
Basic Engineering Science —

A Systems, Accounting, and Modeling Approach

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Course Notes for ES 201 - Conservation & Accounting Principles

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The author welcomes comments, suggestions, and corrections:

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“Engineers, unlike physicists, are after useful artifacts and must predict the performance of the objects they design.”

“Organization according to control-volume ideas is thus not only simpler but brings clearer understanding of the physical principles common to otherwise disparate situations.”

“In the end the requirements that have tipped the scales in favor of control-volume analysis lie in the goal or mission of the engineer—to design and produce useful artifacts.”

“Practicing engineers are always on the lookout for more effective tools with which to think and do.”

“By organizing knowledge according to physical laws rather than known problems, it aids in recognizing a control-volume problem when met in an unfamiliar disguise.”

“Control-volume analysis, by setting up an explicit method of bookkeeping for the various flow quantities, provides such a procedure for the many engineers who must deal with fluid-mechanical devices.”

“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.”

Walter G. Vincenti in *What Engineers Know and How They Know It*¹

Preface

The words above were originally written about the development of the *control volume*² as a tool for analysis in thermodynamics and fluid mechanics. However, if you replace the phrases “control-volume ideas” and “control-volume approach” with the phrase “system, accounting, and modeling approach,” the words apply equally well to the thrust of this textbook.

The current textbook is based on a different paradigm for organizing an engineering science core—a system, accounting, and modeling approach—that emphasizes the common, underlying concepts of engineering science. Although this approach is not necessarily new, as most graduate students have been struck by this idea sometime during their graduate education, its use as the organizing principle for an *undergraduate* curriculum is new. By focusing on the underlying concepts and stressing the similarities between subjects that are often perceived by students (and faculty) as unconnected topics, this approach provides students a framework for recognizing and building connections as they learn new material.

Background

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 in a typical curriculum. The result was an interdisciplinary sequence of four courses called the Texas A&M/NSF Engineering Core Curriculum³ and organized around what they called the conservation and accounting principle. Glover, Lundsford, and Fleming produced an introductory textbook⁴ that used this approach. More recently Holtzapple and

¹ Excerpts from Chapter 4, “A Theoretical Tool for Design: Control-Volume Analysis, 1912-1953,” in *What Engineers Know and How They Know It*, The Johns Hopkins University Press, Baltimore, 1990.

² A control volume is a region in space as opposed to a fixed quantity of matter that is used for analysis. In mechanics, the use of a control volume is called the Eulerian approach while using a control mass, a fixed quantity of matter, is called the Lagrangian approach

³ C. J. Glover, C. A. Erdman, “Overview of the TAMU/NSF Engineering Core Curriculum Development,” presented at the 1992 ASEE/IEEE Frontiers in Education conference, 11-14 November 1992, Nashville, Tennessee. Also see <http://ww-chen.tamu.edu/uesc/> about the Unified Engineering Science Core.

⁴ C. J. Glover, K. M. Lunsford and J. A. Fleming, *Conservation Principles and the Structure of Engineering*, 5th Ed., McGraw-Hill, New York, 1996.

Reece have introduced this approach in a freshman text.⁵ Recently, the author has also learned of a similar approach being promoted and developed by Prof. W. C. Reynolds at Stanford University for a course called ME10: Introduction to Engineering Analysis.⁶ Calls to consider a systems approach have also come from physicists.^{7, 8}

In 1993, seven schools came together as the Foundation Coalition (FC) under the auspices of the NSF Engineering Education Coalitions Program. One of the major thrusts of the FC was curriculum integration. Building on the earlier work at Texas A&M, Rose-Hulman developed a new sophomore engineering curriculum—the Rose-Hulman/Foundation-Coalition Sophomore Engineering Curriculum (SEC). The curriculum is currently required for all Rose-Hulman students majoring in mechanical engineering, electrical engineering, and computer engineering.

The Sophomore Engineering Curriculum

The SEC is a required, eight-course⁹ sequence of engineering science and mathematics courses completed during the sophomore year. The SEC covers material traditionally taught in dynamics, fluid mechanics, thermodynamics, electrical circuits, system dynamics, differential equations, matrix algebra, and statistics. Two faculty-student teams developed the curriculum and its content during the summers of 1994 and 1995. The curriculum was first taught in the fall of 1995. Currently the SEC consists of the eight courses shown in the table below:

Sophomore Engineering Curriculum		Credit Hours
Fall Quarter		8
MA 221	Differential Equations and Matrix Algebra I (4)	
ES 201	Conservation & Accounting Principles (4)	
Winter Quarter		13
MA 222	Differential Equations and Matrix Algebra II (4)	
ES 202	Fluid & Thermal Systems (3)	
ES 203	Electrical Systems (3)	
ES 204	Mechanical Systems (3)	
Spring Quarter		9
MA 223	Statistics for Engineers (4)	
ES 205	Analysis & Design of Engineering Systems (5)	
Total		30

One of the unique features of the SEC is the 1–3–1 sequence for the engineering science courses. The sequence starts with a general course ES201 in the fall. In the winter, the courses are more discipline/phenomena specific with ES 202, 203, and 204. Finally in the spring, the focus again becomes more general with ES 205.

