, it is natural to extend the range of problems to include those involving energy, as well as linear and angular momentum for rigid bodies.

ES205 Analysis and Design of Engineering Systems -- The material covered in the spring course, Analysis and Design of Engineering Systems (ES205) is similar to that covered in a traditional systems class. Equations of motion are obtained for mechanical systems, electrical, electromechanical, thermal, fluid, and hydraulic systems. For single degree of freedom systems, topics of free response, step response and response due to harmonic excitation and general periodic forcing, frequency response plots (Bode plots), transfer functions, and Fourier Series are discussed. The concepts of natural frequency and damping ratio are discussed for mechanical as well as electrical and thermal problems. Associated with this course is a three-hour lab devoted primarily to the writing of product design specifications, although there are two more traditional labs. One of the labs is focused on system identification for a draining tank and the other involves modeling a DC motor/generator system with a flexible shaft in Simulink.

VI. Example Problems

One of the ways to describe the impact of using the conservation and accounting framework in teaching engineering science is to describe problems that students work in the new curricula and illustrate differences in the way students approach these problems.

Example 1: Water Hammer

Consider a tank filled with water of constant density ρ. The tank has a constant area A and a pipe at the bottom from which a flow rate of Q exits. The pressure at the bottom of the tank is P. For demonstration purposes, the exiting flow rate is given. The problem could also be solved by expressing a relationship between the pressure at the tank bottom and flow rate. The problem is to derive an equation for the height of fluid in the tank, see Figure 1.

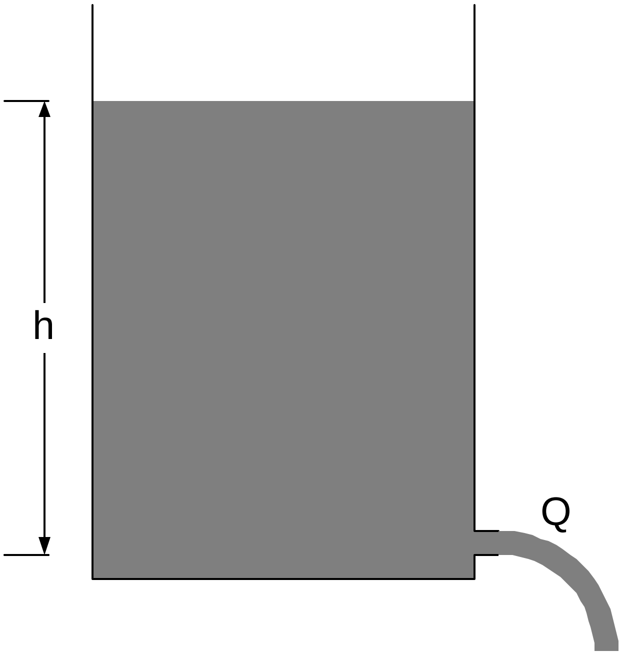


Figure 1 - Water tank with water exiting at a rate of Q.

The process requires the identification of the following:

1. a boundary,

2. properties to count,
3. the degrees of freedom,
4. the order.

If the water motion is “well behaved” with no turbulence or velocity profile, the model has a single degree of freedom. All the water moves together. If 1 unit of mass is removed, the position of all other mass is determinable. The following model will assume one dof.

The properties that can be counted include:

- mass, which can be determined by the height of the fluid in the tank,
- energy, which can be identified by fluid height and velocity,
- momentum, accounted by fluid velocity.

Since fluid position and fluid velocity are independent, the system is at maximum, second order. The conditions that allow velocity to be neglected are small Q and large A.

Suppose the fluid speed is neglected. The model will be order one, degree of freedom one. Since the number of given motions is equal to the dof, the problem only requires expressing a kinematical constraint. That is what the conservation of mass does. The model consists of writing the conservation for the only “important” property, mass, and is:

$$-\rho\, Q = \rho\, A\left(\frac{\partial}{\partial t}h\right) \tag{1}$$

Now suppose the fluid speed is significant. The degree of freedom is still one, but the order is two. The mass conservation is identical to the previous but now the energy and momentum need to be handled. The conservation of linear momentum in the vertical direction can be easily derived. First from the free body diagram shown in Figure 2, ~~figure ?,~~ the vertical force from the gage pressure at the bottom of the fluid is PA.

