View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Research Papers in Economics

HARVARD | BUSINESS | SCHOOL

When Open Architecture Beats Closed: The Entrepreneurial Use of Architectural Knowledge

Carliss Y. Baldwin

Working Paper

10-063

Copyright © 2010 by Carliss Y. Baldwin

Working papers are in draft form. This working paper is distributed for purposes of comment and discussion only. It may not be reproduced without permission of the copyright holder. Copies of working papers are available from the author.

WHEN OPEN ARCHITECTURE BEATS CLOSED: THE ENTREPRENEURIAL USE OF ARCHITECTURAL KNOWLEDGE

Carliss Y. Baldwin
Harvard Business School
Soldiers Field
Boston, MA 02163
cbaldwin@hbs.edu

Revised October 2010

When Open Architecture Beats Closed:
The Entrepreneurial Use of Architectural Knowledge

Abstract

This paper describes how entrepreneurial firms can use superior architectural knowledge to open up a technical system to gain strategic advantage. The strategy involves, first, identifying "bottlenecks" in the existing system, and then creating a new open architecture that isolates the bottlenecks in modules and allows others to connect to the system at key interfaces. An entrepreneurial firm with limited financial resources can then focus on supplying superior bottleneck modules, and while outsourcing and allowing complementors to supply non-bottleneck components. I show that a firm pursuing this strategy will have a higher return on invested capital (*ROIC*) than competitors with a less modular, closed architecture. Over time, the more open firm can drive the *ROIC* of competitors below their cost of capital, causing them to shrink and possibly exit the market. The strategy was used by Sun Microsystems in the 1980s and Dell Computer in the 1990s.

Key words: architecture — innovation — knowledge — modularity — dynamics — competition — industry evolution

JEL Classification: D23, L22, L23, M11, O31, O34, P13

When Open Architecture Beats Closed: The Entrepreneurial Use of Architectural Knowledge

Introduction

Entrepreneurial firms are often rich in knowledge but poor in other resources. Such firms must use their superior knowledge to compete against larger and better endowed rivals. The question is, how? This paper describes how entrepreneurial firms can use superior architectural knowledge to open up a technical system and thereby gain strategic advantage.

The concept of an "architecture" for man-made systems dates back to Herbert Simon's (1962), classic paper "The Architecture of Complexity." The term entered the management literature when Henderson and Clark (1990) introduced the concept of "architectural innovation," defined as follows:

> [Architectural] innovations … change the way in which the components of a product are linked together, while leaving the core design concepts (and thus the basic knowledge underlying the components) untouched. (p. 10)

Notably, at the time of their writing, there was no universal concept of architecture that could be applied to all technical systems. Several engineering disciplines used the concept of architecture (e.g., computer architecture), but definitions of the term were domain-specific.

Building on the work of Nam Suh (1990), Ulrich (1995, p. 419) offered the first general definition of product architecture, calling it "the scheme by which the function of a product is allocated to physical components" including "the specification of *interfaces* between interacting components." Subsequently, in the engineering systems literature, Whitney et. al. (2004) defined architecture broadly to include (1) a list of functions; (2) the components needed to perform the functions; (3) the detailed arrangement and interfaces between the components; and (4) a description of how the system will operate through time and under different conditions. All complex man-made systems, including all products and processes, have architectures.

Architectures can be the focus of study and a means of improving the performance of a technical system. In this context, *architectural knowledge* may be defined as knowledge about the components of a complex system and how they are related. It includes knowledge about (1) how the system performs its functions (the function-to-component mapping); (2) how the components are linked together (the interfaces); and (3) the behavior of the system, both planned and unplanned, in different environments (the dimensions of performance). In their case study of the photolithographic industry, Henderson and Clark (1990) showed that incumbent firms may lack architectural knowledge, hence may fail when faced with architectural innovations by challengers. This paper builds on that insight: it derives a strategy based on superior architectural knowledge that can be used by entrepreneurial firms seeking to displace incumbent rivals.[1]

The rest of the paper is organized as follows: I first position this work within the literatures of strategy and innovation. I then describe specific types of architectural knowledge and identify those most useful to entrepreneurial firms. In the core of the paper, I describe a particular strategy that uses superior architectural knowledge to create an open architecture. I construct a stylized model to show how the strategy allows a small challenger to displace a larger incumbent with a closed architecture. I show how the strategy was used by Sun Microsystems and Dell Computer to unseat larger incumbent rivals and discuss the origins of their superior architectural knowledge. I end by discussing implications of the theory, limitations of the strategy, and opportunities for further work.

Literature Review

This paper is related to three distinct strands in the literatures on strategy and innovation. First and most directly, it applies modularity theory to a problem of strategy. Second, it builds on recent work in strategy that seeks to apply resource-based and dynamic capabilities theories of the firm to entrepreneurial ventures and to predict which ventures will succeed. Third, it extends theories in the strategy literature that match different organizational forms with different types of innovations or problem-solving strategies.

---

[1] The main challengers in Henderson and Clark's study were Japanese firms. However, the time period of their study (1962-1986) largely pre-dated the rise of venture-capital-backed entrepreneurial firms in the US (Gompers and Lerner, 1999).

This paper has direct roots in modularity theory (Simon, 1962; Henderson and Clark, 1990; von Hippel, 1990; Langlois and Robertson, 1992; Garud and Kumaraswamy, 1995; Ulrich, 1995; Sanchez and Mahoney, 1996; Baldwin and Clark, 1997, 2000; Schilling, 2000; Sako, 2003). From this literature comes the basic idea that product and process architectures are targets of design, hence potentially a source of competitive advantage for firms. Baldwin and Clark (2000) explain in detail how the architecture of a technical system can be changed by applying modular operators such as splitting and substitution. This paper describes a strategy that relies on modularization of a technical system plus selective openness with respect to suppliers and complementors (Adner and Kapoor, 2010). As shown below, both the modularization and sourcing decisions must be guided by architectural knowledge. The net result is to give the entrepreneurial firm a "smaller footprint" in the technical system than its rivals, leading to a higher return on invested capital (*ROIC*).

The resource-based view (RBV) of competitive advantage argues that firms derive sustainable competitive advantage through having control of resources that are valuable, rare, inimitable and non-substitutable (Wernerfelt, 1984; Barney, 1991). However simply having resources is not enough: a firm must not only generate rents, but also appropriate them. Hence resources must be protected by "isolating mechanisms," which prevent *ex post* re-equilibration of the rent stream (Rumelt, 1987).

The RBV has recently been extended to entrepreneurial firms by Alvarez and Busenitz (2001) and Alvarez and Barney (2004). These papers argue that the entrepreneurial firm's most critical resource is knowledge, including knowledge about how to assemble other resources to pursue an opportunity. They also suggest that the boundaries of an entrepreneurial firm can serve as isolating mechanisms to prevent the diffusion of valuable knowledge to potential competitors (Alvarez and Barney, 2004). In this paper, I translate the entrepreneurial firm's dual problem of generating and appropriating rents into a problem of architectural design. I specify the properties of an open technical architecture that permit a small entrepreneurial firm to compete with larger, entrenched rivals. Then, building on the idea that the boundaries of the firm serve as isolating mechanisms, I locate these boundaries at key points in the open architecture.

A related body of literature views firms as bundles of path-dependent capabilities separated by transactions (Coase, 1937; Penrose, 1959; Nelson and Winter, 1982; Barney, 1984; Teece, Pisano and Shuen, 1997). On this view, the boundaries of a firm are shaped by the interaction of a firm's specific competencies and its transactional opportunities. Firm and industry boundaries will shift in response to firms' perceptions of gains from trade or gains from coordination (Jacobides, 2005; Jacobides and Winter, 2005; Cacciatori and Jacobides, 2005).

Reasoning from this perspective, Jacobides and Winter (2007) recently analyzed the optimal choice of vertical scope for an entrepreneurial firm operating under transaction costs and capacity and financing constraints. They showed, among other results, that financially constrained firms will optimally choose a narrower initial scope than those not facing such constraints. The model developed below also shows that financially constrained firms will choose narrower scope (a smaller footprint), but differs from Jacobides and Winter in that it explicitly considers dynamic competition between an entrepreneurial challenger and incumbent rival(s). Somewhat counterintuitively, the model shows that constraints on external funding may be advantageous for entrepreneurial firms.

In addition to the literature on firm boundaries, there is a growing literature in strategy on firm origins as determinants of success. Across a range of industries, this work attempts to determine whether origin or other forms of pre-entry experience are predictive of success (Klepper and Simons, 2000; Klepper, 2002; Helfat and Lieberman, 2002; Agarwal, Echambadi, Franco and Sarkar, 2004; Klepper and Sleeper, 2005; Bayus and Agarwal, 2006). A basic argument in this literature is that firms "inherit" knowledge from parent companies or their founders' previous employers. These different knowledge endowments lead the firms to pursue different strategies, which then have systematically different effects on long-term survival (Klepper and Sleeper, 2005; Agarwal, Audretsch and Sarkar, 2007).

This paper focuses on knowledge content rather than origin. Following Henderson and Clark (1990), I argue that a particular type of knowledge—architectural knowledge—exists and that some persons and firms may have more of it than others. I then ask, can a firm that is disadvantaged in terms of financial and organizational resources use superior architectural knowledge to succeed against a larger rival? And if so, by what strategy can this be accomplished? The standard I set for success of the strategy is high: the incumbent and entrant compete head-to-head and the entrant succeeds by driving the incumbent out. I am thus investigating a particularly pure form of creative destruction (Schumpeter, 1934), rather than strategies involving product differentiation, complementarity or other forms of mutual accommodation (Agarwal et. al. 2007).

The reasons to look at this extreme form of competition are twofold. In the first place, knowledge can be built by examining outlying as well as average forms of behavior. Understanding the disruptive potential of architectures is useful when evaluating investments in architectural knowledge. Secondly, when a small entrant (David) confronts a larger incumbent (Goliath), both would like to know whether David's slingshot can deliver a killing blow. Below I establish criteria that determine whether a particulary open architecture has "killer potential." Both offensive and defensive strategies can be predicated on this assessment.

Finally, two lines of prior literature propose a correspondence or matching between different organizational forms and types of innovation or problem-solving strategies. In the first, Teece (1996, 2000) and Chesbrough and Teece (1996) distinguish between autonomous innovations, which can be incorporated into an existing technical system without significant changes, and systemic innovations, which require many adaptations in many different parts of the existing system. Building on transaction cost economics, they argue that smaller firms, e.g. entrepreneurial firms, are well-suited to carry out autonomous innovations, whereas systemic innovations require the resources and capabilities of a large, vertically integrated enterprise. The second line originates in the knowledge-based theory of the firm (Kogut and Zander, 1992, 1996; Conner and Prahalad, 1996; Grant, 1996). Building on this work, Nickerson and Zenger (2004) argue that there is a critical match between forms of governance and problem-solving strategies. They characterize problem solving as a search in a high-dimensional space or landscape (Kaufmann, 1993; Levinthal, 1997; Rivkin and Siggelkow, 2003, 2007; Ethiraj and Levinthal, 2004; Ethiraj, Levinthal and Roy, 2008) and then compare three modes of governance in terms of knowledge transfers and hazards. They argue that while markets can provide good solutions to highly decomposable problems, hierarchies (i.e., firms) are needed to solve less decomposable problems.

