BUILDING THE SYSTEMS ENGINEERING **WORKFORCE OF THE FUTURE**

A COMPLEMENT TO THE INCOSE SYSTEMS ENGINEERING VISION 2035

GUIDANCE FOR EDUCATION, TRAINING & DEVELOPMENT OF SYSTEM ENGINEERS

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The intention of this White Paper, in view of a shortage of experienced System Engineers and the growing need for such competencies, is to solicit the endorsement and application of its guiding principles by professional organizations, industry, academia and government agencies.

THIS GUIDANCE PAPER IS APPLICABLE TO ALL TYPES OF SYSTEMS E.G.

- Hardware-Intensive Systems
- Software-Intensive Systems
- Cyber-Physical Systems
- Data & IT Systems
- Autonomous Systems
- Small & Large Systems
- Conceptual Systems
- Social Systems
- Verification & Test Systems
- Production Systems
- Maintenance & Support Systems
- Mechatronic/Robotic Systems
- Logistics Systems
- Operations Systems
- Systems of Systems (SoS)

THIS GUIDANCE PAPER IS APPLICABLE TO ALL TYPES OF APPLICATION DOMAINS E.G.

- Energy
- Business Information
- Financial
- Global Change/Climate Assessment
- Aerospace & Defense
- Natural Resources Processing
- Chemical Processing
- Biological Systems
- Social & Economic
- Government Policy
- Medicine
- Public Health
- Education
- Infrastructure
- Smart Cities
- Smart Agriculture
- Sustainability

EXECUTIVE SUMMARY

SCIENCE & ENGINEERING

progress is often a result of the integration of multi-disciplinary contributions. Examples are artificial organs, robotics, and smart cities. At the same time, knowledge is becoming accessible faster than ever before. Because Systems Engineering (SE) is an integrative-discipline, these developments have strong effects upon education in general and SE in particular.

This white paper provides guidance for development of SE competencies and for the retention of System Engineers (SEs). As a complement to the INCOSE SE Vision 2035, it offers experience-based recommendations to enterprises and educational institutions.

KEY MESSAGES OF THIS WHITE PAPER

Complex systems need well trained SEs from every discipline at almost every product tier or service level. While knowledge of process is important, SEs must be able to lead engineering solutions.

As SE education is fundamentally multi-disciplinary, development and retention will rely heavily on continuing education, provided by enterprises, universities and specialized training businesses.

SEs most often develop by expanding from traditional disciplines such as physics and computer/information science, and engineering disciplines, such as control systems, electrical or mechanical engineering, to broader systems integration capabilities.

UN Sustainable Development Goals (SDGs) Identify Broad System Needs

The 17 United Nations SDGs, accepted unanimously by 193 Nations, stand for the transformation of our world, and represent a proxy for human needs. Their realization relies upon a broad system approach and global cooperation. Education is one of the 17 goals.

Industry 4.0 Projects Major Changes for the Realization of Systems

Industry 4.0 (and Society 5.0) rest on the top of increasingly complex software and information technology (IT) solutions. The fourth industrial phase focuses on cyber-physical systems which integrate advanced technologies for the development and manufacturing of future products and services. The associated complexity growth and sustainability expectations need strong SE to ensure viable, socially responsible products.

SE is Practiced at Many Tiers of an Enterprise

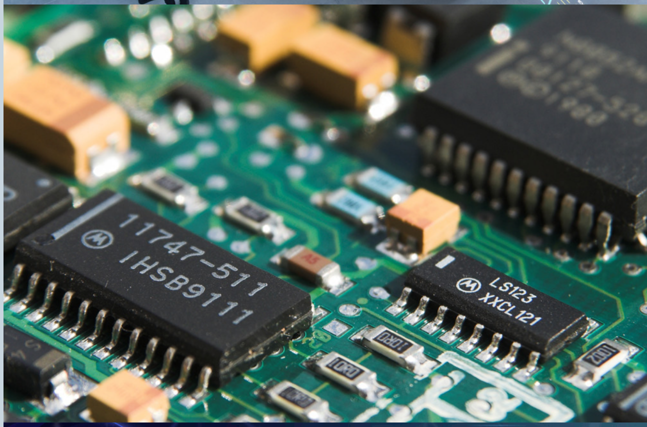
Complex products, such as automobiles, infrastructures, spacecraft, global IT systems, and supply chains, are characterized by several tiers of competencies at Original Equipment Manufacturers (OEMs) and suppliers, often Small and Medium Enterprises (SMEs). These products are built from sub-systems, needing special competencies, such as structural, electrical, or software, design, into the system product. SE competencies are needed at many tiers to ensure product functionality and market success.

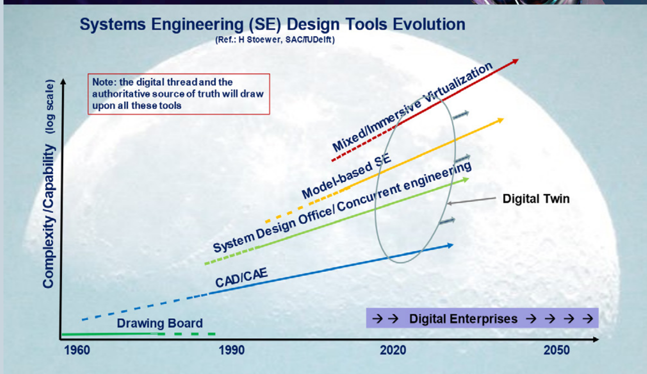
Technology Advances Affect SE Solutions, Methods and Practices

The digital and cyber-physical transformations along with technology advances profoundly affect the practice of SE. For example, MBSE, simulations, digital twins, AI, automation, robotics, and virtualization environments enable faster and better SE practices and solutions. They require careful introduction and extensive employee training.

SE Tools Become More Critical and Diverse

Enterprise digital transformation demands more powerful digital SE tools. Their application requires process adaptations and SE training. The integration of different generations of often incompatible enterprise tools, such as for systems modeling (MBSE), product lifecycle management, software engineering, virtualization, or digital twins, into coherent SE practices and system solutions requires substantial education and training.



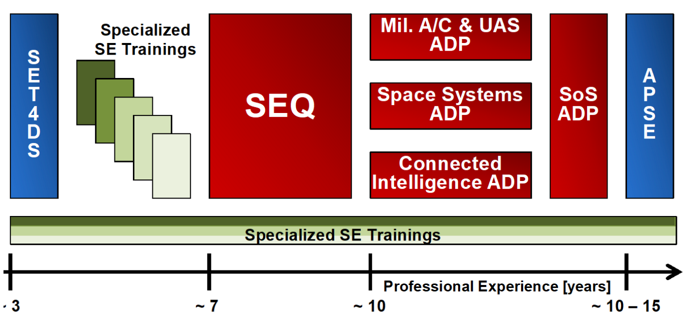


SE Roles Will Diversify

As system complexity grows, SE education and training will also need to focus on SE specializations. This creates new education and training demands for different SE roles such as systems analyst, SE tools curator, ideation engineer, or system assembly and verification SE. New SE education and training demands will arise in three areas: digitalization, increasing complexity of traditional SE specialties, and adaptation to additional product domains.

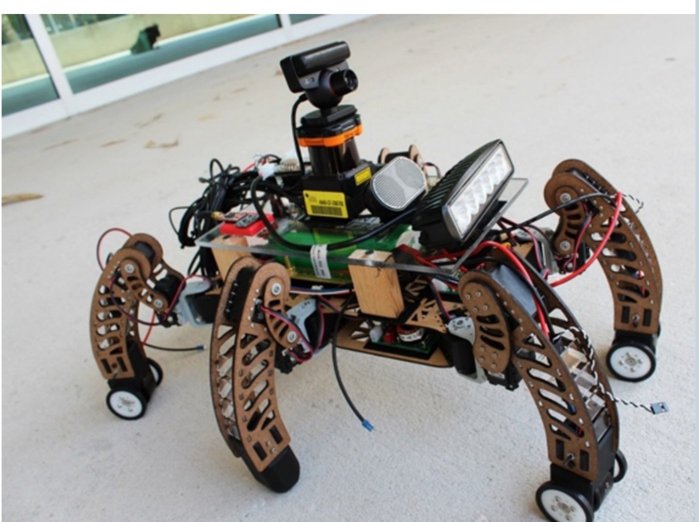
Educational Demands for SE Change

Growing multi-disciplinary developments and widely available knowledge have profound effects upon the education and training of students and the enterprise workforce. SE education needs to respond, more than in the past, by partially integrating technical with social and economic disciplines. This integration is needed, along with aspects of project management, at advanced levels of education or professional growth, to ensure projects success. Hybrid classes and video supported tools will eventually become commonplace. SE education must start in primary schools, continue through universities, and be sustained during professional careers.



