Academic Perspectives of Systems Engineering

Samuel J. Seymour and Ronald R. Luman

Systems engineering at APL addresses the disciplined design, integration, testing, and decision support necessary to develop complex systems that contribute to meeting critical national challenges. Systems engineering is so essential to meeting the needs of the public and private sectors that academic education in systems engineering will continue to increase in demand. However, the field of systems engineering is relatively young and dynamic, with significant upward trends apparent in graduate education at both the master's and the doctoral levels, emphasis on research and quantitative methods, and competition from regional and national universities for students and research funding. As we look to the future, The Johns Hopkins University Whiting School of Engineering and APL are taking measures to meet the challenges associated with these continuing trends, to identify needs in systems engineering education as they emerge, and to determine how to best address those needs. It is an exciting time to be a systems engineer.

INTRODUCTION

Understanding of the context, evolution, and maturity of the systems engineering field is important for projecting future academic directions and issues. In this article, a perspective of this environment will set the stage for examining the plans of the academic community and The Johns Hopkins University (JHU) to educate future systems engineering professionals. The professional organization for systems engineers, the International Council on Systems Engineering (INCOSE), is also advancing the field by publishing a guidebook[1] and by starting a professional certification program for systems engineers. It is important to recognize the need for a strong "pipeline" starting in secondary schools that fosters interest and careers in science, technology, engineering, and mathematics (STEM) to provide sufficient numbers of qualified individuals to fill future systems engineering positions. Finally, our look into the future will conclude with a discussion of the challenges that exist for all levels and locations of academic programs.

PERSPECTIVES OF SYSTEMS ENGINEERING

Although the systems engineering field has matured rapidly in the past few decades, a variety of different perspectives will continue to exist as more is learned about the potential and the utility of systems approaches to solving the increasingly complex problems around the world. Table 1 defines these emerging conceptual approaches to systems engineering.

Because tackling the most complex and challenging problems often requires professional experience in addition to education, developing a "systems mindset"—that is, the ability to "think like a systems engineer"—is a high priority at any stage of life. As the field matures, three principal, complementary conceptual approaches are emerging: systems thinking, systems engineering, and engineering systems.

An approach to understanding the environment, process, and policies of a systems problem requires one to use *systems thinking* (sometimes known as *systems analysis*). This approach to a problem examines its domain and scope and defines it in qualitative terms. One first looks at the parameters that circumscribe the problem; then, through research and surveys, develops observations about the environment in which the problem exists; and finally generates options that could address the problem. This approach would be appropriate for use in secondary schools and undergraduate curricula to help young students gain an appreciation of the "big picture" as they learn fundamental science and engineering skills, as well as in more nontechnical fields where concepts have more importance than products.

The *systems engineering* approach addresses the products and solutions to a problem required to develop or build a system. The approach is technical, seeking detailed information from future users and developers of the envisioned system regarding their top-level needs, requirements, and concepts of operations before then creating a functional and physical design, developing detailed design specifications, and finally producing and testing a system solution for the problem. Rigorous attention is given to the subsystem interfaces and the need for viable and tangible results. The approach and practical end has been applied to many degrees of complexity, and successful field operation of a product is expected. The proven reliability of the systems engineering approach for product development is evident in many commercial and military sectors.

The broader *engineering systems* approach addresses extensive, complex societal problems by integrating appropriate domain expertise in engineering, science, management, and the social sciences as necessary with the use of advanced modeling. The intent is to tackle some of society's grandest challenges having significant global impact by investigating ways in which complex systems behave and interact with one another, including social, economic, and environmental factors. The approach integrates engineering, social sciences, and management disciplines without the implied rigidity of the systems engineering process. Hence, applications to critical infrastructure, medicine, health care delivery, energy, environment, information security, and other global issues are likely areas of attention.

Much like the proverbial blind men examining the elephant, the field of systems engineering can be considered in terms of the various domains and areas where it is applied. Based on the background of the participants and on the needs of the systems problems to be solved, the systems environment can be discussed in terms of the fields and technologies that are used in the solution sets. Another perspective can be taken from the methodologies and approaches used to solve problems and develop complex systems. As in any mature discipline, there exist for systems engineering a number of processes to organize and enhance the effectiveness of the systems engineering professional. Each of these perspectives is discussed in the following sections.

Table 1. Comparison of systems perspectives.

Systems Thinking	Systems Engineering	Engineering Systems
Focus on process	Focus on the whole product	Focus on both process and product
Consider issues	Solve complex technical problems	Solve complex interdisciplinary technical, social, and management issues
Evaluate multiple factors and influences	Develop and test tangible system solutions	Influence policy and processes and use systems engineering to develop systems solutions
Include patterns of relationships and common understanding	Meet requirements, measure outcomes, and solve problems	Integrate human and technical domain dynamics and approaches

Systems Scope

To understand the scope of systems engineering and what a systems engineer must learn to carry out the responsibilities involved in guiding the engineering of a complex system, the general scope and structure of that system must be defined. Yet, the definition of a "system" is inherently applicable to different levels of aggregation of complex interacting elements. Graphically, this is shown in Fig. 1, where increased system scale is compared with increased complexity of the system entity. As the complexity increases, typically the number of participants or players increases, from a single investigator or developer, to small technical teams, to larger development groups, to corporations, even to multinational systems development teams.