Without contradicting these arguments, this paper shows that architectural knowledge may be used to change the scope of an innovation and the dimensions of a firm's problem search space. Specifically, an entrepreneurial firm can use architectural knowledge to open up an architecture and in this fashion convert systemic innovationa to autonomous innovations. When it redraws its boundaries and opens up its architecture, the entrepreneurial firm is in effect repartitioning the problem search space to its advantage. The next section describes how architectural knowledge can be used to identify these advantageous divisions.

Types of Architectural Knowledge

In this section I describe two specific forms of architectural knowledge needed by an entrepreneurial firm seeking to confront a larger and wealthier incumbent: knowledge of (1) bottlenecks in the technical system; and (2) potential remodularizations.

To gain architectural knowledge, system designers typically experiment with different ways of putting the system together; study the system in different environments; and meter its internal states to see what levels of activity or stress arise at different junctures (Bell and Newell, 1971; Hennessy and Patterson, 1990; Patterson and Hennessy, 1994; Baldwin and Clark, 2000; Colwell, 2005). From these investigations, the architects will find *bottlenecks* in the system, that is, places where performance is constrained by one or more components (Ethiraj, 2007). They will also learn how to separate some components from the rest of the system and encapsulate them as *modules* of the system (Parnas, 1972; Parnas et.al., 1985; Baldwin and Clark, 2000). Finally the architects may discover that arranging some or all of the components in a new way will deliver new functionalities or higher levels of performance.

The first two types of knowledge—knowledge of bottlenecks and new potential modularizations—are critical to the entrepreneurial strategy I describe below. In the next two subsections, I explain in greater detail what such knowledge entails. (The third type of knowledge—new ways of linking components—can also be used strategically, but it generally gives advantage to vertically integrated incumbents. I will return to this point at the end of the paper.)

Knowledge of Bottlenecks

The performance of a complex system on some dimension is often constrained by one or more of its components (Ethiraj, 2007). Such locations in the system are called *bottlenecks*. Knowledge of bottlenecks is generally domain-specific: knowing how to find bottlenecks in a production line does not help to find them in a power grid or a computer chip. Across all domains, however, there are two generic types of bottleneck: absolute and fractional.

An *absolute bottleneck* arises when the performance of the system equals that of its least-good component. Let X denote the performance the system and $x_1,...,x_n$ denote the performances of each of n separate components. An absolute bottleneck exists if:

$$X = \min(x_1,...,x_n) \quad . \tag{1}$$

For example, an assembly line is only as fast as its slowest station; the security of a system is only as good as its most vulnerable portal; a chain is only as strong as its weakest link.

On dimensions with an absolute bottleneck, there is no point in seeking to improve any part of the system that does not involve the bottleneck (Ethiraj, 2007). Addressing the bottleneck, however, may require redesigning components outside the bottleneck itself. For example, architects may be able to shift some of the activities in the bottleneck to other parts of the system. (In manufacturing, this is known as "line-balancing;" in power grid engineering, "load-balancing.") Or they can directly add capacity at the bottleneck itself, for example, by putting two components where there was one.

Fractional bottlenecks arise when system performance is additive, i.e., equals the sum of the performance of individual components:

$$X = x_1 + ... + x_n \qquad (2)$$

For example, the time needed to run a software program is the sum of the times needed to complete its instructions.[2] And the cost of manufacturing a product equals the sum of the costs of each input.

On dimensions with additive performance, although all components contribute to the whole, components with high x's are more significant than those with low x's. A given percentage improvement has a greater impact on total system performance if the component has a high x vs. a low x. High x components are thus targets of architectural improvement. In computer architecture, a maxim known as Amdahl's Law recommends to "make the common case fast" (Hennessy and Patterson, 1990; Patterson and Hennessy, 1994). In quality control, Juran's famous "80-20" rule states that 80% of the problems come from 20% of the products (or customers) (Juran, 1960, 1992). These principles, taken from very different domains, draw attention to the fractional bottlenecks in particular technical systems.

Knowledge about Potential Modularizations

Architectural knowledge also allows designers to change the modular structure of the system. A complex product or process can be envisioned as a set of components connected by dependencies or links, which can be physical, energetic, or informational. (Eppinger, 1991; Baldwin and Clark, 2000; Baldwin, 2008.) In general, dependencies among components can be managed in one of two ways. On the one hand, designers can communicate in real time and work out by mutual adjustment how to handle the dependencies. Alternatively, architects can specify the allowed dependencies a priori, by establishing a set of interfaces, bounds, and tolerances. The a priori specification replaces real-time co-ordination with a rule—a design rule—that is binding on all parties (Mead and Conway, 1980; Baldwin and Clark, 2000).

Design rules place more restrictions on the system than real-time communication and mutual adjustment, hence can detract from system performance. However, architectural knowledge can be used to determine which design rules offer little or no harm. In particular, knowledge of bottlenecks helps with

---

[2] In general, architectures based on parallel processing are subject to absolute bottlenecks, while those based on sequential processing are subject to fractional bottlenecks.

the placement of design rules. For example, in a system of 10 components, architectural knowledge might reveal that Component 1 is a bottleneck. The architects can then create design rules that segregate Component 1 from the rest of the system (Parnas, 1972). The designers can then focus on improving Component 1 through multiple rounds of trial-and-error learning while keeping the rest of the system the same.

Complex Architectures

The science of representing complex architectures in a general and formal way is still in its infancy (Fixson, 2005, MacCormack, Rusnak and Baldwin, 2006, Rosenkopf and Schilling, 2007). Nonetheless, a strategically useful description of a technical system's architecture must have three parts: (1) a list of architectural components; (2) a description of the interdependencies between the components; and (3) the (expected) performance of the system on dimensions that are critical to its success.

The *components* of an architecture are design decisions made early on that will guide the later development and building of the system. For firms, architectural components of the technical system generally include the physical parts of its product (the so-called bill of materials), software programs governing the product's behavior, and the processes needed to design, produce and deliver the product.[3] These parts, programs and processes may be insourced or outsourced. Sourcing decisions determine the boundaries of the firm, and thus are critical architectural decisions.

Interdependencies between architectural components (equivalently the system's modular structure) can be represented using Design Structure Matrix or DSM (Eppinger, 1991; Baldwin and Clark, 2000; MacCormack, Rusnak and Baldwin, 2006). Also known as an influence matrix (Ethiraj and Levinthal, 2004; Rivkin and Siggelkow, 2007), a DSM is an $n \times n$ matrix in which the architectural components are arrayed along rows and columns and dependencies recorded in the cells. If element a_i depends on element a_j (in the sense that a change in j may require a change in i), then a mark is placed in

---

[3] The product itself may be a physical good, an intangible good, or a service.

the row of *i* and the column of *j*.

Finally, the *performance* of the architecture (along a particular dimension, *X*) is a mapping from the architectural components and the DSM to the real line: $X \equiv f : \{a_1, ..., a_n; DSM\} \rightarrow R$. In any strategic evaluation of architecture, managers must be concerned with at least three types of performance: unit cost (*c*); invested capital (κ); and quality (which may have several dimensions). Cost, capital and quality are different dimensions of performance, hence each has a bottleneck: an element that if changed would improve performance on that dimension to the maximal degree. If there are no dependencies between components (the DSM has only zeros in its off-diagonal cells), then the firm is free to address each bottleneck independently. However, in most cases, interdependencies will constrain the firm's sphere of action. For example, if all elements are co-specialized (the DSM is fully filled in), then changing one architectural component, e.g., outsourcing a part, will affect all other components in unpredictable, potentially disastrous ways.

Thus to address bottlenecks on one dimension, e.g., cost, the bottleneck components must be isolated from the rest of the system. Ideally, architects will set up a modular structure (a modular DSM) such that each bottleneck component is in a separate module. Each bottleneck can then be addressed without affecting the rest of the system. In reality, however, the components might not sort themselves out so nicely: for example a component which can be purchased cheaply on the market and thus is a candidate for outsourcing, might turn out to be a quality bottleneck, which should be redesigned and produced inhouse. In such cases (which are common), architects will make tradeoffs by adjusting both the architectural components and the dependency graph (the DSM). Conceptually, the space of all possible architectures —all possible combinations of components and dependencies —is vast, thus in practice, architects find acceptable solutions using heuristic search methods and the criterion of satisficing (Simon, 1981).

In the next section, I define a three-pronged test that can be used to compare a challenger's proposed architecture to an incumbent's existing architecture. This test can be viewed as a stopping rule for what would otherwise be an unbounded and possibly non-convergent search process. If the proposed architecture satisfies the three criteria, and the incumbent's architecture is not modular with respect to the bottlenecks being addressed, then the challenger will have a sustained competitive advantage vis à vis the incumbent (Barney, 1991). Armed with its superior architecture, a small, financially constrained firm can use the stategy described below to compete with a larger, wealthier incumbent and have a reasonable chance of success. David can win against Goliath if the architectural slingshot passes this test.

The Strategic Use of Architectural Knowledge

In this, the main section of the paper, I explain how an entrepreneurial firm can use architectural knowledge to create an open architecture in order to unseat a larger incumbent. In brief, the entrepreneurial firm first uses its knowledge to (re)modularize the system and isolate the bottleneck(s). It then creates an open technical architecture in which the focal firm supplies bottleneck components, while allowing suppliers and complementors to provide non-bottleneck components. This architectural strategy results in a higher return-per-unit-of-invested-capital (*ROIC*) for the entrepreneurial firm. I use a stylized model to show how in multiple rounds of competition, a firm with an *ROIC* advantage can surpass the incumbent and force it to shrink.

Applying Architectural Knowledge

To begin, consider Firm C (Challenger), which has architectural knowledge about a particular product and related production processes. Firm C's designers know about the system's bottlenecks, and have ideas about how to remedy them. They also know how to remodularize the system to separate bottleneck from non-bottleneck components.

The industry Firm C seeks to enter has one or more incumbents. For simplicity, I will speak as if there is only one incumbent (Firm I), but there may in fact be several following similar strategies. Firm I, by definition, does not have as much architectural knowledge as Firm C, but it is established and profitable. (Henderson and Clark (1990) showed that incumbents often do lack architectural knowledge.

The case studies discussed below shed light on the origins of such knowledge asymmetries.)

As discussed above, with its superior architectural knowledge, Firm C can create an open system with equivalent performance and cost by (1) isolating the bottlenecks in separate modules; (2) creating superior designs for the bottleneck components; and (3) delegating the provision of non-bottleneck components to suppliers and complementors. A system with more modules by definition has more "thin crossing points," that is, places in the product design or production process where the dependencies between components are few and simple. Thin crossing points have low transaction costs (Langlois, 2006; Baldwin, 2008). Thus Firm C can place transactions at key points within its architecture. It can outsource components that can be purchased cheaply on the market and/or allow consumers to purchase complementary components directly. Because the outsourced and complementary components are not in a bottleneck, they can be technologically inferior to the incumbent's components, but have little or no negative impact on overall system performance.