This Textbook

This textbook is based on over five years experience in teaching the first engineering science course in the SEC, called ES201: Conservation and Accounting Principles. ES201 is taken during the first

⁵ M. T. Holtzapple and W. D. Reece, *Foundation of Engineering*, McGraw-Hill, Boston, 2000.

⁶ W. C. Reynolds, *Introduction to Engineering Analysis: An integrated approach to the fundamental principles that underlie all engineering analysis*. Notes under development by Prof. W. C. Reynolds at Stanford University.

⁷ H. Burkhardt, "Systems physics: a uniform approach to the branches of classical physics," *American Journal of Physics*, Vol. 55, pp. 344-350.

⁸ H. U. Fuchs, *The Dynamics of Heat*, Springer-Verlag, New York, 1996.

⁹ Eight courses on a quarter system for a total of thirty quarter-credit hours spread over three quarters.

quarter of the sophomore year and introduces the systems, accounting, and modeling approach as the basis for engineering analysis. The content of ES201 as mapped to traditional engineering science courses is shown in the table below:

Content Map for ES201— Conservation & Accounting Principles	
<p>Fluid Mechanics</p> <p>Pressure</p> <ul style="list-style-type: none"> Absolute vs. gage pressure Forces due to uniform pressure <p>Integral equations for control volumes</p> <ul style="list-style-type: none"> Reynolds transport equation Conservation of mass <ul style="list-style-type: none"> mass and volume flow rate continuity equation Conservation of linear momentum Conservation of angular momentum Conservation of energy <p>Thermodynamics</p> <p>Basic concepts: system, property, state</p> <p>P-v-T relation for ideal gas: $pV = mRT$</p> <p>Simple substance models with constant specific heats</p> <ul style="list-style-type: none"> Ideal gas model Incompressible substance model <p>Conservation of energy and the First Law of Thermodynamics</p> <ul style="list-style-type: none"> Mechanical concepts of work and energy Thermodynamic work Energy of a system: internal, kinetic and gravitational potential Energy transfers by work: pdV work, shaft work, electrical work <ul style="list-style-type: none"> Energy transfer by heat transfer Energy balance for open and closed systems <p>Entropy and the second law of thermodynamics</p> <ul style="list-style-type: none"> Reversible and irreversible processes Second law of thermodynamics Entropy transfer by heat transfer Entropy production in irreversible processes Entropy balance for open and closed systems <p>Analysis of simple thermodynamics cycles</p> <ul style="list-style-type: none"> Power, Heat Pump and Refrigeration Cycles Measures of Performance Performance of internally reversible cycle. <p>Material and Energy Balances</p> <ul style="list-style-type: none"> Molar and mass flow rate Mixture composition Balanced chemical equations Production/consumption of chemical species in chemical reactions Chemical species accounting for systems with chemical reactions 	<p>Electrical Circuits</p> <ul style="list-style-type: none"> Conservation of net charge Kirchhoff's Current Law Node voltages Simple dc circuits <p>Engineering Statics</p> <ul style="list-style-type: none"> Equilibrium of rigid bodies <p>Engineering Dynamics</p> <p>Kinematics of particles</p> <ul style="list-style-type: none"> Rectilinear and curvilinear motion Rectangular components Relative motion <p>Kinetics of particles</p> <ul style="list-style-type: none"> Newton's second law of motion Equations of motion Dry (Coulomb) friction Principle of impulse and momentum Impulsive motion Mechanical work Kinetic and potential energy Principle of work and energy <p>Systems of particles</p> <ul style="list-style-type: none"> Mass center Application of Newton's laws Linear and angular momentum of a system of particles <ul style="list-style-type: none"> Principle of impulse and momentum Kinetic energy Principle of work and energy Variable systems of particles (Open systems or Control volumes) <ul style="list-style-type: none"> Steady stream of particles Systems gaining or losing mass <p>Kinematics of rigid bodies</p> <ul style="list-style-type: none"> Translation <p>Kinetics of rigid bodies with translation</p> <ul style="list-style-type: none"> Newton's second law of motion Principle of impulse and momentum Impulsive motion Principle of work and energy Conservation of mechanical energy

After a general discussion of the approach in the first two chapters, six fundamental physical laws are formulated using the systems and accounting framework. The fundamental laws are related to six extensive properties—mass, charge, linear momentum, angular momentum, energy, and entropy. In each case, the physical law is introduced by answering four questions about the pertinent extensive property:

- What is the property in question?
- How can it be stored in a system,
- How can it be transported across the system boundary?
- How can it be generated or consumed inside the system?

