Integrating the Mechanical Engineering Core

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Abstract

This paper describes a new paradigm for integrating engineering courses—a systems, conservation and accounting, and modeling approach. The paper presents a historical background of this approach and discusses the motivation. The overall framework is presented, including the important concepts and definitions, the basic conservation and accounting equations, and a common problem solving approach. A detailed development is presented for conservation of linear momentum to illustrate how the equations are developed. Several examples are included to demonstrate how students solve problems using problem-specific models developed from the general equations instead of using a "plug-and-chug" approach. Experience with using this approach for teaching and curriculum design is discussed. Results to date indicate that this approach can improve student performance and help them develop a more integrated understanding of material that has traditionally been taught as unrelated topics.

Introduction

Imagine for a moment what it is like to be a freshman or sophomore engineering student. After a heavy dose of physics, chemistry, and mathematics, you are excited to finally be taking engineering courses. Although you may have done well in physics, you discover that engineering courses are noticeably different, and you may struggle with them. Faced with a plethora of apparently unrelated courses, you (and sometimes the faculty teaching the courses) miss the underlying concepts and themes. To you, it seems these courses are a set of unrelated topics each with its own special set of tricks.

As faculty teaching these courses, we are frequently struck by our students' failure to make connections. Why can't they see the connections? Who among us hasn't felt frustration when a student asks "Which free-body diagram do you want, the physics one, the statics one, the dynamics one, or the one from fluid mechanics?" Or "Which energy balance should I use, the one from physics, dynamics, fluid mechanics, heat transfer, or thermodynamics."[a]

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[a] My thanks to Lynn Bellamy and Don Evans for sharing the stories underlying these quotations.

Out of this frustration, faculty members continually seek ways to help our students understand the material, especially to see the connections between what students perceive as unrelated material. Transfer of learning from one course to another is one of the effects most sought after by educators and one of the most difficult to produce (or at least observe) in our students. Rugarcia, Felder, Woods, and Stice in an excellent article[1] on the future of engineering, stress that both components of engineering education—knowledge and skills—should focus on the big picture. This issue was also discussed in a recent white paper on thermal systems education[2].

Now recall your first days as a graduate student. As you reviewed notes from a week of classes, it suddenly dawned on you that you had just spent the entire week developing the same set of equations—possibly the differential form of the conservation equations for mass, energy, and momentum—in all your courses. The developments and possibly the notation differed but the underlying concepts were the same. Suddenly the light went on; you began to see how everything fit together. Why hadn't anyone told you this earlier?

In 1988, a group of faculty members at Texas A&M University began work on a new integrated curriculum to replace the core engineering science courses within the typical engineering curriculum. The result was an interdisciplinary sequence of four courses called the Texas A&M/NSF Engineering Core Curriculum[3] organized around what they called the conservation and accounting principle. Glover, Lundsford, and Fleming produced an introductory textbook[4] that used this approach. Similar calls to consider a systems approach also come from physicists[5, 6].

In 1993, seven schools came together as the Foundation Coalition under the auspices of the NSF Engineering Education Coalitions Program. One of the major thrusts of this group was curriculum integration. Building on the early work at Texas A&M, Texas A&M and Rose-Hulman developed new sophomore engineering curricula organized around the conservation and accounting principle to help students see the connections within their courses. At Texas A&M, this resulted in the Sophomore Engineering Science Sequence consisting of five courses covering mechanics, thermodynamics, materials, continuum mechanics, and electrical circuits and electronics.[7] At Rose-Hulman, this resulted in a new core curriculum called the Rose-Hulman/Foundation-Coalition Sophomore Engineering Curriculum (SEC). The SEC is a required eight-course sequence of engineering science and mathematics courses completed during the sophomore year. The SEC covers dynamics, fluid mechanics, thermodynamics, electrical circuits, system dynamics, differential equations, matrix algebra, and statistics.[8]

This paper describes a new paradigm for organizing an engineering core—a systems, conservation and accounting, and modeling approach—that emphasizes the underlying concepts upon which engineering science is based and provides students a framework for recognizing and building connections as they learn new material. Although applicable to most engineering disciplines, this approach is especially applicable to the mechanical engineering core because of its breadth. The goal

of the paper is to introduce the basic approach and challenge you to consider how this might help your students.

Common Concepts in the Core

For purposes of discussion, let's assume that the mechanical engineering core consists of eight courses: statics, dynamics, mechanics of materials, fluid mechanics, thermodynamics, heat transfer, electrical circuits and system dynamics (See Figure 1).

What are the common threads that run through these courses? From a student's perspective, you might ask yourself some concrete questions: "How do Newton's laws in dynamics relate to the integral-momentum equation in fluid mechanics?" or "How does the work-energy principle in dy-

Typical Core Engineering Courses

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Statics	Fluid Mechanics
Dynamics	Thermodynamics
Electrical Circuits	System Dynamics
Mechanics of Materials	Heat Transfer

Extensive Property

Mass
Electric Charge
Linear Momentum
Angular Momentum
Energy
Mechanical Energy
Entropy

System Boundary

System

Interaction

Interactions with Surroundings

Electric Current
Force
Torque
Work
Heat Transfer
Mass Transfer

Constitutive Relations

Ohm's Law
Ideal Spring
Dry Friction
Ideal Gas Model
Steam Tables
Friction Factor
Newtonian Fluid
Viscous Drag

