



A Foundational Engineering Science Course and Its Impact on Those Who Teach It

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Curricular innovations are difficult to implement and sustain. Many innovations were developed through the NSF-funded Engineering Education Coalitions in the early 1990's; however, few survived the end of funding or the loss of the key innovators. This paper considers the experience of one institution and the long-term success of one of these curricular innovations. In this paper, we argue that the long-term survival and success of this curriculum can be traced to the general framework presented in the foundational course in the curriculum and its positive influence on the faculty members who have taught (and are teaching) the course. To support this argument, we will present the results from a survey of the faculty members who have taught this foundational course.

Introduction

In the fall of 1995, Rose-Hulman Institute of Technology introduced a radically new curriculum, the Sophomore Engineering Curriculum (SEC), for electrical and computer engineering majors [1]. The SEC was developed through Rose-Hulman's participation in the Foundation Coalition, an NSF-funded engineering education coalition [2]. By 1998, this curriculum grew to include mechanical engineering majors and later added biomedical engineering majors. The curriculum originally consisted of eight courses representing 30 credit hours in a 10-week quarter system. By restructuring the material, the SEC tried to explicitly demonstrate common threads within the topics typically covered by a course on statistics, two courses on differential equations, and five engineering science courses: Fluid Mechanics, Thermodynamics I, Dynamics, Circuits I, and System Dynamics. Over its 23-year-life, the SEC has evolved and currently focuses only on engineering science excluding electrical circuits, and it stresses a unique system approach to applying the basic conservation and accounting laws (conservation of mass, linear momentum, etc.). The evolution of this curriculum and its efficacy for student learning have been presented in previous papers [3-4].

Unlike many other NSF-funded projects, this curriculum has survived long past the NSF funding and the advocacy of the original developers. In fact, none of the original developers of the curriculum still teach the introductory, foundational course for the SEC – Conservation and Accounting Principles (ES201) – and only one of them still works at Rose-Hulman. There has been some research on barriers and drivers for proposed changes in teaching practices, but the literature examining why large scale curricular changes succeed or fail is lacking. In regard to changes in teaching practice, researchers identified 18 categories of barriers and 15 categories of drivers [5]. The barriers and drivers were identified by interviewing faculty members and analyzing their responses to general questions about changes in teaching practice. In this study, however, we ask faculty members about a specific curricular innovation that has been successful.

The primary focus of this paper is on the sustainability of the curriculum and its effect on the faculty members teaching it. See the appendix for a detailed discussion of the unique characteristics of the Sophomore Engineering Curriculum (SEC).

Goals and Methods

We hypothesized that the long-term survival and success of the SEC can be traced to the general framework presented in its foundational course, ES201, its positive influence on the faculty members who have taught (and are teaching) the course, and the fact that faculty members enjoy teaching the foundational course. To test our hypothesis, we designed a simple survey to collect responses from the faculty members who have taught the course about their reactions to and experiences in teaching ES201. Questions in this survey included

- a) Do you like teaching ES201? Why or Why not?
- b) How has teaching ES201 influenced the way you teach other courses?
- c) What do you believe to be the strengths and weaknesses of ES201?

The survey was not anonymous, so we could obtain further clarification on specific answers. Each of the authors also completed the survey.

Results and Discussion

Since its initial offering in 1995, 25 different faculty have taught ES201. Surveys were sent to 20 of these faculty, and we had a 100% response rate. The remaining five were not available because of death, retirement, or other reasons. The instructors had a wide variety of backgrounds as shown in Table 1. This is not surprising as the SEC was originally developed and taught as an interdepartmental curriculum that focused on engineering without a discipline emphasis.

