Share the Future IV Conference

March 16-18, 2003 – Tempe, AZ

A Unified Approach to Engineering Science Education

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Rose-Hulman Institute of Technology

Foundation Coalition

Foundation Coalition

An NSF Engineering Coalition since 1993

"Creating an enduring foundation for student development and life-long learning" by rebuilding engineering curricula from the foundation up."

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Outline for Today

- Engineering Science and the Motivation for Change
- Framework for a Unified Approach
- One Implementation -- the Rose-Hulman Sophomore Engineering Curriculum

Group Activity 1

Answer the following questions:

(a) Is there an engineering science and mathematics core curriculum that should be common for all engineering students?

(b) Assuming that such a core is desirable, what courses or topics would you place in the core?

Engineering Science & Engineering Education

- Pre-1950's
- Grinter Report(1952-1955)

  "Report on the Committee on Evaluation of Engineering Education," *J. of Engr. Educ.* 46 (Sept 1955) 1955, pp. 25-60
- Post Grinter Report
- Today

Courses	Recommendations of Grinter Report						Today
	Solids	Fluids	Thermo	Transfer Processes	Electrical	Materials	????
Statics	X						
Mechanics of Materials	X					X	
Dynamics	X						
Fluid Mechanics		X	X	X			
Thermodynamics		X	X				
Heat Transfer			X	X			
Mass Transfer				X			
Circuit Theory					X		
Materials						X	
?????							

Motivation for Change

Improve --

- **student learning** by responding to latest research on teaching and learning, and
- **curricular efficiency and effectiveness** to meet demands for “new” material while maintaining or reducing credit hours.

Research on Teaching & Learning

- ***How People Learn: Brain, Mind, Experience, and School.* (HPL)**

  J. D. Bransford et al. editors, National Academy Press, Washington DC, 2001, expanded edition. Available online at http://www.nap.edu.

- ***Teaching Introductory Physics.* (TIP)**

  A. B. Arons, John Wiley & Sons, New York, 1997.

- ***Cooperative Group Problem Solving in Physics.* (CGPiP)**

  P. Heller and K. Heller, University of Minnesota, 1999. Available for download at http://www.physics.umn.edu/groups/physed.

How People Learn - Bransford**

- Nature of expertise
  - experts' knowledge is hierarchically organized around major principles and concepts.
  - experts "construct" solutions from major principles.
  - experts monitor their activities to assess their success.
- Current view of learning
  - individuals construct the knowledge they possess.
  - prior knowledge affects students' ability to learn new knowledge.

How People Learn - Bransford**

- Learning and transfer
  – all learning involves transfer from previous learning.
  – amount and context of learning affects transfer.
  – abstract representations of knowledge combined with understanding can promote transfer.

**Summarized in J. P. Mestre, “Implications of research on learning for the education of prospective science and physics teachers,” *Physics Education*, Vol. 36, No. 1 (Jan 2001), pp. 44-51.

Implications of HPL

- Help students organize their knowledge around important ideas and concepts.
- Provide opportunities for students to “learn how to see” a problem like an expert.
- Stress “Why and When?” as well as “What” and “How?”

Implications of HPL

- Help students integrate their new knowledge with existing knowledge. (constructivism)
- Provide multiple contexts for learning and explicitly address transfer of knowledge.
- Help students learn to monitor their learning and problem solving (metacognition).

Lessons from TIP - Arons

- Teaching for *understanding* not just memorization.
  - **Importance of language** and **operational definitions**.
  - **Spiralling back** - allow students to review or re-encounter important ideas and lines of reasoning in increasingly rich or sophisticated context.
  - Understand and address **common misconceptions**
  - **Help students see their reasoning**, both flawed and correct, and incorporate new knowledge into this structure.
  - **Test and reward understanding** not just memorization.
- Promote Critical Thinking.

