

## The First Course

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### Abstract

Determining the proper pedagogy for our first course has been a key challenge for the Department of Systems Engineering at the United States Military Academy. When our department was formed in 1989 we did not design a first course that provided the foundation for the curriculum. In a major curriculum redesign in 2000, we designed a gateway course for all department majors, titled “*Introduction to Engineering Design and Systems Management*.” As we are a problem solving systems engineering program, the course was designed around a systems design decision process: the Systems Engineering and Management Process. After a very good start, the course drifted because we lacked sufficient documentation defining the process and the techniques. In 2006, unable to find an appropriate text for our course, the first author used his sabbatical to lead the development of a book to be the text and a reference for our capstone research course that culminates our engineering programs. With tremendous help from our colleagues, the first draft of our text was completed and used in Fall 2006. We designed the text and the first course based on three core foundations: systems thinking, the profession of systems engineering, and a new value-focused Systems Decision Process. After several revisions, our text, *Decision Making for Systems Engineering and Management*, was published in the Wiley Systems Engineering Series in early 2008. The authors redesigned the introductory course, now titled “Fundamentals of Systems Design and Management,” around a system thinking presentation, an individual decision problem, and a group design project. We have continued to improve the course for the past two years.

### Introduction

Designing the first course of any academic program is always challenging. There are more foundational concepts than time in one semester. The first course of any engineering program is especially challenging. Several key questions need to be answered. What are the foundational topics that will be needed in future courses to provide the knowledge for follow-on courses? Will students have the necessary prerequisites? What pedagogy should be used?

In the Department of System Engineering at the United States Military Academy, we have two ABET accredited programs: systems engineering and engineering management. There are many types of systems engineering programs. The programs range from discipline systems engineering programs (e.g., computer systems engineering) to programs that emphasize problem solving for complex technological systems involving many engineering disciplines. Our department is a problem solving systems engineering program. Our problem solving focus includes stakeholder analysis for problem definition; system design; modeling and analysis for design evaluation; decision making; and implementation using project management techniques. After commissioning in the Army, our graduates will serve as

operational leaders for first five years of their career. Later in their careers, some will have the opportunity to work as systems engineers and engineering managers, especially officers assigned to the Corps of Engineers and the Acquisition Corps. However, the skills we teach are critical for all branches of the Army.

In addition, we have some unique West Point constraints. First, our cadets choose their major in the Fall of their sophomore year and generally the second semester of their sophomore year is the first time they can take a course in their chosen major. Also, with a maximum of 18 students per class and approximately 150 majors, we have multiple sections and multiple instructors for most of our courses. We have a mix of Ph.D. and M.S. faculty and a mix of military and civilian faculty. The permanent military faculty and the civilian military faculty have Ph.Ds. in relevant disciplines. Our non-permanent, M.S. military instructors have significant Army operational experience but limited experience in their academic discipline since they come to West Point directly after receiving their degree. However, with their operational experience, they are able to demonstrate to cadets how our problem solving approach can be applied to Army operational problems and make outstanding contributions to cadet education and development.

### **Department background**

The Department of Systems Engineering at West Point was established in 1989 as an outgrowth of the former Department of Engineering (now the Department of Civil and Mechanical Engineering.) Brigadier General (Retired) James L. Kays was the first head of the newly formed department and had the responsibility for not only developing the academic programs under the department but also most of the courses. The department was designed with four overarching objectives that have endured through three department heads [1]: focus on cadet education; foster faculty growth and development; remain linked to the industry we serve - the Army; and integrate state-of-the-art computer and information technology into the education process.

The Department established the Systems Engineering major after benchmarking other existing SE programs throughout the country.<sup>1</sup> The SE major was accredited by ABET in 1997 and again in 2003. Additionally, the department offered a five-course engineering sequence for non-engineering students which used the courses offered by the department.<sup>2</sup> This required that the SE major be built around this five course sequence: SE387 *Deterministic Models*, SE388 *Stochastic Models*, SE381 *Engineering Economy*, SE401 *Introduction to Systems Engineering*, and SE402 *Systems Engineering Design*. The pedagogical rationale for this scheduling was to first introduce the tools required of systems engineers and only then be introduced to the more advanced concepts of how to do systems engineering. SE majors would take more courses than these five, but would take SE387 during the Spring term of their sophomore year and then take SE388 and SE381 during the Fall term of their junior year. This meant that they would wait until the Spring of their junior year to take SE401, the introductory course to their major!