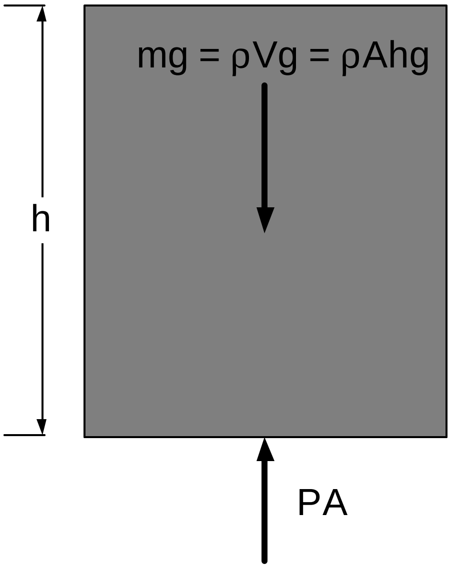


Figure 2 Freebody of the Water in the Tank.

The gravity force is $-mg = -rVg = -rAhg$. The momentum of the fluid in the tank is

$$mv = rVv = rAhv = rAh\left(\frac{1}{2}\frac{\partial h}{\partial t}\right)$$

(students sometimes miss the ½ because they forget that they are computing the velocity of the center of mass of the fluid). With these expressions, the conservation of linear momentum says:

$$PA - \rho A h g = \frac{\partial}{\partial t}\rho A h\left(\frac{\partial}{\partial t}\left(\frac{1}{2}h\right)\right) \qquad (2)$$

Now consider what these say. Suppose the flow rate is held constant for a while, the rate of change of h is a constant so the pressure at the tank bottom is equal to the fluid weight. Now suppose the flow rate is suddenly stopped. In other words, $Q \neq 0$ at t^- and $Q = 0$ at t^+, Q is discontinuous. When this happens equation 1 says $\frac{\partial h}{\partial t}$ (which was negative) suddenly becomes zero, $\frac{\partial h}{\partial t}$ is discontinuous. This which means $\frac{\partial^2 h}{\partial t^2} = +\infty$. Using this in the momentum equation (2) indicates that the pressure at the bottom of the tank suddenly jumps to $+\infty$ for a very short time. Of course in the real world the pressure will not go to infinity because some of the fluid will leak, the container will expand slightly etc. but the pressure will be large. This large pressure for a short period is what is called water hammer. So what causes water hammer? Water hammer is caused by a sudden change in flow rate in a system where fluid momentum is not negligible.

What this example demonstrates is that (1) the conservation principles can derive the water hammer equations easily, (2) the use of degree of freedom helps to identify that the motion of the fluid height is directly related to the flow rate, (3) the use order helps to identify how many and what type of equations are required.

Before we leave this example, consider what conservation of momentum tells you in a system where the momentum and its change is insignificant. If the momentum and its change is insignificant, the term on the right of equation (2) is zero, hence: $PA - rAhg = 0 \Rightarrow P = rgh$ in other words, the pressure equals the static fluid weight (obviously). The point here is that the conservation equations are always valid and when written they will tell you something. Because of this point, some of the authors make a habit of teaching students to always write every conservation equation for every problem (this is an exaggeration of course but it makes the point). Order however is a useful tool to help determine the number and type of differential equations that are required for the model. The number and type of differential equations is important to know from a system dynamics or control point of view.

Example 2: Jumping a Spark

Consider the circuit given in Figure 3.

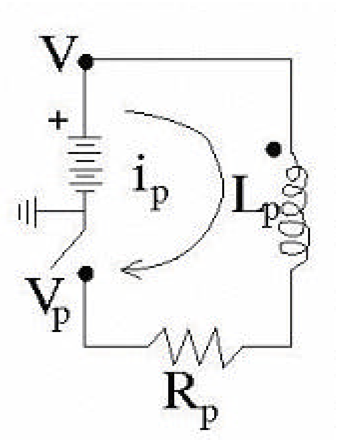


Figure 3 A Switched Circuit.