Given a technical system with *n* components, each of which can be supplied by the focal firm or an outsider, there are (at least) 2^n candidate architectures that Firm C might consider. The incumbent, having less architectural knowledge, originally selected its architecture from a subset of these possibilities. As indicated, each architecture determines the performance of the corresponding technical system along three dimensions: unit cost, invested capital, and quality. I assume that the performance characteristics of the incumbent's architecture are known to the challenger.[4] Formally, let:

$\kappa_C, \kappa_I \equiv$ The capital utilized per unit of production by the challenger and incumbent respectively.

$c_C, c_I \equiv$ The per-unit variable cost of the system for the challenger and incumbent respectively. For the challenger, this cost includes the price of all out-sourced components.[5]

---

[4] Performance on quality dimensions can be obtained from customer reviews and by directly studying the incumbent's products. If the incumbent is a publicly traded firm, performance on cost and capital dimensions can be gleaned from published financial statements.

[5] It does not matter whether the challenger purchases the outsourced components and assembles the whole system or customers purchase the components and assemble the system themselves. Either way the challenger must consider the whole system's variable cost.

$p_C(p_I) \equiv$ Given a price p_I of the incumbent's system, $p_C(p_I)$ is the price of the challenger's system that makes purchasers indifferent between the two.

(The function $p_C(p_I)$ collapses multiple dimensions of quality into a single willingness-to-pay function. Note that this is the price consumers pay for a *whole system*. Payments to complementors are subtracted from this price when determining the price charged by the focal firm.)

I now define three conditions that a candidate architecture must meet for the challenger to succeed in dynamic competition against the incumbent. Using its superior knowledge, the challenger must create a new architecture such that:

$$\kappa_C < \kappa_I \tag{3a}$$

$$c_C \leq c_I \tag{3b}$$

$$p_C(p_I) = p_I \quad . \tag{3c}$$

That is, the challenger's architecture must have the same quality as the incumbent's (3c), the same or lower variable cost (3b) and require less capital per unit of production (3a). Less capital per unit of production in general means that the challenger delegate to suppliers and complementors more of the activities that go into desiging and producing the system as a whole. By concentrating on bottlenecks, the challenger can reduce its span of activities with no penalty in terms of system unit cost or quality. Perforce it will have created an open architecture which relies on external agents—other firms and user communities—to supply key modules of the system.

Conditions 3a-c taken together ensure that the challenger's return on invested capital (*ROIC*), defined below, will be higher than the incumbent's for all prices the incumbent might charge. The challenger with an open architecture satifying these conditions thus has an "*ROIC* advantage."

A Model of Industry Dynamics

This subsection sets up a formal model of dynamic competition between the challenger and incumbent.

Starting Conditions. The incumbent and the challenger sell similar products. At the start of the competition ($t=0$), the incumbent has the capacity to sell $N_I(0)$ units of the good. Its "invested capital," $I_I(0)$, is defined as its capacity times the capital needed per unit of production:

$$I_I(0) \equiv \kappa_I \cdot N_I(0) \quad .$$

The challenger has $N_C(0)$ units of capacity with corresponding invested capital of: $I_C(0) \equiv \kappa_C \cdot N_C(0)$. (In principle, κ_I and κ_C might be functions of N. Such an assumption complicates the analysis without changing the basic results.)

Like Jacobides and Winter (2007), I assume the challenger is financially constrained. Thus at the start of the competition, the challenger is both poorer and smaller than the incumbent:

$$I_C(0) \ll I_I(0) \text{ and } N_C(0) \ll N_I(0) \quad .$$

Timing. Time is marked out in discrete intervals, $(t, t+1)$. At the start of each interval, each firm has capacity, $N(t)$ with corresponding invested capital, $I(t) \equiv \kappa \cdot N(t)$. (Unsubscripted relationships apply to both firms.) The firms set prices at the start of each interval, and sell products during the interval. A firm cannot sell more units than it has the capacity to produce.

Suppliers and Complementors. I rely on Adner and Kapoor's (2010) decomposition of an ecosystem into end-users, complementors and suppliers of the focal firm. Suppliers' components are purchased by the focal firm and incorporated into its products. Complementor's components are purchased by the end-user and combined with the focal firm's product to make a functioning whole system. End-user demand is determined by the system price (see below).

For simplicity, I assume that complementors and suppliers (of the challenger and incumbent) charge fixed prices. This can come about one of in three ways: (1) suppliers and complementors participate in competitive markets where prices are driven down to marginal cost; (2) suppliers and complementors are voluntary associations of users that supply goods (e.g., software) at marginal cost; or (3) system demand is small relative to each supplier's and complementor's total demand, hence does not materially affect their prices.

Mechanically, in what follows, complementor's prices are added to each firm's own price to determine its total system price to consumers. Supplier's and complementor's prices are also added to each firm's cost. As a result, prices and unit costs are measured at the system level and are comparable for the challenger and incumbent. (Even though the challenger does less inhouse, end users must pay for every component in the system.)

Demand. Demand for the system is characterized by a downward-sloping demand function, $Q(p)$ where $Q'(p) < 0$. The demand function is invariant through time and has a well-defined inverse: $p(\cdot) \equiv Q^{-1}Q(p)$. The firms (and complementors) do not price-discriminate thus all customers buying systems from one or the other firm in a given time interval pay the same price.

By condition (3c), if the challenger sets its system price (its own price plus price of complements) equal to the incumbent's: $p_C = p_I$, customers will be indifferent between systems made by either firm. I assume that if $p_C < p_I$, customers will buy from the challenger first, and the incumbent will sell products only after the challenger's capacity is exhausted. Symmetrically, if $p_C > p_I$ customers will buy from the incumbent first, and the challenger will sell products only after the incumbent runs out of capacity.

Capacity Dynamics. The firms' capacity depreciates at a fixed rate, δ (the same for both). Depreciation reflects the wearing out and technical obsolescence of physical capital and the spoilage and technical obsolescence of working capital. Technically this assumption ensures that capacity once created does not endure forever, but must be replaced with new investments over time.[6]

Each firm can use the cash collected during the interval, $(t, t+1)$, to replace depreciated capacity and add new capacity at the end of the interval. Thus at the beginning of the next interval, $t+1$, each firm's capacity will equal its initial capacity, $N(t)$, less depreciated capacity, $\delta N(t)$, plus replaced capacity, $R(t)$; plus new capacity purchased with its incremental investment, $\Delta I(t)/\kappa$:

$$N(t+1) \equiv \quad N(t) - \delta \cdot N(t) + [R(t) + \Delta I(t)/\kappa]$$

This is simply an accounting identity. The term in brackets refers to capital expenditures that are at the

---

[6] Consistent with standard accounting practice, in the model depreciation is recognized as a non-cash expense and deducted from revenue in the calculation of profit. The non-cash aspect of depreciation is accounted for in the model.

discretion of each firm. (Note that $\Delta I(t)$ denotes a dollar amount of new capital; dividing by κ converts this dollar expenditure into equivalent units of new capacity.)

As long as a firm elects to grow, its replacement capital will equal depreciated capital and thus:

$$N(t+1) = N(t) + \Delta I(t)/\kappa \quad .$$

But if the firm chooses not to invest in the business, its capacity will shrink at the rate of depreciation:

$$N(t+1) = N(t) \cdot (1-\delta) \quad .$$

Non-invested earnings and depreciation cash flow are assumed to accumulate in a cash account, which earns a market rate of return.

Profit and ROIC. For simplicity, I assume the firms pay no income taxes. (Taxes complicate notation without changing the basic results.) A firm's profit, $\Pi(t)$, during the interval *(t, t+1)* is given by:

$$\Pi(t) = [\,p(t) - c\,] \cdot q(t) - \delta \cdot \kappa \cdot N(t) \quad ;$$

where:

- $p(t)$ is the price charged by the firm in the interval *(t, t+1)*;
- *c* is the firm's variable cost per unit;
- *q(t)* is units sold by the firm during the interval; and
- $\delta \kappa N(t)$ is the depreciation of the firm's capital base.

(The prices set and quantities sold by each firm are determined through their competitive interaction as discussed below.)

The return on invested capital (*ROIC*) of either firm is defined as its profit during the period divided by its invested capital at the start of the period:

$$ROIC(t) \;\equiv\; \frac{\Pi(t)}{I(t)} \;=\; \frac{[\,p(t)-c\,]\cdot q(t) - \delta\cdot\kappa\cdot N(t)}{I(t)} \quad . \qquad (4)$$

A firm's *ROIC* can be compared to the cost of capital for assets of comparable risk. If the *ROIC* is greater than or equal to the cost of capital, then adding to the firm's capacity is an attractive investment. Otherwise investors are better off purchasing assets of equivalent risk in the capital markets.

Decision Rules. To complete the specification of the model, I must define the decision rules the two firms apply in setting prices and investing in new capacity. To clarify fundamental patterns, I begin with a set of simplistic decision rules, and then systematically explore the impact of changing them.

First, with respect to pricing, I assume that the firms *set prices to utilize all their capacity*. This means the firms do not engage in strategic pricing games. Strategic pricing games for this type of competition have been analyzed by Kreps and Scheinkman (1983), but the Nash equilibrium strategies they derive require an unrealistic degree of common knowledge. In contrast, "set prices to utilize all capacity" is a simple decision rule that each firm can implement unilaterally. The Kreps-Scheinkman results are discussed in greater detail below.

Second, with respect to investment, I assume the firms' managers *are myopic value maximizers*. The fact that managers are myopic means that they cannot forecast future prices or profits, although they do know the current price, their firm's *ROIC*, and the cost of capital. As value maximizers, the managers will invest in new capacity if and only if their firm's current *ROIC* is above the cost of capital.

Third, with respect to financing, I assume that, after their initial founding, the firms *do not have access to an external capital market*. Thus each firm can grow only by reinvesting its own earnings.

These are simple decision rules, which do not require complex strategic thinking on the part of the managers of the two firms. The results of the model will change if the managers can behave strategically, can collude, or have access to external sources of finance. Below I will consider the impact of each of these changes on industry dynamics, but first, I will show how competition unfolds under these simple rules.

Equilibrium Prices and Growth Rates for the Challenger and the Incumbent.

The model relies on three propositions. The first determines equilibrium industry prices; the second determines each firm's maximum growth rate; the third shows that the challenger's *ROIC* will be higher than the incumbent's in every period, and it will grow faster. (Proofs are in the Appendix.)

Proposition 1 (Pricing). In each time interval, the challenger and the incumbent will charge the same price, $p^*(t)$, which clears the market.

Discussion. For Proposition 1 to hold, customers with the highest willingness to pay must buy from the cheapest firm; and both firms must behave non-strategically, that is, without predicting the other firm's response. If customers with the highest willingness to pay buy from the more expensive firm, then it is possible for both firms to sell out their capacity while one of them charges a price above the market clearing price, $p^*(t)$. If the firms behave strategically, then, for low levels of capacity, there is a Nash equilibrium in which both firms charge $p^*(t)$. For higher levels of capacity, however, there is no Nash equilibrium in pure strategies. Kreps and Scheinkman (1983) show that there is a mixed-strategy equilibrium in which both firms name prices above $p^*(t)$ with positive probability, and the larger firm's prices stochastically dominate the smaller firm's. (That is, the larger firm charges higher prices on average, hence has more excess capacity on average than the smaller firm.)