Continuing Education is a Must for Successful SEs and Enterprises

Digital enterprises and their workforces need to anticipate ever changing markets, technologies, and business environments. Quality continuing education will hence become an even stronger differentiation for successful organizations. The Airbus D&S and the US DoD are excellent examples of post-graduate continuing education and training approaches.



Capstone Projects Should Become Building Blocks of SE Education

Learning SE requires, in addition to theoretical knowledge, an understanding of how to realize systems. Capstone projects allow SE students and practitioners, at any stage of their education, a transition from book knowledge to practical understanding. They progressively gain confidence for domain integration challenges and system realization. Customer review and team presentations should be part of capstone projects to enhance quality and SE comprehension.

BUILDING THE SYSTEMS ENGINEERING WORKFORCE OF THE FUTURE

GUIDANCE FOR EDUCATION, TRAINING AND DEVELOPMENT OF SYSTEM ENGINEERS

Demand is growing enormously for engineering talent, especially engineers who can steer the development and operation of large, complex systems composed of mechanical, electrical, biologic, software, human, environmental and societal elements. These engineers must be able to integrate technical as well as programmatic and social issues across the many disciplines making up the systems of today and of the future. But in addition to the needs for large systems, there are many Small to Medium Enterprises (SMEs) that build more limited, but still often complex, products. These SMEs also have a strong and growing need for integrative engineering talent. Systems Engineering (SE) is a discipline, performed by Systems Engineers (SEs), that applies engineering analyses, processes, techniques and viewpoints to the realization and maintenance of systems—both social and technical. The many global factors and trends driving the need for SEs are described in the Systems Engineering Vision 2035 incose.org/sevision.

This white paper is intended to inspire individuals, educational establishments, and enterprises to reflect deeply on how to develop SE competencies and to retain SEs in their workforce. As such, it is part of, and complementary to, the INCOSE SE Vision 2035. It describes the factors influencing the educational environment for the SE workforce and provides ideas as to how this workforce can be developed and nurtured by an enterprise. It also offers some approaches that educational institutions, as well as enterprises, can take to enhance the academic underpinnings and continuing education necessary to assure a highly competent SE workforce for the future.

1.0 FACTORS INFLUENCING THE EDUCATION AND TRAINING ENVIRONMENT

Historian and futurist Y.N. Hirari writes "To develop a future educational offer for the coming generations is more difficult today when compared to the past, since the prospective technologic manipulation of body, brain and soul evades the certainty of being". *(Ref 1)*. Fruehwald & H Poeppel, in their characterization of knowledge in the 21st century *(Ref 2)*, observe that the challenge of the future is about complexity and simplification, which is the essence of SE.

The United Nations seventeen Sustainable Development Goals (SDG) *(Ref 3)*, endorsed unanimously by 193 nations, address fundamental human and societal needs necessary to move forward as a global society. Most of the UN SDGs require holistic system approaches and well-educated SEs to support their implementation. They are hence an extra motivation for competent systems analysis and engineering education. SDG number four focuses on education. In a world conference, UNESCO expanded on the educational theme number four and passed the Brussels declaration, *(Ref 4)* stating: "Ensure inclusive and equitable quality education and promote life-long learning opportunities for all."

Figure 1.1 UN Sustainable Development Goals (SDGs) highlight quality and continuous education as highly relevant to the achievement of many other goals

1.1 Digital Transformation and Industry 4.0

Industry 4.0 (and Society 5.0) rest on the top of increasingly complex software and information technology (IT) solutions. Many enterprises are entering into programs to advance the automation of ideation, design, realization, operations, manufacturing, and logistical support processes, along with business and human capital functions interactions. This enterprise-level digital transformation demands an alignment with the SE workforce and their education. Two specific initiatives of the past few years- Industry 4.0 *(Ref 5)* and Society 5.0 *(Ref 6)* have set new goals and visions for our social and industrial developments and will shape future education needs. Industry 4.0, a German Academy of Technology initiative, characterizes the fourth industrial phase, towards which we are transitioning, as one of cyber-physical systems. It envisions the need for the integration of automation, big data, autonomy, augmented reality, and other specialties which too often are constrained to a stovepipe environment *(Figure 1.2)*.

Education and training for SE need to adapt to such changing industrial and societal demands. Industry 4.0, Society 5.0, advanced technologies, the digital transformation and evolving virtual environments will substantially change demands for engineering education. The recently released Digital Engineering Competency Framework (DECF) developed a logical structure for emphasizing five digital competencies in the SE domain: data engineering, modeling and simulation, digital engineering and analysis, systems software, and digital enterprise environment *(Ref 12)*. This framework describes digital skills that need to be added to general SE skills.

Multi-disciplinary and IT competencies, as well as personal and professional skills, will enable students to cope with new demands and a changing society. The complexity growth associated with widespread digital transformation will drive the need for SEs with broad analytical, technical, and integrative competencies to ensure that the resulting products are viable and conform to sustainability expectations and regulatory standards.

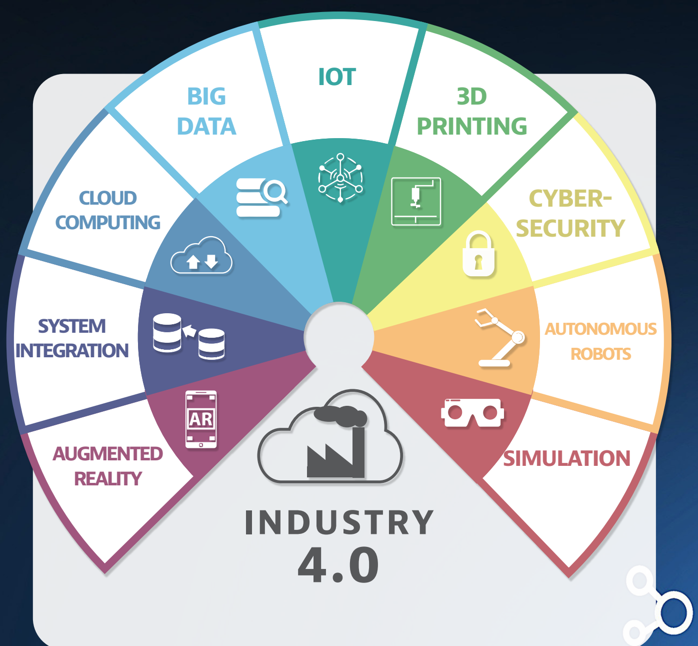


Figure 1.2 Industry 4.0 major elements

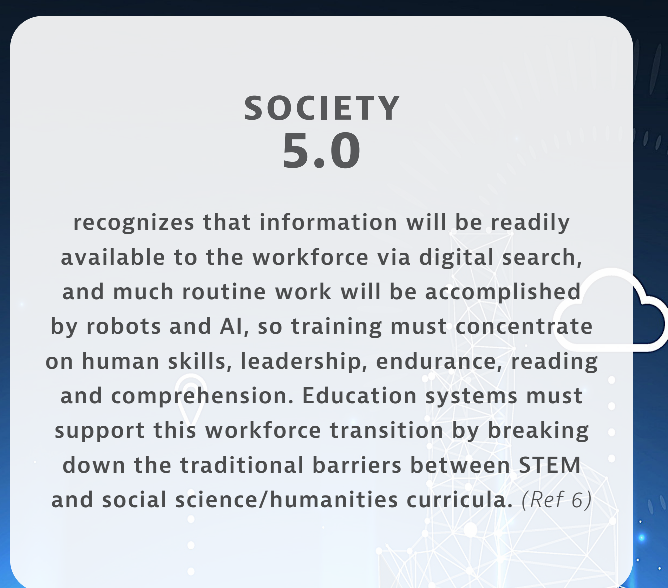


Figure 1.3 Society 5.0

1.2 Global Access to Knowledge

In today's world, information and knowledge are increasing at an astronomical rate. Fortunately, due to modern knowledge management systems and search technologies, accessing that knowledge is easier than ever. Given the widespread availability of information today, engineering students no longer need teachers to lecture them on simple facts because that information is readily available- and often in more engaging formats than a typical classroom lecture. However, exploitation of the knowledge requires a careful assessment. What may appear true today could be proven to be false tomorrow. Engineers need to be taught how to process, synthesize, parse, critically assess, and use information. They need adaptable skills they can apply in all areas of life. Teaching only ideas and facts, without teaching how to apply that knowledge in real-life settings, is no longer enough.

