Research Statement

C. Jason WOODARD

School of Information Systems, Singapore Management University
Tel: (65) 6828 0270; Email: jwoodard@smu.edu.sg

Updated on 17 January 2012

Introduction

My research is motivated by the simple observation that we are surrounded by objects of astonishing complexity, from the phones in our pockets to the planes in our skies. Amazing feats of coordination are required to produce these objects, some of which consist of millions of components made by thousands of suppliers around the world. More mind-boggling still, these physical devices are only the most tangible elements of a global network whose increasingly interconnected flows of information, material and energy provide both a means to achieve these feats of coordination and a valuable end in itself, namely the advancement of our capacity for social interaction of all kinds.

I want to suggest that these things are not just miracles to be marveled at—let alone taken for granted—but deeply surprising facts that demand a systematic explanation. In the next section, I will further suggest that these facts have resisted some of the most powerful sources of explanation available: the core theories of economics, evolutionary biology and engineering design. I will then frame my own work in the context of a distinguished but often marginalized tradition that attempts to reconcile these theories and derive practical insights from their synthesis. The remainder of the document describes the progress of this work to date and my plans for the future.

Background: Economics, Evolution and Design

Consider first the extraordinarily successful framework of neoclassical economic theory. In its purest mathematical form, this framework explains with brilliant conceptual parsimony how prices and output levels for all of the goods and services in an economy can be determined by decentralized market interactions in a way that achieves an efficient allocation of resources. Many people, including many economists, have taken issue with the assumptions of rational behavior embedded in the neoclassical framework. More problematically for my motivating observation, it also assumes that the set of goods and services is fixed. Under this assumption one cannot explain the creation of new products at all, let alone how the world became filled with products as complex and interconnected as the ones we use every day.

This limitation is well understood (see Beinhocker 2006 for a recent discussion) and by no means precludes the study of innovation using economic methods. However, the vast majority of the work in this area either treats innovation as an exogenous process or accounts only for aggregate properties like the level of investment, number of patents, or degree of market concentration. A relatively small community of economists, of whom Brian Arthur is probably the best known (see Arthur 2009), directly addresses the antecedents and consequences of economic complexity.

Most of these scholars anchor their thinking not in the standard neoclassical framework but rather in the Darwinian theory of evolution. Just as evolution explains the rise of biological complexity as a process of random variation and natural selection, the same principles can explain the emergence of complex product designs. Carliss Baldwin (my doctoral thesis advisor) and Kim Clark of the Harvard Business School were the first to articulate a theory of *design evolution* based on Holland's (1975) model of "complex adaptive systems" (Baldwin and Clark 2000). Their theory, grounded in an extended case study of the computer industry, goes beyond prior work in evolutionary economics by explicitly considering the architecture of an evolving system. They identify a set of *modular operators* by which designers create variation in a population of designs, and study the properties of these operators in a market-based economy.

The central challenge for a theory of design evolution is that intention and foresight play a much larger role than most biologists believe they do in the natural world. Herbert Simon observed this more than four decades ago: "Engineering, medicine, business, architecture, and painting are concerned not with the necessary but with the contingent —not with how things are but with how they might be—in short, with design[.] The possibility of creating a science or sciences of design is exactly as great as the possibility of creating any science of the artificial" (1969, p. xi). Simon insisted on models of human behavior that embrace both the evolutionary process of groping toward solutions (which he called the generate–test cycle) and the notion that people can choose the problems they wish to solve and the way to approach these problems.

In the context of complex engineered products and systems, the specific challenge is to reason about the value of alternative designs—that is, the extent to which a new design will be valued by its users (e.g., in terms of their willingness to pay for it), and the fraction of this value that can be captured by the designer (e.g., in the form of revenue or profit). These outcomes typically depend not only on the designer's preferences and actions, but those of the users and the designers of related products or systems. Although the engineering disciplines have developed mature techniques for estimating costs (e.g., Boehm 1981), and more recent work has addressed economic value in a single-agent setting (e.g., Cai and Sullivan 2005), reasoning about the value of designs in settings with multiple stakeholders whose decisions are interdependent remains at the frontier of current research.

That, in a nutshell, is where I aspire to contribute.