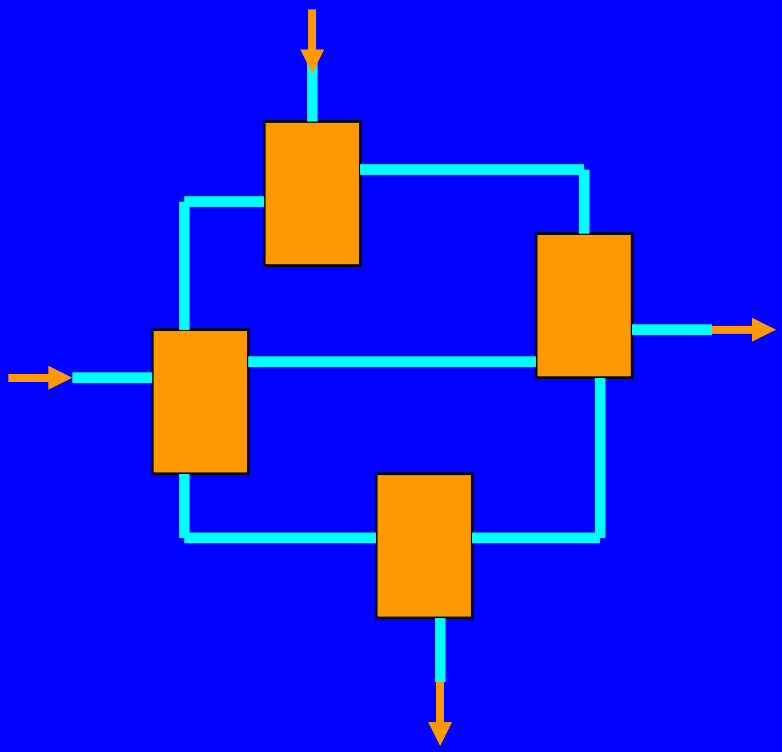
  Arons provides an excellent list of critical thinking processes.

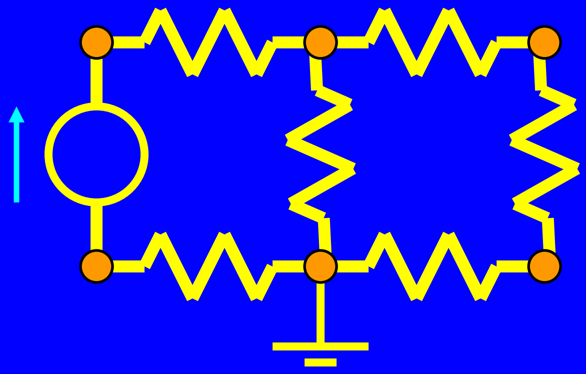
CGPiP - Heller & Heller

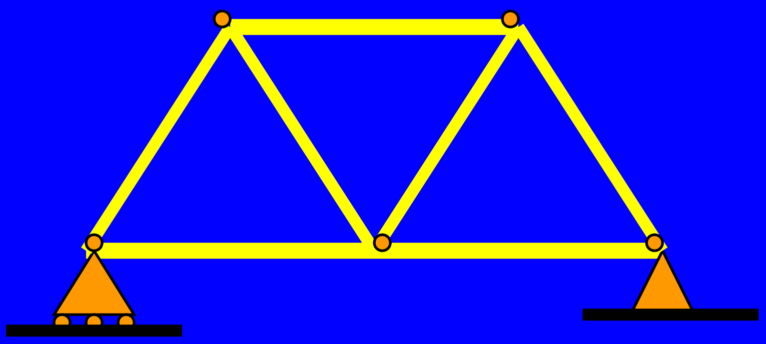
- Modeling-coaching-fading paradigm
- Modeling “culture of expert practice”
  - Conceptual framework or **“story line” ties things together**
  - **Problem-solving methodology** used explicitly by faculty and students.
  - **Explicit decision-making by faculty** solving problems.
  - **Context-rich word problems** that require construction of a solution not just “plug-and-chug” solution.
  - **Grade solution strategy** not just answer.
- Coaching and Scaffolding
  - **Cooperative group problem solving**.

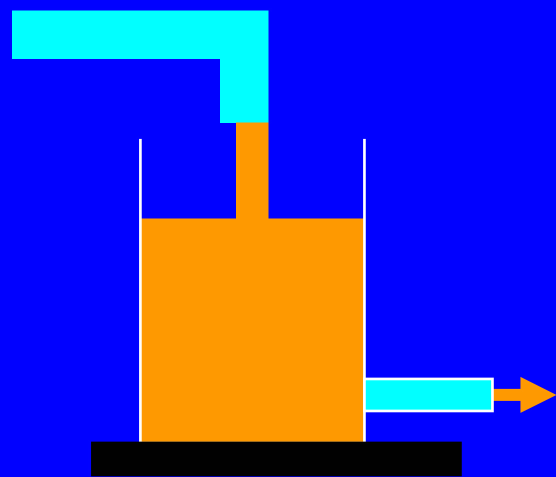
Group Activity 2

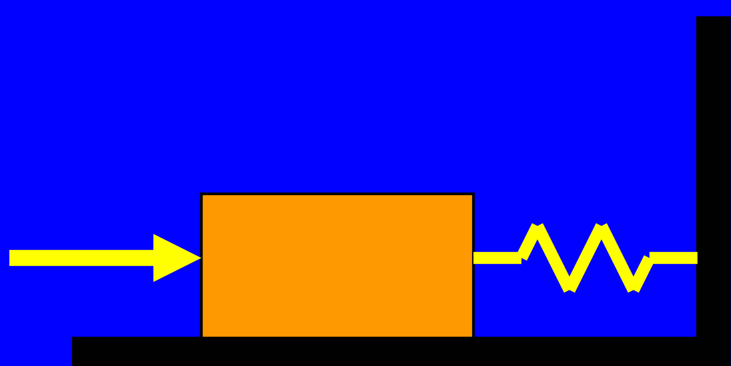
- What, if any, are the *common* concepts or topics that run through an engineering science core?