The circuit has one degree of freedom when the switch is closed and the labeled current gives the flow variable. The problem given to students is to explain what happens to the voltage at V_p when the switch opens after having been closed for a long period of time. With a little help, the student’s thinking proceeds as follows. Conservation of energy tells the students that there is energy stored in the coil due to the flow of current. When the switch opens, and degree of freedom drops to zero and the current drops to zero causing the energy in the coil to leave the coil. Because the energy cannot disappear, it has to go somewhere. The energy cannot be dissipated by the resistance R_p if the current is zero. The students conclude that the voltage at V_p becomes very negative until a spark jumps across the switch. The energy dissipated by jumping the gap is large because even though the current in the spark may be small, the voltage drop is large. Since a significant amount of energy is dissipated across the gap, the students realize that the switch may become damaged.

Next the students are asked to design something to prevent the arc from jumping and damaging the switch. Some students who understand about diodes choose to prevent the degree of freedom from dropping by putting in a clamping diode. Others recognize the real need is to provide a storage location for the energy that leaves the coil. In other words, they increase the order of the system to allow for an additional energy storage mechanism. Their design is shown in Figure 4:

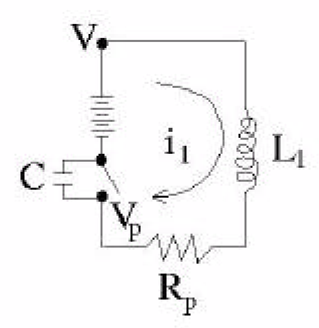


Figure 4 The Protected Switch.

Since a capacitor stores energy, the energy from the inductor enters the capacitor when the current is stopped. This example demonstrates how degree of freedom and order can be used in design.

The previous two examples demonstrate how augmenting the conservation and accounting with degree of freedom and order can help in system analysis and design. These concepts are not essential and need not be taught if the students are not sufficiently advanced. Without them, students should be encouraged to write all conservation equations for every system.

Examples 3 and 4 were taken from the ES205 final at Rose-Hulman Institute of Technology. They illustrate the types of problems that students at Rose-Hulman can solve at the end of the sophomore ES20x sequence. The thermocouple problem illustrates that students can tackle multidisciplinary problems using the conservation and accounting framework. The vibration analysis of the car also illustrates the power of computer algebra systems such as Maple. Entering students at Rose-Hulman are required to purchase a notebook computer with a software suite. Although the car problem can be set up manually, the calculations would be difficult to do by hand, but they are ideal for Maple. This problem is not much different than what students might see in a senior level vibrations course.

Example 3: Analysis of Thermocouple

A thermocouple has the following properties:

$$\rho = 490\frac{lb}{ft^3},\ c_p = 0.11\frac{BTU}{lb-{}^\circ F},\ \frac{\text{Volume}}{\text{Surface Area}} = 0.0025\text{ ft}$$

This thermocouple is used in an application (Figure 4) where the convective heat transfer coefficient is found to be $h = 7.5\text{x}10^{-4}$ BTU/(ft^2-°F-s). A compensating circuit has been added to the thermocouple output as shown in Figure 5. The temperature of the fluid

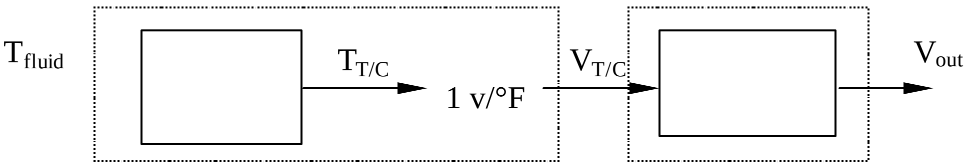


Figure 4. Thermocouple Application

being measured varies as $T_{fluid} = 30 \sin(\omega t)$ °F where $\omega = 0.0035$ rad/s. Assume the thermocouple output is 1 volt per °F.

a) Find the steady-state output of the thermocouple without the compensating network.

b) Sketch the frequency response plots of the thermocouple without the compensating network using the semi log paper on the following page.

c) Find the steady-state output of the thermocouple with the compensating network.

d) On the plot you made for part b) sketch the frequency response plot of the combined thermocouple and compensating network. Be sure to clearly label the curve for the system with and without compensation.

e) What has the compensator done in this problem?

