The Compleat Architect: Being a Primer on the Art of System Modeling

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Abstract

Document-Intensive Systems Engineering (DISE) is inadequate to the task of developing complicated and complex systems. Model-Based Systems Engineering (MBSE) was created to address this gap. System modeling software continues to grow in power and capability but there is a shortage of individuals capable of using these tools to their fullest potential. This dearth of talent is slowing the transformation of systems engineering to a model-based discipline.

A muddle of publications that obscure high-quality content compounds this problem. Every moment spent on a low-value paper or book robs practitioners of growth. This presentation will share a curated collection of heuristics, resources, and techniques aimed at maximizing the return on an individual's investment.

Case studies, philosophy, and discussions from antiquity to today will be compiled into an integrated program for personal development. An emphasis will be placed on resources to help students and practitioners to understand the problem at hand, its context, and how to assess it in a systems context.

The Value of Systems Engineers

The Helix Project was a multi-year study of systems engineers sponsored by the United States Deputy Assistant Secretary of Defense for Systems Engineering (DASD(SE)), the International Council on Systems Engineering (INCOSE) and the Systems Engineering Division of the National Defense Industrial Association (NDIA-SED). It seeks to understand the "DNA" of effective systems engineers. [1] As part of its activities, it interviewed hundreds of systems engineers and others who work with them (e.g.., program managers). The Helix team found that systems engineers were valued because they *personally* brought the following values to their projects:

1. *Keep and maintain the system vision*: Get the true requirements from the customer, see relationships between the disciplines, help team members understand those relationships, and provide the big picture perspective for the system…

2. *Translate technical jargon into business or operational terms and vice versa*: Serve as a human Rosetta Stone. Translate highly technical information from subject matter experts into common language that other stakeholders can understand…
3. *Enable diverse teams to successfully develop systems*: Bring together a diverse team of engineers and subject matter experts…
4. *Manage emergence in both the project and the system*: Envision the future, which includes staying "above the noise" of day-to-day development issues…
5. *Enable good technical decisions at the system level*: Balance technical risks and opportunities with the desired end result…focus on root cause rather than proximal cause.
6. *Support the business case for the system*: Balance traditional project management concerns of cost and schedule with technical requirements… [2]

The Helix project also developed the *Atlas* proficiency model to map systems engineers' abilities against the requirements of various systems engineering roles. This proficiency model groups related "knowledge, skills, abilities, behaviors, and cognitions" (KSABCs) into six proficiency areas:

1. *Math/Science/General Engineering*: Foundational concepts from mathematics, physical sciences, and general engineering;
2. *System's Domain & Operational Context*: Relevant domains, disciplines, and technologies for a given system and its operation;
3. *Systems Engineering Discipline*: Foundation of systems science and systems engineering knowledge;
4. *Systems Engineering Mindset*: Skills, behaviors, and cognition associated with being a systems engineer;
5. *Interpersonal Skills*: 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
6. *Technical Leadership*: Skills and behaviors associated with the ability to guide a diverse team of experts toward a specific technical goal. [3]

Gaps in Current Curricula

Traditional systems engineering education (particularly at the graduate degree level, which assumes the student has a complementary undergraduate degree that satisfies the needs for Area 1, *Math/Science/General Engineering*) stresses Area 3, *Systems Engineering Discipline*. Area 2, *System's Domain and Operation Context*, is usually project-specific and Areas 5 and 6, *Interpersonal Skills* and *Technical Leadership*, are often relegated to the realm of corporate internal training and individual personal development.

Area 4, *Systems Engineering Mindset*, is a critical area that is often overlooked in process-focused curricula. *Atlas* defines it as: [3]

Systems Engineering Mindset	4.1 Big-Picture Thinking	
	4.2 Paradoxical Mindset	4.2.1 Big-Picture Thinking and Attention to Detail 4.2.2 Strategic and Tactical 4.2.3 Analytic and Synthetic 4.2.4 Courageous and Humble 4.2.5 Methodical and Creative

The Graduate Reference Curriculum for Systems Engineering (GRCSE™) v1.1 does include systems thinking but does not address these other KSABCs. [4]

The Challenge of System Modeling

Document-Intensive Systems Engineering (DISE) is demonstrably inadequate to handle the challenges of complicated and complex systems. A shift to Model-Based Systems Engineering (MBSE) has been underway for a decade; however, few academic programs teach pragmatic systems modeling methods. Teaching modeling languages (such as SysML), tools, and methods requires significant hands-on experience that is scarce in both academia and industry.