For example, a missile weapon system has a set of electronic devices consisting of boards or processing components for, say, a navigation subsystem. The navigation subsystem, along with the guidance, control, and sensor subsystems, is included in the missile aerodynamic system. The aerodynamic system, along with, say, the propulsion, payload, and communication systems, make the weapon system-of-systems. This, in turn, could be part of an Aegis Combat System, which could be an element of the national Ballistic Missile Defense System (BMDS). Finally, we encounter even more complexity in the multinational family of systems.

Systems Domains

With a broad view of systems development, it can be seen that the traditional approach to systems now encompasses a growing domain breadth. And much like a Rubik's Cube, the domain faces are now completely integrated into the systems engineer's perspective of the "big (but complex) picture." The systems domain faces shown in Fig. 2 include not only the engineering, technical, and management domains but also social, political/legal, and human domains. These latter, softer dimensions require additional attention and research for their impact and utility in systems development to be fully understood, especially as we move to areas at the enterprise and global family-of-systems levels of complexity.

Particularly interesting domains are those that involve peculiar scales, such as nanosystems and microsystems, or systems that operate (often autonomously) in extreme environments, such as deep under the sea or in outer space. These are domains in which APL excels in engineering systems, as the articles in this issue show. Much as physical laws change with scale, does the systems engineering approach need to change? Should systems engineering practices evolve to address the needs for submersibles, planetary explorers, or intravascular robotic systems?

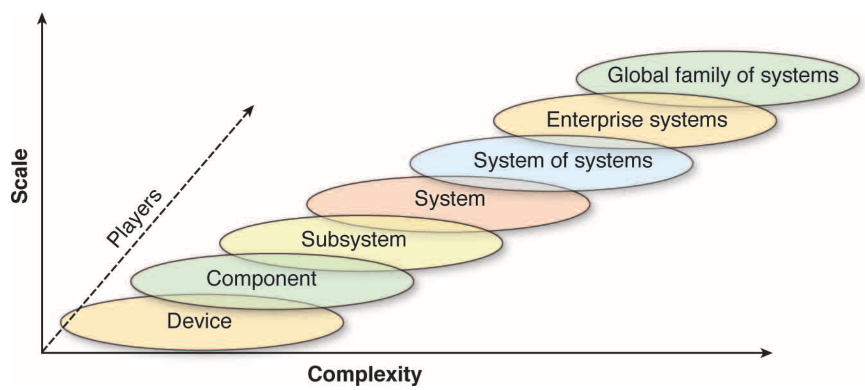

Figure 1. The scope of systems in terms of scale and complexity.

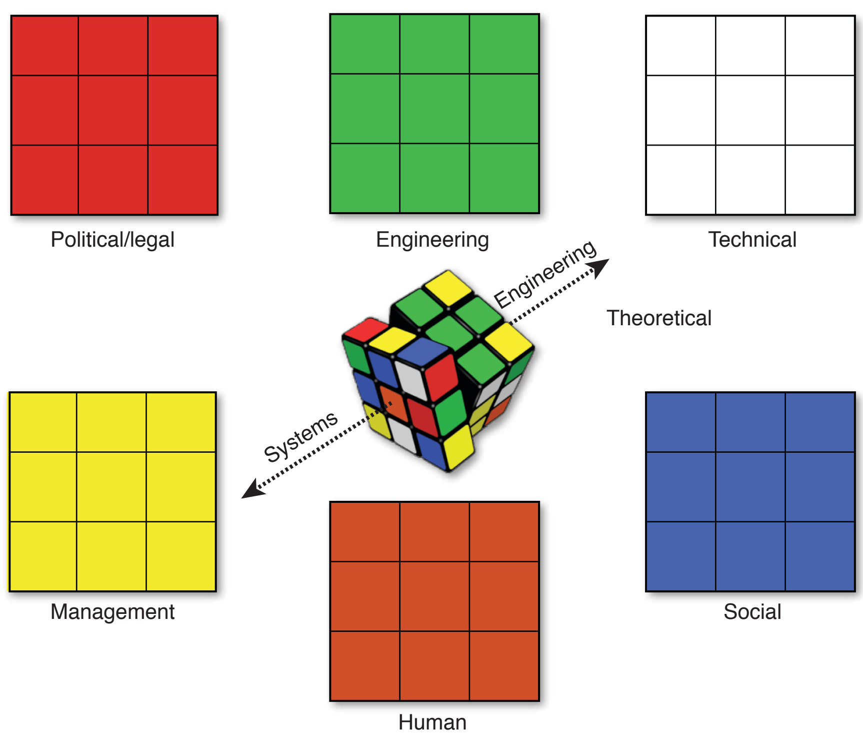

Figure 2. Systems engineering domains.