In 1999-2000, Brigadier General (Retired) Michael L. McGinnis, the new Department Head, re-evaluated the pedagogy and concluded that it would be best to show the cadets the “roadmap” prior to them learning the “toolkits” [2]. To support this pedagogical shift, he directed that the introduction course be the first course in each cadet’s major program. We began with the next class beginning their sophomore year.

### **First course introduced in Spring 2001 for Class of 2003 graduates**

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<sup>1</sup> The Department also assumed responsibility for the previously established Engineering Management major.

<sup>2</sup> All non-engineering majors at USMA are required to take one of seven engineering sequences as part of the required breath for the undergraduate degree. This is currently a three course sequence.

In 2001, the majors were systems engineering, engineering management, and information systems engineering<sup>3</sup>. The original first course, SE301, was titled *Introduction to Engineering Design & Systems Management*. The course was designed to be a gateway course of all majors in the Department of Systems Engineering. SE301 was one of several changes made to enhance the curriculum. The new course “was designed primarily to do two things. First, the course was designed to motivate students’ learning by introducing them to the systems engineering discipline and providing a roadmap of the department’s systems engineering majors to be grouped together and meet the other students in their chosen academic field. This enabled the department to develop a sense of cohesion and identity among the majors” [3].

SE301 provided students an introduction to a process to support decision making for engineering design problems, the Systems Engineering and Management Process (SEMP) (Figure 1)<sup>4</sup>. The SEMP [3] was the foundation for the first course and our problem solving approach to systems engineering. During the course, instructors would highlight the courses in the curriculum that would expand on the topics in the SEMP. In addition, the students were expected to use the SEMP as the problem solving methodology for their capstone senior research project, a year long engineering design course with a team of four or five students. These research projects directly support the needs of a client and are supervised by a senior faculty member.



Figure 1. Systems Engineering & Management Process [3]

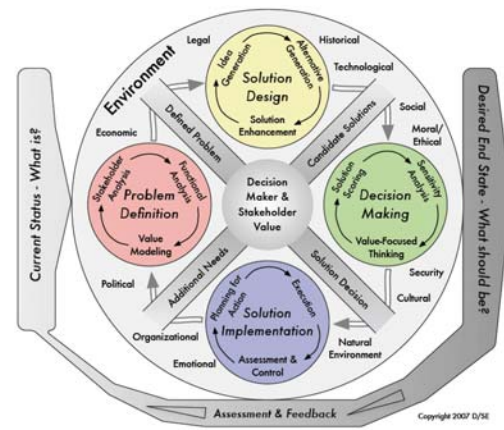


Figure 2. Systems Decision Process [4]

The SEMP was a four phase process that begins with an understanding of the current situation and ends with the implementation of an engineering design to meet the desired end state. The phases are Problem Definition, Design and Analysis, Decision Making, and Implementation. Within each of these phases, there are a number of tasks as depicted in Figure 1. The process is iterative and involves assessment and feedback. Six environmental factors (cultural, historical, technological, historical, political, and moral/ethical) were included in the SEMP to emphasize that systems engineering must explicitly consider the future environment of the system. McCarthy selected the colors to have a clear problem solving meaning [4]: red for stop until you fully define the problem, yellow for caution to not take the first feasible solution you find, green for the green light you hope to receive from the decision maker, and blue for the blue skies and smooth sailing you hope to have in implementation.

Course materials were developed based on previous course material from the Z-Diagram [5] and some new material. Over the five years the course was taught, we were not able to find a systems engineering textbook that covered the course material. After the first couple years, we used a general problem solving

<sup>3</sup> In 2007, Information System Engineering became a concentration area in the Systems Engineering program.

