Capstone Projects: Key to the Lifecycle Development of the Systems Engineer

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The development of an effective systems engineer is a multifaceted and multi-disciplinary process conducted throughout the entire career of the engineer. This process can be accomplished by developing the engineer according to a 'systems engineer' lifecycle. This paper extends the well known systems lifecycle model to the development of the systems engineer while incorporating the use of capstone projects at critical stages of the process. It details the elements of the concept, development, production, utilization, support and retirement stages of the lifecycle as applied to the education and training of the systems engineer. Additionally, this paper emphasizes the importance of strong mentorship in the capstone projects as well as throughout the lifecycle of the engineer.

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Introduction

The increasing complexity of systems under development have pushed both industry and government organizations to have a growing emphasis on systems engineering. These organizations recognize, however, that there is a knowledge gap of qualified systems engineers due to retirements followed by inexperienced replacements. The National Defense Industry Association (NDIA) Systems Engineering Division Task Report identified "The quantity and quality of systems engineering expertise is insufficient to meet the demands of the government and the defense industry" as one of the top 5 systems engineering issues.[1] Systems engineering training and education programs need to help address the increasing and rapidly changing needs of industry and government. NDIA goes on to recommend: "Growing systems engineering expertise through training, career incentives, and broadening 'systems thinking' into other disciplines"[1]. Just as systems engineering stresses a focus on the lifecycle of a system, education and training programs must also address the entire lifecycle of the systems ENGINEER from early education at the undergraduate level, through retirement in order to foster this 'system thinking'. Figure 1 is an adaptation of the International Council on Systems Engineering (INCOSE) Lifecycle that shows the training and education considerations for the development of an effective systems engineer throughout their entire engineering career[2].

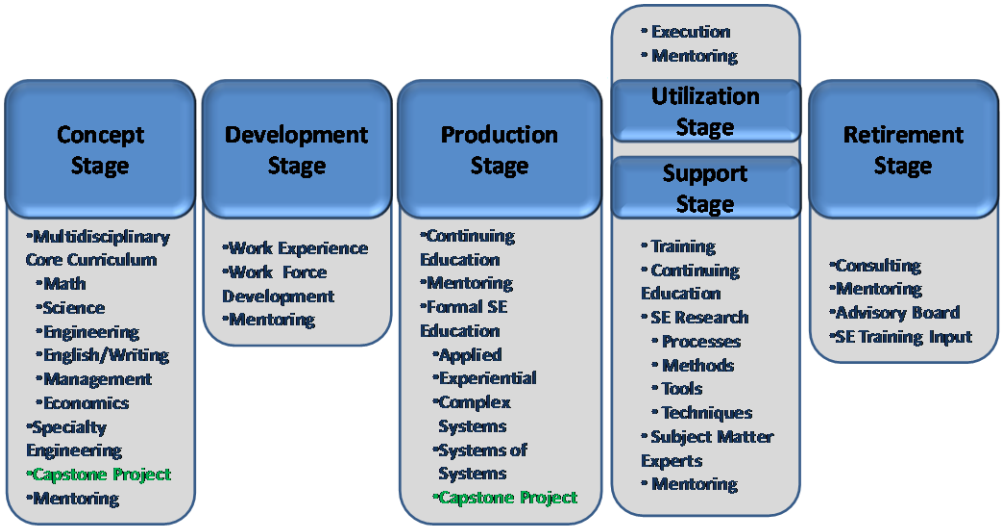

Figure 1. Lifecycle of the Systems Engineer.

One key element of this training is the necessity to have applied engineering / systems engineering experiences. This can happen at all stages of the systems engineer lifecycle but it will have a profound impact in the formal, structured capstone projects in the Concept and Production stages. The following sections provide the details for each stage of a system engineer's education and career development along with the integration of capstone projects at these critical stages.