From Design Evolution to Architectural Strategy

In a landmark *Harvard Business Review* article, Charles Ferguson and Charles Morris advanced the proposition that "architecture wins technology wars." More specifically, the dramatic rise and fall of IBM from the System/360 through the PC era led them to conclude that "competitive success flows to the company that manages to establish proprietary architectural control over a broad, fast-moving, competitive space" (Morris and Ferguson 1993, p. 87). Their claim is echoed in more recent work on platform competition (Gawer and Cusumano 2002), disruptive innovation (Christensen and Raynor 2003), and the dynamics of business ecosystems (Iansiti and Levien 2004).

This is a prime example of a setting in which multiple designers face interdependent decisions about the architecture of an evolving system. As Gawer and Cusumano note, it gets ever harder to establish control when "more and more firms want *their products* to become the foundation on which other companies build their products or offer their services" (2002, p. 6). Many technology strategists now agree that the best way to achieve this is, counterintuitively, "to 'let go' of the lower levels of the platform: to open them up to adaptation and modification by a large segment of the ecosystem" (Iansiti and Levien 2004, p. 158). But although industry lore is replete with advice about which parts of an architecture to hold on to or give away at what stages of its development, we still lack a unifying theory that offers causal explanations and testable predictions.

What is required is a theory of *architectural strategy*: the application of strategic thinking—"the art of outdoing an adversary, knowing that the adversary is trying to do the same to you" (Dixit and Nalebuff 1991, p. ix)—with the aim of capturing economic value through architectural control. Such a theory would help managers in high-technology industries address a variety of practical challenges, especially those involving software-based platforms.

Examples of these challenges and related questions include:

- Platform providers like Microsoft have long benefited from "locking in" their customers and complementors by inducing them to build on proprietary interfaces and protocols. But customers are increasingly demanding adoption of open standards, and hardware advances have made it easier to innovate around proprietary software components.

    - ➢ *So does architectural control still win technology wars, as Morris and Ferguson (1993) argued? If not, will the pendulum swing back toward commoditization, as suggested by Fine (1998)? Or will the control points shift to adjacent layers, as proposed by Christensen and Raynor (2003)?*

- As the media, telecommunications and consumer electronics industries converge around digital products and services, new architectural layers are emerging, creating opportunities for innovation and posing threats to established players.

  - *Which layers will give rise to new technology platforms? Who will become platform leaders (Gawer and Cusumano 2002) and how can they manage their business ecosystems for sustained growth (Iansiti and Levien 2004)?*

- The IT industry is poised to enter an era of "ultra-large-scale" systems with billions of lines of code running on millions of devices (Northrop et al. 2006). These systems will be radically distributed, loosely coupled and continuously evolving, without central ownership or control.

  - *So what does it mean to "manage" the design and implementation of these systems? How can designers' incentives be aligned to promote innovation and deliver value to stakeholders even without the ability to direct their actions explicitly?*

An active research community has begun to grapple with questions like these, bringing to bear a diverse set of theoretical perspectives, analytical tools and empirical methods. (See Gawer 2009 for a sample of recent work.)

My own perspective is equally informed by the conceptual foundations described above and by my experience at IBM, where I worked on marketing and strategy for a variety of technologies spawned by the Internet boom, including Java and XML. At IBM and other high-technology firms, I encountered industry veterans with a keen intuition for the strategic significance of architectural decisions. (Indeed, the fact that Bill Gates appointed himself chief software architect after stepping down as Microsoft's CEO in 2000 suggests an acute awareness of his dual role as manager and designer.) Much of the knowledge behind this intuition was informal and situation-specific, as I discovered in trying to pin down definitions for terms like "architectural control point" and tease out the conventional wisdom on "open" versus "closed" standards.

After thinking about these issues for more than a decade, I remain firmly convinced that a useful theory of architectural strategy must be rooted in a rigorous theory of design evolution. Unfortunately that is a difficult proposition to explain or defend without presuming a widely dispersed body of background knowledge, which makes it hard to engage a broad audience for my work. Nonetheless, I continue to pursue both objectives as part of the same research agenda, with the hope that targeted audiences will see value in different parts of it.

Main Research Streams and Results to Date

My research output can be loosely divided into three streams: theory development, modeling and simulation, and empirical analysis. Each stream contains several lines of research. This section elaborates briefly on each stream, highlighting significant outputs and commenting on the status of recent work.

