SYSTEM ARCHITECTURE

Strategy and Product Development
for Complex Systems

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Foreword

Norman R. Augustine

A particularly promising trend that has been taking place in healthcare is the marriage of biomedical research with engineering practices. A friend of mine, an engineer, recently described to me a meeting that took place at one of America's most prestigious universities between the faculties of the engineering department and the cardiology department exploring just such opportunities. Having decided to focus on constructing a practicable mechanical human heart, the head of cardiology began his presentation with a description of the properties of the human heart. Almost immediately an engineer interrupted, asking "Does it have to be in your chest? Could it be, say, in your thigh where it would be easier to reach?" No one in the room had ever considered that possibility. Nonetheless, the presentation continued. Soon another interruption occurred; this time it was another engineer asking, "Instead of just one heart could you have three or four small hearts integrated in a distributed system?" No one had thought of that either.

System Architecture, so insightfully presented in this book by three of the field's most highly regarded leaders, is about asking—and—answering just such questions. In my own career I have encountered system architecture questions in fields ranging from engineering to business to government. When established practices of the field of system architecture are applied, far superior outcomes seem to result.

Applying such practices has not always been the case. Early in my career I recall asking various of my colleagues who were working "together" on a guided missile program why they had chosen a particular design approach for their specific element of the product. One replied, "Because it is the lowest weight." Another assured me that his part would have the lowest radar cross-section. Still another answered because her component would be less costly. And yet another had focused on minimizing volume. And so it went.

What was missing? The answer is a *system architect*.

This shortcoming is too often encountered, usually in more subtle ways. Consider the case of the Near-Sonic Transport aircraft that was in the early stages of development a few years ago. A marketing survey had indicated that airline passengers want to get to their destinations faster. To an aerodynamicist (my own early field), if one wishes to avoid the penalties of supersonic flight, that translates into more closely approaching Mach One, creeping up on the drag curve into a regime wherein fuel consumption abruptly increases. This was, in fact, the underlying concept of the Near-Sonic Transport.

But when viewed from a system architecture perspective, the appropriate question is not how to fly faster; rather, it is how to minimize the time to get from one's home, to the airport, check-in, pass through security, board the aircraft, fly, collect baggage and travel to one's final destination. Placed in this context, an even more fundamental question arises: "How much will a passenger pay to save five or ten minutes of flying time?" The answer turns out to be, "not much"—and the Near-Sonic Transport aircraft thus met its early, and deserved, demise. There are clearly better

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opportunities in which to invest if one's objective is to help passengers reach their *destinations* more rapidly. The failing in this case was to not recognize that one was dealing with a problem of *system architecture*... not simply a problem of aerodynamics and aircraft design.

My own definition of a "system" evolved over years of experience. It is "two or more elements that interact with one another." The authors of this book wisely add that the resultant functionality must exceed the sum of functionalities of the individual elements. Thus simple in concept, the complexity of most real-world systems is enormous. In fact, the equation describing the number of possible states a system of several elements (that interact in the simplest of all manners) has been aptly named, "The Monster!" And when a system includes humans, as many systems do, the challenge of system architecting becomes all the more immense due to the presence of unpredictability. But these are the kind of systems that one encounters, and are the kind of systems that the authors show how to deconstruct and address.

One such system that I had the occasion to analyze concerned provisioning the (human occupied) U.S. station at the Earth's South Pole. Setting the specific objective of the evaluation in itself required care... as is often the case. Was it to minimize expected cost? Or to minimize worst-case cost in the face of uncertainty, say, due to weather? Or perhaps to minimize "regret"—that is, when supplies are not delivered at all? Or...?

In the case of this particular system there are a number of elements that must interface with one-another: cargo ships, ice breakers, aircraft of various types, ice piers for off-loading, storage facilities, traverse vehicles, communications... and, underlying all decisions, was the ever-present danger of single-point failure modes creeping into the architecture.

In the business world one of the more complex problems faced in my career was whether—and how—all or major parts of seventeen different companies could be combined to create the Lockheed Martin Corporation. Each of the "elements" had its strengths and its weaknesses; each involved large numbers of humans, each with their own goals, capabilities, and limitations; and critical to the decision, the whole had to have significantly greater functionality than the sum of the parts. If the latter were not the case, there would be no reason to pay the financial premium that is implicit in most mergers and acquisitions.

Sadly, in engaging complex questions of this type there is no simple mathematical formula that will reveal the "right" answer. However, the discipline of systems thinking proves to be an invaluable tool in assessing exposure, opportunities, parametric sensitivities, and more. In the above case, most people judge that the answer came out "right"—which, incidentally, contrasts with nearly 80 percent of similar undertakings.

One of the authors of this book and I, along with a group of colleagues, had the occasion to propose to the President of the United States a human spaceflight plan for America for the next few decades. In this instance perhaps the most difficult challenge was to define a useful *mission*, as opposed to the (non-trivial) task of defining an appropriate hardware configuration. Fortunately, such issues are amenable to solution through system thinking.

As the authors point out in the material that follows, the process of establishing the architecture of systems is both a science and an art. But, as is so elegantly portrayed herein, there is a Darwinian phenomenon wherein systems embodying the mistakes of the past do not survive; whereas those that embody sound architectures generally do survive—and even prosper.

That, of course, is what architecting complex systems is all about.

Preface

We wrote this book to capture a powerful idea. The idea of the "architecture of a system" is growing in recognition. It appears in diverse fields including the architecture of a power grid or the architecture of a mobile payment system. It connotes the DNA of the system, and the basis for competitive advantage. There are over 100,000 professionals with the title system architect today, and many more practicing the role of the architect under different titles.