System

Node
Free-Body Diagram
Control Mass
Open System
Control Volume
Closed System

Modeling Assumptions

Equilibrium
Steady state
Rigid Boundary
Pinned Joint
Linear Translation
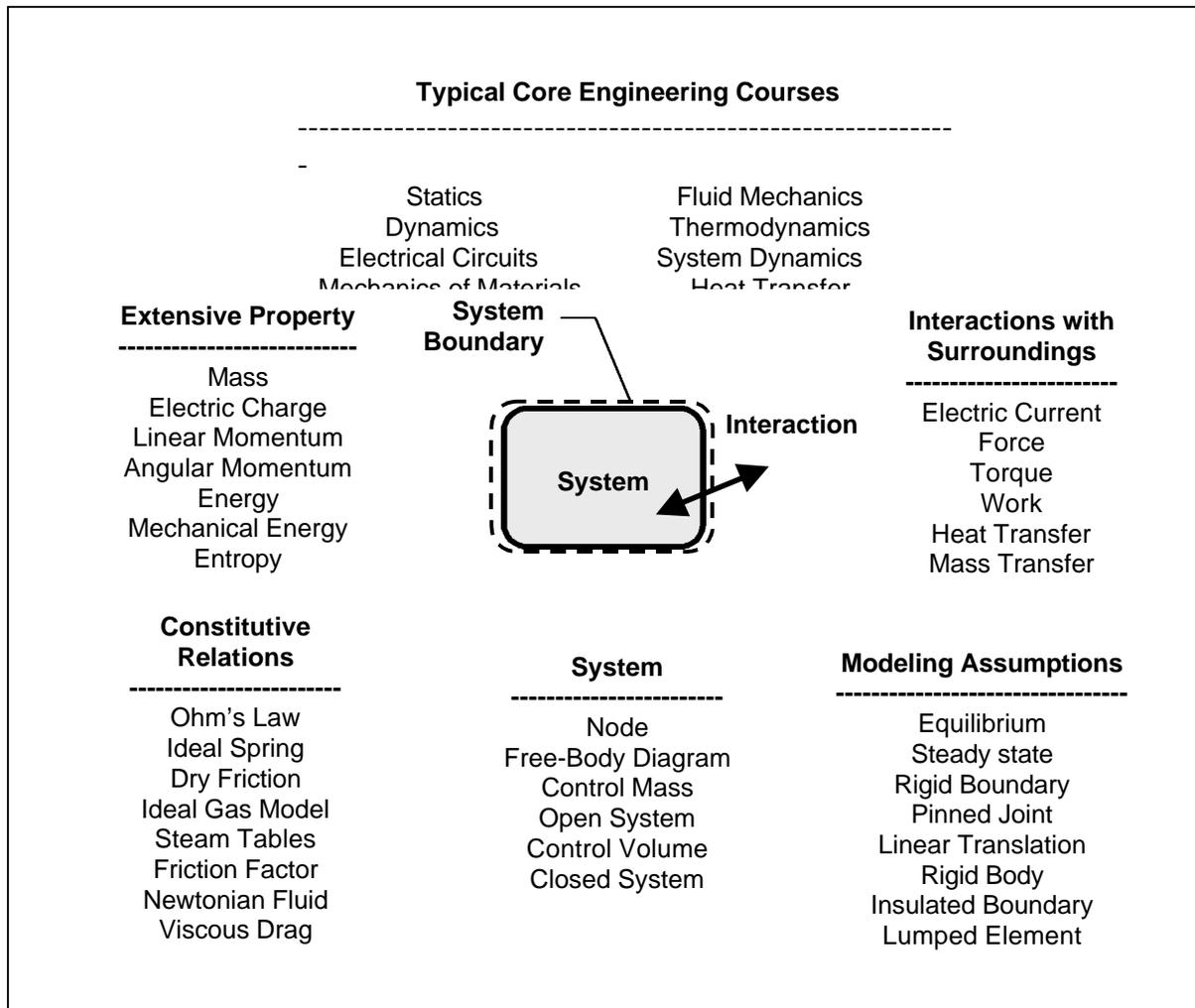Rigid Body
Insulated Boundary
Lumped Element

Figure 1 -- Common Concepts in Core Courses

namics relate to the mechanical energy balance in fluid mechanics and the general energy balance in thermodynamics?" Most faculty members would recognize that problem solving is a major thread.

Before you can begin to solve a problem, you must carefully read the problem statement. Before you can do any analysis, you will typically develop a mathematical **model**. To do this, you must first isolate a part of the physical world and identify the **system**. Next you must describe the **state** of the system and identify its important **properties**. Then you must identify the **processes** that change the state of the system and the **interactions** the system has with its surroundings during these processes.

Once you have done this, you will apply the 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** like mass, charge, energy, linear momentum, angular momentum, and entropy. Five of these are **conserved properties** and the sixth one, entropy, can only be generated.

As you continue your solution, you will make **modeling assumptions** to capture the essential features of the problem and select **constitutive relationships** to supplement the fundamental laws. With this information collected, it is now possible to solve the problem.

If you have not been referring back to Figure 1, do so now and look for the terms you find familiar. As you reflect on the lists, you will recognize that each course has its own special term for a generic concept. You will find definitions in Figure 2 for the bold-faced terms used in the previous paragraphs.

The Accounting Principle

The underlying organizing principle for this approach is what I will refer to as the *accounting principle*. The key ideas here are that every system has associated with it numerous extensive properties and that the behavior of the system can be determined by monitoring changes in these properties. Any change in an extensive property within the system can be accounted for by counting the amount of the property *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 (control volumes) is presented by W. G. Vincenti in his fascinating book *What Engineers Know and How They Know It*[9])

Model	a purposeful representation.
System	a region of space or quantity of matter set aside for analysis.
Property	a characteristic of a system that can be assigned a numerical value at a specified time without considering the history of the system. An **extensive property** is a property whose value depends on the mass or extent of the system, e.g. mass, volume, and energy. An **intensive property** is a property whose value does not depend on the extent of the system, i.e. an intensive property has a value at a point. Pressure, temperature, and velocity are all intensive properties.
State of a System	a complete description of the system in terms of its properties.
Process	the means by which a system changes its state.
Steady-State System	a system that behaves in such a manner that all of its intensive properties and interactions with the surroundings are independent of time.
Interaction	the transport of an extensive property across a system boundary.
Conserved Property	an extensive property that cannot be generated or consumed.
Accounting Principle	a simple balance relationship for an extensive property (e.p.): the accumulation of an e.p. within a system equals the transport of the e.p. into the system minus the transport of the e.p. out of the system plus the generation (or production) of the e.p. within the system minus the consumption (or destruction) of the e.p. within the system.
Constitutive Relation	a mathematical relationship between variables that describe a physical phenomenon, that by its very nature is specific and cannot be applied in general, and is only valid under a restricted set of conditions.