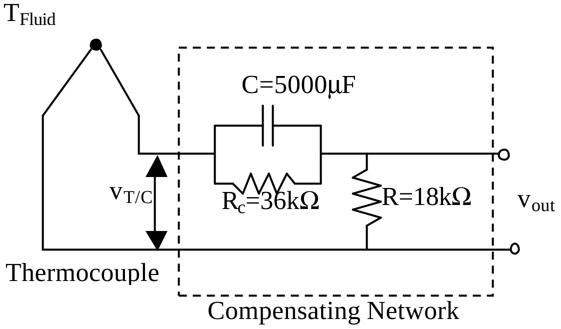


Figure 5. Thermocouple Compensating Network

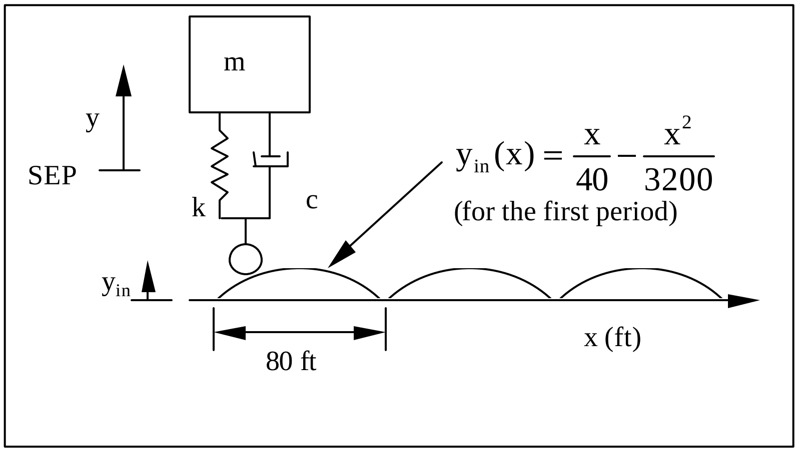
Vibration Analysis of a Car

In your summer internship at Ford motor company you have been asked to analyze a simple model of a car driving over a rough road. A single degree of freedom model is used for the car and the road is to be modeled as the periodic forcing function shown. Assume the car is being driven at 60 mph (88 ft/s). Hint: The period for the forcing frequency and y(t) will depend on the velocity.

Determine:

a) the equation of motion of the car in terms of m, c, k, y and y_{in}.

b) the equation of motion of the car in terms of ζ, ω_n, y



and y_{in} (i.e. put the equation you found in part a) in standard form).

c) the transfer function for the car

d) find the Fourier series for the input function $y_{in}(t)$. Write out the first few non-zero terms of the Fourier series.

e) Assuming that the car has a natural frequency of 1 Hz and a damping ratio of $\zeta = 0.08$ determine the steady state response of the car. Write out the first few non-zero terms of the solution. How many terms did you need to keep?

f) What speed would you suggest going to minimize the steady state amplitude?

VII. Student Performance/Faculty Reactions

Two important questions about the impact of a major curriculum restructuring effort are 1) Were participating students negatively impacted? And 2) Were participating students positively impacted. This section will present data on student performance that addresses these two questions for each of the three curriculum structures being studied.

