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.”

www.foundationcoalition.org
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)
• Post Grinter Report
• Today
<table>
<thead>
<tr>
<th>Courses</th>
<th>Recommendations of Grinter Report</th>
<th>Today</th>
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<tbody>
<tr>
<td></td>
<td>Solids</td>
<td>Fluids</td>
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<tr>
<td>Statics</td>
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<td>Mechanics of Materials</td>
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<td>Dynamics</td>
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<td>Fluid Mechanics</td>
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<td>Thermodynamics</td>
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<td>Heat Transfer</td>
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<td>Mass Transfer</td>
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<td>Circuit Theory</td>
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<td>Materials</td>
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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)

• *Teaching Introductory Physics.* (TIP)

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

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

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

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

F=ma
KCL
Energy Equation
Bernoulli’s Eqn

Electric Current
Torque
Force
Work
Heat Transfer
Mass Flow

Equilibrium
Steady state
Rigid Boundary
Pinned Joint
Linear Translation
Rigid Body
Insulated Boundary
Lumped Element
What are the topics and concepts in the core?

- Mass
- Electric Charge
- Linear Momentum
- Angular Momentum
- Mechanical Energy
- Energy
- Entropy
- 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
- Node
- Free-Body Diagram
- Closed System
- Open System
- Control Mass
- Control Volume
- Equilibrium
- Steady state
- Rigid Boundary
- Pinned Joint
- Linear Translation
- Rigid Body
- Insulated Boundary
- Lumped Element
- Electric Current
- Torque
- Force
- Work
- Heat Transfer
- Mass Flow
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

\[
\frac{d}{dt} B_{sys} = \left[ \dot{B}_{in} - \dot{B}_{out} \right] + \left[ \dot{B}_{generated} - \dot{B}_{consumed} \right]
\]

net rate transported across the boundary into the system

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

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

\[
\text{Rate of Storage} = \text{Net Transport Rate In} + \text{Net Generation Rate}
\]
Fundamental Physical Laws

<table>
<thead>
<tr>
<th>Extensive Property</th>
<th>Physical Law</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>Conservation of Mass</td>
</tr>
<tr>
<td>Charge</td>
<td>Conservation of Charge</td>
</tr>
<tr>
<td>Momentum</td>
<td>Conservation of Momentum</td>
</tr>
<tr>
<td>Energy</td>
<td>Conservation of Energy</td>
</tr>
<tr>
<td>Entropy</td>
<td>Entropy Production &amp; Accounting</td>
</tr>
</tbody>
</table>
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 $V$:

$$P = mV$$
Conservation of Linear Momentum

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

\[
P_{\text{sys}} = \int_{V_{\text{sys}}} V \rho \, dV
\]

\[
P_{\text{sys}} = \sum P_j = \sum m_j V_j
\]
Conservation of Linear Momentum

How can it be transported across the system boundaries?

– External Forces
  • Contact Forces
  • Body Forces
– Mass Transport

\[ F_{\text{external}} \]
\[ \dot{m}V \]
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.

\[ \dot{P}_{\text{gen}} = \dot{P}_{\text{cons}} = 0 \]
Conservation of Linear Momentum

\[ \frac{dB_{\text{sys}}}{dt} = \left( \dot{B}_{\text{in}} - \dot{B}_{\text{out}} \right) + \left( \sum_{\text{in}} \dot{m}_i b_i - \sum_{\text{out}} \dot{m}_e b_e \right) + \left( \dot{B}_{\text{gen}} - \dot{B}_{\text{cons}} \right) \]

Non-flow boundary
Flow boundary

\[ \frac{dP_{\text{sys}}}{dt} = \left( \dot{P}_{\text{in}} - \dot{P}_{\text{out}} \right) + \left( \sum_{\text{in}} \dot{m}_i V_i - \sum_{\text{out}} \dot{m}_e V_e \right) + \left( \dot{P}_{\text{gen}} - \dot{P}_{\text{cons}} \right) \]

Non-flow boundary
Flow boundary

\[ \sum F_{\text{external}} \]
Conservation of Linear Momentum

\[ \frac{dP_{\text{sys}}}{dt} = \sum F_{\text{ext}} + \left[ \sum_{\text{in}} m_i V_i - \sum_{\text{out}} m_e V_e \right] \]