However, the Kreps-Sheinkman mixed-strategy equilibrium imposes high common knowledge requirements on the two firms (Samuelson, 2004). They must first know (and know that the other knows, etc.) that they are playing the game. They must then jointly determine the distribution functions of their respective equilibrium strategies, each as a function of the other. The probability that two firms engaged in a finite number of rounds of competition would be able to converge on this equilibrium is remote, and thus the Nash equilibrium is not a realistic characterization of firm behavior. In contrast, the rule "raise prices if you are short of capacity and lower them if you have excess capacity," can be applied by each firm unilaterally.

A different model of strategic behavior is for the two firms to collude in setting prices. They could agree to set a monopoly price and restrict capacity to a level that supported that price. However, this cartel-type arrangement is potentially unstable (as well as illegal in many countries). The smaller firm (C) would always have incentives to reduce its price, hoping that the larger firm (I) would refrain from doing so. (This is indeed what happens in the Kreps-Scheinkman equilibrium.) The smaller firm also has incentives to reinvest its profits to increase its own capacity, something not envisioned in the Kreps-Scheinkman model.

Proposition 2 states that without access to an external capital market, a firm's maximum growth rate equals its return on invested capital. This is a well known tenet of corporate finance, sometimes known as the "sustainable" or "balanced" growth formula (Donaldson, 1984).

Proposition 2 (Max Growth = ROIC). Let *g(t)* denote the maximum growth rate of a firm's capacity in the interval *(t, t+1)* and assume that a firm pays no dividends and receives no capital infusions in the form of debt or equity. Then:

$$g(t) = ROIC(t) .$$

Discussion. Under the assumptions, the firm will apply its entire net income to adding new capacity. The capacity added relative to the value of capacity already installed equals the firm's *ROIC*.

Proposition 3 combines the first two propositions to show that the challenger will be able to grow faster than the incumbent for any level of capacity.

Proposition 3 (Relative ROIC and Growth Rates for Incumbent and Challenger) . If prices are set as in Proposition 1, then under conditions 3a-c, the challenger's ROIC and maximum growth rate are higher than the incumbent's for any level of capacity:

$$ROIC_C > ROIC_I \text{ and } g_C(t) > g_I(t) \quad \text{for all } N_C(t), N_I(t) \quad .$$

Discussion. Under conditions 3a-c, if both firms charge the same price, the challenger's *ROIC* is strictly greater than the incumbent's. Hence by Proposition 2, the challenger's maximum growth rate is higher than the incumbent's for any level of capacity.

Results of the Model: Epochs of Competition

In this subsection, Propositions 1 – 3 are used to characterize the industry's dynamics over four "epochs" of competitive interaction. Consistent with the notion that Firm C is a small challenger facing a larger, established incumbent, I assume that, at *t=0*, the incumbent is earning more than its cost of capital, and the challenger is very small relative to the incumbent: $ROIC_I(0) > \rho$ and $N_C(0) << N_I(0)$.

First Epoch of Competition. During the first epoch of competition, both firms will grow, but the challenger will grow faster than the incumbent and thus the challenger's market share will increase. Prices and thus *ROIC*s and growth rates will decline over time. This pattern will continue until the incumbent's *ROIC* drops below its cost of capital. At this point, the industry enters the second epoch of competition.

Second Epoch. Given the decision rules, when the incumbent's *ROIC* drops below the cost of capital, it will stop growing and not replace depreciated capacity:

$$N_I(t+1) = N_I(t) \cdot [1-\delta] \quad .$$

Meanwhile the challenger will continue to grow at its *ROIC*:

$$N_C(t+1) \quad = \quad N_C(t) \cdot [1 + ROIC_C(t)]$$

During this transitional epoch, aggregate capacity will shrink if the challenger's new capacity is less than the incumbent's depreciated capacity. If this happens, the market clearing price during the next interval will go up. Indeed it may go up enough to make the incumbent's *ROIC* higher than its cost of capital, in which case, the incumbent will begin investing again.

But the challenger's capacity will continue to increase, until at some point its new capacity is greater than the incumbent's depreciated capacity. Then and thereafter, the incumbent will only shrink. This marks the beginning of the third epoch of competition.

Third Epoch. During this period, the challenger will grow at its *ROIC* and the incumbent will shrink. At some point the incumbent will account for such a small share of capacity that the challenger can ignore it in setting the price. This marks the beginning of the fourth and last epoch, when the challenger faces no effective competition.

Fourth Epoch. With no competition, the challenger is free to behave as a monopolist. It can then set price in one of two ways: First, if there are no other potential entrants, then the challenger can set its price to maximize monopoly profits. However, if there are potential entrants, then the market is contestable (Baumol, 1982; Baumol et.al. 1983), and the challenger must set its price at a level that deters entry. If the threat of entry comes from firms like the incumbent, this means setting the price below the point where the incumbent's *ROIC* equals the cost of capital.

A Numerical Simulation

Table 1 presents the results of a numerical simulation of twenty rounds of competition between an incumbent and a challenger. For purposes of the simulation, I assumed a demand function characterized by constant elasticity of substitution: $p = a \cdot q^{-b}$, with a = 2000 and b = .2. Invested capital per unit of production (κ) was set at $1000 for the incumbent and $500 for the challenger, thus the challenger was twice as efficient as the incumbent. The starting levels of capacity were 1000 units for the incumbent and 10 units for the challenger. Variable costs per unit were $10 for each firm; the depreciation rate was 20%; and the cost of capital 20%. The rows of the table show results for successive rounds of competitition. The columns show: (1) the capacity of each firm; (2) the market clearing price; (3) ROICs and growth rates of the two firms; (4) the industry growth rate; and (5) profits minus the rental cost of capital for each firm. Horizontal lines mark off the four epochs of competition.

Table 1
Simulated Results for 20 Rounds of Competition

	Capacity			**ROIC**			**Growth Rate**		**Profits less Cost of Capital**	
Time	**Incumbent**	**Challenger**	**Price**	**Incumbent**	**Challenger**	**Incumbent**	**Challenger**	**Industry**	**Incumbent**	**Challenger**
0	1,000.0	10.0	501.4	29.1%	78.3%	29.1%	78.3%	29.6%	91379	2914
1	1,291.4	17.8	476.0	26.6%	73.2%	26.6%	73.2%	27.2%	85261	4743
2	1,634.9	30.9	453.6	24.4%	68.7%	24.4%	68.7%	25.2%	71338	7523
3	2,033.2	52.1	433.7	22.4%	64.7%	22.4%	64.7%	23.4%	48199	11655
4	2,488.1	85.8	415.8	20.6%	61.2%	20.6%	61.2%	21.9%	14495	17666
5	3,000.2	138.3	399.7	19.0%	57.9%	-20.0%	57.9%	-16.6%	-31038	26234
6	2,400.2	218.5	414.4	20.4%	60.9%	20.4%	60.9%	23.8%	10551	44653
7	2,890.7	351.5	397.1	18.7%	57.4%	-20.0%	57.4%	-11.6%	-37390	65746
8	2,312.6	553.2	407.0	19.7%	59.4%	-20.0%	59.4%	-4.7%	-6969	108982
9	1,850.1	881.9	410.9	20.1%	60.2%	20.1%	60.2%	33.0%	1665	177165
10	2,221.8	1,412.6	388.1	17.8%	55.6%	-20.0%	55.6%	9.4%	-48652	251579
11	1,777.4	2,198.2	381.2	17.1%	54.2%	-20.0%	54.2%	21.0%	-51195	376329
12	1,421.9	3,390.5	366.9	15.7%	51.4%	-20.0%	51.4%	30.3%	-61274	532000
13	1,137.5	5,132.6	348.0	13.8%	47.6%	-20.0%	47.6%	35.3%	-70532	708283
14	910.0	7,575.7	327.6	11.8%	43.5%	-20.0%	43.5%	36.7%	-75022	890608
15	728.0	10,872.1	307.7	9.8%	39.5%	-20.0%	39.5%	35.8%	-74472	1062281
16	582.4	15,171.1	289.4	7.9%	35.9%	-20.0%	35.9%	33.8%	-70218	1205150
17	465.9	20,615.6	273.1	6.3%	32.6%	-20.0%	32.6%	31.4%	-63808	1299909
18	372.7	27,338.5	258.5	4.9%	29.7%	-20.0%	29.7%	29.0%	-56463	1326539
19	298.2	35,459.3	245.7	3.6%	27.1%	-20.0%	27.1%	26.7%	-49002	1264922
20	238.6	45,081.0	234.3	2.4%	24.9%	-20.0%	24.9%	24.6%	-41915	1095482

As predicted by the model, in Epoch 1 (periods 0 – 4), both firms grow profitably, but the challenger grows faster than the incumbent. In period 5, the incumbent's ROIC drops below the cost of capital, and Epoch 2 begins. Consistent with the value-maximizing decision rule, the incumbent does not replace or add new capital, thus its capacity shrinks by 20% (the rate of depreciation). The challenger does invest, but is still relatively small, thus industry capacity shrinks by 16.6%. As a result, prices increase in period 6; the incumbent's ROIC bounces back above the cost of capital; and at the end of period 6, it invests in new capacity. But in period 7, the incumbent's ROIC again drops below its cost of capital: it shrinks in periods 7 and 8, then grows again in period 9.

Throughout Epoch 2 (periods 5 – 9), the challenger grows profitably, but remains small relative to the incumbent. However, in period 10, the challenger's increase in capacity exceeds the incumbent's decrease. This marks the beginning of Epoch 3. During this epoch (periods 10 – 18), the challenger consistently adds capacity while the incumbent shrinks at a rate determined by how fast its capacity wears out.

Period 18 marks the end of Epoch 3 and the transition to Epoch 4. Up to this point in time, the challenger's profits (less the rental cost of capital) have increased in every period. However, as the last column of the table shows, if the challenger continues to add new capacity after period 18, its profitability will fall. The extra units sold will not make up for the corresponding drop in price. From this point on, the challenger is better off if it replaces depreciated capital but does not grow.

By period 18, the incumbent has shrunk dramatically and accounts for only around 1% of total industry capacity. Its ROIC is well below the cost of capital, thus even if the challenger does stop growing, the incumbent will not begin to invest, but will continue to shrink.

The dynamics of competition between the incumbent and challenger are affected by the specific parameters of the simulation. In other cases (not shown), the industry can make a direct transition from Epoch 1 to Epoch 3: this occurs, for example, if the depreciation rate, the cost of capital, or the elasticity of demand are low. Alternatively, if the capital efficiency parameter, κ, of the two firms is very close, and the challenger starts out relatively small, Epoch 2 with its cycles of industry expansion and shrinkage, may go on for a long time. In Epoch 4, the challenger may also find that the price that maximizes its own profitability (the monopoly price) gives the incumbent incentives to invest. The two firms can then either reach an accommodation, i.e, collude, or the challenger may accept a permanent reduction in profitability to be sure that the incumbent (or a similar firm) does not enter under its price umbrella.