Relationship of Systems Engineering to Other Fields

From both an academic and a professional perspective, systems engineering bridges the traditional engineering disciplines—such as electrical, mechanical, aerodynamic, and civil engineering, and others—because systems engineering often requires multiple disciplines to develop a complex system. Each engineering specialist looks at systems engineering with a perspective most strongly from his or her own engineering discipline. Similarly, because systems engineering is a guide to the design of systems often exercised in the context of a project or program, the functional, project, and senior managers consider the management elements of planning and control to be key aspects of systems development. The management support functions that are vital to systems engineering success—such as quality management, human resource management, and financial management—can all claim an integral role within and perspective about the systems development.

These perceptions are illustrated in Fig. 3. Additional fields that represent a few of the traditional areas associated with systems engineering methods and practices are also shown. An example is the area of operations research in which the view of systems engineering includes an approach that will lead to quantitative analysis of alternatives and optimal decisions. The design of systems also has a contingent of professionals who focus on the structures and architectures. In areas as diverse as manufacturing and autonomous systems, another interpretation of systems engineering comes from engineers who develop control systems and who lean heavily upon the systems engineering principles that focus on management of interfaces and feedback systems. Finally, the overlap of elements of modeling and simulation with systems engineering provides a perspective that is integral to cost-effective examination of systems options to meet the requirements and needs of the users. As the field of systems engineering matures, an increasing number of perspectives from various fields will adopt it as their own. This evolution will influence the academic content of future systems engineering programs.

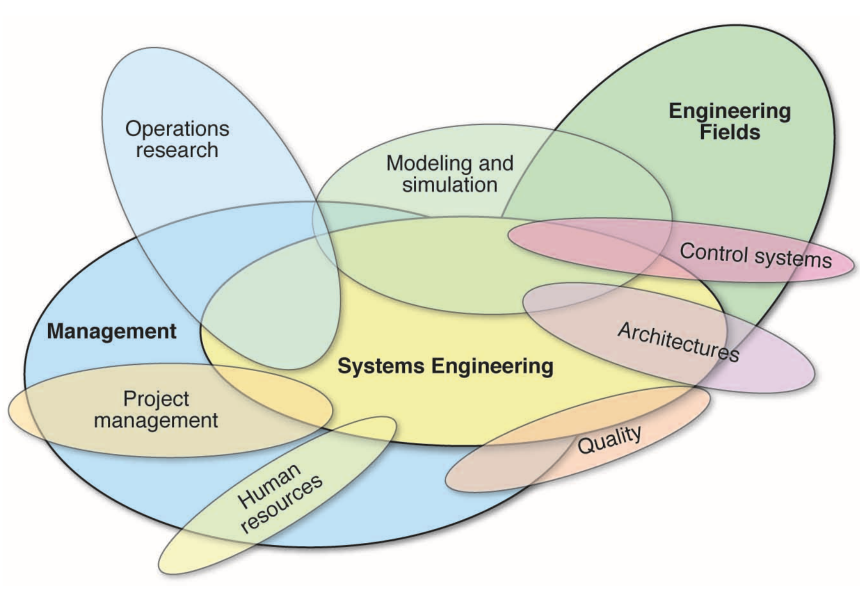

Figure 3. The interfaces of systems engineering to other fields.

Evolution of Systems Engineering Models

Significant attention is given to systems engineering processes and methodologies used in the execution of design, development, integration, and testing of a system. Figure 4 shows several well-known examples of systems engineering process models. Although each model has served a particular need, the sheer variety of process models has fueled controversy as to the essence of systems engineering, in and of itself, and has contributed to the evolution of the three perspectives discussed above and outlined in Table 1. Early graphic representations of systems engineering show linear process flow with sequences of steps that are often iterative to illustrate the logical means to achieve consistency and viability. Modest variations resulted in waterfall charts that provide added means to illustrate interfaces and broader interactions. The recognition that many steps are repeated and depend on each other then leads to the spiral conceptual diagrams. The popular systems engineering "V" diagram provides a view of life-cycle development with explicit relationships shown between requirements and systems definition and the developed and validated product.

The systems engineering "loop" diagram discussed throughout this issue (see the Guest Editors' Introduction) was derived primarily from the linear and waterfall models described by Kossiakoff and Sweet.[2] It captures the unique attributes and best practices learned from decades of systems engineering work at APL. A broader perspective, shown in Fig. 5, provides a full life-cycle view and includes the management activities in each phase of development.