<sup>4</sup> The original department decision making process was the Z Diagram [5]. The SEMP build on this process.

text [6] supplemented by readings and notes prepared by instructors. With the departure of the original course designer, the course evolved into a problem solving text, a collection of readings, course notes, and PowerPoint® lesson slides.

The SEMP provided a comprehensive problem solving framework and McCarthy designed the course to use one comprehensive illustrative problem<sup>5</sup> throughout the course with which the cadets would have some basis of knowledge to apply the SEMP in order to explain each step in the process. With the lack of an appropriate textbook and a decision to make the course all individual effort and no team projects, subsequent instructors evolved the course so that it was taught like an operations research survey course (Revised SE301 in Table 1). SEMP techniques were illustrated with different problems designed to show the important features of each technique. While this is a good approach to highlight the techniques, the students were not able to see the important connections between the techniques in the SEMP. Also, the course did not have an integrated course project that required cadets to apply to SEMP to develop a solution to an engineering design problem. We assigned our junior military faculty to teach the course. While many of instructors has degrees in systems engineering and engineering management, none had every worked in these jobs. This made it difficult for them to understand and teach the practice of systems engineering and engineering management.

Table 1. Comparison of SE301 Pedagogy

	<b>Revised SE301</b>	<b>SE301 experiment</b>	<b>Redesign SE301 with text</b>
Course director (designs course and develops lesson plans)	MS in systems engineering or operations research	Experienced faculty MS in systems engineering or operations research	PhD in engineering with job and research experience in systems engineering
Instructors	New faculty		Civilian and senior military faculty with PhD
Decision making process	Systems Engineering and Management Process		Systems Decision Process
Pedagogy	Techniques illustrated with multiple examples using taken from Army operational problems or local decision problems		Techniques illustrated with one illustrative example, the Rocket Problem
Course projects	Team project worked all the way to the course. (Revision: All individual homework sets on various problems.)	<ol style="list-style-type: none"> <li>1. Car buying problem (individual)</li> <li>2. System design problem involving a military problem (class)</li> </ol>	<ol style="list-style-type: none"> <li>1. Systems Thinking Presentations</li> <li>2. Car buying problem (individual)</li> <li>3. System design or integration problem involving a military problem (4 person team)</li> </ol>
Reading material	Problem solving text, supplemental reading, and notes written by faculty		New text with illustrative problem (Rocket Problem) and exercises.

In the Spring term of 2005, a course assessment was performed [7] that documented the above challenges and recommended using two course projects. The first individual project would be a car buying project to introduce the decision process and the underlying mathematics of multiple objective decision analysis for a problem that had one major decision maker/stakeholder, the cadet. The second project would be a class project involving a system design for an Army related problem to develop the students understanding of the decision process by applying it to a real world problem. The program director decided to experiment with the two project concept (SE 301 experiment in Table 1). The experiment was successful. Next, we describe the development of the text and the SE301 redesign based on the text (Table 1).

<sup>5</sup> The initial problems were problems that the cadets understood, e.g. redesign the cadet laundry system.

## **Development of our textbook**

The first author of this paper decided to begin writing the text during his sabbatical and volunteered to teach our first course “until he got it right.” His original plan was to write the text over several years. When he presented his plan at a department offsite in January 2006, almost every senior faculty member agreed with the need for the text and volunteered to help write a chapter for the text. Based on their enthusiasm he became the editor instead of the author<sup>6</sup>. We determined the book had four purposes. The first purpose was to codify the fundamental knowledge that we wanted our systems engineering and engineering managers to learn as a foundation for their curriculum. Second, we wanted to provide our students a framework to understand the roles of subsequent courses in their curriculum. Third, we wanted the text to provide a resource for additional study and techniques that could be used in their senior capstone research project [8 and 9]. Fourth, we wanted to document our system decision making knowledge based on many successful studies for research and consulting sponsors.