Figure 2 -- Key Definitions

Given a generic extensive property *B*, it is possible to write a general accounting principle for any system. In its simplest form, the accounting principle can be stated in words as follows:

> The accumulation of a property within a system equals the transport of the property into the system minus the transport of the property out of the system plus the generation (or production) of the property within the system minus the consumption (or destruction) of the property within the system.

Singling out the various components and illustrating the terms in a more mathematical form we have the following relation:

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

$$\begin{bmatrix} \text{Accumulation of } B \\ \text{inside system} \\ \text{during time period} \end{bmatrix} = \begin{bmatrix} \text{Net amount of } B \\ \text{transported into system} \\ \text{during time period} \end{bmatrix} + \begin{bmatrix} \text{Net amount of } B \\ \text{generated inside system} \\ \text{during time period} \end{bmatrix}$$

This is commonly referred to as the finite-time form of the accounting principle because it is applied over a specified time interval.

The rate form of the accounting principle can also be written in words; however, it lends itself to a compact mathematical representation. Three different forms of this relation are presented in Figure 3 for the generic extensive property B. Equation (a) in Figure 3 is the most compact mathematical statement of the rate form of the accounting principle clearly showing the means by which the property can change. The left-hand side of this equation represents the time derivative, the rate of change, of the amount of property B inside the system, dB_{sys}/dt. The right-hand side of the equation gives the transport rates $\dot{B}_{\text{in/out}}$ and the generation and consumption rates $\dot{B}_{\text{gen/cons}}$. (Note that as used here, the "dot" notation *does not* indicate a derivative, e.g. $dB/dt \neq \dot{B}$.)

The amount of extensive property B within the system can be determined by summing up the amount of B associated with mass inside the system. For discrete masses, this is a simple summation; for a distributed system, it is calculated by integrating the product $b\mathbf{r}$ over the volume of the

Generic Extensive Property B

$$B_{\text{sys}} = \int_{V_{\text{sys}}} b\mathbf{r}\, dV$$

$$\frac{d}{dt}B_{\text{sys}} = \underbrace{\left[\dot{B}_{\text{in}} - \dot{B}_{\text{out}} \right]}_{\substack{\text{net rate transported} \\ \text{across the boundary} \\ \text{into the system}}} + \underbrace{\left[\dot{B}_{\text{generated}} - \dot{B}_{\text{consumed}} \right]}_{\substack{\text{net rate generated} \\ \text{within the system}}} \quad \text{(a)}$$

$$= \left[\dot{B}_{\text{net,in}}\Big|_{\substack{\text{without} \\ \text{mass flow}}} + \dot{B}_{\text{net,in}}\Big|_{\substack{\text{with} \\ \text{mass flow}}} \right] + \left[\dot{B}_{\text{generated}} - \dot{B}_{\text{consumed}} \right] \quad \text{(b)}$$

$$= \left[\dot{B}_{\text{net,in}}\Big|_{\substack{\text{without} \\ \text{mass flow}}} + \sum_{\text{in}} \dot{m}_i b_i - \sum_{\text{out}} \dot{m}_e b_e \right] + \left[\dot{B}_{\text{generated}} - \dot{B}_{\text{consumed}} \right] \quad \text{(c)}$$

Figure 3 --- Rate form of the Accounting Principle for Property B

system, where b is the intensive form of the extensive property B and r is the mass density of the material in the system (See Figure 3). For a case where b and r are both uniform throughout the system, the amount of B in the system is easily calculated as $B_{\text{sys}} = br V_{\text{sys}}$.

Because the accounting principle can be applied to both open and closed systems, e.g. systems with and without mass flow across the boundaries, it is useful to separate out the transport of B across the boundary with mass flow (Equation (b) in Figure 3). Any mass that crosses the boundary of the system carries with it some amount of extensive property B, and the rate at which B is transported across the boundary is the product of the mass flow rate $\dot{m}$ and b, the intensive form of B, i.e. $\dot{m}b$. This is shown in Equation (c) in Figure 3. The mass flow rate $\dot{m}$ is always calculated using the flow velocity measured relative to the boundary where the flow occurs.

Fundamental Conservation and Accounting Equations

The usefulness of the accounting principle is that it provides a common framework for presenting and applying the fundamental laws of physics routinely used by engineers. Although not traditionally presented this way for undergraduates, all of these laws can be formulated as conservation or accounting principles (See Figure 4). When presented using this framework, students can begin to see the underlying connections early in their education. In the Rose-Hulman / Foundation-Coalition Sophomore Engineering Curriculum, all of these laws are introduced in a course called "Conservation and Accounting Principles" using a common approach that builds on a student's experience with physics.

As each new principle is introduced, we ask four basic questions to place it in the context of the accounting principle:
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?
4. How can it be generated or consumed inside the system?

