

# How Industry Structure Retards Diffusion of Innovations in Construction: Challenges and Opportunities

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## Abstract

*Extant research on innovation diffusion has primarily focused on the adoption decision and makes the implicit assumption that implementation is easy. We build on and extend research by John Taylor who proposes that this is not always the case. Taylor showed that when the implementation process of an innovation is misaligned with existing industry structure, as is the case for “integral innovations” in fragmented supply chains, diffusion is slow. By contrast, “modular innovations” diffuse more rapidly. He proposed that, for what he called “systemic innovations”, inter-organizational learning mechanisms were disrupted by relational instability in the supply chain from project to project. We assert that the underlying mechanism retarding integral innovations is the lengthy process by which network-level architectural knowledge is accumulated, and that the speed with which this knowledge can accumulate is a function of relational stability within the network, as Taylor proposed. Failure of diffusion for these integral innovations, in turn, reinforces existing industry structure, thus barring future integral innovations from diffusing. In this paper, we elaborate and extend Taylor’s path-breaking work in this area to develop a broader framework for understanding innovation in mature industries like construction. We introduce the concepts of “modules” and “swim lanes” which helps operationalize Taylor’s framework. Further, we refine the idea of organizational learning to focus on implicit network-level architectural knowledge. Beyond an analysis of the reasons for different rates of diffusion of modular vs. integral innovations, we provide an overarching framework that explains the key structural barriers inherent in the building industry that retard the diffusion of both kinds of innovation. We conclude by suggesting that these market failures constitute significant opportunities for government actions to address the failures and corporate strategy to gain competitive advantage through successful adoption of integral innovations.*

**KEYWORDS:** Integral Innovations, Innovation Diffusion, Supply Chain Fragmentation, Construction Industry, Energy-Efficiency.

*“Knowing is not enough; we must apply. Willing is not enough; we must do.” (Goethe)*

Innovation diffusion has fascinated scholars in a variety of disciplines for decades, including sociology (McAdam, 1986; Mort, 1957; Ryan & Gross, 1943; Soule, 1999), communication (Deutschmann & Danielson, 1960; Mayer, Gudykunst, Perrill, & Merrill, 1990), marketing and management (Bass, 1969; Wiebe, 1952), economics (Griliches, 1957; E Mansfield, 1961), anthropology (Wellin, 1955; Wissler, 1914), and geography (Hagerstrand, 1952, 1967). By the 1960s and 1970s, “innovation has emerged... as possibly the most fashionable of social science areas” (Downs & Mohr, 1976, p. 700). Everett Rogers has written an authoritative review on the subject of innovation diffusion (1962) and has updated it in four subsequent editions (1971, 1983, 1995, 2003). According to Rogers (2003), “although diffusion research began as a series of scientific enclaves, it has emerged as a single, integrated body of concepts and generalizations, even though the investigations are conducted by researchers in different scientific disciplines” (p. 101).

Innovation diffusion research generally defines an innovation as “an idea, practice, or object perceived as new by an individual or other unit of adoption” (Rogers, 2003, p. 36). According to the widely-accepted and authoritative review of innovation research by Rogers, diffusion “is the process in which an innovation is communicated through certain channels over time among the members of a social system” (Rogers, 2003, p. 5). Diffusion is viewed as a “special type of communication concerned with the spread of messages that are perceived as new ideas” (Rogers, 2003, p. 35), a “process in which participants create and share information with one another in order to reach a mutual understanding” (Rogers, 2003, p. 5).

Given that innovations are novel to the adopting community, “communication [is] a necessary condition for adoption” (Strang & Soule, 1998, p. 267). But this is not sufficient. In many cases, once an adopting unit has received communication about an innovation, has gone through all the explicit and implicit processes associated with the adoption decision process, and has decided to adopt the innovation, diffusion fails because of failure to implement it properly and thus the innovation cannot be put to use. While some innovations do not involve difficult implementations, others require substantial efforts and often diffuse slowly or fail to diffuse altogether because of implementation difficulties.