Texas A&M Four Course Structure

One of the goals of the four course engineering science core curriculum was to produce students who were better prepared for more challenging material. One of the measures that was to assess student performance on more challenging material was the student's grade point average (GPA) in subsequent engineering classes. Table 5 shows the average GPA each semester both for students who participated in the four-course curriculum and student in a comparison group for the years 1989 and 1990. Numbers in bold are the grades in the sophomore year, these grades for the Core group were effectively the only grades determined by the faculty involved in the four-course core curriculum.

TABLE 5: Cumulative GPAs for Core and Comparison Groups

Students in 1989:

End of:

	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring	
	1989	**1990**	1990	1991	1991	1992	1992	1993	
Core	3.56	**3.44**	**3.45**	3.50	3.49	3.47	3.49	3.48	3.51
Comp	3.40	**3.42**	**3.41**	3.41	3.38	3.37	3.36	3.25	3.27

Students in 1990:

End of:

	Fall	Spring	Fall	Spring	Fall	Spring	Fall
	1990	**1991**	1991	1992	1992	1993	1993
Core	3.24	**3.05**	**3.05**	3.07	3.09	3.09	3.12

Comp	3.24	**3.05**	**3.03**	2.98	2.99	2.99	3.00

The GPA of the students who participated in the four-course core curriculum dropped somewhat during their core experience but it increased after completion of the core curriculum. For students in the comparison group, their GPA remained constant during the sophomore year, but dropped after their sophomore year. The GPA data shows that participation in the core curriculum has a positive impact on GPA performance after the completion of the core curriculum.

As another measure of performance on challenging problems after completion of the core curriculum, faculty gave a portion of the Fundamentals of Engineering examination to students who participated in the core curriculum as another comparison group with similar population statistics of GPA and SAT scores. The mean score and standard deviations for the two populations were (Core =0.561, 0.163) and (Control = 0.495, 0.125). The data showed that the core group performed better on the portion of the FOE examination. A comparable gain on the actual FOE would raise a student from the 50th percentile to about the 60th percentile.

As a third measure of performance on challenging problems, faculty prepared three achievement tests: Statics, Dynamics, and Thermodynamics, and offered them to students who participated in the core curriculum in 1991-92. Faculty offered one test at the end of their first sophomore semester, and offered the other two at the end of their second sophomore semester. They were compared against comparison groups who had completed similar course material from the traditional curriculum. The exam coverage, mean, standard deviations and population sizes for these exams were:

TABLE 6: Performance on Engineering Science Achievement Examinations

Engineering Science Achievement Examination	**Core Group**			**Comparison Group**		
	Aver.	**Stand. Dev.**	**Pop. Size**	**Aver**	**Stand. Dev.**	**Pop. Size**
Static	0.65	0.06	78	0.78	0.06	173
Dynamics	0.51	0.08	78	0.35	0.08	93
Thermodynamics	0.66	0.07	78	0.57	0.07	165

Average performance of the core group was superior to the comparison group on the dynamics and thermodynamics examinations, but was inferior on the statics examinations. The thermodynamics comparisons are significant because the control students were well into their junior years and have had more engineering courses than the core students, yet the core students greatly outperformed the control. However, it appears that the additional practice on statics problems by students comparison group resulted in superior performance in this engineering science.

In the spring, another four tests were constructed and given to the core and new control groups. The spring exams covered Strength of Materials, Dynamics, Thermodynamics and Fluid Mechanics. The results were: Strength (Core 0.33, 0.20 n=62), (Control Alpha

0.30, 0.17 n=43) (Control Beta 0.57, 0.20 n=34); Dynamics (Core 0.65, 0.31 n=62), (Control Alpha 0.46, 0.26 n=43), (Control Beta 0.60, 0.24 n=34); Thermo (Core 0.60, 0.20 n=62), (Control Gamma 0.53, 0.14 n=98); Fluids (Core 0.33, 0.18 n=62), (Control Delta 0.35, 0.22 n=107).

Core faculty did increase statics and strength of materials content following this analysis, and new testing in Spring of 1994 provided data to determine that the curriculum change was successful with respect to that content.