To provide a concrete example, consider the extensive property linear momentum:

1. What is linear momentum? $\mathbf{P}_{\text{particle}} = m_{\text{particle}} \mathbf{V}_{\text{particle}}$

    The linear momentum of a particle is the product of the mass of the particle m and its velocity $\mathbf{V}$. Students already know this definition from physics. In terms of the accounting framework, linear momentum $\mathbf{P}$ is the extensive property B and the velocity $\mathbf{V}$ is the specific linear momentum corresponding to the intensive property b. (See Figure 3)

Mass	$\dfrac{d}{dt} m_{sys} \;=\; \displaystyle\sum_{in} \dot{m}_i - \sum_{out} \dot{m}_e$
Net Charge	$\dfrac{d}{dt} q_{sys} \;=\; \displaystyle\sum_{in} \dot{q}_i - \sum_{out} \dot{q}_e$
Linear Momentum	$\dfrac{d}{dt} \mathbf{P}_{sys} \;=\; \displaystyle\sum_{external} \mathbf{F}_j \;+\; \sum_{in} \dot{m}_i \mathbf{V}_i - \sum_{out} \dot{m}_e \mathbf{V}_e$
Angular Momentum	$\dfrac{d}{dt} \mathbf{L}_{o,sys} \;=\; \displaystyle\sum_{external} \mathbf{M}_{o,j} \;+\; \sum_{in} \dot{m}_i \left(\mathbf{r}_o \times \mathbf{V}\right)_i - \sum_{out} \dot{m}_e \left(\mathbf{r}_o \times \mathbf{V}\right)_e$
Energy	$\dfrac{d}{dt} E_{sys} \;=\; \dot{Q}_{net,in} + \dot{W}_{net,in} \;+\; \displaystyle\sum_{in} \dot{m}_i \left(h + \dfrac{V^2}{2} + gz\right)_i - \sum_{out} \dot{m}_e \left(h + \dfrac{V^2}{2} + gz\right)_e$
Entropy	$\dfrac{d}{dt} S_{sys} \;=\; \displaystyle\sum_j \dfrac{\dot{Q}_j}{T_j} \;+\; \sum_{in} \dot{m}_i s_i - \sum_{out} \dot{m}_e s_e \;+\; \dot{S}_{gen} \qquad \text{with } \dot{S}_{gen} \ge 0$

Figure 4 -- Fundamental Conservation & Accounting Principles

2. How can it be stored within and quantified for a system? $\mathbf{P}_{sys} = \displaystyle\int_{V_{sys}} \mathbf{V} r \, dV$

    To calculate the linear momentum for any system, integrate the product of the specific linear momentum $\mathbf{V}$ and the mass density r over the system volume. For a system of discrete particles, the linear momentum is simply the sum of the linear momentum of all the particles in the system: $\mathbf{P}_{sys} = \sum \mathbf{P}_j = \sum m_j \mathbf{V}_j$

3. How can it be transported across the system boundaries? $\mathbf{F}_{external}$ & $\dot{m}\mathbf{V}$

    Experience has shown that linear momentum is transported by external forces acting on the system and by mass flowing across the system boundary. External forces $\mathbf{F}_{external}$ are of two types—*body forces* produced by fields like gravity and *surface* (or contact) *forces* that have a point of application on the system boundary. The mass transport of linear momentum can be written as the product of the mass flow rate and the local velocity where the mass crosses the boundary, $\dot{m}\mathbf{V}$. With this interpretation, a force is a mechanism for transporting linear momentum and specifically it is a transport rate with dimensions of [Linear Momentum]/[Time].

4. How can linear momentum be generated or consumed within the system? $\dot{\mathbf{P}}_{gen} = \dot{\mathbf{P}}_{con} = 0$

Experience has shown that it is impossible to create or destroy linear momentum; hence, we say that *linear momentum is conserved*. This means that both the generation and the consumption terms are identically equal to zero.

Putting this all together using the accounting framework shown in Figure 3, we have the **rate-form of the conservation of linear momentum** equation:

$$\frac{d}{dt}\mathbf{P}_{sys} = \sum_{external} \mathbf{F}_j + \sum_{in} \dot{m}_i \mathbf{V}_i - \sum_{out} \dot{m}_e \mathbf{V}_e$$

In words this becomes " the rate of change of the linear momentum of the system equals the net transport rate of linear momentum into the system by external forces plus net transport rate of linear momentum into the system with mass flow." This then becomes the starting point for solving any problem involving linear momentum whether it is from statics, dynamics, or fluid mechanics. In its most general form, the mass transport terms would be written using integrals over the system boundary. This is the form usually developed in fluid mechanics textbooks using the Reynolds transport theorem. The author's experience, however, has been that this simpler form will handle most problems and is easier for students to understand.

It is important to note that this is not the same "conservation of linear momentum" equation found in many physics and dynamics textbooks. As often used, the phrase "conservation" implies that the linear momentum of the system is constant as typically occurs in impact problems. This is a *problem-specific* assumption, and with this interpretation there are many problems where linear momentum is not "conserved." As used in the conservation and accounting framework, saying that a property is conserved makes a global statement about the way the world works; thus, linear momentum is always conserved. The linear momentum of a system remains constant only if it is a closed system and there are no external forces.

Since students are very comfortable applying the familiar equation $\mathbf{F} = m\mathbf{a}$, it is important to show them how this equation is related to the new more general principle. Starting with the rate form of the conservation of linear momentum as developed above, we need make only one modeling assumption—assume a closed system. As shown below, this single assumptions reduces the general equation to one that feels more familiar:

$$\frac{d}{dt}\overbrace{\mathbf{P}_{sys}}^{=m_{sys}\mathbf{V}_G} = \sum_{external} \mathbf{F}_j + \overbrace{\sum_{in} \dot{m}_i \mathbf{V}_i - \sum_{out} \dot{m}_e \mathbf{V}_e}^{0 \text{ closed system}}$$

$$\frac{d}{dt}\left(m_{\text{sys}} \mathbf{V}_{\text{G}}\right) = \sum_{\text{external}} \mathbf{F}_j \quad \rightarrow \quad m_{\text{sys}} \frac{d\,\mathbf{V}_{\text{G}}}{dt} = \sum_{\text{external}} \mathbf{F}_j \quad \rightarrow \quad m_{\text{sys}} \mathbf{a}_{\text{G}} = \sum_{\text{external}} \mathbf{F}_j$$

where the "G" subscript refers to the center of mass. In application, when a student starts from the general relation they *must* recognize they are modeling a closed system to recover the familiar result, $\mathbf{F} = m\mathbf{a}$. This understanding is frequently lost when students just pull $\mathbf{F} = m\mathbf{a}$ from memory. It is the author's belief that the *explicit* use of modeling assumptions to develop the problem-specific relations from a general physical principle helps students understand what is going on and underscores the limits of their analysis.