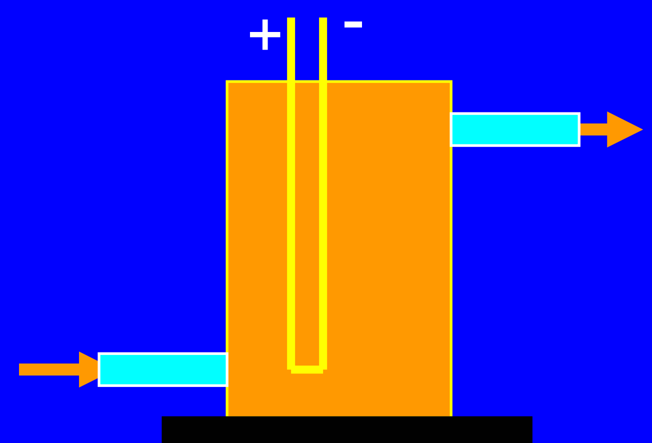












Systems, Accounting, and Modeling Framework

Framework

The **systems, accounting and modeling framework** provides

- A conceptual framework for engineering analysis.
- A unified format for presenting and interpreting the basic laws that is uniquely suited for engineering applications.
- A common,consistent problem-solving approach based on constructing problem-specific solutions from the underlying physical laws.

Engineering Science Core*

Heat Transfer

System Dynamics

Fluid Mechanics

Materials

Thermodynamics

Electrical Circuits

Mechanics of Materials

Dynamics

Differential Equations

Statics

Statistics

Linear Algebra

Chemistry Physics Calculus

* One possible core

What are the topics and concepts in the core?

Mass
Electric Charge
Linear Momentum
Angular Momentum
Mechanical Energy
Energy
Entropy

Electric Current
Torque
Force
Work
Heat Transfer
Mass Flow

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

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

F=ma
KCL
Energy Equation
Bernoulli's Eqn

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

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Equilibrium
Steady state
Rigid Boundary
Pinned Joint
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Insulated Boundary
Lumped Element

What's the method?

System

Node

Free-Body Diagram

Closed System

Open System

Control Mass

Control Volume

Extensive Property

Mass

Electric Charge

Linear Momentum

Angular Momentum

Mechanical Energy

Energy

Entropy

Interactions

Electric Current

Torque

Force

Work

Heat Transfer

Mass Flow

Constitutive Relations

Ohm's Law

Ideal Spring

Dry Friction

Ideal Gas Law

Steam Tables

Friction Factor

Newtonian Fluid

Viscous Drag

Accounting Principle

F=ma

KCL

Energy Equation

Bernoulli's Eqn

Modeling Assumptions

Equilibrium

Steady state

Rigid Boundary

Pinned Joint

Linear Translation

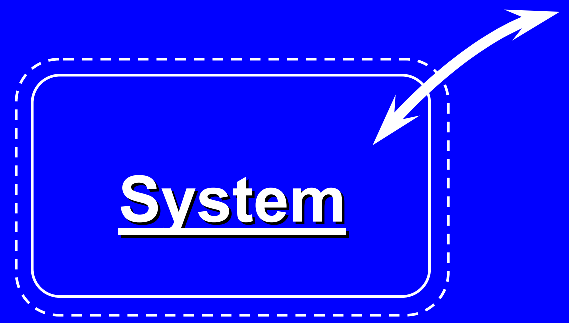
Rigid Body

Insulated Boundary

Lumped Element

Extensive Property

Interactions



Constitutive Relations

Modeling Assumptions

Accounting Principle

Accounting Equation for Extensive Property B

$$\frac{dB_{sys}}{dt} = \left[\dot{B}_{in} - \dot{B}_{out}\right] + \left[\dot{B}_{gen} - \dot{B}_{cons}\right]$$

Rate of Accumulation of B inside the system at time t

Net Transport Rate of B into the system at time t.

Net Generation Rate of B inside the system at time t

Concepts & Definitions

- Model
- System
  - Open system
  - Closed system
- Property
  - Intensive property
  - Extensive property
- State of a system
- Process
  - Steady state
  - Finite time
  - Transient
- Interaction
- Accounting Principle
- Conserved Property
- Constitutive Relation

Group Activity 3

- Individually match the Word with its Definition.
- When completed compare your answer with your team members.