Since materials science had not yet been compared, the 1992 cohort [Louis, is this 1992-93 academic year?] compared this performance. As usual the control group was taken from students studying a similar topic in the traditional curriculum. This time the instructor of the control student's traditional class made up the exam. Results were: (Core 0.52, 0.18), (Control 0.27, 0.20).

Texas A&M Five Course Structure

[Walt, Dimitris - Do you have material that you could contribute to this section?]

Rose-Hulman Institute of Technology Sophomore Engineering Curriculum

Assessment of the sophomore engineering curriculum at Rose-Hulman has focused on the mechanics portion of new sophomore curriculum at RHIT because most mechanical engineering majors were taking a more traditional dynamics course while the electrical and computer engineering majors were taking the sophomore engineering curriculum. Having both sets of students take a similar final exam at the end of the dynamics course (ME majors) and at the end of ES204 (electrical and computer engineering majors) allowed a direct comparison of their performance. During the 1996-97 and 1997-98 academic years (the second and third years that the new curriculum was offered) a similar final was given to students taking ES204 and students taking the traditional dynamics course. There were approximately 125 dynamics students and 90 SEC students. Both finals consisted of 20 multiple-choice problems (40% of the total points) and 3 workout problems (60% of the total points). This format for the final has been used for many years because it is felt that this is the best way to make the final comprehensive. During 1996-97, sixteen of the multiple-choice problems and one of the workout problems were identical for the two finals. It was not possible to give identical finals since some of the faculty members had strong objections. During 1997-98, the two finals were identical.

Figure xx compares the performance on the multiple-choice problems. To reduce the influence of a particular professor the numbers for Tables 1 and 2 were obtained by averaging the results from five dynamics sections (three professors) and from four ES204 sections (three professors). In 1996-97, performance on four multiple-choice questions is not shown because these questions were not common between the two classes. As can be seen from Figure xx, the students in the SEC did better than the students taking the traditional dynamics course on a majority of the multiple-choice problems. It is important to note, however, that the percentage difference is quite minor for a number of problems and that they did significantly worse on some problems. For example, problem number 19 was most easily solved using rotation axis, a topic that was not covered in ES204.