Table 1 – Backgrounds of survey respondents

Department	Primary Specialization	Number
Chemistry	Geochemistry	1
Electrical Engineering	Power and control systems	1
	Electromagnetic fields	1
Biomedical Engineering	Biomechanics	2
	Design	1
Mechanical Engineering	Materials	1
	Thermo-fluids	5
	Vibrations	2
	Controls	2
	Dynamic Systems	1
	Mechanics	2
	Design	1

The first question asked if the respondent liked teaching the course. We recognize that just because an instructor likes teaching a course does not mean it is a good course or that it is beneficial for students. In terms of the sustainability of a new innovative curriculum, however, we do believe that faculty members' view of a course, as indicated by liking to teach it, is potentially one factor in its success. The results are shown in Figure 1. Even with this wide variety of backgrounds, 100% of the respondents said they liked teaching ES201, and 55% indicated they loved teaching the course. The faculty members who said they loved teaching the course included faculty members from each department and with teaching experience ranging from a brand-new assistant professor to full professors with over 30 years of teaching experience.

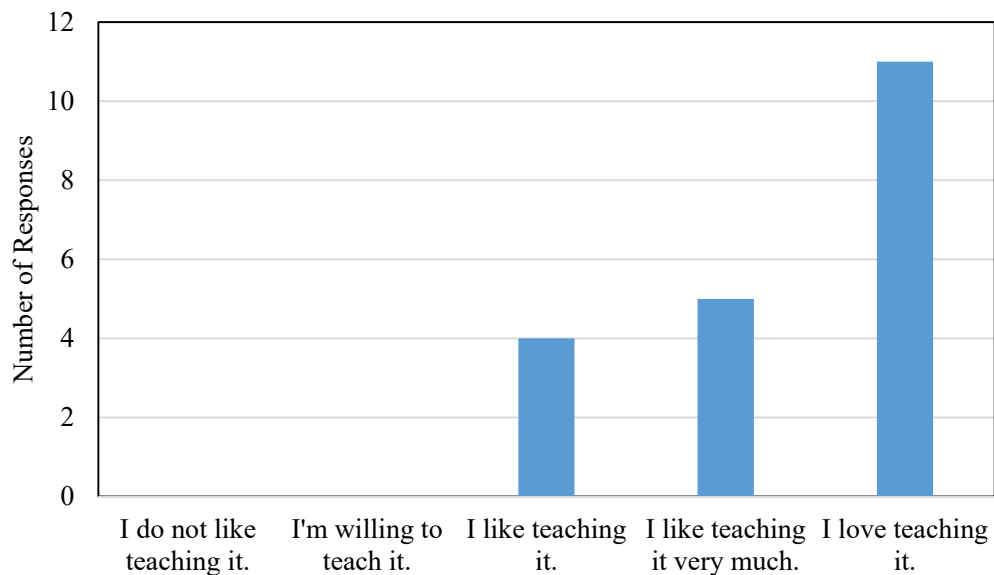


Figure 1 – Responses to the question “Which statement best characterizes your opinion about teaching ES201?”

Faculty members were also asked to explain why they liked teaching the course. The most common reasons provided by the respondents are shown in Table 2. Many other reasons were listed, but these were mentioned by two or more faculty members. The unified framework and the belief that this is a foundational course for all other engineering courses topped the list.

Table 2 – Most common reasons listed for liking to teach ES201

Theme	Number
Unified framework/connections between fluids, thermodynamics, and dynamics	8
Fundamental/foundational course	6
I wish I'd been taught this way/didn't see this until graduate school	2
Teaching students to think like an engineer/engineering mindset	2
Systems approach	2
Problem-solving approach/strategies	2

In the survey, faculty members were also asked to discuss what they felt were the strengths and weaknesses of the course. There were many comments about strengths, but only four major themes appeared. These are listed below, followed by the number of comments that supported each theme:

1. The unified/general/consistent problem-solving approach (9)
2. The focus on fundamentals (7)
3. Students are required to state their assumptions and document their work clearly (6)
4. The emphasis on defining a system for analysis (4)

There were many comments on the weaknesses of the course (faculty members are always willing to point out what they consider to be a weakness), but the themes were much harder to identify. In fact, there were no comments that were made by more than two faculty members, and in some cases, the articulated weakness conflicted with what other faculty members identified as a strength. For example, two faculty members stated that there is not enough emphasis on assumptions whereas five different faculty members stated that the requirement to state assumptions is a strength. Two faculty members were concerned that the course moves too quickly, and we cover a lot of material, but this was not expressed as a concern for most of the faculty members responding. It was obvious from reading the comments that even though faculty members could all find what they perceived to be weaknesses in the course, they felt the strengths clearly outweighed the weaknesses.