It is in this environment of diverse perspectives—in definitions, scope, domains, contributing fields, and methodologies—that academic programs need to sort out, explain, and reintegrate into comprehensive and practical curricula to meet the needs of many stakeholders and users. Whereas early academic courses were driven and focused by DoD needs, increased complexity and breadth of problems have resulted in expanded

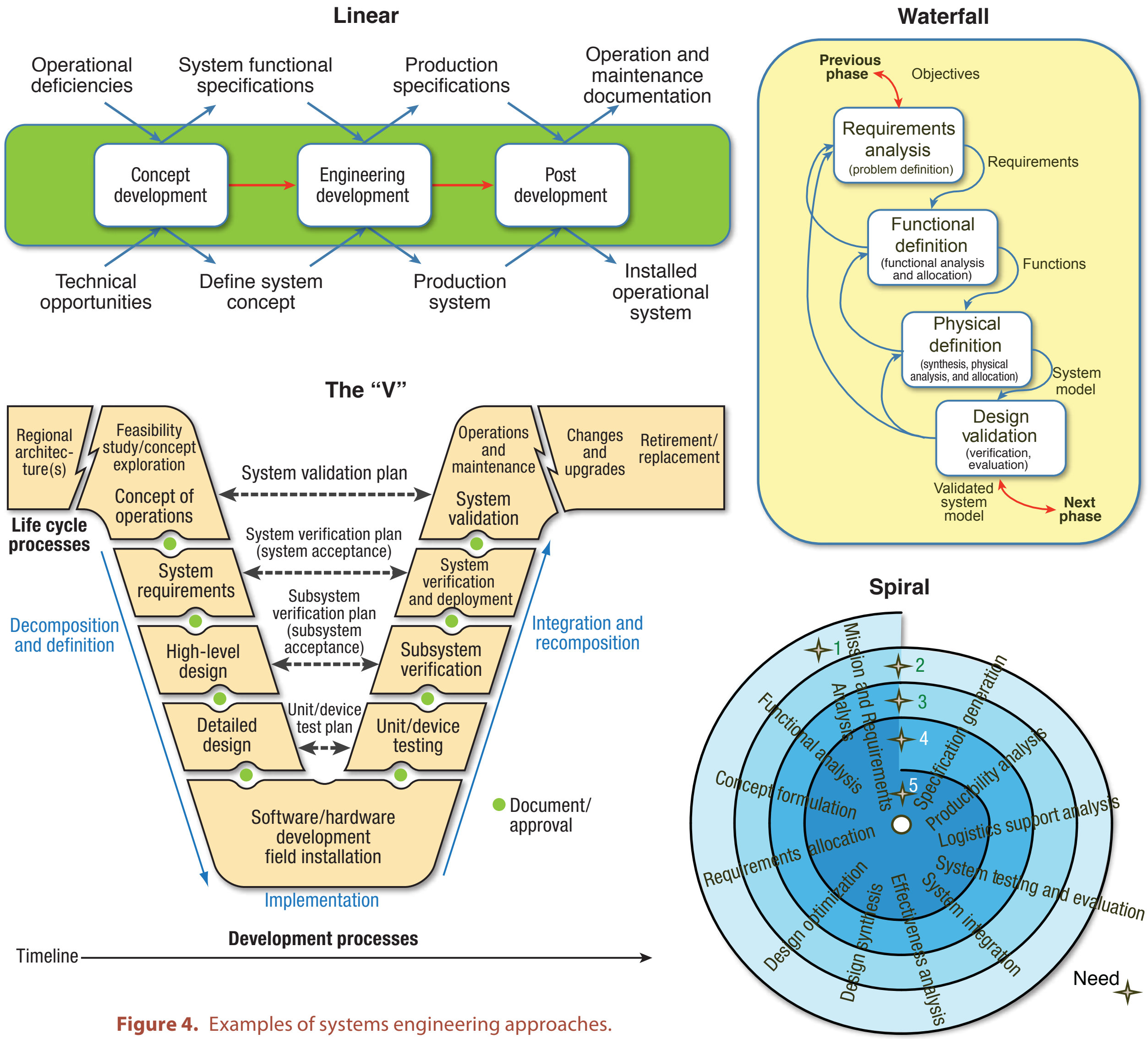

Figure 4. Examples of systems engineering approaches.

curricula in many new domains. In the following sections we show that the JHU systems engineering program has led in many of these trends, with many new systems engineering master's degree concentrations, coverage of new methodologies and tools, and innovative research approaches, including a new Systems Institute.