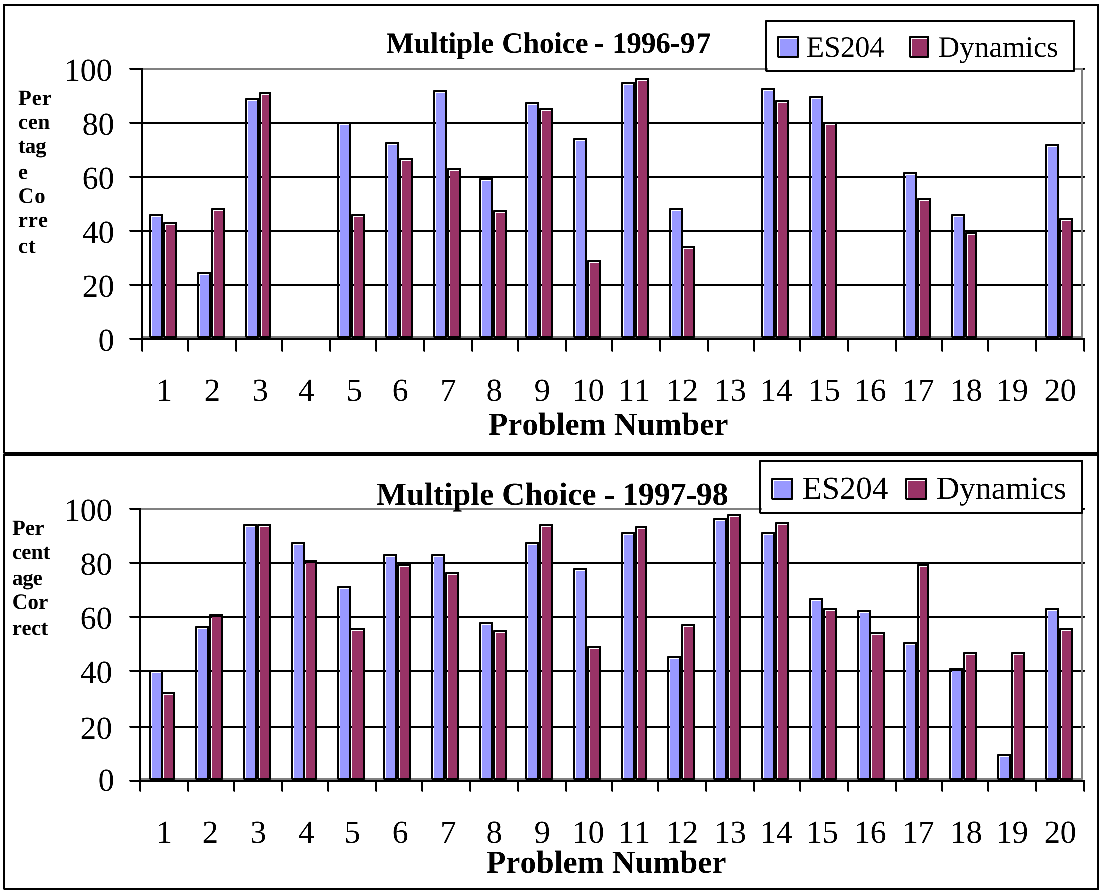


Figure xx. Results on Common Multiple Choice Final Examination Questions

Table 7 compares the percentage of students with correct answers for the workout problems. Again, to reduce the influence of a particular professor the numbers for Tables 1 and 2 were obtained by averaging the results from five dynamics sections (three professors) and from four ES204 sections (three professors). Differences for the workout problems are more dramatic than the differences for the multiple-choice questions. Workout problems were designed to be longer, more difficult and required multiple steps and concepts. The students in the new curriculum did significantly better than those taking the traditional dynamics course. Based on these assessment data, it is clear that the new curriculum does not hurt the students and in fact it appears to help them in mastering the mechanics material.

Table 7 Percentage of students with correct answers for the work-out problems

Prob. #	**First Assessment**			**Second Assessment**		
	SEC ES204	**Dynamics**	**Difference**	**SEC ES204**	**Dynamics**	**Difference**
21	33.3	23.3	10	36.8	17.0	19.8
22				70.1	22.0	48.1

23				46.0	6.0	40.0

For this assessment, the majority of students in the SEC were majors in electrical engineering and computer engineering and the students in the traditional dynamics course were mechanical engineering majors. Therefore, questions remained as to whether the students in the new curriculum performed better because the EE/CO students were academically superior to the ME students or because of the new curriculum. Since this curriculum was required for all mechanical engineering students beginning in the 1998-1999 academic year it has been possible to compare the performance of EE/CO and ME students taking identical courses. A summary of the distribution of final grades for ES201 is shown in Table 8.

Table 8 Grade distribution for ES201 by major

Grade	Major	
	EE/CO	ME
A	8	9
B+	10	10
B	24	25
C+	21	19
C	22	8
D+	7	6
D	10	7
F	2	5
Average GPA	2.46	2.53

On average the mechanical engineering students actually performed better although it is not clear if the difference is statistically significant. Therefore, the authors feel confident that the improved performance of students as indicated in Figure xx and Table 7 can be attributed to the new curriculum rather than their major.

VIII. Conclusions

The paper has presented a unified framework for organizing and teaching the engineering sciences. The framework is built upon four concepts: 1) system, boundary and surroundings, 2) property, 3) conserved property, and 4) accounting for the exchange of properties across the boundary of a system. Using the framework, Texas A&M University and Rose-Hulman Institute of Technology have restructured their curriculum for offering engineering science. At Texas A&M, two curricular implementations have been tried. The second one has been adopted across the college of engineering because it was more compatible with the background of most engineering faculty. Rose-Hulman has offered a single curricular implementation that has been adopted by both the mechanical and electrical and computer departments for their majors. Assessment data indicate that students who have participated in the newer curricular implementations gain a better conceptual understanding than students who took the engineering sciences in a more traditional curricular structure.

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