Lifecycle of the Systems Engineer

Similar to a system lifecycle, the systems engineer lifecycle has distinct stages which result in the completion of major milestones. The capstone projects represent the major milestones for both the concept and the production stages. The capstone projects not only impact these two stages but feed and utilize the expertise developed throughout the systems engineer lifecycle. Note that mentoring is common across all of the systems engineer lifecycle stages. During the first three stages, the systems engineer is primarily the mentee whereas in the later stages, the systems engineer moves increasingly toward the role of mentor. Figure 2 displays the interconnection of the capstone projects throughout the development of the systems engineer.

Concept Stage. This first stage is accomplished primarily through an undergraduate college education and includes a multidisciplinary core curriculum, an integrated focused engineering curriculum including hands-on laboratory experiences, applied engineering challenges that include capstone projects, and a strong engineering mentorship program. An understanding of fundamental engineering disciplines is essential to every systems engineer. Preparing students for engineering design and development requires a strong multidisciplinary core curriculum. Courses in electrical, mechanical, aerospace, and software engineering are the foundation for dealing with the issues systems engineers will grapple with throughout the system development. Equally important, but much less emphasized are courses in English, management, economics, and finance. Through these courses, students learn principles that will help them develop program budgets and schedules as well as how to manage systems engineering teams. Students also learn key communications skills needed to convey their design concepts in writing and through presentations.

Next, to capitalize on the fundamental knowledge developed through this core curriculum, the students need exposure to an integrated focused engineering program that brings these disparate disciplines together. The students are not ready to be systems engineers at this point but encouraging them to start making the connections between the disciplines will led them down the path of becoming "systems thinkers". To augment these learning experiences, interactive laboratories should be incorporated to address specific applications, tools and technologies related to their discipline.

To complete the fundamental engineering educational experience, students must be presented with an applied engineering challenge, the capstone project. The teaching philosophy for this part of the program should be to learn-by-doing. Ideally this would be the development of an actual system but conceptual design

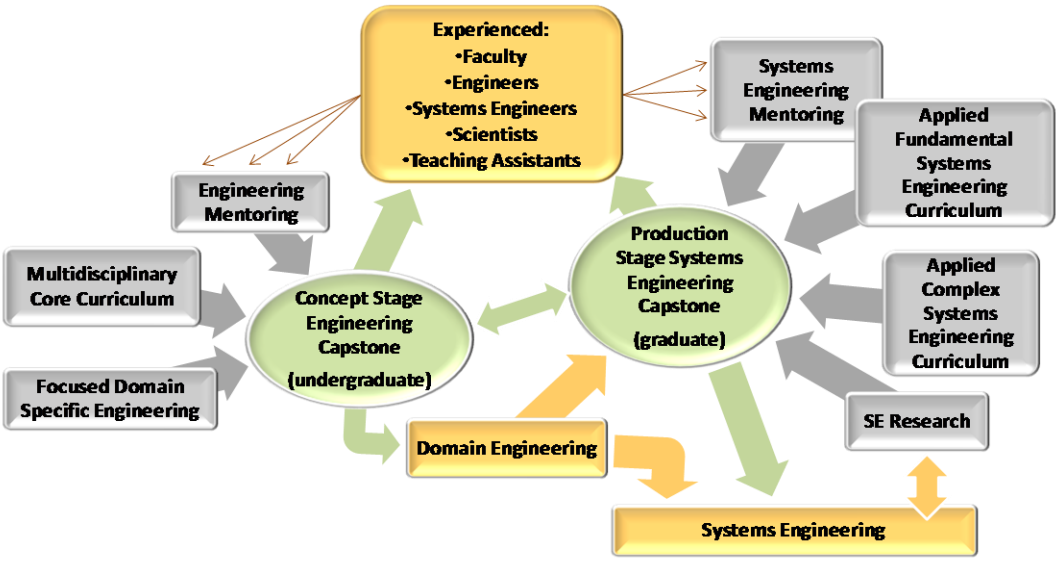

Figure 2. Capstone Role in the Systems Engineer Development

projects can be equally effective. The goal of these challenges is to give students an opportunity to deal with problems that are somewhat open ended, ill defined, and do not have just one right answer. Initially, students may have a difficult time taking the leap to using problem solving techniques that rely heavily on collaboration and creativity. But they should be encouraged and trained to take this critical step in their education since it will set the stage for them to become great systems engineers in the future. Experienced faculty, industry engineers, and teaching assistants take on the role of mentor for this concept stage capstone program. The formulation of this mentor community is detailed in a later section.