THE JHU MASTER OF SCIENCE IN SYSTEMS ENGINEERING PROGRAM

APL has been applying systems engineering practices since its origins in World War II, but not until the late 1980s was the Laboratory experience applied in an academic context. Dr. Alexander Kossiakoff, a former director of the Laboratory, recognized that the process of training systems engineers through on-the-job experience was not ideal. There was a clear need in government and other large defense contractors for more and better-qualified systems engineers to address increasingly complex problems in both the commercial and the military domains. The new program, established within the JHU Whiting School of Engineering and managed by APL, developed rapidly; it currently is the largest systems engineering program, in terms of enrollment, in the United States. The master of science program was discussed in a previous issue.[3]

The JHU master's program in systems engineering balances theory with practice and provides course offerings that enable students to pursue a multidisciplinary degree. The curriculum, with its variety of in-person classes, online classes, and industry partnerships, satisfies the professional needs of employees in government and private industry. The systems engineering concentrations available include systems engineering, program management, biomedicine, software, information assurance, and modeling and simulation.

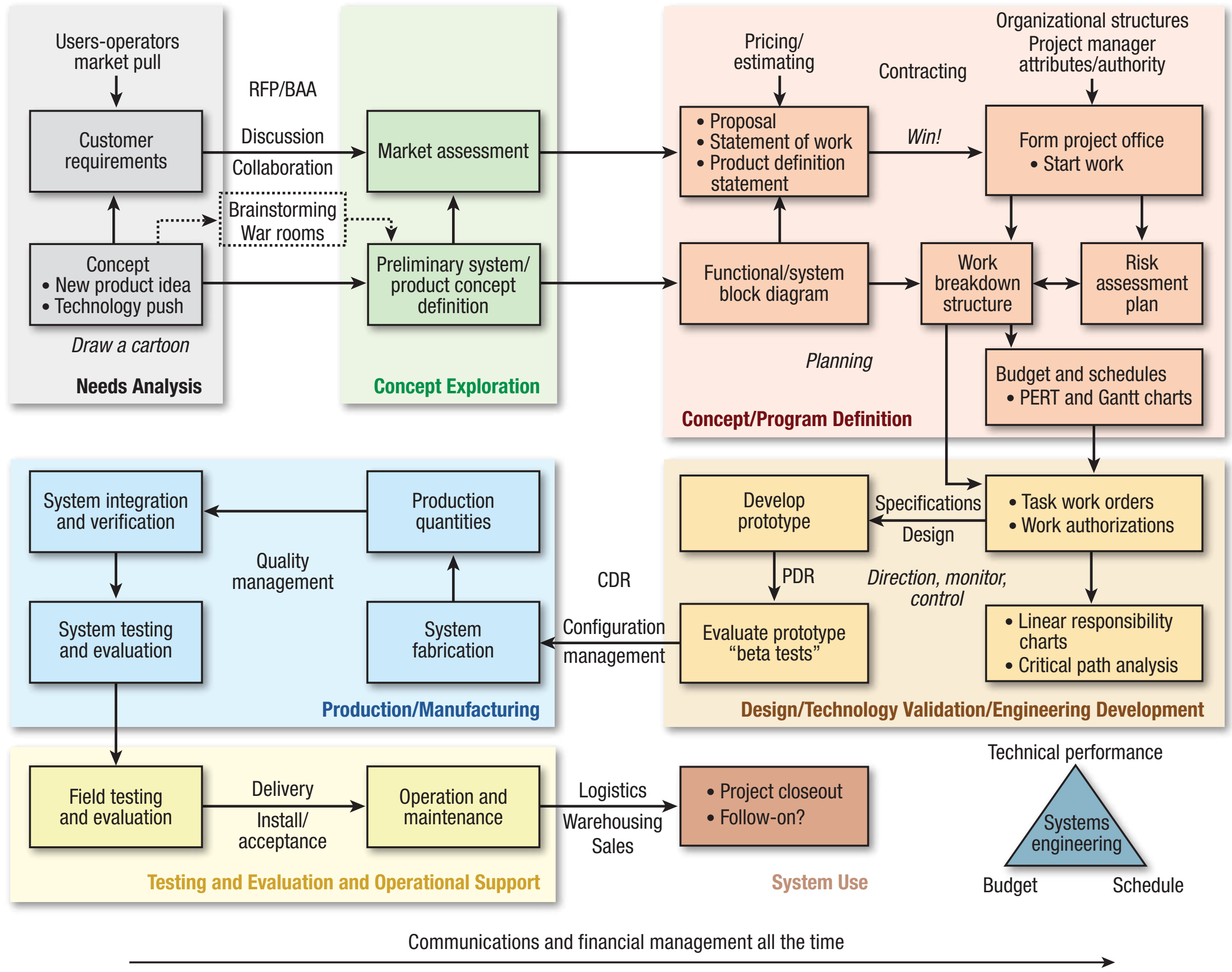

Figure 5. Life-cycle systems engineering view. CDR, critical design review; PDR, preliminary design review; RFP/BAA, request for proposal/broad agency announcement.