Accounting Equation for Extensive Property B

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

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

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

Framework for Presenting and Interpreting Physical Laws

- What's the extensive property?
- How can it be counted?
- How can it be stored in the system?
- How can it be transported?
- How can it be generated or consumed?

Rate of Storage = **Net Transport Rate In** + **Net Generation Rate**

Fundamental Physical Laws

Extensive Property	Physical Law
Mass	Conservation of Mass
Charge	Conservation of Charge
Momentum	Conservation of Momentum
Energy	Conservation of Energy
Entropy	Entropy Production & Accounting

Group Activity 4

- Match the extensive property

An Example

Conservation of Linear Momentum

Conservation of Linear Momentum

What is linear momentum?

The linear momentum of a particle is the product of the particle mass m and its velocity **V**:

$$\mathbf{P} \equiv m\mathbf{V}$$

Conservation of Linear Momentum

How can it be stored in and quantified for a system?

$$\mathbf{P}_{sys} = \int_{V_{sys}} \mathbf{V} \rho \, dV$$

$$\mathbf{P}_{sys} = \sum \mathbf{P}_j = \sum m_j \mathbf{V}_j$$

Conservation of Linear Momentum

How can it be transported across the system boundaries?

- External Forces
  - Contact Forces
  - Body Forces
- Mass Transport

$$\mathbf{F}_{external}$$

$$\dot{m}\mathbf{V}$$

Conservation of Linear Momentum

How can linear momentum be generated or consumed within the system?

Experience has shown that it is impossible to create or destroy linear momentum; hence, we say that ***linear momentum is conserved***.

$$\dot{\mathbf{P}}_{gen} = \dot{\mathbf{P}}_{cons} = 0$$

Conservation of Linear Momentum

$$\frac{dB_{sys}}{dt} = \underbrace{\left[\dot{B}_{in} - \dot{B}_{out}\right]}_{\text{Non-flow boundary}} + \underbrace{\left[\sum_{in} \dot{m}_i b_i - \sum_{out} \dot{m}_e b_e\right]}_{\text{Flow boundary}} + \left[\dot{B}_{gen} - \dot{B}_{cons}\right]$$

$$\frac{d\mathbf{P}_{sys}}{dt} = \underbrace{\left[\dot{\mathbf{P}}_{in} - \dot{\mathbf{P}}_{out}\right]}_{\text{Non-flow boundary}} + \underbrace{\left[\sum_{in} \dot{m}_i \mathbf{V}_i - \sum_{out} \dot{m}_e \mathbf{V}_e\right]}_{\text{Flow boundary}} + \left[\dot{\mathbf{P}}_{gen} - \dot{\mathbf{P}}_{cons}\right]$$

0

$$\sum \mathbf{F}_{external}$$

Conservation of Linear Momentum

$$\frac{d\mathbf{P}_{sys}}{dt} = \sum \mathbf{F}_{ext} + \left[\sum_{in} \dot{m}_i \mathbf{V}_i - \sum_{out} \dot{m}_e \mathbf{V}_e \right]$$

Rate of accumulation of linear momentum ***inside* the system** at time *t*.	=	**Net transport rate** of linear momentum ***into* the system** by **external forces** at time *t*.	+	**Net transport rate** of linear momentum ***into* the system** by **mass flow** at time *t*.

Recovering F = ma

$$\frac{d\mathbf{P}_{sys}}{dt} = \sum \mathbf{F}_{ext} + \left[\sum_{in} \dot{m}_i \mathbf{V}_i - \sum_{out} \dot{m}_e \mathbf{V}_e \right]$$

Closed System

$$\mathbf{P}_{sys} = m_G \mathbf{V}_G$$

$$\dot{m} = 0$$

$$\left.\begin{aligned} \frac{d}{dt}\left(m_G \mathbf{V}_G\right) &= m_G \frac{d}{dt}\left(\mathbf{V}_G\right) = m_G \mathbf{a}_G \\ \sum \mathbf{F}_{ext} &= \mathbf{F}_{net} \end{aligned}\right\} \rightarrow \boxed{\mathbf{F}_{net} = m_G \mathbf{a}_G}$$