The most important editorial decisions were selecting the topics to be included and recruiting the chapter authors. We organized the book in three parts. Part I provides an introduction to systems thinking approaches including system thinking techniques, system life cycles, systems modeling and analysis, and life cycle costing<sup>7</sup>. Part II provides an introduction to systems engineering, the practice of systems engineering, and systems effectiveness. Part III introduces the SDP and describes the four phases. The final chapter provides a summary of the book. We published three draft editions of the text in Fall 2006, Spring 2007, and Fall 2007. Each edition included significant improvements and new material. The final text was published in early 2008 [4].

## **The SEMP was changed to the Systems Decision Process**

Since the SEMP was not fully documented, the editors and the chapter authors had the opportunity to rethink the SEMP and design a new process. Many of the key concepts were retained: current situation, four phases, environment, the desired end state, and the meaning of the colors. The new process was named the Systems Decision Process (Figure 2) to emphasize the problem solving focus of the department and avoid confusion with the system life cycle. However, some changes were made: the center of the chart was changed from engineering design problem to decision maker and stakeholder value (to put the focus on value), more environmental factors were included, the design and analysis phase was changed to solution design, implementation was changed to solution implementation, tasks in three of the four phases were changed, and outputs of each stage were added to the diagram. The SDP process is characterized by:

- Starting with a description of the current system. The current system, or baseline, is the foundation for assessment of future needs and comparison with candidate solutions to meet those needs.
- Focusing on the decision maker and stakeholder value. Stakeholders and decision makers identify important functions, objectives, requirements, constraints, and screening criteria that are essential for systems decision making.
- Focusing on value creation and defining the desired end state that we are trying to achieve. The value modeling step of the problem definition phase plays an important role in defining the ideal solution for evaluation of candidate solutions. The solution enhancement step improves the

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<sup>6</sup> Subsequently, Professor Pat Driscoll became a co-editor and LTC Dale Henderson become the design editor. Pat wrote two chapters and made many editing improvements. Dale typeset three editions of our text before the text was published by Wiley in 2008.

<sup>7</sup> This chapter was added based on the suggestions of the Wiley Systems Engineering Series reviewers.

alternative design solutions. We use Value-Focused Thinking to improve the non-dominated solutions. Finally, we measure performance in solution implementation to insure we deliver the promised system value.

- Having four phases (Problem Definition, Solution Design, Decision Making, and Solution Implementation) and being highly iterative based on information and feedback from stakeholders and decision makers.
- Explicitly considering the environment (historical, legal, social, cultural, technological, environmental, and economic) that systems will operate within and the political, organizational, moral/ethical, and emotional issues that arise with stakeholder and decision makers in the environment.

Armed with the promise of a new textbook, a revised process, and new introductory course, the Systems Engineering program began its “slow loop” process of assessment. This is the detailed and deliberate process of ensuring the program meets all of its objectives and most importantly, that its objectives are the right objectives for that program. In the next section, we explain how the program assessment influenced the first course.

### **SE program background and assessment**

Academic year 2005 marked the confluence of many factors in the SE program. The program was headed by its fifth program director in five years and the first of the five to not be from a predominantly operations research (OR) background. We had begun to prepare for an ABET accreditation visit through our deliberate program assessment cycle (the “slow loop” assessment process in the ABET vernacular.) The program had not significantly modified its objectives or outcomes since the last ABET visit though many courses had changed their focus. The program had the draft of a new textbook.

The incoming program director (the second author) quickly set out to analyze the program. The complete analysis of the program considered the needs, wants and desires of all of our constituents: The Nation, the Army, the Academy and the West Point community, the faculty and staff, and the cadets. These constituents are represented by three main groups we use to review our program outcomes and objectives. These are the faculty, the alumni, and the Board of Visitors. The analysis to prepare for ABET however started at our last visit’s final report. When ABET accredited the Systems Engineering program in 2003, one of the few recommendations was that “*Consideration should be given to the incorporation of systems engineering technical electives that are aimed at accommodating the cadets’ desire to pursue their personal professional career interests*” [10]. Immediately following the last ABET accreditation, we added a “free” elective to the program so the cadets could choose from a list of electives. We found that the cadets were primarily choosing from the list of mathematics electives. This created essentially a two course mathematics sequence for most cadets, though this proved to be unappealing to other cadets. There were other problems with this additional free math elective.