Successful modeling is particularly dependent upon the modeler's proficiencies in Area 4: *Systems Engineering Mindset*, because models exist as abstractions at varying levels of detail, encompass the "big picture" and details, support strategic and tactical needs, and require individuals comfortable with operating with ambiguity while the model is under development.

In addition, a recently published Model-Based Engineering (MBE) Manifesto states:

"We Value:

- Information over artifacts
- Integration over independence
- Expressiveness with rigor over flexibility
- Model usage over model creation

We value the items on the right, but not at the sacrifice of the items on the left." [5]

Seeing the need for information that expresses system concepts with rigor while maintaining a usage focus requires a particular modeling mindset that must be consciously cultivated.

Curated Readings

Reading is a time-honored way to gain knowledge; accompanying an author on a journey allows the reader to gain context and depth that are both lost when works are summarized. The following papers and books have been found useful by the author in his personal development as a systems architect, engineer, and modeler. Several have been made required supplemental reading in course that he teaches; they are presented here, grouped by topic. All collectively address the deficit in Area 4 and help shape the students' systems engineering mindset.

General Mindset Development

The Design of Design: Essays from a Computer Scientist, Frederick P. Brooks, Jr.; [6] If possible, the author would make this text mandatory reading for every engineering undergraduate. It is insightful, candid, and thought-provoking. Each essay is short and illustrates principles that resonate with students and provide useful topics for in-class discussion. Suggested courses: Systems Architecture, Product Development, or general engineering

How Not To Be Wrong: The Power of Mathematical Thinking, Jordan Ellenberg; [7] This book explains how mathematics approaches can be a "force multiplier" for common sense. The author does touch on a few contentious political topics to illustrate his points (e.g., "How Much Welfare Should We Provide,"), but he does so in a way that is inoffensive. Suggested courses: Any.

On Grand Strategy, John Lewis Gaddis; [8] The book's website proclaims that it is "The best education in grand strategy available in a single volume . . . a book that should be read by every American leader or would-be leader."—The Wall Street Journal." This is not far from the truth; it explains key concepts such as "align aspirations and capabilities" and "use checklists, not commandments." It is better targeted at a graduate-level audience and should be read in its entirety to gain maximum effect. It also includes discussion of heuristics and is a fitting complement to *Discussion of the Method*. Suggested courses: Systems Architecture, Product Development.

Discussion of the Method: Conducting the Engineer's Approach to Problem Solving, Billy Vaughan Koen; [9] This book is more suitable for the graduate level (or every professor). It rewards thoughtful consideration and includes a discussion of heuristics: "Engineering design is the use of *heuristics* to cause the best change in a poorly understood situation within the available resources." [9]

"Although difficult to define, a heuristic has four definite signatures that make it easy to recognize:

1. A heuristic does not guarantee a solution,
2. It may contradict other heuristics,

3. It reduces the search time for solving a problem, and
4. Its acceptance depends on the immediate context instead of on an absolute standard." [9]

Suggested courses: Systems Architecture, Product Development.

The Mind of War: John Boyd and American Security, Grant T. Hammond; [10] This book outlines Colonel John Boyd's strategic thinking (he was instrumental in the development of the F-16 through his work on energy maneuverability theory). He originated the observe-orient-decide-act (OODA) loop that is widely used in strategic discussion (and equally applies to cybersecurity). Suggested courses: Systems Architecture, Product Development.

Outcomes

How Do We Fix Systems Engineering, Michael D. Griffin; [11] A seminal paper that discusses the need for systems engineers to focus on outcomes, not just process. It also introduces elegant design and other important principles. It references (and should be paired with) Rickover's "Paper Reactors" paper. It is excellent as a basis for an introductory short paper (asking students to comment on both) at the beginning of a systems engineering course. Suggested course: Systems Engineering.