Rate Form of Basic Laws

$$\frac{dm_{sys}}{dt} = \sum_{in} \dot{m}_i - \sum_{out} \dot{m}_e$$

$$\frac{dq_{sys}}{dt} = \sum_{in} \dot{q}_i - \sum_{out} \dot{q}_e$$

$$\frac{d\mathbf{P}_{sys}}{dt} = \sum_{j} \mathbf{F}_{ext,j} + \left[\sum_{in} \dot{m}_i \mathbf{V}_i - \sum_{out} \dot{m}_e \mathbf{V}_e \right]$$

$$\frac{d\mathbf{L}_{o,sys}}{dt} = \sum_{j} \mathbf{M}_{o,j} + \left[\sum_{in} \dot{m}_i \left(\mathbf{r}_i \times \mathbf{V}_i \right) - \sum_{out} \dot{m}_e \left(\mathbf{r}_e \times \mathbf{V}_e \right) \right]$$

$$\frac{dE_{sys}}{dt} = \dot{Q}_{net,in} + \dot{W}_{net,in} + \left[\sum_{in} \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_{out} \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) \right]$$

$$\frac{dS_{sys}}{dt} = \sum_{j} \frac{\dot{Q}_j}{T_j} + \left[\sum_{in} \dot{m}_i s_i - \sum_{out} \dot{m}_e s_e \right] + \dot{S}_{gen}$$

Rate Form of Basic Laws

$$\frac{dm_{sys}}{dt} = \sum_{in} \dot{m}_i - \sum_{out} \dot{m}_e$$

$$\frac{dq_{sys}}{dt} = \sum_{in} \dot{q}_i - \sum_{out} \dot{q}_e$$

$$\frac{d\mathbf{P}_{sys}}{dt} = \sum_j \mathbf{F}_{ext,j} + \left[\sum_{in} \dot{m}_i \mathbf{V}_i - \sum_{out} \dot{m}_e \mathbf{V}_e\right]$$

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A common, consistent problem solving approach.

Common Problem Solving Format

- Known
- Find
- Given
- Analysis
  - Strategy
  - Constructing model
  - Solution
- Comments

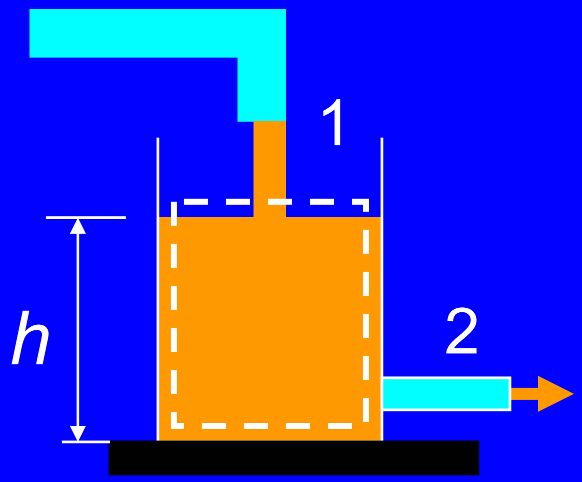
→

Typical Questions

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

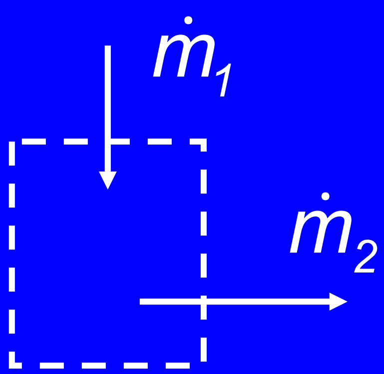
A couple of examples

Find $h(t)$.

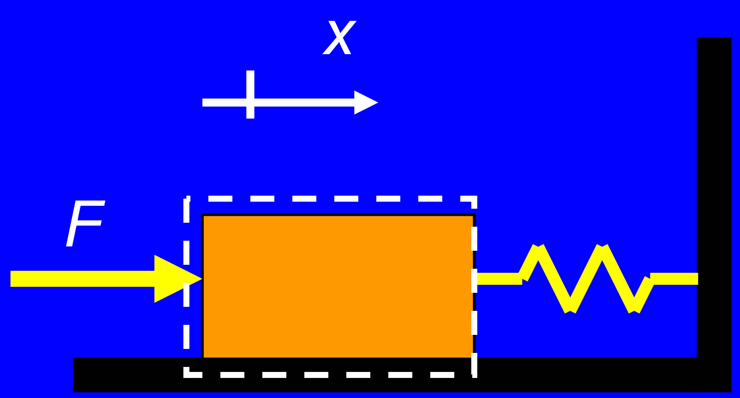


Extensive Property?

System?

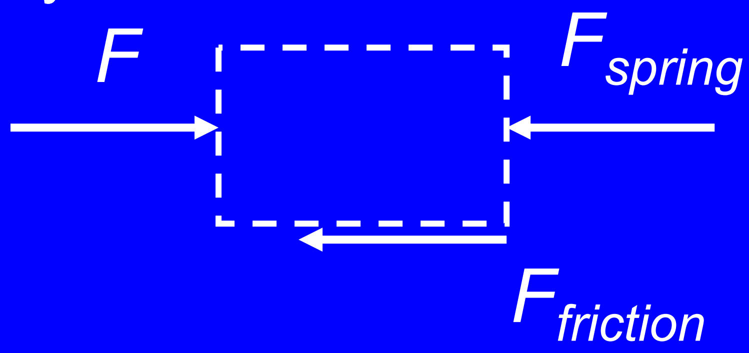


Find $V_x(t)$.