1.3 The Multi-Disciplinary Nature of SE

Complex systems applications will continue to grow in many fields, e.g., energy, mobility, communications networks, aerospace, smart cities, biological and health systems, and large construction and infrastructure projects. Increased domain specialization, which is necessary, leads to higher fragmentation of design work and thus the need for end-to-end system-wide integration to ensure stakeholder value. Enterprises will require multi-disciplinary team competencies to analyze, evaluate, plan, realize, operate, and sustain these systems within environmental, regulatory, programmatic, and socially acceptable boundaries. This growing need for systems specialists complements the trend of deep and narrow engineering specializations in many enterprises of today as well as the future.

As systems become more multi-disciplinary, digital, and smarter, enterprises will need to attract and retain a workforce with an extensive variety of skills, to support or apply rapidly changing technologies in response to shifting stakeholder demands. This workforce will need to provide not only broad and focused technical and business competencies, but also engineering and leadership talent, often operating in a muti-site and multi-cultural context, to architect, integrate and coordinate the system of interest to a specific business. To be successful in the next decade, enterprises, regardless of engineering discipline focus, will need to shape their workforce to meet the imperatives as described in the INCOSE Systems Engineering Vision, Chapter 1. These enterprise imperatives are:

- **Competitiveness in global and diverse environment**
- **Establishment of a sustainability ethic**
- **Development of systems thinking**
- **Anticipation of technology and a culture of innovation**
- **Supply chain integration and optimization**
- **Advancing enterprise intelligence, decision making, and learning**
- **Embracing the digital transformation**

1.4 SEs Need Domain-Specific Bodies of Knowledge

The trends towards increasing automation and autonomy, ever more sophisticated digital ecosystems, rapidly changing technologies, and the need for cyber-secure and trusted systems have further fueled the need for SE competencies. Increasing data, the growing availability of AI, self-learning capabilities, modeling, simulation, and virtual environments are catapulting systems analysis, SE, and data analytics into the forefront of many social and industrial undertakings. These trends have also led to a recognition that depending on the domain, SEs need to acquire mastery of specialized complementary areas. *Figure 1.4* provides examples of complementary SE competencies for some selected domains, illustrating the need for well-educated traditional SEs with deep technical domain expertise aligned with domain-specific applications.

SEs are also needed with special competencies in systems of systems, business intelligence, and enterprise modeling.

DATA ANALYTICS

- **IT, AI, machine learning, software, cloud computing and systems analysis.**

COMPLEX PROCESSING PLANTS

- **E.g for chemical production**
- **Require solid fluid dynamics, thermal and logistics knowledge combined with process, controls, and design competencies.**

COMMUNICATION and ENERGY NETWORKS

- **Electrical, advanced electronics, control, operations, and communications engineering along with systems analysis expertise.**

AUTOMATED or AUTONOMOUS SYSTEMS

- **Such as automobiles, or harbor/airfield logistics require skills in IT, software, sensors, communication, cyber security, control theory, design for safety, security and social science skills.**

SMALL MEDICAL or SMART HOME DEVICES

- **Such as blood pressure or body temperature measurement equipment's require skills in sensor, IT, software, and communication fields.**

Figure 1.4 Examples of domain-specific knowledge necessary for SEs

1.5 SE is Practiced at Many Tiers of an Enterprise

Complex products, such as automobiles, infrastructures or aerospace are characterized by several tiers of design, development, assembly, and integration. These tiers build up from individual analyses (e.g., structural) to sub-assemblies to major subsystems and then the final product. Each of these tiers is itself a system, albeit generally limited. Therefore, system competencies are needed at many product tiers and often throughout the entire supply chain such as suspension, electrical, software, or passenger comfort (a cross-cutting subsystem) for the automotive example. The domain competence requirements for most of these subsystems are different, but all need a certain degree of system competence, coupled with software competence, to understand specialties such as Original Equipment Manufacturers (OEM) system requirements, verification and test processes, or interfaces/ interactions with other subsystems. Systems knowledge and education is hence different at the various tier levels. On the job progression for SEs leads most often from assembly SE to subsystem SE to overall system integration SE.

SYSTEMS ENGINEERS WORK AT MANY TIERS OF A PRODUCT

AUTOMOTIVE SYSTEMS

- Suspension
- Electrical
- Acoustics/Passenger Comfort
- Testing-Certification
- Production-Quality
- Spares/Repair- Logistics
- Sustainability, RAMS, Etc.
- Vehicle Mechanical
- Vehicle Electronics/Software
- Integrated Vehicle
- Autonomous Driving

Ref: H Stoewer, P. Schreinemakers

PUBLIC INFRASTRUCTURE SYSTEMS

- Civil Construction
- Electro/Mechanical Equipment
- Traffic Control
- Safety,RAMS
- Testing and Commissioning
- Production
- Rolling Stock
- Ground Mechanics
- System Deliverables
- Architecting and Geographic Areas
- Infrastructure Network
- Quality and Certification

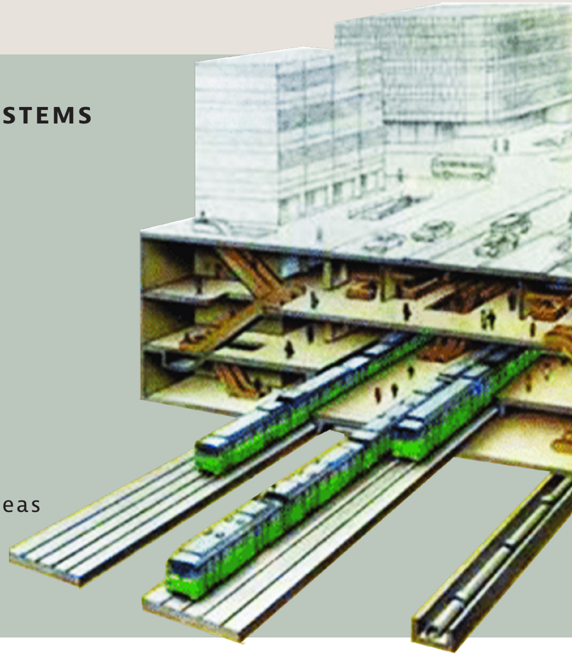


Figure 1.5 Example of product tiers that are the scope of interest of SEs

1.6 Continual Innovation and Maturation of Technologies

The digital and cyber-physical transformations along with other technology advances enable new products and services, and profoundly affect the discipline of SE. For example, MBSE, simulations, digital twins, AI, automation, robotics, and virtualization environments enable faster and qualitatively improved SE practices and solutions. At the same time, they require advances in education and training for SEs. Enterprises and SEs hence need to invest increasingly more efforts into SE training to stay current and effective.

But recognize that SE does not always begin with a clean design slate. SEs are most often challenged to integrate advanced technologies into systems of systems (SoS). Component systems must integrate with separately evolving and managed system elements, such as infrastructure – an example being the placement of autonomous vehicles into the existing roadway network.

1.7 SE Tools Become More Critical and Diverse

Enterprise digital transformation is demanding ever more powerful digital SE tools. Their application requires enterprise commitment, process adaptations and engineer training, especially for SEs. The integration of different generations of often incompatible enterprise tools, such as MBSE, product lifecycle management, virtualization, or digital twins, into coherent engineering practices and thus system solutions is a complex enterprise undertaking. SE is at the center of many of the use cases for these integrated tool suites. Successful integrated tool suites will themselves be engineered as systems and accompanied by extensive education and training. SEs will need to master the use of these tools. Familiarization and awareness will not be sufficient.