Finally, we asked faculty members if teaching this course influenced how they approach their other courses. Seventeen faculty answered this question. Of these, fifteen (88%) indicated that teaching this course has influenced the way they teach other courses. The two who said it had not influenced their teaching were faculty members who only taught the course once or twice. One of them was an electrical engineer, and the other, with a specialization in system dynamics, said he already used a similar approach to the one used in ES201. Typical comments on this question are shown below:

- It influenced the way I teach my fluids and thermo courses, as well as the way I teach the prerequisite course, Statics.
- Every course I teach, I tie back to ES201. I reinforce the general problem-solving approach and going back to the basics rather than specialized equations.
- I emphasize system choice in follow-up classes.

- I use the approach in all my biomechanics classes and design courses.
- I use it in all my other classes including Measurements and ME lab.

The Mechanical Engineering Department Head routinely assigns new faculty to teach ES201 since it is such a foundational course in the curriculum and a strong prerequisite for other courses. It is a well-organized and structured course, and former instructors are always willing to share their notes with new faculty members teaching the course. It is also team-taught, meaning that all the sections use the same syllabus, calendar, homework, and exams. Even though loss of autonomy was listed as a barrier in [5], we have not experienced this at Rose-Hulman. This may be because many of our courses require all the sections to use the same syllabus, calendar, homework, and exams. We typically offer six to eight sections of ES201 during the Fall term and one or two trailer sections in the Winter term.

From this survey, we learned that faculty members who teach this foundational course have an overwhelmingly positive attitude toward it. The authors could not find research on why some curricular innovations survive long past the funding and the participation of the program developers. Our survey has provided insight into why this is the case for our sophomore engineering curriculum. From this data we have identified two primary reasons:

1. Faculty members buy into the approach and recognize its value, as evidenced by its strong impact on how faculty members teach subsequent courses, and
2. The course is recognized as foundational to the rest of the mechanical engineering curriculum.

It was not mentioned by any of the faculty members in the survey, but the authors also believe the school is successful in bringing new teachers into the course because of the support provided for new faculty members and the team-taught nature of the course.

Conclusions

At Rose-Hulman a Sophomore Engineering Curriculum has survived long past the NSF funding and the participation of the curriculum developers. In this paper we have argued that the success of this curriculum can be traced to the success of its foundational course, ES201 – Conservation and Accounting Principles. Survey results indicate that faculty members enjoy teaching this course, they buy into the unified framework, they view this course as foundational to all other mechanical engineering courses, and finally, teaching this course has had a strong influence on how they teach other courses.

References

1. Richards, D.E., “A New Sophomore Engineering Curriculum -- The Rose-Hulman Experience,” *Proceedings of the 1996 ASEE Annual Conference*, 1996.
2. Frair, K., J. Froyd, G. Rogers, Karan Watson, “The Foundation Coalition: Past, Present, and Future”, *Proceedings of the 1996 Frontiers in Education Conference*, Salt Lake City, Utah, November 6-9, 1996.

3. Richards, D.E., "Integrating the Mechanical Engineering Core," *Proceedings of the 2001 ASEE Annual Conference*, Albuquerque, NM, 2001.
4. Cornwell, P.J., J.M. Fine, "Mechanics in the Rose-Hulman Foundation Coalition Sophomore Curriculum," *International Journal of Engineering Education*, Vol. 16, No. 5, 2000, pp. 441-446.
5. Shadle, S.E, A. Marker, and B. Earl, "Faculty drivers and barriers: laying the groundwork for undergraduate STEM education reform in academic departments," *International Journal of STEM Education*, Dec. 2017.
6. Richards, D.E., and M. A. Collura, "Understanding a New Paradigm for Engineering Science Education Using Knowledge about Student Learning," *Proceedings of the 2015 ASEE Annual Conference*, Seattle, WA, 2015.
7. Brown, P.C., H.L. Roediger, M.A. McDaniel, *Make it Stick: The Science of Successful Learning*, Belknap Press, 2014.