Powerful ideas often have nebulous boundaries. We observed that many of our co-workers, clients, students had a shared recognition of system architecture issues, but used the term in very different scopes. The term is often used to differentiate between existing systems, as in "the architecture of these two mountain bikes is different."

What exactly constitutes the architecture of a system is often a subject of great debate. In some fields, the term is used for a singular decision that differentiates two types of systems at a high level, as in "packet-switched architecture" vs. "circuit-switched architecture." In other fields, the term is used to describe a whole implementation, save for some smaller details, as in "our software as a service architecture."

Our goal was to capture the power of the idea of architecture, and to sharpen the boundaries. Much of the power of idea originates with the potential to trade among several architectures early, to look downstream and identify which constraints and opportunities will be central to value. It isn't possible to trade among early ideas if the architecture encompasses all details, nor is it a meaningful exercise if important drivers of value are missing.

We wrote this book to build on the idea that the architect is a specialist, not a generalist, as proposed by Eberhardt Rechtin. Our intent is to showcase the analysis and methodologies of system architecture, and to develop the 'science' of system architecture. This text is less prescriptive in places than the discipline of product design, as the systems tackled are more complex. Where the product development community has a stronger focus on design, our focus centers more on emergence—the magic of functions coming together to produce a coherent whole.

We've imbued this book with our past experience. We've been fortunate to be involved in the early development of a number of complex systems in communications, transportation, mobile advertising, finance, robotics, and medical devices, ranging in complexity from farm equipment to the International Space Station.

Additionally, we have included case studies from the experience of other system architects, in disciplines ranging from hybrid cars to commercial aircraft. Our intent was that this book can only advance system architecture if it works from challenges faced by system architects today.

We wrote this book for two core audiences—professional architects and engineering students. System architecture as an idea grew out of practitioners' wisdom and attempts to codify the challenges of developing new architecture. One core audience is senior professionals who are faced with architectural decisions. The field encompasses a variety of professionals in senior technical and managerial roles in technical industries—software, electronics, industrial goods, aerospace, automotive, and consumer goods.

This book is also focused on engineering students as a core audience. This text grew out of the graduate course we have taught at MIT for the past 15 years, where we've been fortunate to educate many leaders in the private sector and government. The lens of architecture helps us understand how a system operates today, but moreover, we believe that it is a necessary competency to learn in the management of technical organizations.

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About the Authors

Edward F. Crawley

Edward Crawley is the President of the Skolkovo Institute of Science and Technology (Skoltech) in Moscow, Russia, and a Professor of Aeronautics and Astronautics and Engineering Systems at MIT. He received an S.B. and an S.M. in Aeronautics and Astronautics and an Sc.D. in aerospace structures, all from MIT.

From 1996 to 2003, he was head of the Department of Aeronautics and Astronautics at MIT. He has served as founding co-director of an international collaboration on the reform of engineering education and was the lead author of *Rethinking Engineering Education: The CDIO Approach*. From 2003 to 2006, he was the Executive Director of the Cambridge-MIT Institute, a joint venture with Cambridge University funded by the British government and industry; the Institute's mission was to understand and generalize how universities can act effectively as engines of innovation and economic growth.

Dr. Crawley has founded a number of companies. ACX, a product development and manufacturing firm; BioScale, a company that develops biomolecular detectors; Dataxu, a company in Internet advertising placement; and Ekotrope, a company that supplies energy portfolio analysis to businesses. From 2003 to 2012, he served on the Board of Directors of Orbital Sciences Corporation (ORB).

Professor Crawley is a Fellow of the AIAA (American Institute of Aeronautics and Astronautics) and Royal Aeronautical Society (UK) and a member of the Royal Swedish Academy of Engineering Science, the Royal Academy of Engineering (UK), the Chinese Academy of Engineering, and the National Academy of Engineering (US).

Bruce G. Cameron

Bruce Cameron is the founder of Technology Strategy Partners (TSP), a consulting firm, and the Director of the System Architecture Lab at MIT. Dr. Cameron received his undergraduate degree from the University of Toronto, and graduate degrees from MIT.

As a Partner at TSP, Dr. Cameron consults on system architecture, product development, technology strategy, and investment evaluation. He has worked with more than 60 Fortune 500 firms in high tech, aerospace, transportation, and consumer goods, including BP, Dell, Nokia, Caterpillar, AMGEN, Verizon, and NASA.

Dr. Cameron teaches system architecture and technology strategy at the Sloan School of Management and in the School of Engineering at MIT. Previously at MIT, Dr. Cameron ran the MIT Commonality Study, which comprised over 30 firms spanning 8 years.

Previously, Dr. Cameron worked in high tech and banking, where he built advanced analytics for managing complex development programs. Earlier in his career, he was a system engineer at MDA Space Systems, and has built hardware currently in orbit. He is a past board member of the University of Toronto.

Daniel Selva

Daniel Selva is an Assistant Professor in Mechanical and Aerospace Engineering at Cornell. He has degrees in electrical engineering and aeronautical engineering from Polytechnic University of Catalonia (UPC), Supaero, and MIT.

Professor Selva's research focuses on applications of system architecture, knowledge engineering, and machine learning tools to early design activities. His work has been applied to the NASA Earth Science Decadal Survey, the Iridium GeoScan Program, and the NASA Tracking and Data Relay Satellite System (TDRSS), where he developed architectural analysis in support of system architects and executives. He is the recipient of Best Paper and Hottest Article awards.

Between 2004 and 2008, he worked for Arianespace in Kourou, French Guiana, as a member of the Ariane 5 Launch team, specializing in the On Board Data Handling, and Guidance, Navigation and Control. He has previously worked for Cambrian Innovation in the development of novel bioelectromechanical systems for use on orbit, and at Hewlett Packard on the monitoring of banking networks. He is a member of the Board of Advisors for NuOrion Partners, a wealth management firm.