Theory development

The main objective of the theoretical stream is to clarify the conceptual foundations of architectural strategy.

- In a book chapter on platform architecture coauthored with Carliss Baldwin [1], we argue that the diverse array of products and services that are commonly called platforms share a fundamental set of architectural features. These features not only give rise to economies of scale and scope, as recognized in previous literature, but also support the evolvability of platform systems. We describe three ways of representing platforms (network graphs, design structure matrices, and layer maps), and address four strategic questions suggested by a unified view of platforms: when is a platform architecture useful, when can it be contained within the boundaries of a single firm, when should a platform owner encourage outsiders to develop complements to the platform, and which complementary components should be controlled by the platform architect?

- In a separate line of work based on the first chapter of my dissertation, I have collaborated with several leading scholars to explore the core concepts of architectural strategy and architectural control [2, 3, 4]. The most recent work in this line is a paper with Joel West [5], in which we develop four interlinked perspectives on architectural strategy. Building on the "mirroring hypothesis" (Baldwin and Colfer 2010), which posits a duality between technological and organizational architecture, we highlight a second, orthogonal duality between components and interfaces: designers of both products and organizations must decide what information to hide within component boundaries and what to expose to other designers. Although the component–interface duality appears in many settings, it presents especially vexing strategic challenges in the design and production of complex digital artifacts. We present a conceptual framework for studying these kinds of strategic design problems, and discuss the tensions that can arise between the four perspectives we identify. We conjecture that the ability to resolve these tensions may be a significant and underappreciated source of competitive advantage.

- To address the challenge of reasoning about architectural strategy, I developed the concept of a design structure network (DSN). A DSN is a graphical representation of a system's design space. DSNs improve on existing architectural representation schemes by providing a compact and intuitive way to express design options, the ability to replace all or part of one design with another. In a paper based on the second chapter of my dissertation [6], I show how DSNs can serve as a formal foundation for economic models of architectural strategy, which I call *system design games*.

Modeling and simulation

Architectural strategy and design evolution are complex phenomena that can be difficult to study directly using empirical methods. Analytical and computational models are thus valuable ways to bridge the gap between abstract theoretical constructs and raw observational data.

- In another joint paper with Carliss Baldwin [7], we develop an analytical model of competition in layered industry architectures. We investigate the possibility that a vertical pricing externality operating across complementary products can offset horizontal competition between substitutes, such that a decentralized network of firms can mimic the pricing behavior and profitability of a vertically integrated monopoly. We use our model to compare open and closed standards regimes, and study the forces that give rise to commoditization and value migration.

While analytically tractable models are useful and desirable, it is generally infeasible to study both strategy and dynamics in complex designs in a way that admits closed-form mathematical solutions. I therefore turned to agent-based computational modeling for the core of my graduate work (starting at the Santa Fe Institute's Complex Systems Summer School in 2002 [8]), and continue to employ computational methods in most of my current research.

- In a paper drawn from the third chapter of my dissertation [9], I explore strategic behavior by firms who repeatedly choose whether to transact with each other in a value network such as a supply chain, thus designing the pattern of active links in the network. As is typical in complex networks, there is a tension between economic efficiency and link stability. In a series of computational experiments, firms frequently became locked into inefficient network configurations or endless cycles of mutual frustration. However, simple coordinating mechanisms such as property rights (the ability to refuse a link) and bilateral bargaining (the ability to exchange side payments) led to dramatically improved outcomes.

- In paper based on my fourth dissertation chapter [10], I model firms that develop systems with layered architectures in which products at one layer serve as platforms for applications and services in adjacent layers. Platform owners face a difficult balancing act. On one hand, they need to make their platforms attractive to potential complementors by mitigating the threat of architectural lock-in. On the other hand, they must be careful not to give away too much too soon, or risk being unable to recoup their own investments. The paper explores this tension at both the firm and industry levels. Computational experiments show that boundedly rational platform owners learn to attract complementors by voluntarily limiting their exercise of architectural control. When rents from architectural control are strongly appropriable, firms enjoy substantial first-mover advantages. Later entrants do surprisingly well, however, because they are able to be more selective in choosing product niches to develop. Consistent with the analytical model of [7], the results suggest that architectures with more layers, which are fostered by more "open" technologies and practices, may enhance industry innovation and profitability.