Investor Returns

How will the investors in the incumbent and the challenger firms fare over the four epochs of competition? Obviously, the challenger's investors will earn more per dollar invested in every period. However, as long as the incumbent's managers behave as value maximizers, its investors may do quite well. Their initial investment will earn more than the cost of capital for some amount of time—the period before the challenger enters plus the time it takes the two firms to move down the demand curve. And when its *ROIC* falls below its cost of capital, the incumbent will begin to return cash to the investors. There will be some amount of time in which the invested capital remaining in the business is not earning its cost of capital, but the excess returns of Epoch 1 can outweigh the inadequate returns in Epochs 2 and 3. Furthermore, if the incumbent sees that it is over-matched, it may exit voluntarily, bringing the period of inadequate returns to an early close.

Investors suffer if either firm has access to external sources of finance. A firm with access to external capital can exceed the "sustainable" growth rate determined by its *ROIC*. However, by Proposition 1, faster industry growth simply accelerates the decline in prices and *ROIC*s, destroying value for both firms. Thus, somewhat counterintuitively, the model shows that constraints on external financing may be advantageous for entrepreneurial firms. Under the assumptions of the model, investors in an entrepreneurial firm (e.g., venture capitalists) are better off if the firm does not access external capital markets, but uses only its own internally generated funds to grow. Too-rapid destruction of the existing order undercuts the goal of capturing value for investors.

Empirical Evidence

In this section, I offer evidence that entrepreneurial firms have employed strategies based on open architectures with some success. The model showed that the same basic strategy gives rise to to heterogeneous outcomes, hence industry dynamics will play out in different ways in different settings, depending on initial conditions and the firms' access to external finance. For this reason, it would be difficult, if not impossible, to detect this strategy in large data sets. Nevertheless, it is possible to show that the strategy has been used in specific cases.

My empirical evidence is based on two case studies. In each case, a smaller challenger took on and defeated a larger incumbent. For each one, I will:

- pinpoint the superior architectural knowledge and remodularization adopted by the challenger;
- show that the challenger was able to outsource activities that were insourced by the incumbent;
- verify that the challenger had a higher *ROIC* than the incumbent during the competition; and
- show that the challenger grew faster than the incumbent and drove the incumbent's *ROIC* below the cost of capital.

Sun Microsystems vs. Apollo Computer[7]

Apollo Computer, founded in 1980, was the first company to enter the engineering workstation market. (An engineering workstation is a desktop computer capable of supporting engineering analysis.) By 1984 Apollo had 60% of the market and was growing at 50% per year. It was then challenged by Sun Microsystems.

New Architectural Knowledge and Remodularization of the Technical System. Apollo designed its workstations as an interconnected bundle consisting of hardware, a proprietary operating system, and a network management system. Each of these components was specifically tailored to work with the other two. In addition, Apollo built a manufacturing facility to make its workstations in high volumes. The factory was the fourth component in a highly interdependent, closed technical system.

However, in the early 1980s, computer scientists John Hennessy of Stanford and David Patterson of Berkeley began to look at computer architecture in a new way. They advocated quantitative methods aimed at identifying fractional bottlenecks (Hennessy and Patterson, 1990; Patterson and Hennessy, 1994). Such bottlenecks, they argued, should be the focus of architectural design effort. Components

---

[7] This case study is based on the following sources: Freeze and Clark (1986); Hall and Barry (1990); Soll and Baldwin (1990); Salus (1994); Zachary (1994), Gilder (1995); Garud and Kumaraswamy (1995); and Baldwin and Clark (1997a).

outside the bottlenecks were less important, hence could be sourced cheaply without compromising overall system performance.

Sun Microsystem's designers, several of whom studied under Hennessy or Patterson, used their architectural knowledge of bottlenecks to get high performance out of machines made mostly from purchased off-the-shelf components. For example, in the Sun 2 product line, Sun's architects identified memory access as a bottleneck. As a remedy, they developed two special hardware components that made memory access speedier.[8] Virtually all other hardware components were purchased from external suppliers (Baldwin and Clark, 1997a).

In further contrast to Apollo, Sun did not create a proprietary operating system or networking technology for its workstations. It used the Unix operating system, which could be licensed at low cost from AT&T and adopted Ethernet, a non-proprietary standard, as the basis of its networking architecture. Finally Sun used architectural knowledge to reduce bottlenecks in manufacturing. It developed a "single board design" for the Sun 2, in contrast to Apollo's design which used three or four boards. Having only one board simplified the flow of production, reduced work-in-process inventory, and made testing systems faster and easier.

Sun's open technical architecture reduced its span of inhouse activities, which in turn reduced capital employed per unit of production. Buying off-the-shelf hardware components and utilizing a low-cost operating system like Unix and open standards like Ethernet kept the cost per machine low. Because it addressed bottlenecks effectively in both its product design and production processes, Sun was able to build machines that performed as well or better than Apollo's, cost the same amount to build, provided users with more design flexibility, and required less capital from Sun.

Competitive Dynamics. Sun used architectural knowledge about bottlenecks and modularization, in conjunction with outsourcing, to satisfy conditions 3a-c above. As predicted by the model, the resulting

---

[8] The components were a "no wait state" memory management unit (MMU) that eliminated many situations where the CPU had to wait to access memory and a high speed 32-bit internal memory bus, which connected the internal memory chips (1-4 MB of DRAM) and the video controller chips to the CPU.

ROIC advantage allowed Sun to grow faster and to drive Apollo's *ROIC* below the cost of capital. Table 2 presents data on Apollo's and Sun's financial performance over sixteen quarters of competition beginning in the second quarter of 1985 and ending in the first quarter of 1989.[9] The table is set up to parallel Table 1. Quarterly sales figures serve as a proxy for unobservable production capacity; invested-capital-to-sales is the proxy for capital utilized per unit of production (κ).[10] The table shows that Sun was indeed substantially more efficient than Apollo in terms of invested capital per dollar of sales (.31 vs. .57 on average). As a result, its *ROIC* was higher in every one of the sixteen quarters, averaging 20% vs. Apollo's 2%. In fact, Apollo's *ROIC* was below the Treasury bill rate in most quarters, evidence that it was not able to earn its cost of capital.

Table 2
Competitive Dynamics of Sun (Challenger) and Apollo (Incumbent)
Sixteen Quarters: Q2 1985 – Q1 1989

	Quarterly Sales			Invested-Capital-to-Sales (Annualized)		ROIC (Annualized)		Growth Rate in Sales (Annualized)		
Time	**Incumbent**	**Challenger**	**Industry**	**Incumbent**	**Challenger**	**Incumbent**	**Challenger**	**Incumbent**	**Challenger**	**Industry**
1985 Q2	87,548	37,322	124,870	0.49	0.21	17%	27%	na	na	na
Q3	55,232	33,690	88,922	0.83	0.31	-40%	10%	-148%	-39%	-115%
Q4	70,675	42,173	112,848	0.70	0.32	1%	12%	112%	101%	108%
1986 Q1	82,021	57,578	139,599	0.67	0.30	1%	20%	64%	146%	95%
Q2	88,382	76,663	165,045	0.65	0.27	2%	29%	31%	133%	73%
Q3	100,408	91,572	191,980	0.61	0.32	4%	23%	54%	78%	65%
Q4	120,874	115,275	236,149	0.53	0.31	8%	24%	82%	104%	92%
1987 Q1	123,420	141,705	265,125	0.56	0.30	9%	24%	8%	92%	49%
Q2	132,214	185,902	318,116	0.53	0.25	11%	23%	29%	125%	80%
Q3	135,041	191,709	326,750	0.54	0.32	-4%	21%	9%	12%	11%
Q4	162,985	235,090	398,075	0.46	0.31	14%	19%	83%	91%	87%
1988 Q1	168,933	259,685	428,618	0.47	0.34	13%	16%	15%	42%	31%
Q2	143,453	365,130	508,583	0.56	0.28	-10%	25%	-60%	162%	75%
Q3	157,095	388,469	545,564	0.55	0.33	-4%	16%	38%	26%	29%
Q4	184,055	448,281	632,336	0.48	0.34	4%	19%	69%	62%	64%
1989 Q1	204,715	497,420	702,135	0.43	0.39	6%	16%	45%	44%	44%
Average				0.57	0.31	2%	20%	29%	78%	52%

Interestingly, both firms grew faster than their ROIC's during this period. They did so by accessing external capital markets (counter to the assumption of Proposition 2). Sun was particularly aggressive in this respect: in the period shown, it issued equity four times and increased debt as well.

---

[9] This was the period ranging from one year before Sun's initial public offering to the time Apollo was purchased by Hewlett Packard.

[10] If prices are falling (as they were), the invested-capital-to-sales ratio will overstate capital utilized per unit of production, but the bias will apply to both firms equally.

Contempory reports indicate that Sun's top managers, especially its CEO, McNealy, believed the "prize" of market dominance justified moving down the demand curve very rapidly (Hall and Barry, 1990).

By the end of 1988, Apollo was running out of cash and facing potential bankruptcy. It was acquired by Hewlett-Packard (HP) in April 1989. Over the next several years, HP abandoned all of Apollo's product lines. Sun, the challenger with the small footprint architecture and the *ROIC* advantage, survived. (It was acquired by Oracle Corporation in 2010.)

Dell Computer vs. Compaq[11]

The second case features Compaq as the incumbent and Dell as the challenger. In the mid-1990s, Compaq was the leading manufacturer of IBM compatible personal computers (PCs). In 1993 it reported sales of $7 billion and net income $462 million. At this time, Dell was a second-tier manufacturer of PCs with sales of $2.8 billion and a loss of $36 million.[12]

New Architectural Knowledge and Remodularization of the Technical System. Unlike Sun, whose superior architectural knowledge derived from advances in computer science, Dell developed its architectural knowledge in response to a series of financial crises. In 1992, Dell experienced a very high growth rate (126%), which depleted its cash reserves. In 1993, it reduced its inventory (freeing up cash), but reported a loss on inventory writedowns. In 1994, Dell experienced another cash crunch because of quality problems in two of its product lines. However, beginning in 1993, Dell began focusing on developing information systems and creating incentives to reduce invested capital and increase *ROIC* in all parts of the business.

As with Sun, Dell's strategy was based on a remodularized product and production flow and the judicious use of outsourcing and open standards. Designated core activities—order-taking, assembly, and shipment—were brought inhouse and redesigned to take place quickly and efficiently (Fine, 1998;

---

[11] This case study is based on the following sources: Baldwin and Feinberg (1999); Park and Burrows (2001); Shook (2001); Breen (2004); Holzner (2005); and Vance (2006a,b).

[12] Dell's fiscal year ends in the last week of January, while Compaq's ends on December 31. Thus Compaq's calendar year 1993 has eleven months in common with Dell's fiscal year 1994. I have relabeled Dell's fiscal years to make appropriate comparisons.

Holzner, 2005). To achieve this high level of performance, Dell designed new manufacturing cells, located its factories close to its major markets, and employed just-in-time inventory management techniques. By concentrating on these bottleneck activities, Dell made the flow of products through its factories faster without compromising cost or quality.