Similar equations can be developed for the other fundamental laws and are presented in Figure 4. Notice that all of these equations with the exception of the one for entropy are conservation laws. Although we cannot write a conservation relation for entropy, we can write a useful accounting equation because the second law of thermodynamics does place constraints on the entropy pro-duction rate, e.g. $\dot{S}_{\text{gen}} \geq 0$ and approaches zero under the conditions of an internally reversible process. Note that all of the equations have a similar format and appearance. Each has an accu-mulation term and each have transport terms. It is believed that by presenting all of the equations in a common format students should have an easier time seeing how they are connected.

Problem Solving and Examples

One of the advantages of using the conservation and accounting framework is that it lends itself to the use of a common problem solving approach regardless of the problem. When a student is

Written Format	Typical Questions
• Known	• What's the system?
• Find	• What properties should we count?
• Given	• What's the time interval?
• Analysis	• What are the important interactions?
-- Strategy	• What are the important constitutive relations?
-- Constructing Model	• How do the basic equations simplify?
-- Symbolic Solution	• What are the unknowns?
-- Numerical Solution	• How many equations do I need?
• Comments	

Figure 5 -- Problem Solving Format and Questions

faced with a problem, he or she has a consistent set of questions to ask about the problem. These are illustrated in Figure 5. 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.

To give you more exposure to this approach, solutions to three typical problems are solved on the following pages using the conservation and accounting framework. The differences in approach are most apparent in the formulation of the problem-specific governing relations from the general equations. Notice how each of the solutions has a system-interaction diagram that identifies transports of the extensive property across the system boundary.

Example 1 -- Cable Car

Known: A small inspection car is pulled along a fixed overhead cable by a cable attached at point A

Find: (a) The magnitude and direction of force R exerted by the overhead cable on the wheels of the car, in newtons.
(b) The magnitude and direction of the acceleration of the car, in m/s^2.

Given:

$T = 2400$ N

$m_{car} = 200$ kg

$\theta = 22.6^o$
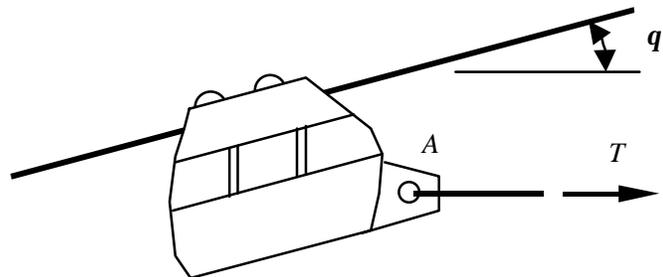
Analysis:

Strategy --- Since the problem involves forces, try conservation of linear momentum.

System: Closed system including only the car as shown in the momentum system diagram at right.
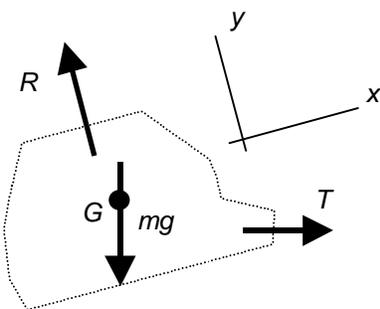Property: Linear Momentum
Time Period: Instantaneous

Without selecting a coordinate system the conservation of linear momentum equation becomes

$$\frac{d}{dt}\mathbf{P}_{sys} = \sum_{external} \mathbf{F}_j \; + \; \sum_{in} \cancel{\dot{m}_i \mathbf{V}_i}^{=0} - \sum_{out} \cancel{\dot{m}_e \mathbf{V}_e}^{=0,\;closed\;system}$$

$$\frac{d}{dt}\mathbf{P}_{sys} = m\mathbf{g} + \mathbf{T} + \mathbf{R}$$

where there are only three external forces—the force on the wheels **R**, the weight of the car $m\mathbf{g}$, and the cable force **T**. Also because this is a closed system, the linear momentum of the system $\mathbf{P}_{sys} = m_{sys}\mathbf{V}_G$ where $\mathbf{V}_G$ is the velocity of the center of mass of the system. Thus, the conservation of linear momentum can now be written as

$$\frac{d}{dt}\left(m_{sys}\mathbf{V}_G\right) = m_{sys}\mathbf{g} + \mathbf{T} + \mathbf{R} \qquad \rightarrow \qquad m_{sys}\frac{d\mathbf{V}_G}{dt} = m_{sys}\mathbf{g} + \mathbf{T} + \mathbf{R}$$

Now selecting a coordinate system that is aligned with the cable, the conservation of linear momentum can be written in two components. In the y direction, the linear momentum equation becomes

$$m_{sys}\frac{dV_{G,y}}{dt} = -\left(T \cdot \sin q\right) + R - \left(m_{sys}g \cdot \cos q\right)$$

$$m_{sys}\underset{\substack{=0 \\ \text{no motion} \\ \text{in y-direction}}}{\cancel{\frac{dV_{G,y}}{dt}}} = -\left(T \cdot \sin q\right) + R - \left(m_{sys}g \cdot \cos q\right)$$