- Eric Clemons and I are currently exploring the evolution of platform architectures. In our first project [11], we built on the well-known *NK* family of models (Kauffman 1993) to show that platforms can arise spontaneously under technological evolution driven by highly myopic designers. We observed phenomena such as path dependence and lock-in under much simpler assumptions than my earlier model of platform competition. In a new working paper [12], we introduce environmental turbulence and consumer heterogeneity, and show that platform architectures can evolve as a byproduct of natural selection for products that work well in novel and diverse combinations.

Empirical analysis

Despite identifying myself primarily as a modeler, I am also an empiricist in the sense that I see modeling as a complement to, rather than a substitute for, rigorous empirical study of real-world phenomena. Over the past several years, I have been pursuing opportunities to do this kind of work.

- In 2008, I supervised two guided research projects by undergraduate students, both involving the analysis of network data related to software architectures. Siu Chun Lai investigated the structure of code dependencies in the Mozilla browser and Apache web server projects. Shuli Yu studied the relationships between Web 2.0 APIs and mashups [13].

- In 2009, motivated by Microsoft's reputation for "embracing and extending" technology standards in order to "lock in" developers with proprietary features, Joel West and I investigated the company's response to twelve software technologies in the period between 1990 and 2005 [14]. Our analysis revealed surprising diversity in responses, which we classified using a typology that treats "embrace" and "extend" as orthogonal decisions. Our results suggest that firms tend to publicly embrace a standard with the aim of gaining *legitimacy* with a community of adopters, while efforts to extend a standard tend to be motivated by the intent to *leverage* the underlying technology to achieve or strengthen architectural control. We argue that legitimacy and leverage are strategic complements, making the "embrace and extend" strategy attractive to firms like Microsoft, but that the resulting outcome is unstable. Firms that pursue this strategy ultimately face a choice between contributing their extensions back to the standard and losing proprietary advantage, or giving up the legitimacy associated with standards compliance in exchange for freedom from the constraints of compatibility.

- In 2010, I began collaborating with Narayan Ramasubbu, Ted Tschang, and V. Sambamurthy on a project to study the way architectural strategy is actually practiced by system designers [15]. Synthesizing Baldwin and Clark's (2000) concept of a modular operator with Pentland's (1992) concept of an organizing move, we explore the sequences of *design moves* through which firms create and modify complex digital artifacts. We theorize that the cumulative results of these moves—the stock of designs owned or controlled by a firm—can be viewed as a strategic resource, which we call *design capital*. Using four case studies, we explore the dimensions of design capital (focusing on *option richness* and *technical debt*), and characterize the design moves we observe in terms of their effects on the four firms' design capital. We develop propositions linking design moves to design capital, and investigate the factors moderating their relationship. This project contributes to a growing body of insights on how digital business strategy is formulated and executed, and supports the broader goal of establishing an empirically traceable link between the design of digital artifacts, competitive strategies built on these designs, and firm-level performance.

Additional Research in Related Areas

In addition to the main body of work described above, I have conducted research in several related areas.

- To facilitate building agent-based models and running computational experiments, I developed as part of my dissertation a set of software tools called Kuala to extend popular modeling toolkits such as Repast (North et al. 2006) and MASON (Luke et al. 2004). With the support of the SIS Research Centre, Darshan Santani and I improved, modularized and packaged these tools as a software platform. In 2007, we released the software under the first open-source license authorized by SMU [16].

- To hone my empirical skills and explore the behavior of a real-world complex adaptive system, namely the Singapore taxi fleet, I helped initiate the SMU Taxi Data Analytics project (along with Rajesh Balan and Shih-Fen Cheng). Partnering with a Singapore taxi operator, we have studied over 5 billion GPS observations from 16 months of continuous taxi traces. Our initial efforts focused on improving the spatio-temporal efficiency of the system [17]. We also investigated the feasibility of using cloud computing technologies to improve the speed and scale of our data analysis [18].

- While much of my research has a descriptive orientation, I am also interested in contributing to the design (and design process) of real-world artifacts. In a paper with David Parkes that was motivated by the problem of arranging the links in a peer-to-peer network [19], I proposed a strategyproof mechanism for ad hoc network formation. More recently, I have been working with Steven Kimbrough on ways to apply interactive evolutionary computation to assist designers in discovering new designs and refining solutions to difficult design problems.