Outside of its core set of activities, Dell used components based on open standards to encourage competition among its suppliers and complementors. It did not extend credit to dealers (as Compaq did), or to individual customers, yet, based on the size of its orders, it demanded generous credit from its own suppliers. The result for Dell was a negative cash cycle: more often than not Dell received cash from product sales before it had to pay for the components or labor in the products. A negative cash cycle reduces a firm's invested capital and perforce increases its *ROIC*. Indeed, invested capital can become negative, in which case the *ROIC* increases "beyond infinity."

Competitive Dynamics. Table 3 presents data on Compaq's and Dell's financial performance over nine years of competition beginning in 1993 and ending in 2001.[13] During this time, Dell's invested capital averaged 2% of sales vs. 22% for Compaq. Notably in three of the nine years, Dell's invested capital was negative: the money it received early from customers paid for all of its capital investment with some left over. After the first crisis year (1993), Dell's *ROIC* was also substantially above Compaq's. Compaq's *ROIC* improved greatly from 1993 to 1997, but Dell's was always higher. As predicted by the model, Dell also grew faster in every year.

Table 3
Competitive Dynamics of Dell (Challenger) and Compaq (Incumbent)
Nine Years: 1993 – 2001

	Annual Sales			Invested-Capital-to-Sales		ROIC		Growth Rate in Sales		
Time	Incumbent	Challenger	Industry	Incumbent	Challenger	Incumbent	Challenger	Incumbent	Challenger	Industry
1993	7,191	2,873	10,064	0.31	0.02	21%	-73%	na	na	na
1994	10,866	3,475	14,341	0.34	0.02	24%	254%	51%	21%	42%
1995	14,755	5,296	20,051	0.30	0.12	18%	44%	36%	52%	40%
1996	18,109	7,759	25,868	0.15	-0.03	49%	nm	23%	47%	29%
1997	24,584	12,327	36,911	0.11	-0.04	70%	nm	36%	59%	43%
1998	31,169	18,243	49,412	0.23	-0.02	-39%	nm	27%	48%	34%
1999	38,525	25,265	63,790	0.20	0.07	8%	92%	24%	38%	29%
2000	42,383	31,888	74,271	0.16	0.03	8%	212%	10%	26%	16%

---

[13] This was the period ranging the year of Dell's first financial crisis to the time when Compaq was acquired by Hewlett Packard.

2001	33,554	31,168	64,722	0.19	0.03	-12%	128%	-21%	-2%	-13%
Average				0.22	0.02	16%	109%	23%	36%	28%

Beginning in 1998, Dell reached a size where it began to put pressure on Compaq's margins, driving the latter's *ROIC* below the cost of capital. Then in 2001, when faced with a downturn in demand, Dell started a price war. Compaq could not match Dell's prices, thus its sales dropped dramatically (21%) and its profits and *ROIC* both turned negative. In September of that year, Compaq and HP agreed to merge. By all accounts, the contribution of Compaq to HP's performance was disappointing, and contributed to the removal of HP's CEO, Carly Fiorina, in 2005.

The Origins of Asymmetry between Challenger and Incumbent

The histories of Sun and Dell show that challengers can enter and succeed against larger incumbents using an open technical architecture based on modularity, open standards and outsourcing. In this respect, the cases offer "existence proofs" for the theory and model presented above. The cases also provide a window into the underlying causes of asymmetries. Specifically, they shed light on two questions: (1) How does a challenger obtain superior architectural knowledge? And (2) what prevents an incumbent from imitating the challenger's strategy once it has been revealed?

Sun's superior architectural knowledge arose from its founders' access to leading-edge scientific research at universities: in this respect, the case is consistent with the knowledge spillover theory of Agarwal et. al. (2007). In the mid-1980s, Professors John Hennessy and David Patterson worked out the logic of fractional bottlenecks in computer architecture. Andreas Bechtolscheim (a Sun founder) designed the first Sun workstation while he was a graduate student in John Hennessy's lab at Stanford. Bill Joy (another founder) worked on hardware-software interfaces under David Patterson at Berkeley. When Bechtolscheim and Joy were graduate students (the mid-1980s), Hennessy and Patterson's quantitative approach was not widely known and was highly controversial among academic computer scientists. Apollo's Boston-based managers may not have been aware of this work, did not have the means to resolve the academic controversies. They certainly did not have had access to early experimental results (which ultimately settled the controversies in favor of Hennessy and Patterson's approach).

In contrast, Dell's superior architectural knowledge arose, not from knowledge spillovers, but in response to several brushes with bankruptcy. As described above, Dell's first cash crunch arose when business was booming: its second came about because of quality problems arising from lack of control of internal operations. Both crises resulted in inventory writedowns. The period 1993-94 was a time of shakeout for PC manufacturers: many of Dell's and Compaq's competitors did not survive. However, Dell had a positional advantage over many its peers: from its founding, it sold PCs directly to consumers rather than through dealers or its own retail stores. As a result, Dell's need to finance accounts receivable was always low. Back-to-back cash crunches and inventory write-downs then caused its managers to make inventory reduction their highest priority and to make *ROIC* the main measure of performance and basis for incentive compensation. (The CFO at the time, Thomas Meredith, reportedly put "ROIC" on his license plate (Holzner, p. 132).)

Thus on the evidence of these two cases, it appears that superior architectural knowledge can arise from many sources. It may grow out of early access to scientific research (Sun) or from trial-and-error learning in day-to-day operations (Dell). It may be built into the company's initial business plan (Sun) or learned in response to a crisis (Dell). In each case, however, managers played a crucial role in converting superior architectural knowledge into strategically effective actions. They brought the strategy into focus at two levels: first, by establishing a corporate-wide goal (with commensurate incentives) to increase *ROIC*, and, second, by translating this goal into operational sub-goals, such as buying off-the-shelf components (Sun), integrating assembly (Dell), reducing inventory (both) and using open standards (both).

When Sun and Dell emerged as competitors with superior ROICs, why did Apollo and Compaq not change their own architectures to imitate the challengers? Here the two cases tell a consistent story. At an earlier point in their history, both incumbents invested in highly interdependent architectures with co-specialized components. Because of this underlying interdependence, they could not adapt their architectures in response to the challenge. As described above, Apollo created an interdependent technical system comprising hardware, network protocols, a proprietary operating system, and a manufacturing plant. No part of this system could be changed without redesigning the whole. (For example, when Apollo attempted to use the Unix operating system to run its machines, their performance suffered.)

For its part, Compaq always sold its products through dealers. In early days, its carefully cultivated dealer network was a source of competitive advantage. Then, in the mid-1990s, it invested in a global production system with high-volume, low-unit-cost factories located offshore. However, Compaq's dealers needed trade credit and its far-flung production system could not function without a certain amount of inventory. Thus even though Compaq's managers understood the merits of a high *ROIC*, and made it a focus of management effort and compensation from 1995 onward, they could not drive their invested-capital-to-sales ratio as low as Dell's. And, as was the case for Apollo, Compaq's managers could not change any part of their architecture without redesigning the whole. Recognizing their strategic dilemma, they attempted to move into other markets, by acquiring Tandem Computer in 1997 and Digital Equipment Corporation in 1998. In the end, however, they could not shift the firm's revenue base quickly enough, and thus were not able to escape an eventual confrontation and price war with Dell.

Conclusion

This paper describes an open architecture can be employed by entrepreneurial firms with superior architectural knowledge to compete against larger, established rivals. An entrepreneurial firm may use architectural knowledge about bottlenecks and potential new modularizations to create an open technical architecture, which isolates the "bottleneck" components. The firm then insources bottleneck components and outsources or allows complementors to supply non-bottleneck components. Employing this strategy, the entrepreneurial firm will have a smaller span of internal activities with no loss of quality or increase in the cost per unit produced. Its lesser scope in turn yields an *ROIC* advantage: at any system price, the entrepreneurial firm will have a higher return on invested capital than its rival(s). Over time the challenger can grow faster and drive its competitors' *ROICs* below the cost of capital. I have explained how architectural knowledge makes this strategy feasible and modeled its impact on dynamic competition through successive stages of industry evolution. I then offered evidence that the strategy was used by Sun Microsystems in the 1980s and Dell Computer in the 1990s. In this concluding section, I discuss how this paper fits into the broader strategy literature, the limitations of the strategy, and opportunities for future work.

Modularity theory is a growing body of scholarship that addresses how dependencies within a technical system can be changed and manipulated. Scholars working in this tradition view the architecture of a technical system as malleable, albeit at a cost. Seen from this vantage point, architecture becomes a potential source of competitive advantage, hence a topic of interest in the field of strategy. The question is, what technical architectures are advantageous for which types of firms?

Strategy scholars have already begun to address this question. Scholars in the resource-based tradition have theorized that firm boundaries serve as isolating mechanisms for critical resources (Barney, 1991; Alvarez and Barney, 2004). Scholars in the knowledge-based tradition argue that knowledge flows differently within a firm vs. between firms (Kogut and Zander, 1992, 1996; Conner and Prahalad, 1996; Grant, 1996). At the same time, scholars in the dynamic capabilities tradition see firms as shifting bundles of routines and competencies arising from the interplay of transactions and production costs, both of which are influenced by technology and investments in new knowledge (Teece, Pisano and Shuen, 1997; Jacobides and Winter, 2005). To these traditions, modularity theory adds the insight that transaction costs and knowledge flows, hence firm boundaries, are influenced by patterns of technical dependency, which in turn are determined by the technical system's architecture. The technical architecture itself is a target of design, and thus a firm with superior architectural knowledge can open up its architecture, and thereby relocate transactions and boundaries to its own advantage.

Other strategy scholars have proposed that there is a match between certain modes of governance (markets and hierarchies) and different types of innovation or problem-solving ability. Specifically, Teece

(1996, 2000) and others have argued that systemic innovations must be introduced by large, established firms with a broad range of capabilities and/or complementary assets. Nickerson and Zenger (2004) theorize that non-decomposable problems are best solved by hierarchies that span the dimensions of the search space. Implicitly, more complex problems (in the sense of having more dependencies) must be solved by larger firms. Modularity theory adds a new dimension to these arguments, stating that the nature of an innovation and the very structure of the problem space are determined by an underlying technical architecture, which again, is a target of design. Thus a firm with architectural knowledge can make an innovation more autonomous or systemic and decompose its problem search spaces in new ways.

In this paper, I have presented a model and supplied examples showing that architectural knowledge can be applied strategically to change a firm's boundaries, to make innovations more or less autonomous, and to change the nature of problems it must solve. If this argument is accepted, even provisionally, then a question immediately follows: what types of architectural knowledge are useful for which firms? This paper has taken the perspective of a small entrepreneurial firm with limited resources facing larger rivals. For such firms, the most valuable architectural knowledge pertains to bottlenecks and modularizations. Such knowledge can form the basis of an open technical architecture that delivers an *ROIC* advantage.

An open technical architecture has important long-run limitations and hazards, however. The model developed in this paper is a model of dynamic competition, but the dynamics involve only one generation of technological innovation. Over multiple generations, the location of bottlenecks will shift as new technical possibilities and user demands emerge (Ethiraj, 2007). The original challenger, now an incumbent, must stay abreast of the shifting bottlenecks, and adapt its architecture accordingly. Thus while an open architecture can be a means of entry, the advantage it confers will be transient. To succeed over time, firms competing in a design space of shifting architectures must actively invest in architectural knowledge, identify emerging bottlenecks, and have the ability to consistently invent new ways around them. Such firms perforce must "know more than they do" (Brusoni, Prencipe, Pavitt, 2001).