Now solving for the force R of the cable on the wheels gives

$$R = \left(T \cdot \sin q\right) + \left(m_{sys}g \cdot \cos q\right)$$

Substituting in the numerical information gives

$$R = \left(2400 \text{ N}\right) \cdot \sin\left(22.6^\circ\right) + \left(200 \text{ kg}\right)\left(9.81\frac{\text{m}}{\text{s}^2}\right) \cdot \cos\left(22.6^\circ\right)$$

$$= \left(2400 \text{ N}\right)\left(0.3843\right) + \left(1962 \text{ N}\right)\left(0.9232\right)$$

$$= 922.3 \text{ N} \quad + \quad 1811 \text{ N}$$

$$= 2733 \text{ N}$$

In the x direction, the linear momentum equation becomes

$$m_{sys}\frac{dV_{G,x}}{dt} = \left(T \cdot \cos q\right) - \left(m_{sys}g \cdot \sin q\right)$$

$$\frac{dV_{G,x}}{dt} = \frac{\left(T \cdot \cos q\right) - \left(m_{sys}g \cdot \sin q\right)}{m_{sys}} = \left(\frac{T}{m_{sys}}\cos q\right) - \left(g \cdot \sin q\right)$$

Recalling the definition of acceleration, the x-momentum equation can be solved for acceleration as

$$a_{G,x} \equiv \frac{dV_{G,x}}{dt} = \left(\frac{T}{m_{sys}}\cos q\right) - \left(g \cdot \sin q\right)$$

Substituting in the numerical information gives

$$a_{G,x} = \left(\frac{2400 \text{ N}}{200 \text{ kg}}\right)\cos(22.6°) - \left(9.81\frac{\text{m}}{\text{s}^2}\right)\sin(22.6°)$$

$$= \left(12.0\frac{\text{m}}{\text{s}^2}\right)(0.9232) - \left(9.81\frac{\text{m}}{\text{s}^2}\right)(0.3843)$$

$$= 7.31 \frac{\text{m}}{\text{s}^2}$$

Example 2 -- Weighing Water

Known: Water flows steadily through a tank that rests on a scale.
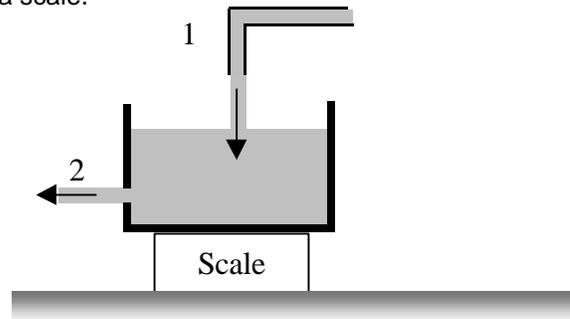
Find: The scale reading.

Given:

    Inlet Pipe @ 1

        Volumetric flow rate $\dot{V}_1 = 30$ m^3/h

        Diameter $D_1 = 6$ cm

    Outlet Opening @ 2

        Diameter $D_2 = 6$ cm

Volume of water in tank at steady-state: $V_{water} = 0.6$ m^3;   Weight of tank: $W_{tank} = 500$ N

Analysis

Strategy --- Since the problem involves forces, try conservation of linear momentum.

System: Open system that includes all water in the tank and the tank as shown in the momentum system diagram.
Property to count: Linear momentum and mass
Time Period: Instantaneous

Writing the rate-form of the conservation of linear momentum equation for this problem gives
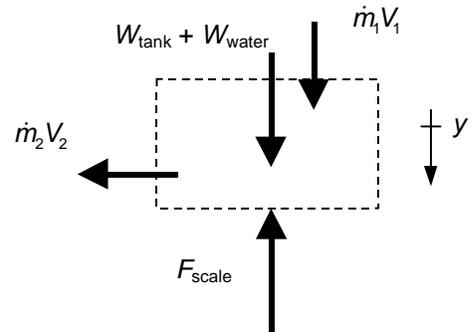
$$\frac{d\mathbf{P}_{sys}}{dt} = \sum_{external} \mathbf{F}_j + \sum_{in} \dot{m}_i \mathbf{V}_i - \sum_{out} \dot{m}_e \mathbf{V}_e$$

$$\frac{d\mathbf{P}_{sys}}{dt}^{\,0 \text{ steady state}} = \left(\mathbf{W}_{tank} + \mathbf{W}_{water}\right) + \mathbf{F}_{scale} \quad + \quad \dot{m}_1 \mathbf{V}_1 - \dot{m}_2 \mathbf{V}_2$$

$$0 = \left(\mathbf{W}_{tank} + \mathbf{W}_{water}\right) + \mathbf{F}_{scale} \quad + \quad \dot{m}_1 \mathbf{V}_1 - \dot{m}_2 \mathbf{V}_2$$

Now writing the component of this equation in the y-direction as defined in the figure above

$$0 = \left(W_{tank} + W_{water}\right) - F_{scale} \quad + \quad \dot{m}_1 V_{1,y} - \dot{m}_2 V_{2,y}$$

$$0 = \left[W_{tank} + W_{water}\right] - F_{scale} \quad + \quad \dot{m}_1 V_{1,y} - \dot{m}_2 \overset{0}{\cancel{V_{2,y}}} \text{No y component @ 2}$$

Solving for F_{scale} we have

$$F_{scale} = W_{tank} + W_{water} \quad + \quad \dot{m}_1 V_{1,y}$$

Now solving for the weight of the tank W_{tank}

$$W_{water} = m_{water} g = \left(\rho_{wwater} V_{water}\right) g = \left(1000 \ \frac{kg}{m^3}\right)\left(0.600 \ m^3\right)\left(9.81 \ \frac{m}{s^2}\right) = 5886 \ N$$

The y-component of the velocity at 1 and the mass flow rate at 1 are

$$V_{1,y} = V_1 = \frac{\dot{V}_1}{A_1} = \frac{\dot{V}_1}{\left(\frac{\pi}{4} D_1^2\right)} = \frac{\left(30 \ \frac{m^3}{h} \times \frac{1 \ h}{3600 \ s}\right)}{\frac{\pi}{4}\left(0.06 \ m\right)^2} = 2.95 \ \frac{m}{s}$$

$$\dot{m}_1 = \rho_1 \dot{V}_1 = \left(1000 \ \frac{kg}{m^3}\right)\left(30 \ \frac{m^3}{h} \times \frac{1 \ h}{3600 \ s}\right) = 8.33 \ \frac{kg}{s}$$