The students are committed, serious, and interested in learning. The students' employers are equally divided among commercial, federal government, and defense contractors. The majority of students take courses in pursuit of a professional master's degree that will help them with their careers. A small percentage of students later seek to pursue a doctor of philosophy (Ph.D.) degree, and more will seek to do so in the future. The capstone Systems Engineering Project course is very challenging, and students often use it to enhance a major systems engineering program for their employers or clients.

The faculty members are devoted to teaching and to sharing their knowledge and experience in a classroom setting. They routinely receive excellent student reviews. They have strong technical backgrounds in systems engineering and management, and they bring a balanced perspective to their courses. The extensive professional experience of the faculty often gives them the flexibility to teach multiple subjects.

JHU systems engineering faculty recruitment and retention statistics over the past 4 years reveal a dynamic situation, reflecting program growth and naturally high career demands on faculty who are full-time professional systems engineers and managers:

- There were 52 part-time faculty in 2005–2006 and 90 in 2010–2011, an increase of 73%.
- Only 22 members of the current faculty were teaching systems engineering in 2005–2006, a cumulative turnover rate of 58%.
- A total of 54% of the 2005–2006 faculty and 48% of the 2010–2011 faculty are from APL.
- Of the 90 current faculty members, 43 are from APL, 17 are from Raytheon, 7 work for the U.S. government, 5 are from MITRE, 4 work for Northrop Grumman, and 14 are otherwise affiliated.

The quality of the program is addressed in a very proactive manner. Student questionnaires are administered every term, and faculty members are encouraged to refine their teaching based on these reviews. Faculty members are also encouraged to attend regular faculty workshops offered by the Whiting School of Engineering. In 2007, a comprehensive review of the program was conducted that resulted in development of new courses, new concentrations, and an effort to integrate more quantitative methods into the curriculum. In 2011, JHU's program will be reviewed by the Accreditation Board for Engineering and Technology (ABET) under its new graduate systems engineering accreditation process.

The need for a strong academic program is evidenced not only by high student demand but also by growing dissatisfaction with the cost overruns and delays in many large government programs. Major contractors continue to face stop-work and termination orders because of ongoing problems with large systems. It is apparent that there is a major and continuing crisis in advanced systems development that requires a stronger educational systems engineering foundation.

In addition to defense and aerospace systems, other domains have recognized that systems engineering principles and methods are essential for successfully addressing broad challenges. Among them are health systems, environmental systems, enterprise systems, telecommunications systems, and advanced manufacturing systems. All of these systems involve complex hardware and software, extensive technical support, life-cycle engineering, and advanced user interfaces for successful application.

The growth of systems engineering is also evidenced in the number of academic programs and graduates in the area, at both the master's and the doctoral levels. Some surveys note that systems engineering is a favored and potentially excellent career path (for example, systems engineering was ranked number 1 in *CNN Money Magazine*'s 2009 survey of the best jobs in America[4]), which will only continue the acceleration in demand for education in systems engineering. Employers in all sectors, private and government, seek experienced and credentialed systems engineering candidates. Since 2000, the number of systems engineering graduate programs has quadrupled to 80 universities offering academic advanced systems degrees.

JHU SYSTEMS INSTITUTE AND PH.D. PROGRAM

This growth in demand for systems engineering education has also created upward pressure on systems engineering research and associated doctoral programs. Indeed, many universities that offer the master's in systems engineering now also offer the doctorate. Graduates of the JHU Systems Engineering Master's Program have gone on to doctoral studies in systems engineering at George Washington University, George Mason University, Stevens Institute of Technology, University of Virginia, and Old Dominion University. In fact, 15 of the top 25 engineering schools in the nation now offer the Ph.D. or doctor of science (Sc.D.) in systems engineering.[5]

JHU is now creating a Systems Institute and forming a new Ph.D. program in engineering systems. The purpose of the new institute is to provide a structure to foster systems engineering education and research throughout the university, to enhance economic development in the mid-Atlantic region, and to establish JHU as the preeminent leader in systems engineering. The Systems Institute will administratively report to the Whiting School of Engineering but operate as a central, interdivisional entity that enables the university to focus its broad research talent on "grand systems" challenges that are critical to the national interest. It is envisioned that teams of faculty and students from the Whiting School, the Schools of Education, Public Health, Medicine, and Business, and APL will form the institute and participate through joint appointments. Plans are to establish the Systems Institute in 2011 to meet the pressing demand for systems research collaboration across JHU divisions and to enable Ph.D. students to matriculate in the near future.

The structure and mission of the Systems Institute will be modeled in part after the very successful Engineering Systems Division (ESD) at the Massachusetts Institute of Technology (MIT). Rather than defining research interests along systems engineering competency areas, the Institute's research areas are defined by grand systems challenges in five domains of national interest. Initially these domains will be medicine, health care delivery, network-enabled systems, information assurance, and national infrastructure.