There also other types of architectural knowledge that can be employed strategically. Consider the case of Shimano, which in 1980 was an established firm in the bicycle drive train industry (Fixson and Park, 2008). Relative to its competitors, Shimano had a *large* span of activity although it was not vertically integrated. In 1980, it made all six components of the drive train system, although each of its components could be combined in a modular fashion with those made by other manufacturers. Shimano then used superior architectural knowledge to create a non-modular technical system with higher performance. It linked its components more tightly and specifically, in a way that achieved a new dimension of quality (gear shifting while gripping the handlebar). In the five years following the introduction of its new system, Shimano greatly expanded its market share at the expense of its more focused rivals. In Shimano's new system, there was simply no place to attach non-Shimano components. Its former complementors were forced to exit the industry. Basically, Shimano invested in a different type of architectural knowledge from Sun or Dell. It did not look for bottlenecks and opportunities to further open the system, but for ways of co-specializing parts in order to close the system.

Shimano's experience shows definitively what should be no surprise: that openness is not a strategy for all firms or all seasons. A contingent theory connecting architecture with firm strategy under varying external conditions is needed to span the cases of Shimano, Sun and Dell. Specifically, what are the indicators that a technical system is susceptible to being modularized around bottlenecks? Such systems are targets of opportunity for entrepreneurial firms. Conversely what are the indicators that a technical system is ripe for integration? Such systems provide firms with greater scope with the opportunity to initiate an industry consolidation and drive out more focused suppliers and complementors. Answers to these questions are critically important to managers (of both entrepreneurial and established firms) for they offer guidance on where to place bets and where to look for threats. The questions also offer a promising avenue for future research in strategy and entrepreneurship.

Acknowledgments

I am grateful to Rajshree Agarwal, Christopher Aden, Amar Bhide, Lee Fleming, Andrei Hagiu, Michael Jacobides, Thorbjorn Knudsen, Karim Lakhani, Francisco Lima, Jianxi Luo, Alan MacCormack, Jackson Nickerson, Eric von Hippel, and Todd Zenger, as well as participants in seminars and colloquia at London Business School, the Academy of Management, Washington University, SCANSOR, the Wharton Technology Conference, and DRUID for many helpful comments that led to significant improvement of the arguments presented in this paper. Special thanks go to Venkat Kuppuswamy and Sebastian Fixson for reading several drafts and for comments that led to major improvements. An earlier version of this paper entitled "Architectural Innovation and Dynamic Competition: The Smaller Footprint Strategy," was coauthored with Kim B. Clark, and I thank him for many conversations that contributed to the views expressed here. I alone am responsible for any errors or oversights.

Appendix —Proofs of the Propositions

Proposition 1 (Pricing). Under the assumptions given in the text, in the time interval *(t, t+1)*, the challenger and the incumbent will charge the same price, which clears the market.

Proof. Formally, the proposition can be written as:

$$p_C^*(t) = p_I^*(t) = p^*(t) \equiv Q^{-1}[N_C(t) + N_I(t)] \quad ;$$

where $p^*(t)$ denotes the market clearing price in the interval *(t, t+1)*; $N_C(t) + N_I(t)$ equals the sum of Firm C and Firm I's capacity at the start of the interval, and Q^{-1} denotes the inverse function of Q: $Q^{-1}Q(p) = p$.

Total units sold, Q during the interval, cannot be higher than $N_C(t) + N_I(t)$ because the firms cannot make and sell products beyond their capacity. Thus a firm charging a price below $p^*(t)$ can increase profits without reducing its own unit sales, by raising its price to $p^*(t)$.

If both firms set their prices above $p^*(t)$, then one or both will have excess capacity. Under the decision rule, a firm with excess capacity will drop its price until all its capacity is utilized. At that point, the other firm will have excess capacity and will drop its price. The price declines will continue until $p_C(t) = p_I(t) = p^*(t)$. *QED*

Proposition 2 (Max Growth = ROIC). Assume that a firm pays no dividends and receives no capital infusions in the form of debt or equity. Then:

$$g(t) = ROIC(t) .$$

Proof. If the firm pays no dividends, then all of its profit is available for investment in the business. If it obtains no external capital infusions in the form of new debt or equity, then this is *all* the money available for investment:

$$\max \Delta I(t) = \Pi(t) = [\,p(t) - c\,] \cdot q(t) - \delta \cdot \kappa \cdot N(t) \quad .$$

Dividing through by *I(t)* obtains:

$$\max \frac{\Delta I(t)}{I(t)} = \frac{\Pi(t)}{I(t)} \equiv ROIC(t)$$

(by equation 4). But $I(t) \equiv \kappa \cdot N(t)$, thus by substitution:

$$g(t) \equiv \max \frac{\Delta N(t)}{N(t)} = ROIC(t) \quad .$$

QED.

Proposition 3 (Relative Growth Rates for Incumbent and Challenger) . If prices are set as in Proposition 1, the challenger's maximum growth rate is higher than the incumbent's, for any level of capacity:

$$g_C(t) > g_I(t) \quad \text{for } \forall \; N_C(t), N_I(t) \quad .$$

Proof. By Proposition 2 for each firm:

$$g(t) = ROIC(t) \equiv \frac{[p(t) - c] \cdot q(t) - \delta \cdot \kappa \cdot N(t)}{I(t)} \quad .$$

By Proposition 1, for each firm, $q(t) = N(t)$ and $p(t) = p^*(t)$. Finally, $I(t) \equiv \kappa \cdot N(t)$ for each. Substituting specific values for each firm and cancelling terms, we have, for all $p^*(t) \geq c_I$:

$$g_C(t) = ROIC_C(t) = \frac{[p^*(t) - c_C - \delta \cdot \kappa_C]}{\kappa_C} > \frac{[p^*(t) - c_I - \delta \cdot \kappa_I]}{\kappa_I} = ROIC_I(t) = g_I(t) \quad .$$

The central inequality follows from the fact that $\kappa_C < \kappa_I$ and $c_C \leq c_I$ (conditions 3a and 3b above). Under these conditions, within the prescribed range of prices, the challenger's numerator is strictly greater and its denominator strictly less than the incumbent's. *QED.*

References

Adner, Ron and Rahul Kapoor (2010) “Value Creation in Investment Ecosystems: How the Structure of Technological Interdependence Affects Firm Performance in New Technology Generations,” *Strategic Management Journal* 31:306-333.

Agarwal, Rajshree, David Audretsch and M. B. Sarkar (2007) "The Process of Creative Construction: Knowledge Spillovers, Entrepreneurship, and Economic Growth," *Strategic Entrepreneurship Journal*, 1:263-286.

Agarwal, Rajshree, Raj Echambadi, April F. Franco and M. B. Sarkar (2004) "Knowledge Transfer Through Inheritance: Spinout Generation, Development and Survival," *Academy of Management Journal, 47(4):501-522.*

Alvarez, Sharon A. and Jay B. Barney (2004) Organizing Rent Generation and Appropriation: Toward a Theory of the Entrepreneurial Firm, *Journal of Business Venturing* 19:621-635.

Alvarez, Sharon A. and Lowell W. Busenitz (2001) "The Entrepreneurship of Resource-Based Theory, *Journal of Management*, 27:755-775.

Baldwin Carliss Y. and Barbara Feinberg, (1999) “Compaq: The DEC Acquisition,” 9-800-199, Harvard Business School Publishing Company, Boston, MA.

Baldwin, Carliss and Jack Soll (1990) "Sun Microsystems, Inc. – 1987 (A), (B), and (C)" Harvard Business School Publishing Division, Boston, MA.

Baldwin, Carliss Y. (2008) "Where Do Transactions Come From? Modularity, Transactions and the Boundaries of Firms," *Industrial and Corporate Change* 17(1):155-195.

Baldwin, Carliss Y. and Kim B. Clark (1997b) “Managing in the Age of Modularity,” *Harvard Business Review* Sept/Oct: 81-93.

Baldwin, Carliss Y. and Kim B. Clark (2000). *Design Rules, Volume 1, The Power of Modularity*, Cambridge MA: MIT Press.

Baldwin, Carliss Y. and Kim B. Clark, (1997a) "Sun Wars: Competition within a Modular Cluster," in *Competing in the Age of Digital Convergence*, D. B. Yoffie, ed. Boston: Harvard Business School Press.

Barney, Jay (1986) "Strategic Factor Markets: Expectations, Luck and Business Strategy," *Management Science*, 32(10):1231-1241.

Barney, Jay (1991) "Firm Resources and Sustained Competitive Advantage," *Journal of Management*, 17(1):99-120.

Baumol, William J. (1982) "Contestable Markets: An Uprising in the Theory of Industry Structure," *American Economic Review*, 72(1):1-15.

Baumol, William J., John C. Panzar, and Robert D. Willig (1983) "Contestable Markets: An Uprising in the Theory of Industry Structure: Reply," *American Economic Review* 73(3):491-96.

Bayus, Barry L. and Rajshree Agarwal (2007) "The Role of Pre-Entry Experience, Entry Timing and Product Technology Strategies in Explaining Firm Survival," *Management Science*, 53(12):1887-1902.

Breen, Bill (2004) "Living in Dell Time," *Fast Company*, 88(November), available at http://www.fastcompany.com/magazine/88/dell.html (viewed 7/29/07).

Brusoni, Stefano, Andrea Prencipe and Keith Pavitt (2001) "Knowledge Specialization, Organizational

Coupling and the Boundaries of the Firm: Why Do Firms Know More Than They Make?" *Administrative Science Quarterly*, 46(4):597-621.

Cacciatori, Eugenia and Michael G. Jacobides (2005) "The Dynamic Limits of Specialization: Vertical Integration Reconsidered," *Organization Studies*, 26(12): 1851-1883.

Chesbrough, Henry and David J. Teece (1996) "When is virtual virtuous? Organizing for innovation" *Harvard Business Review* 74(1):65-74.

Coase, Ronald H. (1937) "The Nature of the Firm," *Economica,* 4(4):386-405.

Colwell, Robert P. (2005) *The Pentium Chronicles: The People, Passion, and Politics Behind Intel's Landmark Chips*, Hoboken, NJ: Wiley-IEEE Computer Society

Conner, Kathleen R. and C. K. Prahalad (1996) "A Resource-based Theory of the Firm: Knowledge vs. Opportunism," *Organization Science*, 7(5): 477-501.

Donaldson, Gordon (1984) *Managing Corporate Wealth*, New York, NY: Praeger.

Eppinger, Steven D. (1991) "Model-based Approaches to Managing Concurrent Engineering" *Journal of Engineering Design*, 2: 283-290.

Ethiraj, Sendil and Daniel Levinthal (2004) "Modularity and Innovation in Complex Systems," *Management Science*, 50(2):159-174.

Ethiraj, Sendil K. (2007) "Allocation of Inventive Effort in Complex Product Systems," *Strategic Management Journal*, 28(6):563-584.