Development Stage. The development stage provides the future systems engineer the opportunity to the gain work experience and exposure to a number of engineering and program related tasks. The goal at the completion of the systems engineer's development stage is to obtain extensive experience in a technical field, be it engineering, science, software development, or other technical concentration. This experience is the foundation that the systems engineer will draw from in the future. As Malcom Gladwell writes in his book, *Outliers: The Story of Success*, "Ten thousand hours is the magic number for true expertise"[3]. The future systems engineering should be striving to develop this kind of expertise in their chosen technical field.

The engineer at this stage of development draws heavily from their concept stage, where the capstone program should play a significant role in preparing them for this continued development. Most successful companies also have training programs in place to develop their workforce for the company's future needs. Job rotations also provided an applied experience in a variety of different engineering and program management jobs throughout the company. The key to the success for the job rotation experience is a strong mentoring program as well.

Production Stage. In the production stage, the engineer begins to develop skills specific to systems engineering through formal systems engineering training programs. Formal programs look at the systems engineering process as a multifaceted and multi-disciplined function within and between organizations. They focus on the engineering of systems and the development of a systems engineering mindset through "systems thinking". Here the systems engineer receives education and training through continuing education programs, systems engineering master's degree, and of course, mentoring.

These formal programs provide a continuum of lifelong learning opportunities for the systems engineer and should be geared toward the practicing engineer with substantial engineering experience. They should provide the students with practical knowledge that can be applied immediately at the work place and further the systems engineer along the lifecycle. The application of systems engineering processes, methods, and tools applied to real world problems leads quite practically to another capstone project opportunity. Again, the capstone project is a major milestone in the completion of this stage. The objective of the production stage capstone project is to present the students with a complex systems engineering problem that encompasses multiple domains. Students work as teams in applying the methods and techniques taught and developed through their formal training as well as their own work experience. This capstone project provides an addition benefit beyond the students learning opportunity. It can also opens up opportunities to collaborate with the students' training sponsors to develop projects that address the specific systems engineering needs of their companies. Industry ties at this stage can and should be utilized to develop realistic, attainable, and meaningful capstone projects.

The end result of the production stage for the systems engineer is the development of a systems perspective that addresses a number of issues. First, the systems engineer must learn to define, develop, and understand customer requirements, which is enabled through effective communication with a customer, both graphically and in writing. He/she must effectively work using established systems engineering methods, techniques, and tools, which requires understanding terminologies associated with systems engineering and managing cost, schedule and risk associated with program management functions. The goal is to gain a true appreciation for the multidisciplinary aspects of systems engineering.

Utilization Stage. During the utilization stage, the systems engineer develops through execution of the skills learned as applied to their day to day job, in other words, through "real world" experience. Here, the systems engineer utilizes those established methods, tools, and processes developed primarily through research and refined from previous experience and application. The utilization stage results in an experienced systems engineer that can capitalize on the leading edge systems engineering research to support their programs. The system engineer also transitions from the mentee to the mentor, with an opportunity to provide valuable input to the capstone projects in the Concept and Production stages.

Support Stage. In the support stage, the systems engineer begins to develop him/herself as a subject matter expert, and now is able to provide formal mentoring to systems engineers in early phases of development in addition to receiving valuable mentoring from more senior systems engineers. The support stage is where methods, processes, and tools are

developed and transitioned to enable utilization and should also be fed back to earlier training programs.