A distinguishing feature of the engineering systems approach is that, rather than seeing prevailing economics and public policies as boundary conditions to systems solutions, they are considered part of the systems' trade space. Hence, broad collaborative teams are invited to address these grand systems challenges. This engineering systems perspective is particularly suited to capitalize on the strength of the JHU research community and will enable the university to truly make a difference in these critical domains. Moreover, because most of the doctoral students will be drawn from the ranks of working professional systems engineers, their dissertation research time will effectively be a dedicated intellectual sabbatical to address critical systems challenges, after which they will return to even more significant leadership in their respective private or public sector domains.

ACADEMIC RESEARCH

An additional academic challenge is where to focus research in the field and how to make it useful in effectively addressing future systems challenges. Typical research in systems engineering will focus on surveys for best practices and will advance systems engineering processes and tools. Research in engineering systems will begin with addressing a critical aspect of a grand systems challenge but will also end up advancing systems engineering processes and tools, perhaps tailored to the domain of interest. The challenge will be to make the research practical and readily available to the acquisition and development communities for application to a broad range of systems problems. Research will revitalize and sustain undergraduate programs on a regular basis, providing up-to-date case studies, references, new approaches, and trends that students can help to define.

THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

In 1990, INCOSE was founded to advance the field of systems engineering and raise professional standards. This organization is important to any university or organization involved in systems engineering. All of the major defense contractors are involved in INCOSE, and several leading universities are dominant players, including JHU, which is a member of the Corporate Advisory Board. INCOSE has developed a systems engineering guidebook[1] and has certified professionals in systems engineering based on the content of the guidebook. It is likely that the number of professional systems engineers will increase substantially in the future through graduate degree programs and through INCOSE certification. Federal contracts are likely to require such credentials for participation in future systems acquisition development.

APL SYSTEMS ENGINEERING EDUCATION

APL is intensively engaged in systems engineering through its contracts with the DoD and NASA. Its future success depends in part on excellence in systems engineering. Like its industrial counterparts, APL needs continuing education, active research and development programs, and visibility in systems engineering to compete successfully for new opportunities.

APL will continue to address critical challenges that will require broader and more advanced application of systems engineering knowledge and skills. As part of the APL Quality Management System, APL systems engineering processes and best practices have been documented, as described in the article by Fong et al. elsewhere in this issue. Each summer, APL staff members have the opportunity to take, for graduate credit, the Whiting School of Engineering onsite Introduction to Systems Engineering course. This past year, 15 APL staff members completed the course. A new APL initiative for early-career staff was started in 2010 with a cohort who addressed a challenging systems engineering problem for the U.S. Pacific Command. The format is based on a program held for many years at APL called the Associate Staff Training Program. Another systems engineering initiative, the APL Systems Engineering Competency Advancement (ASECA) program, was started in 2010 to provide an understanding of the APL approach to addressing complex systems problems. Targeted to large numbers of APL early- to mid-career professionals, the 40 h of discussions, lectures, and group activities follow the systems engineering loop. The program is led by seasoned APL experts and leaders who will make use of materials from the Whiting School of Engineering master's program as well as many examples and stories of APL-sponsored work. APL will continue such activities to maintain a leadership position and develop new products that are fit for use in an evolving and complex environment.

SCIENCE, TECHNOLOGY, ENGINEERING, AND MATHEMATICS (STEM) EDUCATION

It has long been recognized that our nation is falling behind in educating our youth and encouraging them to pursue science and engineering careers.[6] Experts in workforce development look for ways to encourage more secondary school and college students to pursue degrees in STEM disciplines. With experience and additional knowledge, these students would mature into capable systems engineers. APL continues to engage in secondary school and college STEM projects and mentoring activities to sustain a vital pipeline of highly qualified graduates, many of whom return as regular employees. In the future, these activities will become increasingly important to APL's ability to capture and retain the skilled engineers needed to address national critical challenges. Table 2 lists a number of examples of STEM-related programs that APL either created or now supports to address the critical education needs in this area. After many years, APL benefits by having many very talented individuals who started in the APL high school mentoring program eventually return to full-time employment at the Laboratory.

SYSTEMS ENGINEERING ACADEMIC CHALLENGES

As the field of systems engineering matures, increased diversity, demand, and academic responses should be expected. Achieving success will also require addressing the following challenges by the academic community.

Reference Curriculum

The growth of systems engineering graduate programs has produced a very great diversity of content. A few programs, such as that at JHU, have systems

Table 2. Examples of STEM-related programs at APL.