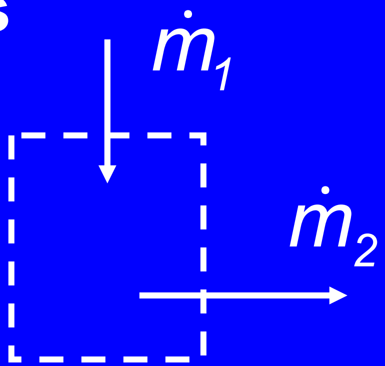


Extensive Property?

System?



Mass

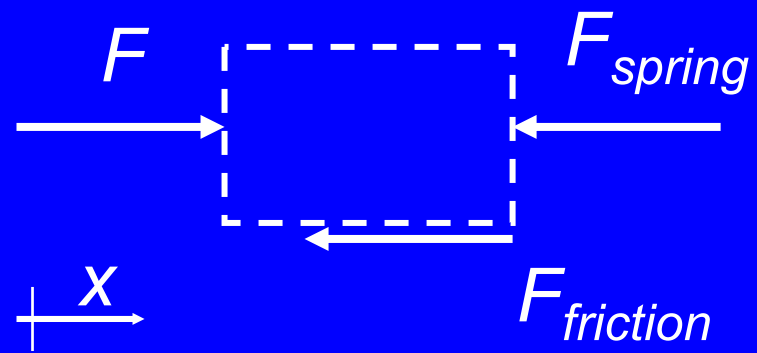


$$\frac{dm_{sys}}{dt} = \dot{m}_1 - \dot{m}_2$$

$$\frac{d}{dt}\left(\rho A_{tank} h\right) = \dot{m}_1 - C\sqrt{gh}$$

$$\frac{dh}{dt} = \frac{\dot{m}_1}{\rho A_{tank}} - \frac{C\sqrt{gh}}{\rho A_{tank}}$$

Linear Momentum



$$\frac{dP_{x,sys}}{dt} = F - F_{friction} - F_{spring}$$

$$\frac{d}{dt}\left(mV_x\right) = F - \mu_k mg - kx$$

$$\frac{dV_x}{dt} = \frac{F}{m} - \mu_k g - \frac{kx}{m}$$

Advantages of this Approach

- Provides a conceptual framework for the engineering science core.
- Provides a unified format for presenting and understanding the basic laws that is uniquely suited for engineering applications.
- Enables the use of a common, consistent problem solving approach.
- Helps students (and faculty) see links between apparently unrelated topics by reinforcing the underlying similarities.

How could you use this?

- As the basis for modifying an existing course.
- As the basis for a new course
  - ME 10 - Introduction to Engineering Analysis (Stanford)
  - BioE 252 - Conservation Principles in Biology & Medicine (Rice)
- As the basis for a new curriculum
  - Sophomore Engineering Science Sequence (TAMU)
  - Sophomore Engineering Curriculum (Rose-Hulman)

Where did this approach come from?

- 1987 - Unified Engineering Science Curriculum Project
  - NSF-funded project at Texas A&M
  - Developed a four-course sequence of sophomore engineering courses (the "20X sequence"):
    - Conservation Principles in Engineering
    - Properties of Matter
    - Modeling/Behavior of Engineering Systems
    - Conservation Principles of Continuous Media
  - http://www-chen.tamu.edu/uesc/

Where did this approach come from?

- L. Prandtl’s fluid mechanics work in the early 1900’s.
  - What Engineers Know and How They Know It *Walter G. Vincenti, Johns Hopkins Press, 1990*.
- Discipline of System Dynamics
- References from physics
  - H. Burkhardt, “System physics: A uniform approach to the branches of classical physics.” Am. J. Phys. 55, 344-350, 1987.
  - Chapter 1 in H. Fuchs, The Dynamics of Heat. Springer-Verlag, 1996.

What Engineers Know and How They Know It

Walter G. Vincenti, Johns Hopkins Press, 1990.

- "Organization according to control-volume ideas is thus not only simpler but brings clearer under-standing of the physical principles common to otherwise disparate situations."
- "Control-volume analysis is useful precisely because it provides a framework and method for thinking clearly about a large class of the often confusing problems that arise in engineering design."