Combining this to solve for the force of the scale on the tank F_{scale}

$$\begin{aligned}
F_{scale} &= W_{tank} + W_{water} \quad + \quad \dot{m}_1 V_{1,y} \\
&= \left(500 \ N\right) + \left(5886 \ N\right) \quad + \quad \left(8.33 \ \frac{kg}{s}\right)\left(2.95 \ \frac{m}{s}\right) \\
&= \left(6386 \ N\right) \quad + \quad \left(24.6 \ N\right) \\
&= 6411 \ N
\end{aligned}$$

If the operator had neglected the effect of the water flowing into the tank on the reading, he or she would have overestimated the amount of water in the tank by roughly 0.4%.
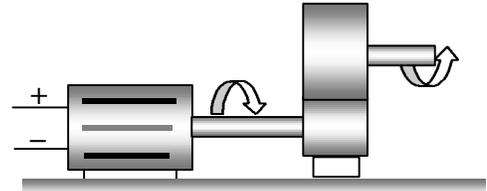

Example 3 -- Gear Reducer

Known: An electric motor drives a gear reducer under steady-state conditions.

Find: The *minimum* electric power input required to produce 25 hp at the outlet shaft of the gear reducer.

Given:

Required output shaft power, $\dot{W}_{shaft,\,out} = 25$ hp

Analysis:

Strategy --- Since the problem involves power, it should involve the conservation of energy. In addition, since it asks for the *minimum* amount it may also require the entropy accounting equation, the second law of thermodynamics.

System: Closed system that includes the motor and the gear reducer
Property: Energy and Entropy
Time Period: Instantaneous
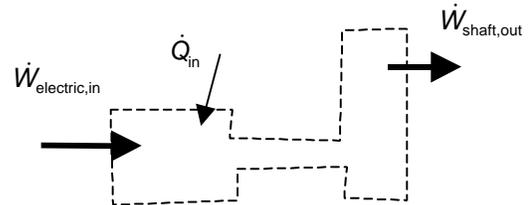
Writing the rate-form of the conservation of energy equation gives

$$\frac{d}{dt}E_{sys} = \dot{Q}_{net,in} + \dot{W}_{net,in} + \sum_{in}\dot{m}_i\left(h+\frac{V^2}{2}+gz\right)_i - \sum_{out}\dot{m}_e\left(h+\frac{V^2}{2}+gz\right)_e$$

$$\frac{d}{dt}E_{sys}^{\,0\;\text{Steady-state}} = \dot{Q}_{in} + \left(\dot{W}_{electric,in} - \dot{W}_{shaft,out}\right) + \sum_{in}\dot{m}_i\left(h+\frac{V^2}{2}+gz\right)_i^{0} - \sum_{out}\dot{m}_e\left(h+\frac{V^2}{2}+gz\right)_e^{0\;\text{Closed system}}$$

$$\dot{W}_{electric,in} = \dot{W}_{shaft,out} - \dot{Q}_{in}$$

Writing the rate-form of the entropy accounting equation gives

$$\frac{d}{dt}S_{sys}^{\,0\;\text{Steady-state}} = \frac{\dot{Q}_{in}}{T_{surface}} + \sum_{in}\dot{m}_i s_i - \sum_{out}\dot{m}_e s_e^{\,0\;\text{Closed system}} + \dot{S}_{gen} \qquad \text{with } \dot{S}_{gen} \geq 0$$

$$\dot{Q}_{in} = -T_{surface}\dot{S}_{gen}$$

Now combining the energy equation and the entropy equation by eliminating the heat transfer rate gives

$$\dot{W}_{\text{electric,in}} = \dot{W}_{\text{shaft,out}} - \dot{Q}_{\text{in}} = \dot{W}_{\text{shaft,out}} - \left(-T_{\text{surface}}\,\dot{S}_{\text{gen}}\right) = \dot{W}_{\text{shaft,out}} + \left(T_{\text{surface}}\,\dot{S}_{\text{gen}}\right)$$

Recall that the entropy production rate $\dot{S}_{\text{gen}}$ is always greater than or equal to zero. (It can only reach zero in the limiting case of an internally reversible process.) Thus $\dot{W}_{\text{electric,in}} \geq \dot{W}_{\text{shaft,out}}$.

The minimum electric power input can be calculated as below:

$$\dot{W}_{\text{electric, in}}\Big|_{\text{minimum}} = \dot{W}_{\text{shaft,out}} = \left(25\text{ hp}\right)\left(\frac{0.74571\text{ kW}}{1\text{ hp}}\right) = 18.6\text{ kW}$$

Notice that this analysis clearly indicates two important results. First, any losses (entropy generation) within the motor or gear reducer increases the electric power required for a fixed output power. Second, it would be impossible to transfer energy into the system by heat transfer and reduce the electric power requirements since this would require a negative entropy production which is impossible.

Experience with this Approach

The systems, conservation and accounting, and modeling paradigm described here can be used in at least two different ways to improve the curriculum. First, it can be used as an integrating feature within a traditional sequence of engineering courses. Ideally, this would occur with the development of a set of textbooks similar to the Series in Thermal and Transport Sciences published by John Wiley in the later 1960's. As originally planned, four University of Michigan professors—R. E. Sonntag, G. J. Van Wylen, A. G. Hansen, and J. A. Clark—were to write a series of textbooks that provided an integrated presentation of thermodynamics, fluid mechanics, and heat and mass transfer[10]. The systems, conservation and accounting, and modeling paradigm, however, provides an even broader framework for making connections with apparently disparate parts of the curriculum.