Ethiraj, Sendil K., Daniel Levinthal and Rishi Roy (2008) "The Dual Role of Modularity: Innovation and Imitation," *Management Science* 54(5): 939-955.

Fixson, Sebastian K. (2005) "Product Architecture and Assessment: A Tool to Link Product, Process, and Supply Chain Design Decisions," *Journal of Operations Management*, 23(2005):345-369.

Fixson, Sebastian K. and Jin-Kyu Park (2008). "The Power of Integrality: Linkages between Product Architecture, Innovation and Industry Structure," *Research Policy* 37(8):1296-1316.

Freeze, Karen and Kim B. Clark (1986) "Sun Microsystems, Inc. (B)" Harvard Business School Publishing Division, Boston, MA.

Garud, Raghu and Arun Kumaraswamy (1995) "Technological and Organizational Designs to Achieve Economies of Substitution," *Strategic Management Journal,* 17:63-76, reprinted in *Managing in the Modular Age: Architectures, Networks, and Organizations,* (G. Raghu, A. Kumaraswamy, and R.N. Langlois, eds.) Blackwell, Oxford/Malden, MA.

Gilder, George (1995) "The Coming Software Shift," *Forbes ASAP* (8/28/95) available at: http://www.seas.upenn.edu/~gaj1/shiftgg.html (viewed 7/30/06).

Gompers, Paul and Josh Lerner (1999) *The Venture Capital Cycle*, Cambridge, MA: MIT Press.

Grant, Robert M. (1996) "Toward a Knowledge-based Theory of the Firm," *Strategic Management Journal,* 17(Winter):109-122.

Hall, Mark and John Barry (1990) *Sunburst: The Ascent of Sun Microsystems* Chicago, IL: Contemporary Books.

Helfat, Constance E. and Marvin B. Lieberman (2002) "The birth of capabilities: market entry and the importance of pre-history," *Industrial and Corporate Change*, 11(4): 725-760.

Henderson, Rebecca M. and Kim B. Clark (1990), "Generational Innovation: The Reconfiguration of

Existing Systems and the Failure of Established Firms," *Administrative Sciences Quarterly* 35: 9-30.

Hennessy, John L. and David A. Patterson (1990) *Computer Architecture: A Quantitative Approach*, Morgan Kaufman Publishers, San Mateo, CA.

Holzner, Steven (2005) *How Dell Does It*, New York, NY: McGraw Hill.

Jacobides, Michael G. (2005). "Industry Change Through Vertical Dis-Integration: How and Why Markets Emerged in Mortgage Banking," *Academy of Management Journal*, 48(3):465-498.

Jacobides, Michael G. and Sidney G. Winter (2005) "Co-evolution of capability and transaction costs: explaining the institutional structure of production," *Strategic Management Journal*, 26(5):395 - 413.

Jacobides, Michael G. and Sidney G. Winter (2007) "Entrepreneurship and Firm Boundaries: The Theory of A Firm," *Journal of Management Studies*, 7:1213-1241.

Juran, Joseph M. (1960) "Pareto, Lorenz, Cournot, Bernouilli, Juran and Others," *Industrial Quality Control*, 17(4):25-27, reprinted in *Joseph M. Juran: Critical Evaluations in Business and Management*, Wood and Wood, eds. (Routledge, New York, NY: 2005)

Juran, Joseph M. (1992) "Appendix to Chapter 3: Then and Now in Quality Control," *Juran on Quality by Design,* (New York: Free Press), reprinted in *Joseph M. Juran: Critical Evaluations in Business and Management*, Wood and Wood, eds. (New York: Routledge) 2005.

Kauffman, Stuart A. (1993) *The Origins of Order*, New York: Oxford University Press

Klepper, Steven (2002) "The Capabilities of New Firms and the Evolution of the U.S. Automobile Industry," *Industrial and Corporate Change*, 11(4):645-666.

Klepper, Steven and Kenneth L. Simons (2000) "Dominance by Birthright: Entry of Prior Radio Producers and Competitive Ramifications for the U.S. Television Receiver Industry," *Strategic Management Journal*, 21(10-11): 997-1016.

Klepper, Steven and Sally Sleeper (2005) "Entry by Spinoffs," *Management Science*, 51(8): 1291-1306.

Kogut, Bruce and Udo Zander (1992), "Knowledge of the Firms, Combinative Capabilities and the Replication of Technology," *Organization Science*, 3(3):383-397

Kogut, Bruce and Udo Zander (1996) "What Firms Do? Coordination, Identity and Learning," *Organization Science*, 7(5):502-218.

Kreps David M. and Jose A. Scheinkman (1983) "Quantity Precommitment and Bertrand Competition Yield Cournot Outcomes," *Bell Journal of Economics*, 14(2): 326-337.

Langlois, Richard N. (2006) "The Secret Life of Mundane Transaction Costs," *Organization Studies*, forthcoming. Working paper available at http://www.econ.uconn.edu/working/2005-49.pdf (viewed 1/22/06).

Langlois, Richard N. and Paul L. Robertson (1992). "Networks and Innovation in a Modular System: Lessons from the Microcomputer and Stereo Component Industries," *Research Policy*, 21: 297-313, reprinted in *Managing in the Modular Age: Architectures, Networks, and Organizations*, (G. Raghu, A. Kumaraswamy, and R.N. Langlois, eds.) Blackwell, Oxford/Malden, MA.

Levinthal, Daniel A. (1997) "Adaptation on Rugged Landscapes" *Management Science*, 43: 934-950.

MacCormack, Alan, John Rusnak and Carliss Baldwin (2006) "Exploring the Structure of Complex Software Designs: An Empirical Study of Open Source and Proprietary Code," *Management*

Science, 52(7): 1015-1030.

Mead, Carver and Lynn Conway (1980) *Introduction to VLSI Systems*, Addison-Wesley, Reading, MA.

Nelson, Richard R. and Sidney G. Winter (1982) *An Evolutionary Theory of Economic Change,* Cambridge, MA: Harvard University Press.

Nickerson, Jack A. and Todd R. Zenger (2004) "A Knowledge-based Theory of the Firm—The Problem-Solving Perspective," *Organization Science*, 15(6): 617–632

Park, Andrew and Peter Burrows (2001) "Dell, the Conqueror," *Business Week* (9/24/01) available at http://www.businessweek.com/magazine/content/01_39/b3750039.htm (viewed 7/27/06).

Parnas, David L. (1972) "On the Criteria to Be Used in Decomposing Systems into Modules," *Communications of the ACM* 15: 1053-58.

Patterson, David A. and John L. Hennessy (1994) *Computer Organization and Design: The Hardware/Software Interface*, San Mateo, CA: Morgan Kaufmann Publishers.

Penrose, Edith T. (1959) *The Theory of the Growth of the Firm*, Oxford, UK: Blackwell.

Rivkin, Jan W. and Nicolaj Siggelkow (2003) "Balancing Search and Stability: Interdependencies Among Elements of Organizational Design" *Management Science* 49:290-311.

Rivkin, Jan W. and Nicolaj Siggelkow (2007) "Patterned Interactions in Complex Systems: Implications for Exploration," *Management Science*, 53(7):1068-1085.

Rosenkopf, Lori and Melissa A. Shilling (2007) "Comparing Alliance Network Structure across Industries: Observations and Explanations," *Strategic Entrepreneurship Journal*, 1:191-207.

Rumelt, Richard P. (1987) "Theory, Strategy, and Entrepreneurship," in David Teece (ed.) *The Competitive Challenge: Strategies for Industrial Innovation and Renewal,* Cambridge, MA: Ballinger, 137-158.

Sako, Mari (2003) "Modularity and Outsourcing: The Nature of Co-Evolution of Product Architecture and Organization Architecture in the Global Automotive Industry, in *The Business of Systems Integration* (A. Prencipe, A. Davies and M. Hobday, eds.) Oxford University Press, Oxford, UK.

Salus, Peter H. (1994) *A Quarter Century of Unix*, Reading, MA: Addison-Wesley.

Samuelson, Larry (2004) "Modeling Knowledge in Economic Analysis," *Journal of Economic Literature* 57(2):367-403.

Sanchez, Ronald A. and Joseph T. Mahoney (1996). "Modularity, Flexibility and Knowledge Management in Product and Organizational Design," *Strategic Management Journal*, 17: 63-76.

Schilling, Melissa A. (2000). "Toward a General Systems Theory and its Application to Interfirm Product Modularity," *Academy of Management Review* 25(2):312-334, reprinted in *Managing in the Modular Age: Architectures, Networks, and Organizations* (G. Raghu, A. Kumaraswamy, and R.N. Langlois, eds.), Blackwell, Oxford/Malden, MA.

Schumpeter, Joseph A. (1934) *The Theory of Economic Development*, Cambridge, MA: Harvard University Press.

Simon, Herbert A. (1962) "The Architecture of Complexity," *Proceedings of the American Philosophical Society* 106: 467-482, repinted in *idem.* (1981) *The Sciences of the Artificial*, *2nd ed.* MIT Press, Cambridge, MA, 193-229.

Simon, Herbert A. (1981). *The Sciences of the Artificial, 2nd Ed.* Cambridge, MA: MIT Press.

Suh, Nam (1990) *The Principles of Design* Oxford UK: Oxford University Press.

Teece, David J. (1996). “Firm Organization, Industrial Structure, and Technological Innovation,” *Journal of Economic Behavior and Organization*, 31(2): 193-224.

Teece, David J. (2000) *Managing Intellectual Capital* Oxford, UK: Oxford University Press.

Teece, David J., Gary Pisano and Amy Shuen (1997) “Dynamic Capabilities and Strategic Management,” *Strategic Management Journal*, 18(7): 509-533.

Ulrich, Karl (1995) “The Role of Product Architecture in the Manufacturing Firm,” *Research Policy,* 24:419-440, reprinted in *Managing in the Modular Age: Architectures, Networks, and Organizations,* (G. Raghu, A. Kumaraswamy, and R.N. Langlois, eds.) Blackwell, Oxford/Malden, MA.

Vance, Ashlee (2006a) "Dell: 'We'll Cut Prices and … er, Cut Prices," *The Register* (5/19/06) available at http://www.theregister.com/2006/05/19/dell_first_model/ (viewed 7/29/06).

Vance, Ashlee (2006b) "Dell Warns of Q2 Bloodbath," *The Register* (7/21/06) available at http://www.theregister.com/2006/07/21/dell_q2_down/ (viewed 7/29/06).

von Hippel, Eric (1990) "Task Partitioning: An Innovation Process Variable," *Research Policy* 19: 407-18.

Wernerfelt, Birger (1984) "A Resource-Based View of the Firm," Strategic Management Journal, 5(2):171-180.

Whitney, Daniel E., Edward Crawley, Olivier de Weck, Steven Eppinger, Christopher Magee, Joel Moses, Warren Seering, Joel Schindall, David Wallace (2004) "The Influence of Architecture in Engineering Systems," Engineering Systems Monograph, MIT, Cambridge, MA (March); available at http://esd.mit.edu/symposium/monograph/ (viewed 7/29/07).

Williamson, Oliver E. (1985) *The Economic Institutions of Capitalism*, Free Press, New York, NY.