From Chpt 4, "A Theoretical Tool for Design: Control-Volume Analysis, 1912-1953"

Textbooks

- C. J. Glover, K. M. Lunsford, J. A. Fleming, *Conservation Principles and the Structure of Engineering,* 5th ed, McGraw-Hill, New York, 1996.
- D. E. Richards**, *Basic Engineering Science - A Systems, Accounting and Modeling Approach*, Rose-Hulman Institute of Technology, 2001.
- W. C. Reynolds**, *Introduction to Engineering Analysis*, Stanford University, Spring 2000.
- L. V. McIntire, A. Saterbak, and K-Y San, *Conservation Principles in Biology and Medicine,* underdevelopment for Prentice-Hall, Rice University.

**Available from the authors.

Rose-Hulman / Foundation-Coalition Sophomore Engineering Curricula

What is the Rose-Hulman Sophomore Engineering Curriculum?

- An eight-course sequence that integrates core material in engineering science and mathematics.
  - Designed for all engineering majors.
  - Developed by a multi-disciplinary team of faculty and students over two years.
  - Taught since 1995-1996.
  - Required for electrical, computer, and mechanical engineering students.

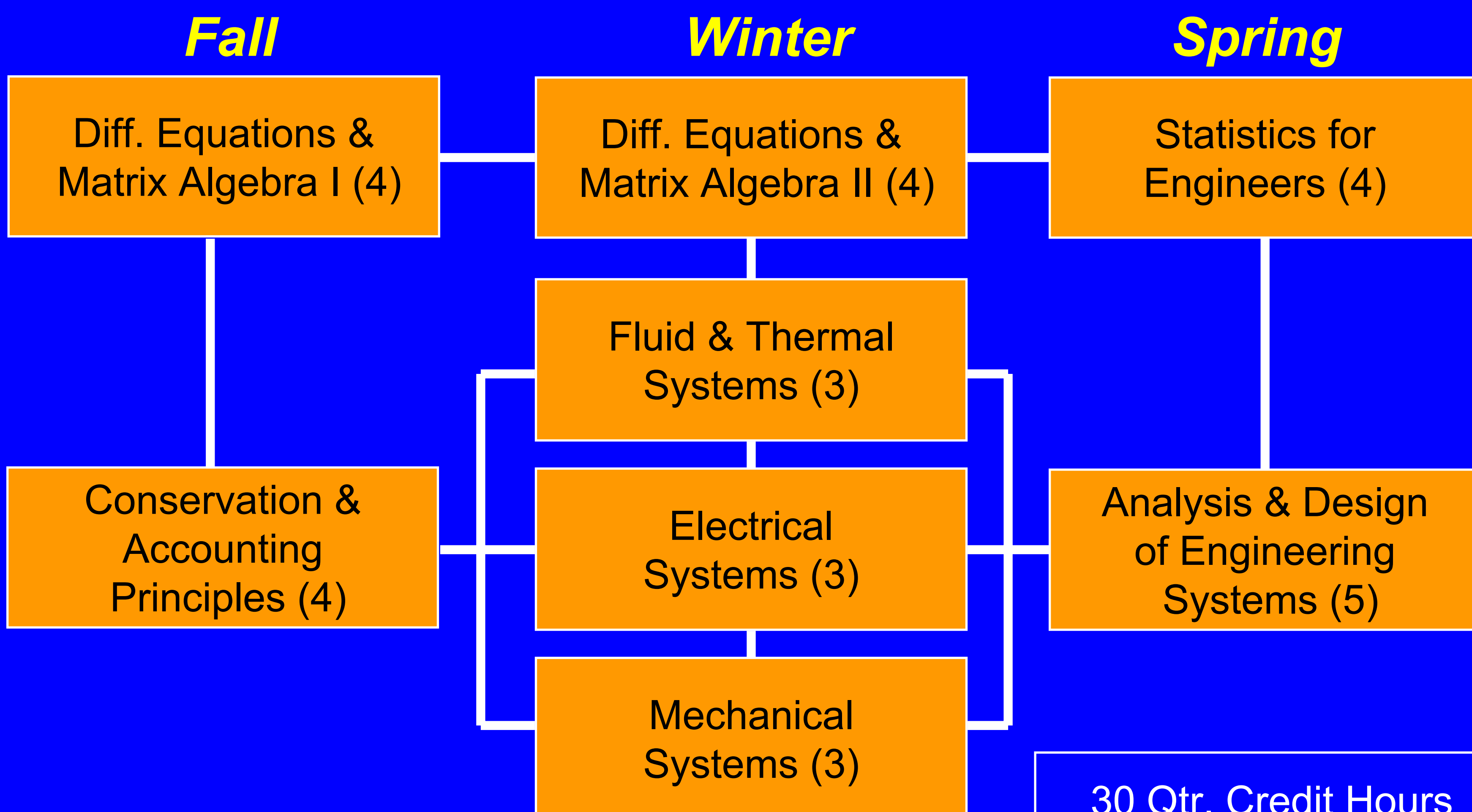
What's in our Core?