Future Plans

The scope of my research has broadened over the last five years, both in terms of research methods (from primarily agent-based modeling to a mix of theoretical, modeling and empirical work) and target audiences (spanning technology strategy, innovation management, and design science). My current priority is to focus on bringing this work to publication in peer-reviewed journals.

Reflecting on the more fundamental challenges of my research agenda, I often feel torn by the desire to anchor my work in the "deep structure" of design evolution while generating actionable insights for technology strategists and system architects. At these times I remember the wisdom of Donald Stokes, who passed away while advising my undergraduate thesis. Stokes proposed the concept of Pasteur's Quadrant to describe "basic research that seeks to extend the frontiers of understanding but is also inspired by considerations of use" (1997, p. 74). Although I have far to go on both dimensions, I find courage in his conviction that these goals are worth pursuing jointly.

Selected Publications and Working Papers

(Electronic versions and complete list available at http://kuala.smu.edu.sg/~jason/papers.)

[1] C. Y. Baldwin and C. J. Woodard (2009). "The Architecture of Platforms: A Unified View." In A. Gawer, ed., *Platforms, Markets and Innovation*, Edward Elgar, 19–44.

[2] A. Bharadwaj, R. K. Chellappa, V. Sambamurthy, and C. J. Woodard (2007). "Architecture and Strategy in Digital Ecosystems." Extended abstract presented at the International Symposium of Information Systems (ISIS), Indian School of Business.

[3] C. J. Woodard (2008). "Architectural Control Points." Short paper presented as a poster at the Third International Conference on Design Science Research in Information Systems and Technology (DESRIST), Atlanta.

[4] J. Woodard and J. West (2009). "Architectural Dualities in Complex Systems: Components, Interfaces, Technologies and Organizations." Accepted for presentation at the DRUID Summer Conference, Copenhagen.

[5] C. J. Woodard and J. West (2011). "Four Perspectives on Architectural Strategy." In *Proceedings of the 32rd International Conference on Information Systems (ICIS)*, Shanghai.

[6] C. J. Woodard (2007). "Modeling Architectural Strategy Using Design Structure Networks." Presented at the 2nd International Conference on Design Science Research in Information Systems and Technology (DESRIST), Pasadena.

[7] C. J. Woodard (2002). "Exploring the Dynamics of High-Technology Product Diversity." Student paper, Santa Fe Institute Complex Summer School.

[8] C. Y. Baldwin and C. J. Woodard (2007). "Competition in Modular Clusters." Harvard Business School Working Paper 08-042. Presented at the 2004 Academy of Management Annual Meeting, New Orleans.

[9] C. J. Woodard (2010). "Local Coordination Under Bounded Rationality: Coase Meets Simon, Finds Hayek." Working paper, 22 October. Presented at the 2007 Academy of Management Annual Meeting, Philadelphia.

[10] C. J. Woodard (2008). “Platform Competition in Digital Systems: Architectural Control and Value Migration.” Working paper, 30 May. Presented at the 2006 Academy of Management Annual Meeting, Atlanta.

[11] C. J. Woodard and E. K. Clemons (2011). “From Primordial Soup to Platform-Based Competition: Exploring the Emergence of Products, Systems, and Platforms.” In *Proceedings of the 44th Hawaii International Conference on System Sciences (HICSS)*.

[12] C. J. Woodard and E. K. Clemons (2012). “The Evolution of Platform Architectures.” Working paper, 10 January.

[13] S. Yu and C. J. Woodard (2008). “Innovation in the Programmable Web: Characterizing the Mashup Ecosystem.” In *Workshop Proceedings of the 6th International Conference on Service Oriented Computing (ICSOC)*, LNCS 5472, 136–147.

[14] C. J. Woodard and J. West (2009). “Strategic Responses to Standardization: Embrace, Extend or Extinguish?” In G. Cattani et al., eds., *Project-Based Organizing and Strategic Management (Advances in Strategic Management, Vol. 38)*, Emerald, 263–285.