The answers to these questions provide the information to formulate each law within a systems and accounting framework. Once these questions are answered, the behavior of the property for a system can be described using an accounting (or balance) equation. All but one of the physical laws are conservation principles. Although not a conservation principle, the sixth law (entropy accounting) is important because entropy can only be produced or in the limit of an internally reversible process conserved. A summary of the basic physical laws formulated in the systems and accounting framework can be found in the appendix.

Once the governing equations are developed the emphasis shifts to the analysis of system behavior. With the basic laws formulated in a consistent fashion, the problem becomes one of identifying the appropriate system, selecting and applying the pertinent accounting equations, and constructing a problem specific model. Throughout the text a consistent problem solving approach is emphasized regardless of the underlying physical laws. Again this is based on a series of generic questions as shown in the tables below:

Written Format	Typical Questions
<ul style="list-style-type: none"> • Known • Find • Given • Analysis <ul style="list-style-type: none"> — Strategy — Constructing the Model — Symbolic Solution — Numerical Solution • Comments 	<ul style="list-style-type: none"> • What's the system? • What properties should we count? • What's the time interval? • What are the important interactions? • How do the basic equations simplify? • What are the unknowns? • How many equations do I need? • What are the important constitutive relations?

This is another benefit of using the systems and accounting framework to organize the material. As an example, all problems involving linear momentum begin from the conservation of linear momentum equation. From this single starting point, problem specific forms can be obtained by applying appropriate modeling assumptions, e.g. closed vs. open system and transient vs. steady state vs. finite time. Using appropriate, problem specific assumptions, we can quickly recover any of the “standard” forms, e.g. $F = ma$, $\Sigma F = 0$, impulse-momentum equation, and the steady-state linear momentum balance for fluid mechanics. In each case, the emphasis is not on the final form of the equation but on the *modeling assumptions* and how they change the basic equations.

A Request of Students and Faculty

As the first effort to generate a complete textbook from a mushrooming set of notes, there are surely errors and omissions in the text. For these the author takes full credit and asks your help in identifying mistakes in this text. To eliminate these in future editions, you are encouraged to contact the author directly with any errors or omissions you identify.

You are also encouraged to contact the author and share your views about the systems, accounting, and modeling approach that forms the basis for this text. It is the author's firm belief that this approach has much to contribute to engineering education and that we have only begun to explore and exploit its potential impact. A major strength of the approach is in how it forms a foundation for advanced work. Faculty members are encouraged to explore how they can use what students learn from this text as a springboard to learning in related and advanced courses.

Acknowledgements

No textbook springs fully formed as an original contribution from the mind of an author, and this book is no exception. Although the author had long considered the use of an integrated approach in teaching of thermodynamics, heat transfer, and fluid mechanics, the Texas A&M group broadened his conception of how an integrated approach could unify engineering science education. Charles Glover and Louis Everett were especially helpful in sharing ideas and encouragement.

On the Rose-Hulman campus, the faculty and students on the SEC team developed an approach that has served us well. Special thanks are due those individuals who taught ES201 in the early the years: Howard McLean, Phil Cornwell, Jerry Fine, and Fred Berry. Their comments and concerns about the approach were freely shared and are reflected in the current text. Bruce Black provided critical insight into how this approach meshes with traditional circuit analysis. More recently Mallory North, Tom Adams, Jim Mayhew, Richard Layton, and Clark Merkel have provided feedback on the course and the text. Thanks are also due the sophomore electrical engineering and computer engineering students who inaugurated the SEC in the fall of 1995. Their comments were many and varied, and the program is better today for their willingness to speak out.

The author is especially grateful for an invitation to join the local Rose-Hulman/Foundation-Coalition management team in spring of 1993. The support of that team—Jeff Froyd, Gloria Rogers, Brian Winkel, and Jim Eifert—and their ongoing friendship over the years has been a significant source of encouragement. The author also wishes to thank the Foundation Coalition for supporting these efforts through the Engineering Education Program of the National Science Foundation (Award Number EEC-9802942). The Foundation Coalition is a network of extraordinary people who care about engineering education, and it has been a privilege for the author to work with this group.

The author wishes to thank the administration, staff, and faculty at Rose-Hulman for its commitment to undergraduate education and for nurturing and supporting innovative efforts like this textbook and the SEC. Rose-Hulman is a unique educational institution because of its unwavering commitment to quality undergraduate education in the sciences, mathematics, and engineering. This does not happen without a continuing effort by the entire Rose-Hulman community.

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