Appendix: Background and Description of the Sophomore Engineering Curriculum

The SEC and its foundational course, Conservation and Accounting Principles (ES201), are unique and differ significantly from typical engineering science curricula. New SEC faculty can't just fall back on how they were taught similar material because the approach is new. This means that all SEC faculty are continually asked to step out of their comfort zone and do things differently. To get some sense of what SEC faculty experience, it is important to briefly explain how the SEC and ES201 differ from the norm.

Motivation for the Sophomore Engineering Curriculum

Unfortunately, a student navigating traditional engineering science and required physics courses often sees a plethora of equations, definitions, and concepts that are perceived by students and often taught by faculty as unconnected pieces of knowledge. Why, we wonder, can't students make connections and transfer knowledge to new situations?

A careful examination of typical engineering science courses, see Figure A1, shows how concepts from these courses can be grouped to identify common concepts that cut across courses. This is an "Aha moment" that most faculty had in graduate school when they discovered the underlying structure and fundamental principles that connected all the engineering sciences. How would student learning change if we started with the big picture, instead of hoping that students perceive the underlying connections after an education that exposes them only to the pieces? The SEC was originally developed to explicitly present our students with a unified framework to help them better understand the basic principles and apply them more effectively in new situations.

Typical Engineering Science Courses

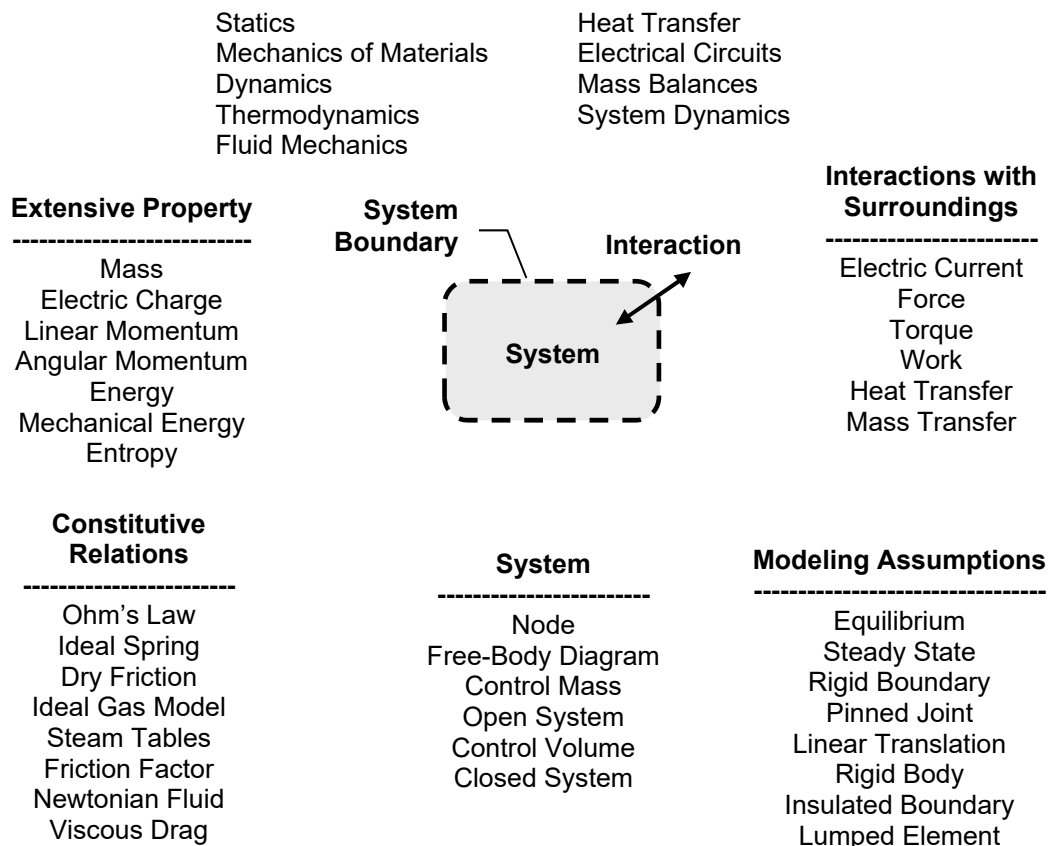


Figure A1 – Common concepts in core engineering science courses

Underlying Framework — The Systems, Accounting, and Modeling (SAM) Approach

Typically, when an engineer faces a problem, he or she will need to work through a series of steps in creating a solution. A broad summary of the steps could include:

- Examine the situation to determine what phenomena are involved (e.g. is this a mechanics problem or a thermodynamics problem) and to define the nature of the problem.
- Identify a part of the physical world to study, the **system** and its **surroundings**.
- Identify the important **properties** that describe the state of the system.
- Identify the **processes** that change the state of the system, the **interactions** between the system and its surroundings during these processes, and any physical **constraints**.
- Construct a mathematical **model** to predict the effect of changing parameters on the state of the system making reasonable assumptions about the properties involved.
- Use the model to try out some solutions.
- Iterate as needed (including modification of the selected properties, model, etc.).