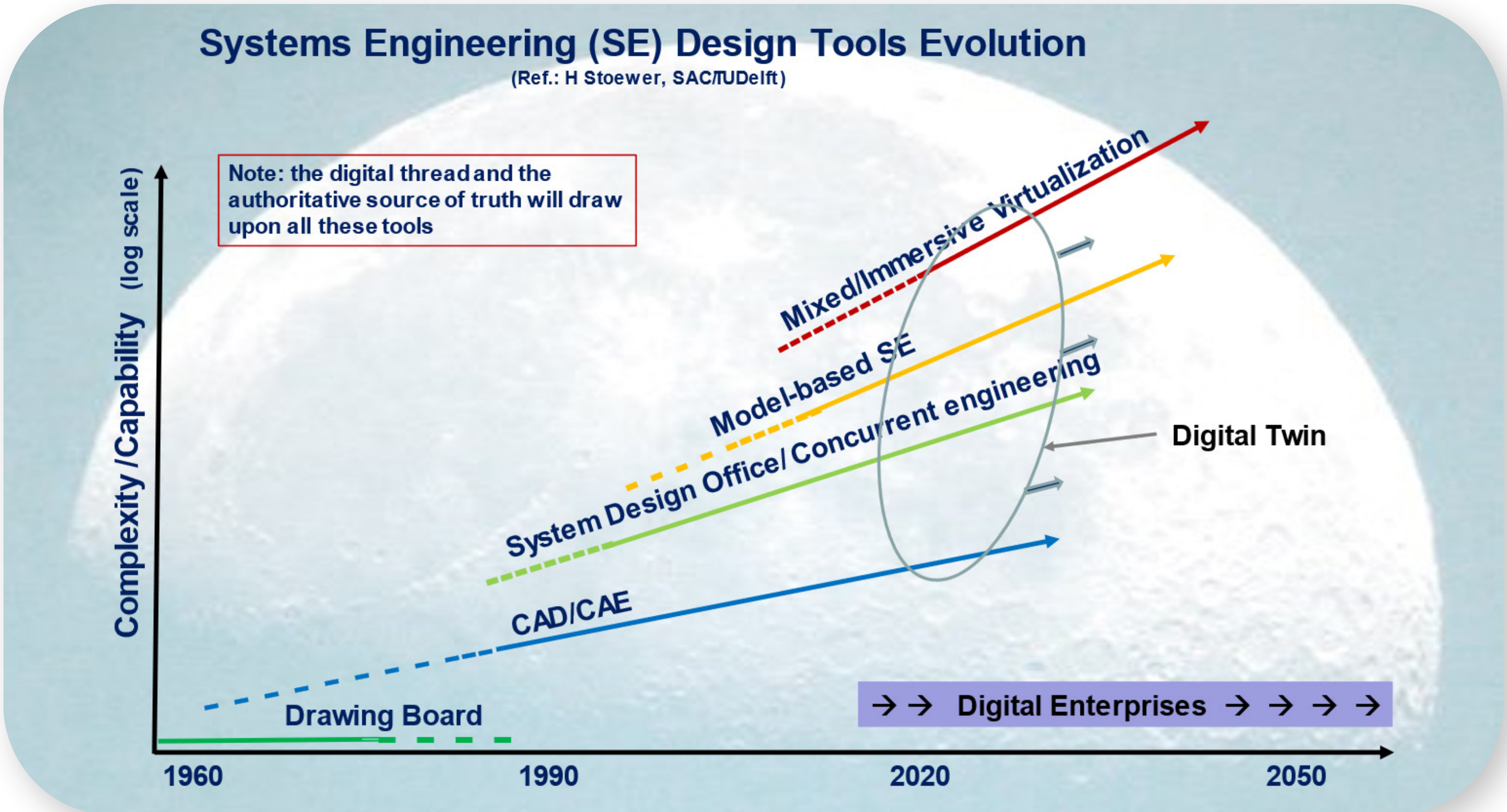


Figure 1.7. SE design tools evolution

1.8 Specialization of SE Roles

Demands on SEs will grow because of system complexity, automation, and domain diversity growth. SE education and training will hence become differentiated into major functional specializations, examples of which are illustrated below:

Moreover, a differentiation for junior, mid-career, senior SEs, and systems architects is an additional set of distinctions that SE education will need to accommodate.

- ARCHITECTING & IDEATION
- BUSINESS ENGINEERING
- MANUFACTURING
- OPERATIONS
- SYSTEMS ANALYSIS & OPTIMIZATION
- RISK ASSESSMENT & DECISION ANALYSIS
- MODELING (MODEL CREATION, CURATION, & EXPLOITATION)
- INTEGRATION, VERIFICATION & VALIDATION
- VALUE ENGINEERING
- MAINTENANCE & SERVICE

2.0 CHARACTERISTICS OF HIGHLY VALUED SYSTEMS ENGINEERS

2.1 Competency and Behavioral Models

Competency in SEs can be assessed in several dimensions. In addition to basic engineering and domain competencies, four useful viewpoints are: 1) mastery of the knowledge associated with the techniques and methods of SE; 2) the systems mindset and related proficiencies associated with systems thinking and complex problem solving; 3) interpersonal skills and behaviors associated with the ability to work effectively in a team environment and to coordinate across the problem domain and solution domain; and 4) technical leadership skills and behaviors associated with the ability to guide a diverse team of experts toward a specific technical goal. These are defined in detail in the ATLAS 1.1 model created on the HELIX project *(Ref 13)*.

The International Council on Systems Engineering (INCOSE) Competency Framework provides a set of 36 competencies for SE within a tailorable framework that provides guidance for practitioners and stakeholders to identify knowledge, skills, abilities, and behaviors crucial to SE effectiveness. *(Ref 7)*. This competency framework is linked to the SE Certification offered through INCOSE.

The Chartered Professional Engineer programs prevalent in many countries are another example of professional knowledge certifications. The practice of SE, however, goes beyond just mastery of knowledge. It must be applied in real world situations involving complex team structures and dynamic programmatic environments. Mastery is also determined by organizational forces, the three most important of which are work experiences, mentoring, and lifelong education and training. These forces are generated by a combination of personal and organizational initiatives – initiatives that reflect the maturity of the individual business and enterprise culture.

The ability to lead and to provide value to the enterprise in these circumstances is determined not just by technical competency, but by the mix of behaviors exhibited by the SE. To illustrate the latter -- in 2005 a study was conducted at NASA to determine the behavioral competencies of high performing SEs. These behaviors are used to formulate training programs, as well as guide career and succession planning. See Appendix A. The study made the following overall observations:

> *The... systems engineers studied typically view the system or subsystem as a non-linear web of connects or disconnects to be solved. They have the ability to view the big picture, zoom in to pinpoint the disconnect, and then zoom back out to the big picture, while at the same time looking at the interrelationships and patterns in the system or design. They have a high degree of curiosity mixed with self-confidence and persistence and are achievement oriented. They may describe themselves as having extraordinary physical insight to see the connections and interrelationships between what they are doing and the world around them. They are drawn to the challenge of solving complex problems and are creative, in the midst of numerous constraints.*

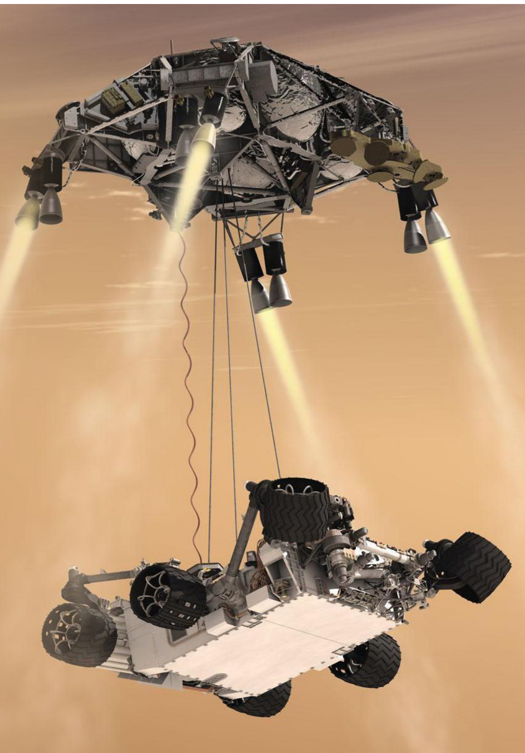


Figure 2.1 NASA Mars Rover Descent Vehicle

2.2 Typical Training and Career Paths for Senior Systems Engineers

The growth of engineers from domain specialists to SEs is well illustrated by the "T Model of Systems Engineering Skills" in *Figure 2.2*. The basic underlying idea is that engineers are in the first instance educated in a special discipline, e.g., mechanical, electrical, physics, biological, controls, or other. Some develop further within the knowledge and skills base of their disciplines. Others want to understand more about neighboring disciplines, thereby developing an ability to analyze issues across several disciplines. They are then on their way towards becoming SEs. The more they learn about other (engineering) disciplines and the more they can interact with a multitude of engineering and programmatic disciplines (schedule, cost, finance, planning, leadership, markets, etc.), the more they grow to become senior SEs or system architects. Moreover, mastery of SE competence specialties, described in Section 1.7, will become a differentiator for junior, mid-career, senior SEs, and system architects. Education and training will need to provide access to those specialties.