Retirement Stage. Finally, at the retirement stage the systems engineer serves primarily as a consultant, mentoring, advising, and providing input to systems engineering training. Unlike a systems retirement stage, the system engineer's retirement stage does not equate to removal and disposal. This stage of the systems engineer's lifecycle requires the continued participation of the "retired" systems engineer to influence future systems engineers progressing through the lifecycle. This influence comes in the form of consulting, mentoring, advisory and review board participation, and training program input.

Role of Capstone Mentorship in the Development of the Systems Engineer

Although classroom instruction is important for successful education programs, dedicated mentors are vital for the success of applied engineering programs. Mentorship is the most powerful and essential element of a thriving program. Mentorship takes on two forms for these programs: formal and informal. Formal mentorship is geared toward faculty and staff sharing their expertise and skills in a given area with students to improve their understanding, confidence in, and application of these skills. For example, the Georgia Tech undergraduate program capitalizes on the expertise its faculty mentors bring from research and prior work experience, such as the Air Force Research Lab, Jet Propulsion Lab, and NASA, to provide technical support and facilitate rapid development of student skills. Industry partners also play a key role in mentoring by their participation in formal reviews, acting as Principal Investigators, and sharing their subject matter expertise through guest lectures and breakout sessions[4].

Informal mentorship, although less structured, provides valuable transfer of knowledge as well. Informal mentorship comes from three main sources: teaching assistants, students from previous classes, and classmates of current students. Teaching assistants (TAs) for these courses should be chosen, when possible, from a pool of graduate students who have successfully completed earlier design programs. TAs should interact frequently with students providing them with support on homework and projects as well lessons learned from their experiences. The TAs should also participate in reviews and breakout sessions. Additionally, other successful graduates should be brought in to participate in classroom panel discussions where they get to tell their "war stories" about the capstone projects. And finally, students enrolled in the program mentor each other through shared co-op, internship, research, and engineering experiences.

Mentorship provides the program with the corporate knowledge necessary for the programs to continue to improve and advance; and the rewards are endless. Students reap the benefits of working with experts in the field enabling them to develop skills beyond what classroom instruction can provide. And when students see how dedicated the mentors are to the success of the program, they too develop a greater commitment to their work. However, the authors strongly believe that mentors gain the most by giving part of themselves to enable the students succeed. The pride mentors take in seeing the students excel is why many do their job.

Conclusion

The development of an effective systems engineer is a multifaceted and multi-disciplinary process conducted throughout the entire career of the engineer. This process can be accomplished by developing the engineer according to a 'systems engineer' lifecycle.

Similar to a system lifecycle, the systems engineer lifecycle has distinct stages which result in the completion of major milestones. The concept stage results in an undergraduate domain specific engineer ready to become a "systems thinker". The development stage results in an experience engineer, competent in their domain. The production stage results in a systems engineer equipped with systems engineering processes, methods, techniques and tools. The stages following production include two parallel tracks; the utilization stage where the engineer develops through execution, and the support stage, where methods, processes, and tools are developed to enable execution. And finally, the retirement stage enables the extensive experiences of the retired systems engineer to be feedback through the lifecycle to benefit upcoming engineers.

Key to the continued growth of the systems engineer is the introduction of capstone projects at critical stages of their training: the concept stage and the production stage. The capstone projects not only impact these two stages but feed and utilize the expertise developed throughout the systems engineer lifecycle.

References

1. National Defense Industrial Association (NDIA), Top 5 Systems Engineering Issues within DOD and Defense Industry Task Report, July 26-27, 2006.
2. INCOSE, *Systems Engineering Handbook v3.1*, 2007.
3. Gladwell, Malcom, *Outliers: The Story of Success*. Little, Brown and Company, New York, 2008.
4. Bishop, C.A., "What Can Undergraduates Really Do? You Might be Surprised." INCOSE INSIGHT Special Feature, Space Systems: Navigating Complexity to Explore the Unknown, Vol. 11, Issue 5, Dec 2008.