Paper Reactors, Real Reactors, ADM Hyman G. Rickover, USN; [12] A memo published by ADM Rickover that discusses the difference between theory and practice. Referenced by Griffin's *How Do We Fix Systems Engineering*, both should be read together and make a good topic for student essays. Suggested course: Systems Engineering.

What Engineers Know and How They Know It: Analytical Studies from Aeronautical History, Walter G. Vincenti; [13] This book details how engineers transformed scientific theories and empirical information (such as "good stick feel") into engineering parameters that could guide development of aircraft. Although focused on aeronautics, it demonstrates to the reader how unformed empirical user statements can be refined into concrete engineering principles. Suggested course: Graduate Engineering courses.

Leadership

Five-Star Leadership: The Art and Strategy of Creating Leaders at Every Level, Patrick L. Townshend, Joan E. Gebhardt; [14] The best general leadership book the author has read; it distills lessons from a variety of military branches (which have a demonstrable interest in leadership excellence). This quote, from Robert Lutz (former Chrysler executive), describes the book well: "All veterans know that leadership, at its best, is never autocratic, abusive, or arbitrary. Rather, it relies on commitment, communication, and character. To anyone interested in what the pros have to say about leadership, I highly recommend this readable and well-researched book." Recommended course: Any.

Against the Tide: Rickover's Leadership Principles and the Rise of the Nuclear Navy, RADM Dave Oliver, USN (Ret.); [15] This book, written by a naval officer who was part of Rickover's nuclear program, gives fascinating insights into the thinking and leadership of the individual arguably most responsible for the success of the United States Navy's nuclear fleet. The leadership principles and anecdotes are particularly applicable to the challenges faced in transforming systems engineering from DISE to MBSE. Recommended courses: Systems Engineering or Systems Modeling.

Turn the Ship Around!: A True Story of Turning Followers into Leaders, CAPT L. David Marquet, USN (Ret.); [16] This book chronicles how the author took a low-performing submarine (SSN-763 U.S.S. *Santa* Fe) and made it into a top performer, winning the Arleigh Burke Fleet Trophy for most improved ship in the fleet. It details the issues the author uncovered and the straightforward approach he took to improving and empowering the crew. Suggested course: Undergraduate engineering leadership.

Kelly: More Than My Share of It All, Clarence L. "Kelly" Johnson with Maggie Smith; [17] This book described Johnson's career at Lockheed and his involvement in numerous seminal aircraft. It emphasizes his focus on finding the least expensive, simplest solution to problems. Suggested course: Any

Creativity

Inventive Engineering: Knowledge and Skills for Creative Engineers, Tomasz Arciszewski; [18] The author describes how to apply a toolbox of methods to the challenges of innovation. He discusses problem definition, concept evaluation and selection, and other useful innovation techniques. Suggested courses: Systems Architecture, Innovation, Systems Engineering.

The Simplicity Cycle: A Field Guide to Making Things Better Without Making Them Worse, Dan Ward; [19] In this, the first of two recommended books by Ward, he discusses the efforts needed to manage development and ruthlessly keep scope creep from dooming projects. Recommended courses: Product Development, Innovation.

F.I.R.E: How Fast, Inexpensive, Restrained, and Elegant Methods Ignite Innovation, Dan Ward; [20] In this book, Ward discusses how small, focused teams often outperform bloated groups. He stresses elegance and the need to maintain self-control. Recommended courses: Product Development, Innovation.

Case Studies

Rocketdyne: Powering Humans into Space, Robert Kraemer; [21] An interesting look into the nuts-and-bolts of designing and testing rocket engines before the advent of supercomputers and simulation. It is readable and showcases the challenges inherent in harnessing properties and principles on the edge of human understanding (and deriving empirical success). Recommended courses: Systems Engineering, Systems Optimization.

747: Creating the World's First Jumbo Jet and Other Adventures from a Life in Aviation, Joe Sutter; [22] This autobiographical account of the development of one of the most successful aircraft in history is direct and unflinchingly honest (see his story of the fate of the expensive PERT chart a consultant created). It gives insight into the design trades and challenges that faced the 747 development team (made up of engineers NOT assigned to work on Apollo). Recommended courses: Any.