The model construction step generally requires the application of fundamental principles or laws, such as 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 the important **extensive properties**. Five of these properties (mass, charge, energy, linear and angular momentum) are **conserved**, and the sixth property (entropy) can only be generated. In addition, the model requires **modeling assumptions** to capture the essential features of the problem and the selection of **constitutive relationships** to supplement the fundamental laws. Once this information is collected, it is possible to analyze the situation and ultimately solve the problem.

In ES201 we introduce a Systems, Accounting, and Modeling (SAM) approach to problem solving in the engineering sciences that embodies these ideas. The underlying organizing principle for the SAM approach is the accounting principle:

Every system has associated with it numerous extensive properties; the system behavior can be determined by monitoring how these properties change; and any change in the amount of an extensive property within the system can be accounted for by considering the amount *transported* across the system boundary and the amount *generated* or *consumed* inside the system.

This approach underlies both the introduction of the basic laws and the application of these laws to solve problems.

Using the accounting principle as a common framework, we introduce each of the fundamental principles of engineering science in a consistent fashion by answering four questions:

- (1) What is the important extensive property?
- (2) How can it be stored within and quantified (expressed using variables) for a system?
- (3) How can it be transported across the system boundary?
- (4) How can it be generated or consumed inside the system?

Answering these questions reinforces the underlying structure common to all the principles and helps students understand these equations in a larger context. The mathematical similarities between the various equations are related to the storage, the transport (with and without mass flow), and the generation and consumption of the extensive property.

Starting with the general rate form of the accounting principle, this process produces five conservation equations—mass, charge, linear momentum, angular momentum, and energy—and an accounting equation for entropy. These equations are shown in Figure A2 and represent the required starting point for any application of the general principles in ES201. This is one of the significant features of ES201 and it bears repeating: *every* application of these principles *always* starts with one of these equations. For example, whether you are looking for the reactions on a loaded cantilever beam, the acceleration of a block sliding on an inclined plane, or the reaction force holding a nozzle on a pipe, the complete Conservation of Linear Momentum equation shown in Figure A2 is always the starting point, not Newton's Second Law in the form of $F=ma$. Then the problem-specific form of the principle is developed using careful system identification and explicit modeling assumptions.