Members of our Board of Advisors (BOA) consistently suggested that our program was too OR-focused and not enough SE-focused. This BOA, which consists of individuals from military, civilian and academic institutions, selected based on their exemplary professional credentials and their association with the armed forces, to represent the Army and the Nation as customers of the Department, assessed that this additional free elective did not have the intended consequences of adding depth to our SE program but rather more OR depth.

We also asked a Capstone Design team to take a “*Systems Engineering Approach to Analyzing the Systems Engineering Program*”. Their findings, conclusions, and recommendations captured the strengths of the program and the directions we needed to take and are listed below in table 2. The bold

entries are taken directly from the feedback from our three main groups we consult for the direction of the program.

Table 2: SE Program Study Findings, Conclusions and Recommendations [11]

Findings	Conclusions	Recommendations
<ul style="list-style-type: none"> <li>• Fifth Program Director in five years</li> <li>• Changes in courses</li> <li>• <b>Re-look program outcomes and objectives</b></li> <li>• New textbook</li> </ul>	<ul style="list-style-type: none"> <li>• Program not completely aligned with Objectives and Outcomes</li> <li>• Courses not completely aligned with program</li> </ul>	<ul style="list-style-type: none"> <li>• Review and update objectives and outcomes</li> <li>• Review and update program to ensure alignment</li> </ul>
<ul style="list-style-type: none"> <li>• Program pedagogy is to introduce in 301, teach depth in main program and apply in capstone.</li> <li>• <b>Program very math heavy</b></li> <li>• <b>Program light on systems architecture</b></li> <li>• <b>Program weak on functional analysis (only taught in SE301)</b></li> <li>• <b>Lack of understanding of how the courses “fit” in program</b></li> <li>• New text includes lifecycle cost analysis important to systems engineers</li> </ul>	<ul style="list-style-type: none"> <li>• Program focus on math topics at the expense of other SE topics</li> <li>• Include Lifecycle cost modeling in program and other topics in courses</li> <li>• No continuity between courses leads to lack of understanding of approach in capstone</li> </ul>	<ul style="list-style-type: none"> <li>• Increase functional analysis and architecture discussion in program</li> <li>• Align courses to systems process throughout program</li> <li>• Focus on SE topics within program</li> </ul>
<ul style="list-style-type: none"> <li>• <b>Recommendation to allow more opportunity for choice in program</b></li> <li>• Information Engineering program waning</li> <li>• Other universities allow sub-specialties within their programs.</li> </ul>	<ul style="list-style-type: none"> <li>• Include choice as either more electives or directed sub-disciplines</li> <li>• Need at least three courses to make a sub-discipline</li> </ul>	<ul style="list-style-type: none"> <li>• Find three course slots for sub-discipline while maintaining ABET “counting” requirements</li> <li>• Integrate Information Engineering into sub-specialties</li> </ul>

Based on this analysis and recommendations, we developed sub-disciplines to allow the cadets to develop their depth of discipline as recommended by ABET. This was benchmarked against other programs throughout the country. Though this is a significant change for our program, the details of this change are beyond the scope of this paper and so we will continue with a more significant change to our program which is the focus of this paper: the alignment of the program from its first course through our capstone course.

To determine whether our graduates would be able to achieve our program outcomes, we knew that they would have to be able to meet all of them in their capstone course. However, for the cadets to apply all of the required skills in their capstone we had to teach them the skills within the program and we had to introduce them somewhere! Many of the skills would be introduced in the first course and developed in follow-on courses. This drove our program alignment and the redesign of our first course.

Our systems engineering program pedagogy became simple: our program outcomes identify all the things that our graduates need to be able to do; our capstone courses require the cadets to do all the things that our program outcomes require; our in-program courses must teach all the things that our cadets will do in

our capstones; and finally, we have to introduce much of the foundational material that our cadets will do in our capstones in our first course. Another significant finding is that with limited lessons in our limited courses, whatever we teach in our first course must be expanded upon and be required by our capstone design courses. With that guidance, we began to redesign our first course.