Mars Rover Curiosity: An Inside Account from Curiosity's Chief Engineer, Rob Manning and William L. Simon; [23] This contemporary example showcases the efforts at Jet Propulsion Laboratory to create the vehicle at the heart of the enormously successful Mars Science Laboratory Mission. Recommended courses: Undergraduate engineering.

Valkyrie: The North American XB-70: The USA's Ill-fated Supersonic Heavy Bomber, Graham M. Simmons; [24] This book stands in counterpoint to Johnson's *More Than My Share of It All* (in which Johnson contrasts choices made in the development of the SR-71 with those made by the XB-70 team). The XB-70 is a beautiful and amazing aircraft but significant architectural flaws doomed it. Recommended courses: Systems Architecture, Product Development.

The Secret of Apollo: Systems Management in American and European Space Programs, Stephen B. Johnson; [25] No other program can compare with Apollo; it culminated in one of the greatest achievements: landing a human being on the Moon. This book is particularly appropriate to include as part of celebrating and recognizing the fiftieth anniversary of the first lunar landing. Recommended courses: Any, Systems Engineering.

NOVA: Ancient Computer, PBS; [26] This documentary details the archaeological investigation of the Antikythera Mechanism, a two-millennia old analog computer. Discovered in 1902, the Mechanism has been the subject of numerous analyses. This video showcases recent work that appears to have fully described the mechanism. It should be watched with students as the basis for discussion of the possibilities inherent in applying fundamental principles (and how much can be achieved with care and skill without advanced computing devices). Recommended course: Any.

Course Assignments

When *The Design of Design* is used as a supplemental textbook (in conjunction with Hillary Sillitto's *Architecting Systems: Concepts, Principles and Practice*), students are expected to weave content from both books and other readings into homework assignments. The following is a typical example:

“Read:

- Rickover on Paper Reactors
- Griffin on “How Do We Fix Systems Engineering?”
- Building a Path to Elegant Design
- Using Maslow’s Hierarchy of Needs to Define Elegance in System Architecture

Write a three- to four-page paper (single-spaced, Arial 10.5) containing the following content:

1. Compare and contrast the architectural principles discussed so far in the lectures, both course books (*Design of Design* and Sillitto), and these papers.
2. Draw upon your personal experiences and explain how you used (or could have benefited from) these principles.
3. Conclusion (summarize lessons learned and final thoughts)”

This allows students to demonstrate their understanding of the material and makes them think critically about its application in practice.

The readings can also be integrated into long-term assignments; the author has found that having students read a book-length, detailed case study often leads to enhanced understanding. This is a typical assignment (given early in the term to allow them ample time to complete the additional reading):

“Find a book about the development of a large, complicated system (aerospace, naval, civil, consumer product). Pick something of interest to <u>you</u>. No anthologies…please find a book about a single system (part of the intent of this assignment is to see a development process from the inception to production/use with some historical perspective about how it all “worked out.” Was it a success? Failure? Did it meet/exceed/fall short of user needs and expectations?)

1. Find a book about the development of this system (approximately 250-300 pages).
2. Post the book and a link (or ISBN) in the discussion board for approval
3. Read the book; capture relevant quotes and pages numbers as you read (this will help you properly cite the work later).
4. Write a paper (5 pages plus appropriate images, diagrams, etc.) discussing the development of the system and relating it to course readings (textbooks, papers, etc.). (50 points)
    a. Introduction
    b. Context
    c. User Needs
    d. Noteworthy systems engineering incidents/content from the book

    e. System “report card”: Was it successful? If it failed, was it a failed architecture or failed execution?
    f. Lessons learned (what did you learn?)
5. Develop an appropriate system model (15 points)
    a. System Context
    b. BDDs/IBDs as appropriate
    c. Use Case / Activity Diagrams as appropriate
    d. Identify at least 2 critical elements in the model with *problems* (something the developers did well or totally failed at executing…example would be the units mismatch in the Mars Climate Orbiter”

Conclusion

The incorporation of supplemental works is necessary to augment the process-focused emphasis of most systems engineering textbooks. This curated list of books, papers, and videos is intended to provide recommendations to instructors seeking to adopt the *Atlas* proficiency model and assist students in developing areas often underserved.

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