Generic Property B	$\frac{d}{dt}(B_{\text{sys}}) = \left[\sum \dot{B}_{\text{transport,in}} - \sum \dot{B}_{\text{transport,out}} \right] + \left[\dot{B}_{\text{generation}} - \dot{B}_{\text{consumption}} \right]$
Mass	$\frac{d}{dt}(m_{\text{sys}}) = \sum_{\text{in}} \dot{m}_i - \sum_{\text{out}} \dot{m}_e \quad \text{(Total mass)}$
	$\frac{d}{dt}(m_{j,\text{sys}}) = \sum_{\text{in}} \dot{m}_{j,i} - \sum_{\text{out}} \dot{m}_{j,e} + \left[\dot{m}_{j,\text{generation}} - \dot{m}_{j,\text{consumption}} \right] \quad \text{(Mass species } j)$
	$\frac{d}{dt}(n_{j,\text{sys}}) = \sum_{\text{in}} \dot{n}_{j,i} - \sum_{\text{out}} \dot{n}_{j,e} + \left[\dot{n}_{j,\text{generation}} - \dot{n}_{j,\text{consumption}} \right] \quad \text{(Moles species } j)$
Net Charge	$\frac{d}{dt}(q_{\text{sys}}) = \sum_{\text{in}} i_j - \sum_{\text{out}} i_j \quad \begin{array}{l} \text{reduces to Kirchoff's Current Law} \\ \text{for a node which cannot store charge} \end{array}$
Linear Momentum	$\frac{d}{dt}(\mathbf{P}_{\text{sys}}) = \sum_{\text{external}} \mathbf{F}_j + \sum_{\text{in}} \dot{m}_i \mathbf{V}_i - \sum_{\text{out}} \dot{m}_e \mathbf{V}_e$
Angular Momentum	$\frac{d}{dt}(\mathbf{L}_{o,\text{sys}}) = \sum_{\text{external}} \mathbf{M}_{o,j} + \sum_{\text{in}} \dot{m}_i (\mathbf{r}_o \times \mathbf{V})_i - \sum_{\text{out}} \dot{m}_e (\mathbf{r}_o \times \mathbf{V})_e$
Energy	$\frac{d}{dt}(E_{\text{sys}}) = \dot{Q}_{\text{net,in}} + \dot{W}_{\text{net,in}} + \sum_{\text{in}} \dot{m}_i \left(h + \frac{V^2}{2} + gz \right)_i - \sum_{\text{out}} \dot{m}_e \left(h + \frac{V^2}{2} + gz \right)_e$
Entropy	$\frac{d}{dt}(S_{\text{sys}}) = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_{\text{in}} \dot{m}_i s_i - \sum_{\text{out}} \dot{m}_e s_e + \dot{S}_{\text{gen}} \quad \text{with } \dot{S}_{\text{gen}} \geq 0$

Figure A2 – Fundamental conservation and accounting equations

The accounting framework also undergirds a common approach to problem solving regardless of the physical principles. When a student tackles a problem, he or she has a consistent set of questions to ask about the problem as he or she constructs a model. These are illustrated in Figure A3. Notice that 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.

By asking and answering these questions, the student constructs a problem-specific model, typically a single equation or a set of algebraic and/or differential equations that contain most of the important variables and parameters for the system. Additional constitutive equations, e.g. the ideal gas equation, Ohm's law, etc., may be needed to augment the ones obtained from the accounting equations. These "laws" can be recalled from earlier work in science courses or provided as needed, but many will reappear or be formally introduced in subsequent engineering courses within the student's discipline.

Written Format	Typical Questions
<ul style="list-style-type: none"> • Known • Find • Given • Analysis <ul style="list-style-type: none"> -- Strategy -- Construct a 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? • What are the important constitutive relations? • How do the basic equations simplify? • What are the unknowns? • How many equations do I need?

Figure A3 – Problem solving format and questions

What's so different about teaching ES201 – Conservation & Accounting Principles?

Engineering faculty will recognize the accounting principle as a fundamental relationship in upper-level disciplinary courses. However, it is unusual to find it used as scaffolding at the sophomore level to help students understand concepts that appear in different engineering science subjects.