Subject matter expert and management careers traditionally develop in parallel. The usual enterprise management promotion and career progression criteria is dominated by size of budget and extent of staff supervision responsibilities. However, some organizations have created parallel expert career promotion tracks. With this model, senior specialists in important technical or administrative domains can have separate career paths and remuneration progressions in parallel with management, at least up to certain levels in a hierarchy. Advancements to Chief Engineer, Chief Architect, Chief Technical Officer (CTO), or Project Manager (PM) typically

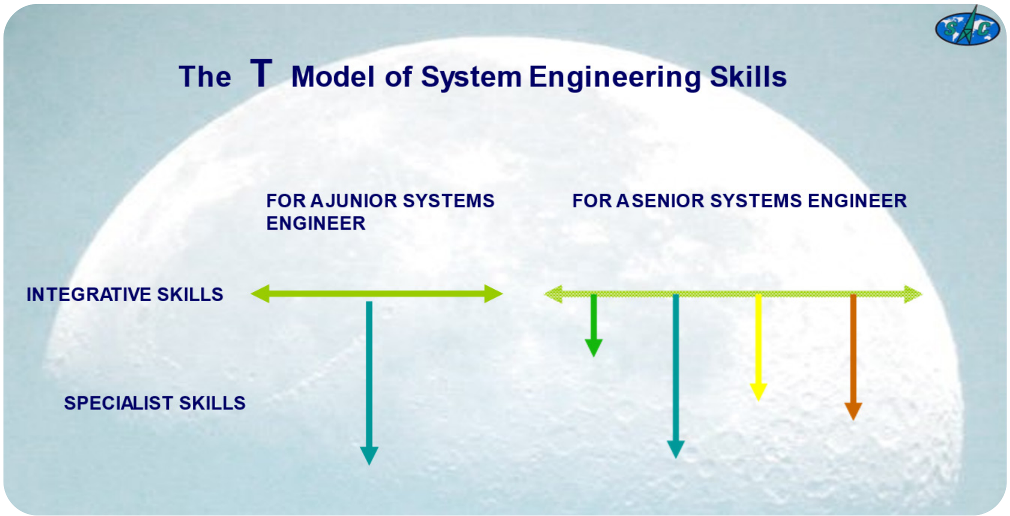


Figure 2.2 The "T" model of systems engineering skills

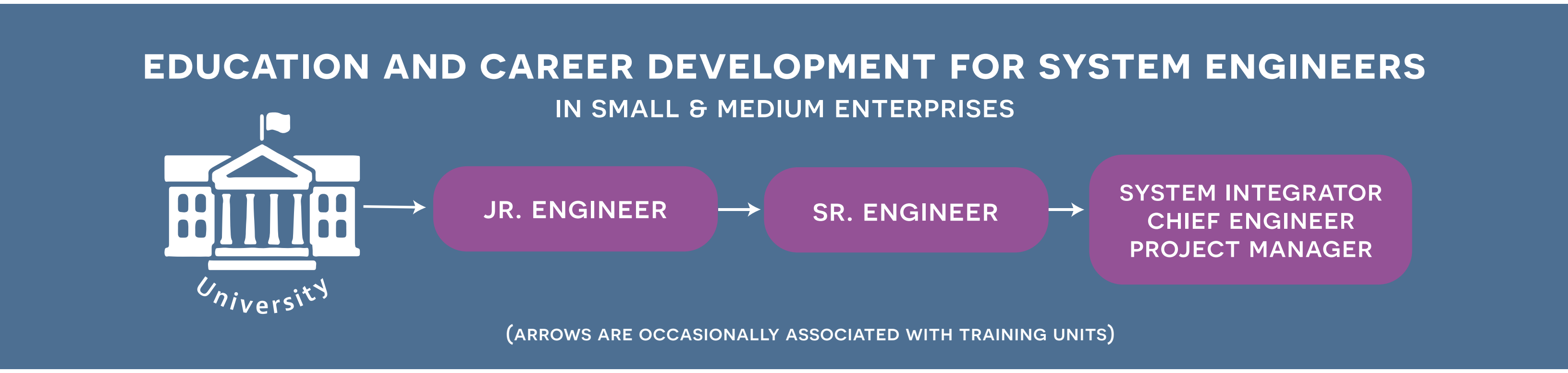


Figure 2.3 Systems engineer development in small and medium enterprises

exist along this path. In small to medium enterprises (SMEs) career progression is often simply from junior engineer to senior engineer to roles such as System Integrator, Chief Engineer, or Project Manager. *Figure 2.3* illustrates, in an oversimplified manner, the fundamental steps of career development in SMEs.

As illustrated in *Figures 2.3* and *2.4*, career tracks for SEs often lead to a project management (PM) role. The SE and project management disciplines are heavily intertwined *(Figure 2.5)* due to a significant interdependence of responsibilities and overlap of concerns. These disciplines traditionally have different educational paths, and alliances with different professional societies. However, because they depend on each other, just as both depend on many other disciplines in the engineering, business, or manufacturing fields, they need to work in multi-disciplinary teams to derive the desired solution(s) and viable products. Their continuing education, methods and implementation practices need alignment, consistent with the strategic direction of the enterprises they support.

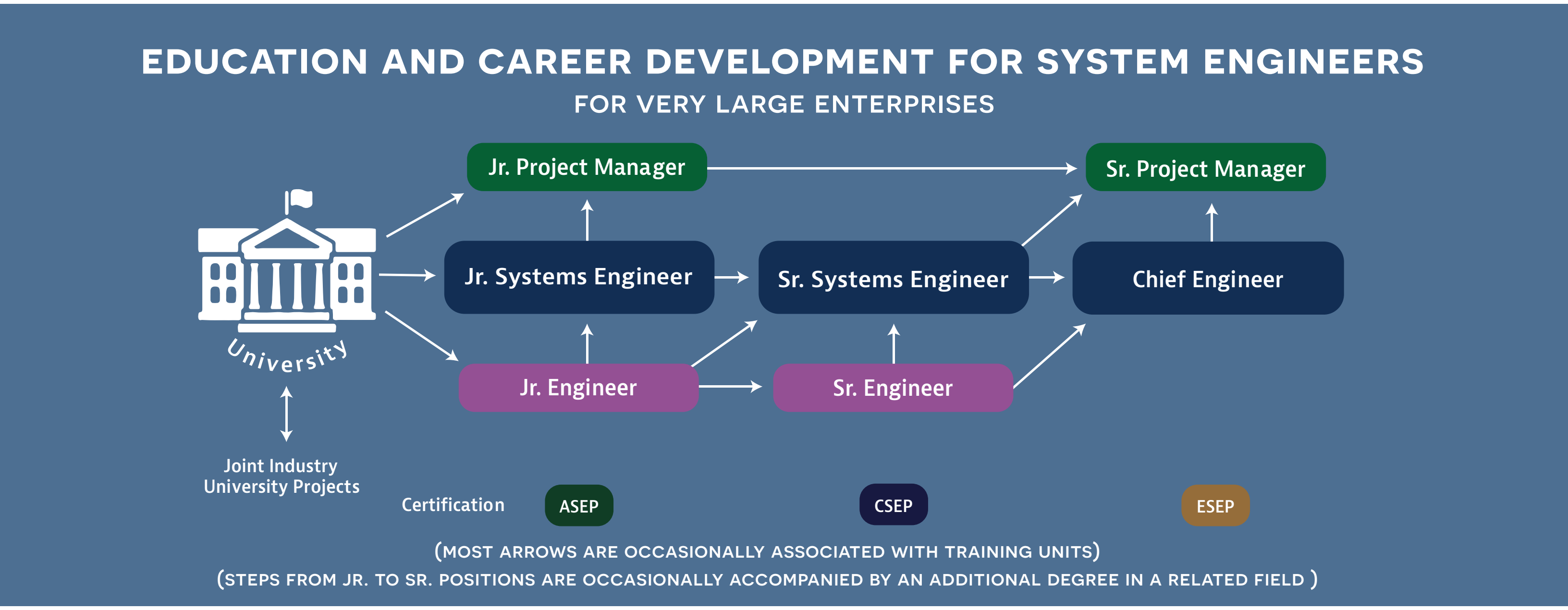


Figure 2.4 Engineering, systems engineering, and project management development options in larger enterprises

Figure 2.5 Project management and systems engineering have significant overlap of concerns

3.0 OVERVIEW AND ROLE OF EDUCATIONAL MODELS

Both formal as well as continuing education are extremely important for the education and growth of SE talent. Each has a crucial role to play.