### **Redesign of SE301**

In 2005, our first course was renamed Fundamentals of Engineering Design and Systems Management<sup>8</sup> to emphasize the course focus was not just an introduction but instead was the foundational material of our curriculum. To meet the SE program objectives and program outcomes, the new SE301 course was designed based on five course objectives:

- Demonstrate a fundamental understanding of systems thinking including systems thinking techniques; systems modeling and analysis; the system life cycle, and system life cycle cost.
- Understand systems engineering including the need for systems engineering, the roles of systems engineers, and techniques for assessment of system effectiveness.
- Understand and apply the SDP to define, develop, refine, and implement high value solutions for stakeholders in future environments.
- Understand the role of ethics in engineering and recognize the ethical implications throughout the systems life cycle and the SDP.
- Present analysis and recommendations to decision makers and stakeholders.

The text was designed around three foundations that directly supported the course objectives: systems thinking (1<sup>st</sup> objective), profession of systems engineering (2<sup>nd</sup> and 4<sup>th</sup> objectives), and the SDP (3<sup>rd</sup> and 5<sup>th</sup> objectives). SDP techniques were illustrated with one illustrative example, the Rocket Problem which was described in our text.

The unique features of the new course design are summarized in right hand column of Table 2. We began teaching the course with our most experience military and civilian faculty. We introduced new course material, e.g., system life cycle, risk analysis, and life cycle costing, from the text. In addition, we added a student system thinking presentation that requires each cadet to research and present a system success or a system failure using the system thinking concepts in the text. This course project has generated high cadet interest and improved their understanding of systems thinking.

We adopted the two project format used in the SE301 experiment; however, we made the second project a team (4-5 cadets) instead of a class project. We kept the first project, the cadet decision to buy his/her first car using the loan they receive in their third year at the Academy.<sup>9</sup> This project had strong cadet interest and allowed the cadets to understand the underlying mathematics and mechanics of the SDP for a problem that they would be the decision maker and the primary stakeholder. To increase their problem definition and solution design skills, we made the second project an Army problem for a notional Army decision maker. In teams of four, the cadets learn to apply to SDP to solve a design problem. The instructors role play the client decision maker for the projects.

In the past two years, we have used two different concepts for the second project requirement. The first problem was to select components for a weaponized, lightweight unmanned aircraft system (UAS). Currently, lightweight UASs are used for only for reconnaissance without weapon. The cadets applied the SDP to select a UAS vehicle and add a weapon. This problem involved vehicle and component selection. The second problem was to design a temporary vehicle check point for an Iraq/Afghanistan

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<sup>8</sup> Patrick Driscoll instituted these changes the year he was SE program director.

<sup>9</sup> USMA Cadets are not allowed to own and store cars in the local area until after Spring Break their junior year.



scenario. The cadets had to design the checkpoint including sensors, soldiers, and systems to negate potential terrorists without causing collateral damage to innocent civilians. This problem involved system design including system layout and component selection.

Finally, an additional change was the use of grading rubrics to describe our expectations for the class projects [4]. The grading rubric defines a C as work that correctly following the SDP and uses the appropriate techniques. An A is work that is done correctly and is creative and innovative. This is in concert with the guidance from the USMA Dean of the Academic Board [12 and 13].

## Conclusion

At West Point, we strive to educate and inspire cadets to become future Army leaders. The course redesign using our new text has directly impacted about 450 students per year (about 150 majors and 300 systems engineering sequencers). We have received excellent cadet feedback for the redesigned course and we have already found the cadets better prepared to perform their senior research projects. A second target audience has been our faculty. Each year 5-10 new faculty members join our department to teach for three, on average and then return to the Army. These officers have also gained from the curriculum and course changes. We believe that our new text will provide a foundation for continual learning and improvement through its subsequent editions. In the spirit of continuous improvement, we are striving to continue to improve our first course and we are developing material to include in the second edition of our text. The continual improvement of the SE program, the development of our new text, and the redesign of our first course are important milestones that have contributed directly to better educated and more inspired cadets.

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