Note also that the problem-solving process described above is like the one a working engineer should use when faced with a new problem, and thus it should be taught in the foundational engineering courses. Unfortunately, students often take a shortcut where they try to find a simplified equation in the textbook or on the internet and just plug in some numbers. The best way to avoid this common student behavior is to require that they develop the specific form of the equations needed by applying general concepts and explicit modeling assumptions which is the essence of the SAM approach.

Because of the breadth of material taught in ES201, the faculty must be comfortable with teaching outside of their area of expertise. To do this effectively, they must “buy in” to the SAM approach which stresses process over short-cuts and tricks and provides a new way of thinking about system behavior. This requires that they must be comfortable using a problem-solving approach that carefully and explicitly identifies a system and then shows all the steps to construct a problem-specific solution from fundamental principles. (Experience shows that doing this is what allows faculty to step outside their area of expertise and tackle unfamiliar problems with confidence.)

Current Sophomore Engineering Curriculum

The current version of the SEC shown in Figure A4 concentrates on engineering science material traditionally covered in courses such as Dynamics, Thermodynamics I, Fluid Mechanics, and

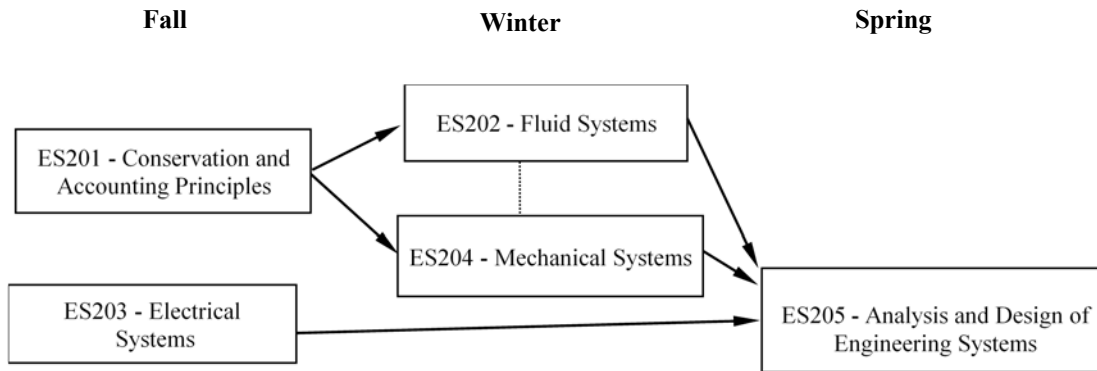


Figure A4 - Summary of the current sophomore engineering curriculum (SEC) at Rose-Hulman. A sequence of three courses can be used since Rose-Hulman is on the quarter system.

System Dynamics. ES201 establishes the foundation for all the other courses in the sequence by teaching the SAM approach described above. Although many students initially perceive some of the homework problems in ES201 to be easy, it is the emphasis on constructing a solution from first principles and effectively communicating the results that challenges even the brightest students.

While much has changed within the SEC, the one constant has been the introductory course ES201, a four-credit course taken during the first quarter of the sophomore year which introduces the SAM approach and sets the tone for the rest of the engineering science courses. ES201, called ConApps by the students, is a rigorous introduction to the conservation principles for mass, linear momentum, angular momentum, and energy and to the accounting principle for entropy. Although conservation of charge was originally included in this course, the current version does not cover this material. For additional information on ES201 see [6].

In the winter quarter, students take two courses that build directly on ES201. Mechanical Systems (ES204) moves beyond one-dimensional kinematics with students who already have a good understanding of momentum and energy conservation in an engineering context. Fluid Systems (ES202) tackles the traditional problems of fluid mechanics, again building on the conservation (and accounting) principles. Both courses force students to repeatedly revisit familiar material in more complicated situations, which has been shown to be an effective pedagogical technique [7].

In the spring quarter, the material in the three systems courses is brought back together in a single course, Analysis and Design of Engineering Systems (ES205), which is a system dynamics course with a lab that examines multi-disciplinary problems. Since material is distributed over a sequence of courses, it is frequently revisited and continually being reinforced at a higher level of learning.