3.1 Formal Education

Formal education at the elementary, high school and university levels will play an ever-increasing role in the education of the SE workforce by laying the groundwork for systems thinking and systems analytics. In fact, INCOSE has established the SysTEAM initiative with the mission of promoting the integration of system thinking and SE skills into educational curricula across the globe, at all levels of education (*Ref 14).*

3.1.1 Primary and Secondary Education

A key mission of primary and secondary education is to teach the fundamental skills necessary to function as an adult in contemporary society, which we can refer to as “21st Century skills.” While the specific skills deemed to be 21st Century skills may be defined differently from person to person, place to place, or school to school, the term does reflect a general, if somewhat loose and shifting, consensus. The following list provides a brief illustrative overview of the knowledge, skills, work habits, and character traits commonly associated with 21st Century skills *(Ref 8).*

By 2035, systems thinking will be embedded in early education to complement learning in sciences, technology, engineering, and mathematics. Early school education will develop systems thinking and team skills to create multi-disciplinary solutions that respond to pre-defined problems and constraints. Secondary education will teach basic systems engineering concepts, such as soliciting and understanding stakeholder needs, developing requirements, identifying, and evaluating conceptual alternatives before arriving at a solution and digital system design.

- **Critical thinking, problem solving, reasoning, analysis, interpretation, synthesizing information**
- **Research skills and practices, interrogative questioning**
- **Creativity, artistry, curiosity, imagination, innovation, personal expression**
- **Perseverance, self-direction, planning, self-discipline, adaptability, initiative**
- **Oral and written communication, public speaking and presenting, listening**
- **Leadership, teamwork, collaboration, cooperation, facility in using virtual workspaces**
- **Information and communication technology (ICT) literacy, media and Internet literacy, data interpretation and analysis, computer programming**
- **Civic, ethical, and social-justice literacy**
- **Economic and financial literacy, entrepreneurialism**
- **Global awareness, multicultural literacy, humanitarianism**
- **Scientific literacy and reasoning, the scientific method**
- **Environmental and conservation literacy, ecosystems understanding**
- **Health and wellness literacy, including nutrition, diet, exercise, and public health and safety**

Figure 3.1 21st Century skills

Students will need to be motivated to acquire the requisite mathematical, scientific, IT, and social knowledge to support systems analyses and decision-making. For this motivation, teaching and mentoring will be practical, based on real-world experiences with hands-on projects, in cooperation with regional industries, when possible.

Generation Z (individuals born between 1997 and 2012) is the first generation of students "living their lives largely digital." Knowledge for these individuals is assumed to be readily and publicly available, challenging educational institutions to guide students beyond the basic competencies of their selected study direction to find and critically evaluate, adopt, and assess the trustworthiness of relevant information. Students are using digital technology in learning and are fluent in programming languages beginning at an early age. Interactions between and among educators and students are thus enriched through digital technologies.

Figure 3.2
Generation Z is growing up and are now beginning to populate the higher education system

3.1.2 University and Postgraduate Education

Many universities worldwide offer degrees in SE *(Ref 9)*, playing an important role in the training and education of the SE workforce. These programs are challenged to continuously adapt their curricula to the future of knowledge being readily available digitally, as well as the changing industrial and societal demands as described in Section 1. As a result, universities are destined for substantial change. The Organization for Economic Co-operation and Development (OECD), the World Economic Forum, the global Engineering Deans Council gedcouncil.org along with others, are calling for a profound change in the university-level engineering education sector. Their call is for fast-paced initiatives to enhance curricula for key enabling technologies, that should include manufacturing and processes. They foresee a major shift in higher education's responsibility and purpose. They also envision a move towards:

- **Socially relevant engineering curricula that offer students more choice**
- **Integrating engineering knowledge with humanities, economics, and social sciences in the form of interdisciplinary learning and education**

SE will diversify along specific needs by various stakeholders into different specialties, as described in Section 1.7. Postgraduate education programs are and will continue to be critical in supporting such in-depth SE specializations. Further examples of such specializations are AI, machine learning, software verification methods, autonomous systems, sensors, edge computing, cyber-security, and communications.

Balancing domain and multi-disciplinary education will be just one of the challenges for university-level education. Engineering, social and science programs, e.g., business, computer science, electrical and mechanical engineering, management, social sciences, etc. will increasingly include systems-oriented courses, especially focused on systems thinking and end-to-end systems analysis. Broadening curricula will advance the skills of decision makers as systems thinkers.

Postgraduate education programs will provide the SEs of 2035 broad multi-disciplinary learning opportunities. These will include, in addition to sound scientific and technical education, socio-technical leadership and entrepreneurship programs to enable engineers to cope with non-deterministic complex systems that span a broad range of applications and involve large teams as well as a large industrial supply chain. SE curricula specifically will expand to include socio-political and soft skills. These curricula will also feature broad digital modeling, simulation, virtualization, and tools skills, incorporating modern processes and methods.

In addition to the discipline training characteristic of traditional engineering departments, universities also play a central role in teaching the foundations of systems analysis. Techniques such as risk assessment, applied probability and statistics, operations research, decision theory, complexity theory, formal software verification, reliability, modeling and simulation, and analysis of alternatives are important tools for SEs to understand emerging behaviors and probability of system success. These skills are necessary to work with technical specialists and project/program management in understanding, avoiding, and mitigating risk.

Closer university-industry collaboration will create a fluid transition from university to industry or government agencies and vice versa. Early exchanges and dialogue between academia and industry, regarding domain and systems curricula, will become the norm. Practical industry support to university teaching or mentoring will expand to achieve a "real life" insight and facilitate students seeking industry employment.

Instructional methods will predominantly be guided by problem definition, finding suitable solutions, and cultivating team productivity. For instructional problem sets to be application oriented, universities will frequently collaborate with industry in addressing real-world needs. This broad move to problem/project-based education in both traditional and on-line education will become the norm as complex problem-solving experience requires a project-based experience.

Educators will learn to reinvent themselves; to unlearn and re-learn continuously along their careers. An element of life-long learning is the ability to recognize that some knowledge continues to be superseded by new science and that consequently the need to let go of outdated knowledge becomes part of the continuous learning process.

University-level education will be a catalyst in the shift from traditional "design-build-test" to "analyze-model-simulate-build" approaches by introducing students to new methodologies. This will often include new industry processes such as "agile," concurrent, or "iterative" SE to cope with or improve emergent behaviors which are difficult to characterize during early definition and design phases – especially with large-scale smart systems.

The use of high-fidelity modeling and simulation coupled with digital twins will enable students to more effectively experiment and understand how engineering decisions and trade-offs are made and implemented as well as support model-based project reviews. Similar processes and techniques will be applied to understanding operations, maintenance, and servicing designs.

3.1.3 Capstone Projects

While individual study and traditional book-based (or on-line) learning will continue to be essential, it will in no way eliminate the value of intense team interactions in education. In fact, learning and teaching SE cannot be accomplished through theoretical in-class knowledge transfer. SEs best comprehend theories by applying knowledge in teams working on representative real-life projects, often termed "capstone projects". This applies to secondary education as well as for postgraduate and professional training. The complexity and orientation of team projects depends upon the experience of the student/teacher teams as well as the resources offered by a particular institution. Bringing in customers or target hiring enterprises for project review roles helps develop a market/customer orientation and provides feedback on product value. Such roles can be simulated from within a team or by a real customer from an enterprise. Structured system design environments will become common place in such educational exercises.

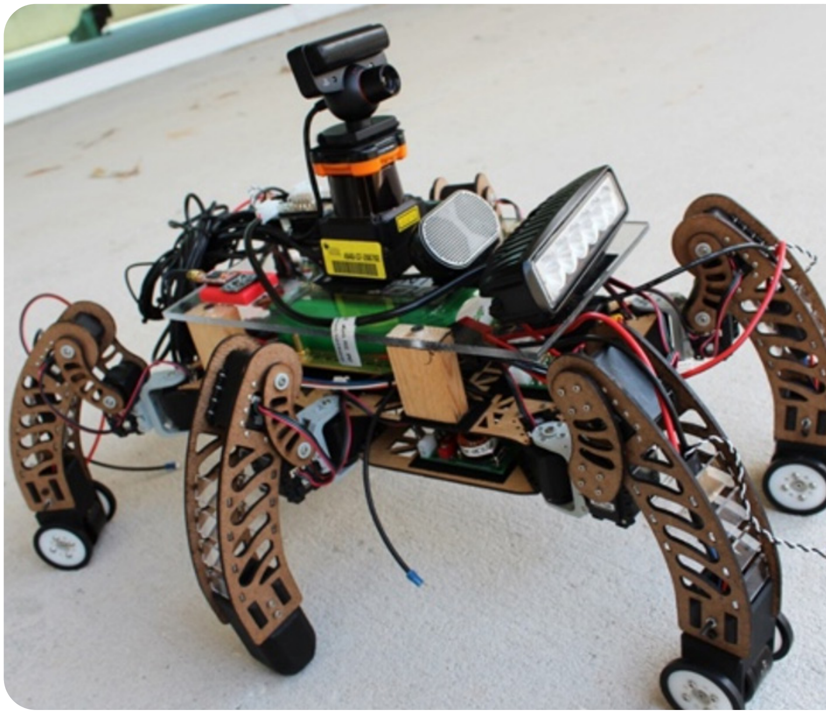


Figure 3.3 Teaching and mentoring will be based on real-world experiences and case projects- University of Central Florida Senior Design Showcase

3.2 Continuing Education

3.2.1 Workplace Training

Employer-sponsored continuous learning programs, prioritizing practical experiences, will expand. Recognizing that university education can be the first step for graduating SEs, employers must bridge the transition from university education to industrial practice - both general and enterprise-specific. Continuing education can focus upon either SE competencies such as evolving methods, technologies, and processes in the fields of digital engineering or non-deterministic systems but can also include domain-focused competencies such as software engineering, cyber security, or autonomy. In real life, SE career developments will need advancements in domain, technology, and systems competencies. Early to mid-career training and education, provided by internal universities or academies, will be focused on enterprise practices, tailored to the systems, technologies and enterprise specific practices and standards used in that organization. Additionally, and perhaps alternatively, enterprises will take advantage of complementary formal training programs such as summer schools, short course offerings, certificate programs, or formal postgraduate programs for systems thinking, design, development, and analysis.