Program Name	Target Group
High School Mentoring Program	High school juniors and seniors
Technology Day	Community college students
Girl Power	Middle and high school girls
Summer Space Camp	Middle school students
Science and Pizza Conference	Middle school students
Mathematics, Engineering, Science Achievement (MESA)	Middle and high school students
Graduate Degrees for Minorities in Engineering and Science (GEM)	College students
APL Technology Leadership Scholars (ATLAS)	College students
Kershner Scholarships	High school students
Groovy Science Shows	Elementary school students
APL Laboratory Tours	Students at all levels
Summer College Internships	Undergraduate students

engineering-centric curricula, while many new programs are domain-specific. The approach to starting a new program often leverages existing courses in the university departments, taking a bottom-up approach and a cafeteria-style program of offerings. In contrast, JHU developed its full curriculum using the many years of practical experience and skills inherent in the staff at APL. The concept of developing a reference curriculum from the top down is now being considered in the academic community, so that a framework and standard learning objectives can be identified. The ongoing debate addresses what should be the set of fundamental, introductory, core, and specialized courses in the reference curriculum. With increasing pressure from government and industry to ensure that systems engineering graduates have a common understanding of the principles, this initiative is expected to move forward successfully in the next few years. JHU will continue to be an advocate for inclusion of applied and practical systems engineering learning objectives.

At the undergraduate level, only a handful of schools have an explicit program in systems engineering. However, an increasing number of educators recognize that their student interdisciplinary projects inherently utilize systems engineering principles. When developing autonomous systems like robotics or unmanned air vehicles or developing energy-efficient vehicles, students would have a context and logical process to follow if they were exposed to more systems engineering. Because a set of undergraduate systems engineering courses does not exist, and because debate over the appropriateness of teaching systems engineering at the undergraduate level continues, it is expected that opportunities in this area for bachelor of science degrees will be limited in the near future.

Curriculum issues exist at the secondary school level as well. Should systems thinking be encouraged in science programs? Many districts today are experimenting with project- or problem-based curricula in high school rather than offering the traditional earth science, biology, chemistry, and physics courses. Instead, all the learning objectives are addressed in the context of large, complex, but interesting problems dealing with the environment, climate, health care, energy, or population. Over time, our school systems will be able to evaluate student performance and retention in STEM careers by using these approaches.

Quality of Content

As academic programs grow, not only should the expectations for standards be addressed but also the content of the curriculum should reflect consistency and nonredundancy. This requires that there be good communication and understanding of the entire program by the entire faculty and that the applications, case studies, and examples build and flow in the curriculum framework. The JHU program uses the systems development life cycle as its framework, which is reflected in the systems engineering loop discussed in the articles throughout this issue. Furthermore, a process to review and audit the program learning objectives, delivery, and student performance is used to ensure continual improvement. The JHU Whiting School of Engineering uses a professional external assessment organization to conduct these assessments.

Academic Rigor

There is continual need also for systems engineering programs to balance growth and content diversity with academic rigor. The principal limitation to growth is maintaining a quality faculty whose talents are aligned with course offerings and teaching modalities (live, online, and partnerships). Review and upgrading of current courses and the development of new advanced courses should build technical depth, including advanced mathematics, modeling and simulation methodologies, and new systems engineering tools and software, as well as improved concepts for systems developments that are derived from systems engineering research fronts. As described above, the perceptions and fields of systems engineering are dynamic, requiring continual attention to the curriculum.

Distance and Online Offerings

The advances in telecommunication and internet tools to enhance collaboration in business are also evident in academic delivery of undergraduate and graduate programs. With higher demand, online programs provide ready access to the experience and reputation of universities from anywhere in the world. In the JHU Systems Engineering Master's Program, the online offering that has been available since 2007 is seeing the highest growth. Issues that arise for those starting online programs are whether to adapt existing courses or develop new ones; assessing whether their systems engineering expert faculty can perform online as well as they do in the classroom; what delivery mode is most effective—fully online, asynchronous, or blended; and dealing with the increased work levels for both students and faculty. These issues will necessarily be addressed and refined in the future because of the high interest in the field. In some people's minds, the extreme approach of using virtual learning environments at all levels is still unproven.

CONCLUSIONS

The future of systems engineering is both challenging and exciting, offering technical professionals the opportunities to use their knowledge and skills in diverse and dynamic environments and to have real impact on engineering problems facing our nation. APL and external members of the systems engineering community are developing new approaches, new academic programs, and new processes to prepare for the challenges ahead. Increased awareness and learning in systems engineering will be needed for future success across a wide range of critical national security and societal problems.

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The Authors

Samuel J. Seymour

Ronald R. Luman

Samuel J. Seymour is a member of the APL Principal Professional Staff and is the APL Business Coordinator. Dr. Seymour serves as the Vice Chair for the JHU Whiting School of Engineering Systems Engineering Program, where he has taught for more than 25 years. **Ronald R. Luman** is a member of the APL Principal Professional Staff and serves as the Chair of the JHU Whiting School of Engineering Systems Engineering Program. Dr. Luman is the former Head of the National Security Analysis Department and is now the APL Assistant Director for Strategy. For further information on the work reported here, contact Samuel Seymour. His e-mail address is samuel.seymour@jhuapl.edu.

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