Diff. Equations I	**Dynamics**
Fluid Mechanics	**Circuits**
Thermodynamics	**Diff. Equations II**
Statistics	**System Dynamics**

Matrix Algebra

32 Qtr. Credit Hours

Sophomore Engineering Curriculum



30 Qtr. Credit Hours

Sophomore Engineering Curriculum
Advantages for Students

- Participate in a coordinated curriculum that consciously stresses the links between engineering science and mathematics.
- Provide a common foundation of engineering science and mathematics knowledge for future learning.
- Learn to apply a common framework for problem solving based upon an understanding of the conservation and accounting principles.
- Learn to handle open-ended problems.
- Work with multi-discipline problems.
- Learn cooperatively and work in teams.
- Use computer technology across the curriculum.

Sophomore Engineering Curriculum
A Brief History

Fall 1993

- Foundation Coalition funded by NSF.

1993-1994

- Institute considered various ideas for Sophomore Curriculum (Friday afternoon meetings)

Summer 1994

- Workshops on teaming, active learning, curriculum design. (Approximately 4 days total)
- Multidisciplinary faculty team developed overall framework for SEC. (12 faculty)

Sophomore Engineering Curriculum
A Brief History

1994-1995

- Met with departments and finalized proposal.
- Proposal for pilot approved by Institute.
- Required by electrical and computer engineering department.

Summer 1995

- Team of 12 faculty and 3 students developed detailed curriculum material for eight courses.

Sophomore Engineering Curriculum
A Brief History

1995-1996

- Offered RH/FC SEC for first time to 90 students
- Rose-Hulman required students to purchase a laptop computer.

1996-1997

- Adopted by mechanical engineering department for Fall 1998.

2002-2003

- Currently taken by 220-240 mechanical, electrical, and computer engineering students.

Sophomore Engineering Curriculum
Curriculum Structure

FALL Quarter . . . . 8 Credit Hours

- MA 221 - Differential Equations & Matrix Algebra I (4)
- ES 201 - Conservation & Accounting Principles (4)

WINTER Quarter . . . . 13 Credit Hours

- MA 222 - Differential Equations & Matrix Algebra II (4)
- ES 202 - Fluid & Thermal Systems (3)
- ES 203 - Electrical Systems (3)
- ES 204 - Mechanical Systems (3)

SPRING Quarter. . . . . 9 Credit Hours

- MA 223 - Engineering Statistics (4)
- ES 205 - Analysis & Design of Engineering Systems (5)

TOTAL CREDITS . . . . 30 Credit Hours

Experience with SEC at RH

- Reduced engineering credit hours from 20 to 18 without sacrificing material.
- Faculty like
  - common problem solving approach that does not reinforce “plug and chug.”
  - emphasis on modeling assumptions and mathematics that apply across disciplines.
  - ability to restructure material and “spiral” back, e.g. dynamics in two courses.

Experience with SEC at RH

- Students comment favorably on “integration” and “big picture” view of curriculum.
- Quantitative comparisons
  - SEC students did better than traditional students on final exam “workout” problems in dynamics, e.g. 20-40% more SEC students got problems right.

Student Comments after Completing the SEC

<u>Student A</u>

"ES201 was an excellent foundation to start on. A solid handle on this class is a must for success in the following classes. All classes were connected to this class."

Student Comments

<u>Student B</u>

"The sophomore curriculum has won me over. At first, I thought it was a complete waste of time. Then during winter quarter I saw the importance of it. Now, I am glad to have gone through it. The book didn't help much, it was vague and made the class more difficult."

Student Comments

<u>Student C</u>

"I was very pessimistic about the course (ES205) at the beginning of the quarter. This course defeated every pessimistic premise I had before it was completed. This course brought all the engineering disciplines together and, at the very least, <u>made this skeptical EE a believer in the SEC.</u> Not only was the course an eye-opener, but it also enhanced my ability to solve general complex-system problems regardless of what discipline they came from?

Student Comments

Student D

"Perhaps one of my other gripes with the class is that it is *so* different from freshman physics. I actually prefer this method of teaching when it comes to frictions, tensions, angular momentum, etc. These are all topics with which I felt uncomfortable during freshman physics although I understand them better now. In the future, I would appreciate seeing the ConApps and Physics curriculums more closely integrated so that students only have to learn concepts once.

Thank You!

For additional information about the RH Sophomore Engineering Curricula *or* the Systems, Accounting, and Modeling Approach contact ---

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