Enterprise competitiveness requires continuous adaptation of technologies, products, manufacturing, services, and processes in ever more rapid cycles. Actively engaging staff in life-long learning is hence a prerequisite to also mastering the changing SE work challenges and the transition towards digital enterprises. Continuous training and staff development will become indispensable to ensure alignment with: 1) digital transformation initiatives and infusion of technologies; and 2) an enterprise's changing product, supply chain, or mission.

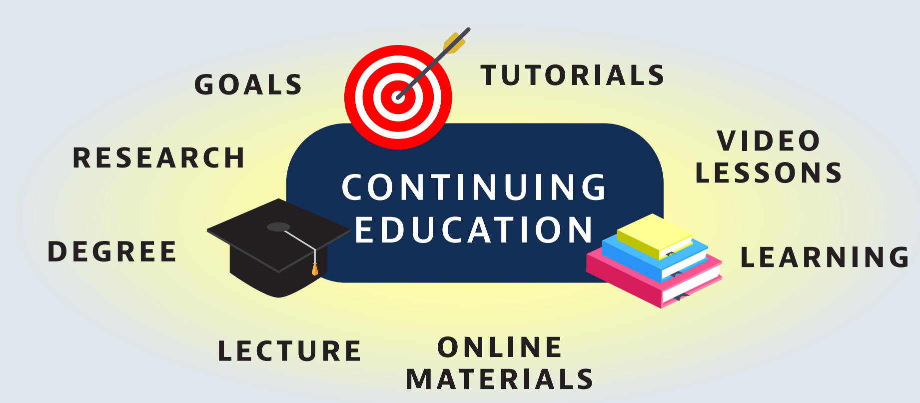
This thinking is consistent with that of Jack Welch, CEO of General Electric Corporation, who aptly stated "when the rate of external change exceeds the rate of internal change, the end of your business is in sight".

In view of the increasing need for life-long learning, commercial SE training providers will serve as gap fillers for teaching both broad and deep SE-related subjects. Training providers should employ experienced system instructors, who have applied SE in industry or government real-life projects, and can flexibly react to changing enterprise needs, new technologies, or new methodologies.

Certification programs can play a role in supporting validation and self-assessment of SE competencies and thus support graduate and postgraduate education initiatives as well as employee career growth. They can provide benchmarks for knowledge and proficiency assessments along an SEs development path. INCOSE, for example, has three different kinds of certifications for SEs for different stages of developments. *(Ref 7)*

Airbus Defense and Space (ADS) has improved their SE competencies and capabilities over the past 20 years via a continuous education and training program. A short description, courtesy of ADS, found in *Appendix B,* can serve as a benchmark for continuous learning advancement for SE.

Additionally, the US Department of Defense has created a model for officer training through the career continuum *(see Appendix C)*. The fundamental ideas in this model are easily extended to continuous education for engineers in general and SEs specifically.



3.2.2 On-the-job training

Most practicing SEs do not have a formal SE education but learned it on the job. The reason for this is that SEs generally establish knowledge in a specific domain and then build on that knowledge while expanding the breadth of expertise.

For early and mid-career SEs, certain roles within a system life cycle can provide a greater training opportunity than others. System validation roles provide insight into how a design meets its intended objective and how individual design decisions either support or detract from customer satisfaction. Integration and testing roles allow an engineer to experience first-hand the results of making subsystems work together and identify the root causes of failures associated with independent subsystem viewpoints and implementations. Operations experience allows an engineer to personally see the result of architecture and design decisions made in the very early phases of a project and make connections that can be applied in later design assignments.

These integrative roles are invaluable for the development of high-performing SEs and therefore, enterprises pursuing career path experiences for developing SEs would do well to place a priority on providing these opportunities.

4.0 SUMMARY AND CONCLUSIONS

Systems analysis and engineering competencies, like many others, will need continuous nurturing and career development to ensure that the workforce remains current with technology, tools and methods, regulations, and many other developments. Digital enterprises moreover need a systems approach to unite and correlate the different value streams of their operations and ensure that their business models and products are resilient.

Changing SE development needs apply to industry, educational institutions, and government organizations, especially to those involved in high-tech, often complex, programs or acquisition and supply chain interactions. All need to advance their traditional approaches to cope with the demands of digital enterprises and remain current in 2035. This will require major investments in human capital.

Since information will be digitally and rapidly available in most all fields, education of SEs needs to focus more and more upon “truth of knowledge” and the integration of competencies across various engineering and programmatic domains. SE will continue to evolve, and its education will be adapted to respond to changing stakeholder and digital transformation needs of the 2030s.

Key for successful enterprises in the 21st Century are people, their education, knowledge, and effectiveness. Ensuring their continued competency development and motivation will be essential to attracting the best employees and retaining them.

APPENDIX A

BEHAVIORS OF HIGHLY SUCCESSFUL SYSTEMS ENGINEERS AT NASA

These behaviors have broad applicability for SEs, regardless of industry domain. An abridged version of the behaviors identified by the study are:

LEADERSHIP

- Influences others
- Works well with a team
- Trusts others
- Communicates a vision and technical steps needed to reach implementation
- Mentors and coaches

ATTITUDES & ATTRIBUTES

- Possesses self-confidence
- Has an objective and comprehensive view of the job
- Is intellectually curious
- Manages change

COMMUNICATION

- Advances Ideas
- Communicates through storytelling and analogies
- Listens effectively and translates information

PROBLEM SOLVING & SYSTEMS THINKING

- Uses critical thinking
- Manages risk
- Exhibits proper paranoia - an abiding focus on what might go wrong

For detail, see Ref 10:

nasa.gov/sites/default/files/atoms/files/behavioral_competencies_highly_regarded_nasa_systems_engineers.pdf

APPENDIX B

AN INDUSTRIAL EXAMPLE FOR POSTGRADUATE SE EDUCATION AND TRAINING: THE AIRBUS DEFENSE AND SPACE COMPANY

A remarkable continuous education and training program for SEs has been developed in the past two decades by Airbus Defense and Space (ADS). This company's program features various stages of development for SEs in line with the need for growing skills, depth and breadth for them to master broader competencies.