- 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 $F = ma$

\[
\frac{dP_{sys}}{dt} = \sum F_{ext} + \left[ \sum_{\text{in}} \dot{m}_i V_i - \sum_{\text{out}} \dot{m}_e V_e \right]
\]

Closed System

\[
P_{sys} = m_G V_G
\]

\[
\dot{m} = 0
\]

\[
\frac{d}{dt} \left( m_G V_G \right) = m_G \frac{d}{dt} \left( V_G \right) = m_G a_G
\]

\[
\sum F_{ext} = F_{net}
\]

\[
F_{net} = m_G a_G
\]
Rate Form of Basic Laws

\[
\frac{dm_{\text{sys}}}{dt} = \sum_{\text{in}} \dot{m}_i - \sum_{\text{out}} \dot{m}_e \\
\frac{dq_{\text{sys}}}{dt} = \sum_{\text{in}} \dot{q}_i - \sum_{\text{out}} \dot{q}_e \\
\frac{dP_{\text{sys}}}{dt} = \sum_j F_{\text{ext}, j} + \left[ \sum_{\text{in}} \dot{m}_i V_i - \sum_{\text{out}} \dot{m}_e V_e \right] \\
\frac{dL_{o,\text{sys}}}{dt} = \sum_j M_{o, j} + \left[ \sum_{\text{in}} \dot{m}_i (r_i \times V_i) - \sum_{\text{out}} \dot{m}_e (r_e \times V_e) \right] \\
\frac{dE_{\text{sys}}}{dt} = \dot{Q}_{\text{net,in}} + \dot{W}_{\text{net,in}} + \left[ \sum_{\text{in}} \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_{\text{out}} \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right) \right] \\
\frac{dS_{\text{sys}}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \left[ \sum_{\text{in}} \dot{m}_i s_i - \sum_{\text{out}} \dot{m}_e s_e \right] + \dot{S}_{\text{gen}}
\]
Rate Form of Basic Laws

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

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

\[
\frac{dP_{sys}}{dt} = \sum_j F_{ext,j} + \left[ \sum_{in} \dot{m}_i \mathbf{v}_i - \sum_{out} \dot{m}_e \mathbf{v}_e \right]
\]

\[
\frac{dL_{o,sys}}{dt} = \sum_j M_{o,j} + \left[ \sum_{in} \dot{m}_i (\mathbf{r}_i \times \mathbf{v}_i) - \sum_{out} \dot{m}_e (\mathbf{r}_e \times \mathbf{v}_e) \right]
\]

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

\[
\frac{dS_{sys}}{dt} = \sum_j \frac{\dot{Q}_j}{T_i} + \left[ \sum_{in} \dot{m}_i s_i - \sum_{out} \dot{m}_e s_e \right] + \dot{S}_{gen}
\]
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 \( h(t) \).

Find \( V_x(t) \).

Extensive Property? System?

\[ F \]

\[ F_{\text{spring}} \]

\[ F_{\text{friction}} \]
Mass

\[ \dot{m}_1 \]

\[ \dot{m}_2 \]

Linear Momentum

\[ F \]

\[ F_{spring} \]

\[ x \]

\[ F_{friction} \]

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

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

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

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

\[ \frac{d}{dt} (mV_x) = F - \mu_k mg - kx \]

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

• Discipline of System Dynamics

• References from physics
  – Chapter 1 in H. Fuchs, *The Dynamics of Heat.*
    *Springer-Verlag, 1996.*
What Engineers Know and How They Know It

- “Organization according to control-volume ideas is thus not only simpler but brings clearer understanding 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


**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.
  – Required for electrical, computer, and mechanical engineering students.
What’s in our Core?

- Diff. Equations I
- Thermodynamics
- Fluid Mechanics
- Statistics
- Matrix Algebra
- Dynamics
- Circuits
- Diff. Equations II
- System Dynamics

32 Qtr. Credit Hours
Sophomore Engineering Curriculum

Fall
- Diff. Equations & Matrix Algebra I (4)
- Conservation & Accounting Principles (4)

Winter
- Diff. Equations & Matrix Algebra II (4)
- Fluid & Thermal Systems (3)
- Electrical Systems (3)
- Mechanical Systems (3)

Spring
- Statistics for Engineers (4)
- Analysis & Design of Engineering Systems (5)

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

Student A
“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

Student B

“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

Student C

“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, made this skeptical EE a believer in the SEC. 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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http://www.foundationcoalition.org