[15] N. Ramasubbu, C. J. Woodard, F. T. Tschang, and V. Sambamurthy (2011). “The Logic of Digital Business Strategy: Exploring the Duality Between Design Capital and Design Moves in Digital Architectures.” Working paper, 19 August.

[16] C. J. Woodard (2006). “Kuala: Agent-based Modeling Tools for the Economics of Design.” Working paper, 26 July.

[17] D. Santani, R. K. Balan, and C. J. Woodard (2008). “Spatio-Temporal Efficiency in a Taxi Dispatch System.” Technical report, SMU School of Information Systems.

[18] A. J. Y. Koh, X. K. Nguyen, and C. J. Woodard (2010). “Using Hadoop and Cassandra for Taxi Data Analytics: A Feasibility Study.” Technical report, SMU School of Information Systems.

[19] C. J. Woodard and D. C. Parkes (2003). “Strategyproof Mechanisms for Ad Hoc Network Formation.” Presented at the 1st Workshop on Economics of Peer-to-Peer Systems (P2PEcon), University of California, Berkeley.

Additional References

Arthur, W. B. (2009). *The Nature of Technology: What It Is and How It Evolves*. Free Press.

Baldwin, C. Y. and K. B. Clark (2000). *Design Rules, Volume 1: The Power of Modularity*. MIT Press.

Baldwin, C. Y. and L. Colfer (2010). “The Mirroring Hypothesis: Theory, Evidence and Exceptions.” Harvard Business School Working Paper 10-058, 4 June.

Beinhocker, E. D. (2006). *The Origin of Wealth: Evolution, Complexity, and the Radical Remaking of Economics*. HBS Press.

Boehm, B. W. (1981). *Software Engineering Economics*. Prentice-Hall.

Cai, Y. and K. J. Sullivan (2005). “A Value-Oriented Theory of Modularity in Design.” In *Proceedings of the Seventh International Workshop on Economics-Driven Software Engineering Research (EDSER)*, 1–4.

Christensen, C. M. and M. E. Raynor (2003). *The Innovator’s Solution: Creating and Sustaining Successful Growth*. HBS Press.

Dixit, A. K. and B. J. Nalebuff (1991). *Thinking Strategically: The Competitive Edge in Business, Politics and Everyday Life*. W. W. Norton.

Fine, C. H. (1998). *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*. Basic Books.

Gawer, A., ed. (2009). *Platforms, Markets and Innovation*. Edward Elgar.

Gawer, A. and M. A. Cusumano (2004). *Platform Leadership: How Intel, Microsoft, and Cisco Drive Industry Innovation*. HBS Press.

Holland, J. H. (1975). *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*. University of Michigan Press.

Iansiti, M. and R. Levien (2004). *The Keystone Advantage: What the New Dynamics of Business Ecosystems Mean for Strategy, Innovation, and Sustainability*. HBS Press.

Kauffman, S. A. (1993). *The Origins of Order: Self-Organization and Selection in Evolution*. Oxford University Press.

Luke, S., C. Cioffi-Revilla, L. Panait, and K. Sullivan (2004). “MASON: A New Multi-agent Simulation Toolkit.” In *Proceedings of the Eighth Annual Swarm Users / Researchers Conference (SwarmFest)*.

Morris, C. R. and C. H. Ferguson (1993). “How Architecture Wins Technology Wars.” *Harvard Business Review* 71(3): 86–95.

North, M. J., N. T. Collier, and J. R. Vos (2006). “Experiences Creating Three Implementations of the Repast Agent Modeling Toolkit.” *ACM Transactions on Modeling and Computer Simulation* 16(1): 1–25.

Northrop, L., P. Feiler, R. P. Gabriel, J. Goodenough, R. Linger, T. Longstaff, R. Kazman, M. Klein, D. Schmidt, K. Sullivan, and K. Wallnau (2006). *Ultra-Large-Scale Systems: The Software Challenge of the Future*. Technical report, Software Engineering Institute, Carnegie Mellon University.

Pentland, B. T. (1992). “Organizing Moves in Software Support Hot Lines,” *Administrative Science Quarterly* 37(4): 527–548.

Simon, H. A. (1969). *The Sciences of the Artificial*. MIT Press.

Stokes, D. E. (1997). *Pasteur’s Quadrant: Basic Science and Technological Innovation*. Brookings Institution Press.