Second, it can be used as an organizing principle or framework for a *new* engineering science core. This is the approach used at Texas A&M and at Rose-Hulman as described earlier in this paper. At Texas A&M the new curriculum consists of five courses that are taken by some or all of the engineering curricula. At Rose-Hulman the Sophomore Engineering Curriculum (SEC) is a sequence of eight engineering and mathematics courses required of all electrical and computer engineers since 1995 and of all mechanical engineers since 1998. It is the author's belief that the most significant curricular improvements can only be achieved by the latter approach. At Rose-Hulman, the new SEC resulted in a reduction in engineering science credit hours from 20 to 18 quarter credit hours and moved a required system dynamics course up three quarters (one year) in the ME curriculum with no significant loss of content.

The development of the SEC at Rose-Hulman was guided by four underlying beliefs:

- There exists a *common core* of engineering science and mathematics that *all* engineers should learn.
- This core should serve as a foundation for discipline specific education not just an add-on.
- Integration of course material within a quarter (horizontal integration) and between quarters (vertical integration) is important.
- Student learning can be improved if the core is built around a few key concepts.

The systems, conservation and accounting, and modeling paradigm described in this paper helped us build a curriculum that was consistent with these beliefs.

The author believes that this paradigm has the following advantages for both students and faculty:
- it provides a conceptual framework which supports all engineering science courses.
- it provides a unified format for presenting and understanding the basic laws taught in physics and chemistry that is uniquely suited for engineering applications.
- it enables a common, consistent problem solving approach for all courses.
- it helps students (and faculty) see connections between what are often perceived as apparently unrelated topics by reinforcing the similarities underlying the basic principles,

The common problem solving approach emphasizes developing a problem-specific solution from the fundamentals for each new problem and is an antidote to "plug-and-chug" solution techniques. Before a student can solve a problem, they must first decide what basic principles apply—what should they count, not what equation applies here? Next they must identify a system. This is extremely important because the basic laws in the conservation and accounting format are framed in terms of accumulation within a system and transport across a system boundary. Using the equations in this format requires explicit knowledge of what your system contains and where the boundary is located. Once the system and the governing principles are identified, the student must simplify the governing equations. This is done using problem-specific modeling assumptions and constraints. This approach requires the student to construct the solution from the problem information and to explicitly state their reasoning. Whereas the "plug-and-chug" approach focuses on what equation should I use, this approach stresses the underlying physical principles *and* the common modeling assumptions. Since modeling assumptions and constraints are common to several subjects, e.g. steady-state or closed system, this again reinforces the similarities between different topics. Finally the student is faced with collecting additional information to relate the unknown variables. This typically takes the form of constitutive relations, e.g. the ideal gas model or Coulomb friction model, that provide the additional equations required to solve for the unknowns.

In general, the response of faculty and students to the new curriculum has been very positive. Students at Rose-Hulman have been surveyed at the end of their sophomore and senior year to assess their feelings about the SEC. Most students comment favorably on their experience in the SEC. Both in their answers to questions and volunteered comments, the students recognize and appreciate the integration within the curriculum, e.g. "how things flowed" and "how things fit to-

gether" as a couple of students put it. Most believe that the explicit attempts to demonstrate the links and similarities between the various courses are beneficial and see the problem solving approach helping in the courses. Student opinion significantly improves by the end of the sophomore year as they complete the entire sequence ending up with a system-dynamics-like course that brings all of the topics back together.

Faculty members often comment that students appear to move farther through the topics in the curriculum, e.g. as opposed to the standard coverage in dynamics. The reorganized curriculum has some advantages in that the student spirals through the material as it is repeatedly reintroduced at higher levels continually building on the common framework. In addition faculty members also indicate that using the framework has helped them learn to explain and solve problems outside their stated areas of expertise. This has been the author's experience as he has learned to handle dynamics problems, and it has been repeated by colleagues in mechanics who can apply the entropy and energy balance with confidence to explain a "

One of the biggest problems for both faculty and students is the lack of textbooks that follow this approach. At both Rose-Hulman and Texas A&M work is continuing on course notes and textbooks to remedy this situation[11,12]. Currently both programs use a combination of locally produced notes and standard textbooks. It is possible to use standard textbooks; however, anyone who has carefully compared, say a fluids, thermodynamics, and a dynamics textbook quickly recognizes that there are significant differences in notation and conventions. "Is lb a pound-force or a pound-mass?", "Are pressures reported as gage or absolute?", and a host of other hidden assumptions are typically embedded within our textbooks. These become glaring inconsistencies when you begin to teach across the disciplines, and you begin to understand the source of our students' frustration as they move on to each new subject.

P. Cornwell, a professor at Rose-Hulman, has done the most detailed study of the impact of this approach in the SEC at Rose-Hulman, especially as it relates to the teaching of dynamics. Having taught both traditional dynamics and the new sequence of courses he was in an excellent position to evaluate the change.[13] He made a quantitative assessment comparing student performance in the traditional and the "new" dynamics course. After comparing the scores of students on identical short answer and work out problems, he found that all three majors—electrical, computer, and mechanical engineers—did better in the new curriculum, especially on the longer work out problems. On the three work out problems, between 20-40% more of the SEC students worked the problems correctly than did students in the traditional dynamics course. In fact after reviewing all of the innovations he has tried in his courses, he found that restructuring the engineering science curriculum using the systems, conservation and accounting, and modeling paradigm is the single change that has most significantly improved student learning.[14]

Conclusion

The systems, conservation and accounting, and modeling paradigm is an exciting new approach to integrating and organizing the material in an engineering curriculum. This approach should be especially applicable to a discipline with the breadth of mechanical engineering. Two different institutions, Texas A&M and Rose-Hulman, have used it as the basis for new curricula. It can be used to radically change the structure of the curriculum or it can be used as a way to sew together existing courses in the curriculum. Both anecdotal and quantitative assessment of this approach indicates that it has helped students see the underlying structure of engineering science and in turn improved their ability to solve problems. Faculty considering ways to improve student learning are encouraged to consider how this approach could be incorporated into courses and curricula. As we search for ways to help students better understand material and how to apply it in solving problems, the systems, conservation and accounting, and modeling paradigm seems to offer significant promise.

Acknowledgements

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