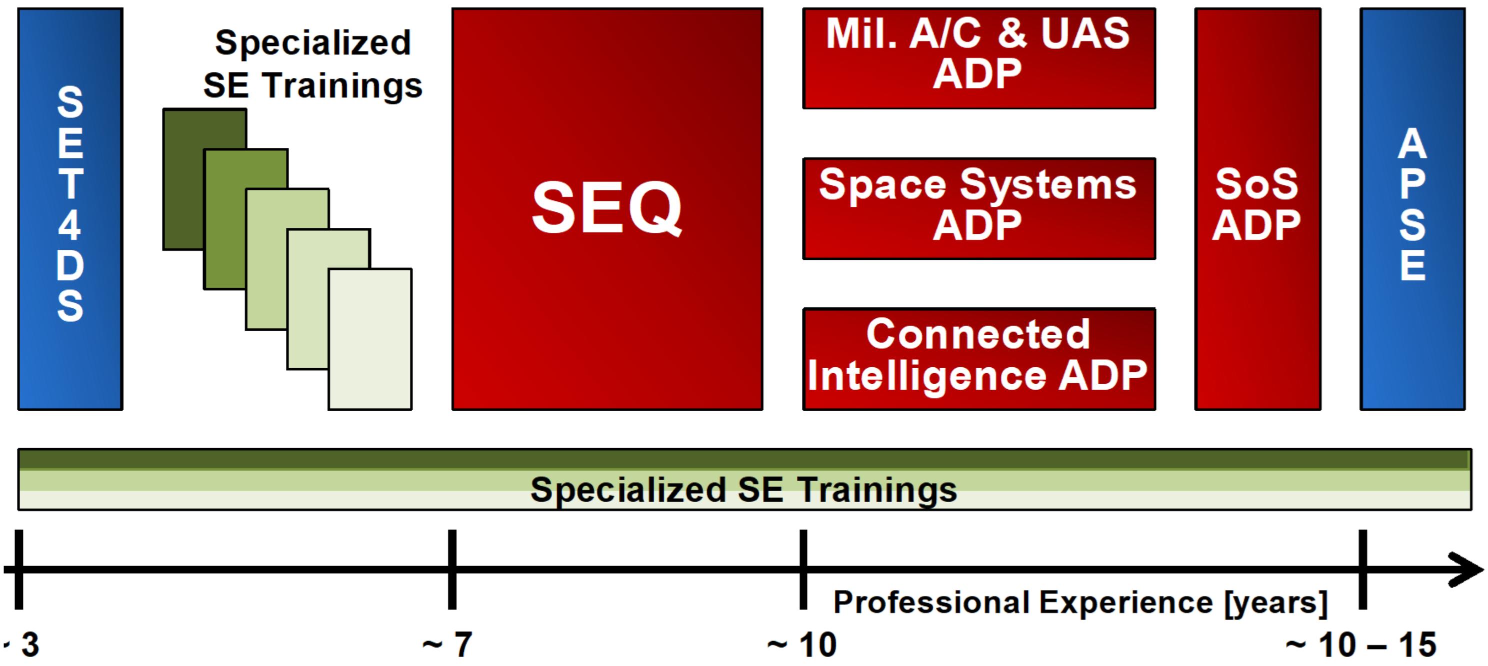
Through this program and additional initiatives, ADS has improved their SE competencies and capabilities over the past 20 years. A short description, courtesy of ADS, can serve as a benchmark for continuous learning advancement for SEs.

THE AIRBUS DEFENCE AND SPACE SYSTEMS ENGINEERING LEARNING PATH

Airbus Defence and Space (AD) promotes set of training and programs in Systems Engineering learning path as recommendations for future Systems, Lead, and Chief Engineers.

For newcomers in the field of Systems Engineering, many e-learnings are available, providing a first introduction to Systems Engineering.

For future Systems Engineers with about three years of professional experience, AD recommends the "Systems Engineering Training for Defence and Space (SET4DS)" program. This is a two week training, consisting of lectures on Systems Engineering Fundamentals and a Show Case Project, to practice the content of the lectures.



At any time, the engineers shall attend individual specialized SE trainings like Processes, Methods and Tools, Technical T epics / Specialty Engineering based on the needs of their project.

For future Systems Engineers with about 7 years of professional experience, AD recommends the "Systems Engineering Qualification (SEQ)" Program, which is an Airbus Defence and Space transversal program consisting of 6 technical modules of one week each and a set of technical online lectures, 3 social skills modules of two days each, a Kick-Off event, a Final Presentation and a real life project that the SEQ students have to execute in parallel. SEQ is a Call for Nomination Program, i.e. the participants have to be nominated by their line manager and HR Business Partner.

After about 10 years of professional experience, the engineer can specialize in one of the Architect Development Paths (ADP):

- Military Aircraft (Mil. A/C) & Unmanned Aerial System (UAS) Architect Development Path: 11 modules of one week each,
- Space Systems Architect Development Path: 7 modules of 3-4 days each.
- System-of-Systems (SoS) Architect Development Path: 2 modules of 3,5 days each,
- Connected Intelligence Architect Development Path, a set of e-learnings and classroom trainings composed individually.

All ADPs are Call for Nomination Programs.

Finally experienced Systems, Lead and Chief Engineers meet in the "Advanced Practices for Systems Engineering" training workshop: a forum to learn and discuss about future trends in Systems Engineering, to see how Systems Engineering is applied in other industries and to discuss topics coming from their own projects.

APPENDIX C

OFFICER PROFESSIONAL MILITARY EDUCATION CONTINUUM

The US Department of Defense has created a model for officer training through the career continuum. The fundamental ideas in this model are easily extended to continuous education for engineers in general and SEs specifically.

EDUCATION ↓	CADET/MIDSHIPMAN PRECOMMISSIONING	O-1/O-2/O-3 PRIMARY	O-4 INTERMEDIATE	O-5/O-6 SENIOR	O-7/O-8/O-9 GENERAL/FLAG
EDUCATIONAL INSTITUTIONS AND COURSES	SERVICE ACADEMIES ROTC OCS/OTS	• BRANCH WARFARE OR STAFF SPECIALTY SCHOOLS • PRIMARY-LEVEL PME COURSES	• Air Cmd and Staff College • Army Cmd and Gen'l Staff College • College of Naval Cmd and Staff •Marine Corps Cmd and Staff College	• Air War College • Army War College • College of Naval Warfare • Marine Corps War College • Eisenhower School • National War College • JFSC: Jt & Combined Warfighting School, AJPME • JFSC: Jt Advanced Warfighting	• CAPSTONE • Jt Functional Component Cmdr Courses • SJIOAC • JFOWC • PINNACLE
LEVEL OF WAR EMPHASIZED	Conceptual Awareness of all Levels	TACTICAL	OPERATIONAL		STRATEGIC
FOCUS OF MILITARY EDUCATION	• Intro to Service Missions • U.S. Constitution • U.S. Gov't	• Assigned Branch of Staff Specialty • Domain Knowledge (Land, air, sea, space & cyber)	• Warfighting w/in context of Op Art • Intro to Theater Strategy, Plans, NMS, NSS • Op Art in All Domains	• Svc Schools: Strategic Leadership, NMS, Theater Strategy • NWC: NSS • Eisenhower: NSS w/emphasis on resource components •All: Interagency; Multi-nat'l Ops; Cross-Domain Ops at Nat'l Strategic Level	• Jt Matters & Nat'l Security • Interagency Process • Multinat'l Ops
CAREER-LONG DEVELOPMENT	LIFE-LONG LEARNING SKILLS/SELF-DEVELOPMENT/ADVANCED EDUCATION CULTURAL EDUCATION: FROM AWARENESS TO COMPETENCE				
JOINT EMPHASIS	Joint Introduction • Nat'l Military Capabilities (in all domains) & Organization • Foundations of Joint Warfare	Joint Awareness • Joint Warfare/Cross Domain Fundamentals • Joint Campaigning • Operational Adaptability	JPME Ph I • Nat'l Mil Capabilities Cmd Structure & Strategic Guidance • Jt Doctrine & Concepts • Jt & Multinat'l Forces at Operational Level of War • Jt Planning and Execution Process • Jt C2--emphasis on Mission Cmd •Operational Adaptability	JPME Ph II • NDS, NSS & NMS • Jt Warfare, Theater Strategy/Campaigning in Jt, IA, Intergov't & Multi-Nat'l Envirnt • Nat'l & Jt Planning Systems and Processes • Integration of Jt, IA, Intergov't & Multinat'l Capabilities • Design • Strategic Adaptability JCWS	CAPSTONE • NSS • Jt Op Art • Jt Func Component CC courses & JFOWC • NSS • Nat'l Planning Systems & Org • Theater Strategy, campaigning and mil ops in Jt, IA, Intergov't & Multinat'l Environments • IO PINNACLE
DESIRED LEADER ATTRIBUTES	1. UNDERSTANDING SECURITY ENVIRONMENT AND INSTRUMENTS OF NATIONAL SECURITY 2. ANTICIPATING AND RESPONDING TO SURPRISE AND UNCERTAINTY 3. ANTICIPATING AND RECOGNIZING CHANGE AND LEADING TRANSITIONS 4. OPERATING IN INTENT THROUGH TRUST, EMPOWERMENT, AND UNDERSTANDING 5. MAKING ETHICAL DECISIONS BASED ON THE PROFESSION OF ARMS 6. THINKING CRITICALLY/STRATEGICALLY AND APPLYING JOINT WARFIGHTING PRINCIPLES AT ALL LEVELS OF WARFARE				

For detail, see Ref 11:

jcs.mil/Portals/36/Documents/Library/Instructions/CJCSI%201800.01F.pdf

CREDITS

This "White Paper" was compiled and edited by Prof. Dipl.-Ing. Heinz Stoewer, M.Sc. SAC GmbH, and TU Delft, and co-edited by David Nichols, JPL/Caltech.

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