Rogers (2003) acknowledges the presence of an implementation phase and includes it in his five-step diffusion process model. The first three steps of the Rogers model have to do with the adoption decision: knowledge, persuasion, and finally a decision. The fourth step is implementation, and the final step is confirmation. Nevertheless, although Rogers included an implementation phase in his framework, and although approximately 6,000 scholarly articles have been written on the subject of innovation diffusion (Rogers, 2003), prevailing literature has largely ignored the implementation phase. This represents a major gap. Most studies of innovation diffusion focus on an individual’s or a firm’s *willingness* to adopt an innovation (Rogers, 2003), not on their *ability* to adopt it. There is an implicit assumption that the critical factor is an adoption decision, and that once made, implementation will be straightforward. Diffusion in these studies is considered to be a function of awareness and persuasion, which give rise to an adoption decision. And once an adoption decision has been made, “everyone lives happily ever after” and an innovation diffuses. We argue that a more complete model of diffusion must place equal emphasis on each of the five phases in the diffusion process: knowledge and persuasion that lead to and culminating in adoption, implementation, and confirmation. Our research seeks to address the gap and focuses on the implementation phase.

Given that implementation is sometimes straightforward, a natural question to ask is under what conditions is diffusion theory inadequate in explaining the diffusion of real world

innovations? Which types of innovations involve problematic implementation procedures that render current diffusion theory insufficient?

Taylor (2005) argues that when an innovation is aligned with the allocation of work within a network, then implementation does not involve the special difficulties that are associated with interorganizational learning. These innovations can be understood with the current innovation diffusion framework (Rogers, 2003). However, when an innovation is misaligned with the allocation of work within a network, it will encounter unique difficulties that current diffusion theory is unable to address.

In the following section, we offer a classification of innovations based on the alignment of their implementation processes within or across “swim lanes” in the supply chain. Next, we show that innovation diffusion takes time and is never instantaneous for any kind of innovation, modular or integral. We review Taylor’s (2005) proposition that integral innovations diffuse slower than modular ones. We then offer the concept of architectural knowledge (Henderson & Clark, 1990) as the main mechanism to explain the slow diffusion of integral innovations. Third, we explain that the natural maturation process that many industries experience involves fragmentation of supply chains. We elaborate on the concept of relational stability as a way to conceptualize varying degrees of fragmentation. We argue that in fragmented industries with low relational stability, accumulating architectural knowledge is difficult and the resulting diffusion of integral innovations is slow. Fragmentation does not affect the diffusion of modular innovations. We conclude this section with a summary of the gaps that we identify in the literature and a proof-of-concept model that summarizes our theory of the effects of alignment with industry structure on the rate of innovation diffusion.

## **Innovation Types**

Innovations can be either in products or processes (Utterback & Abernathy, 1975). Product and process innovations are sometimes called technical and administrative, respectively (Daft, 1978; Damanpour, 1991). It is important to note that product innovations often require and drive process innovations (Utterback & Abernathy, 1975), just as process innovations can drive product innovations (Clark & Fujimoto, 1991). Within product innovations, one can further distinguish between innovations in products that are assembled from multiple modules (such as mobile phones or airplanes) and innovations in non-assembled products (such as glass panes or paint). Our focus is on assembled products.

Innovations in assembled products can affect one or more modules, or the linkages between modules. Henderson and Clark (1990) wrote a seminal piece that largely introduced the view of products as assembled components into the innovation literature. They depart from the common classification of innovations based on their effect sizes as either small (incremental innovations) or large (radical innovations). They argue that this distinction “has produced important insights, but it is fundamentally incomplete. There is growing evidence that there are numerous technical innovations that involve apparently modest changes to the existing technology but they have quite dramatic competitive consequences” (p. 10). In addition to effect size, they offer a more nuanced analysis of where within a product the innovation is located. They distinguish between innovations that induce changes to components within a product (what we call modular innovations) and changes made to the linkages between components within a product (what we call integral innovations).

Based on these two axes, they classify innovations into four types – *incremental*, *modular*, *architectural*, and *radical*. In the first two types, the innovation is contained within

individual – or multiple – subsystems. An *incremental innovation* “refines and extends an established design. Improvement occurs in individual components, but the underlying core design concepts, and the links between them, remain the same” (p. 11). A *modular innovation* “changes a core design concept without changing the product’s architecture” (p. 12). In the other two types, the innovation is located in the connections between subsystems. An *architectural innovation* is one that changes “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). A *radical innovation* is one that “establishes a new dominant design and, hence, a new set of core design concepts embodied in components that are linked together in a new architecture” (p. 11).

Taylor and Levitt (2004) extend the research on architectural innovations to consider whether innovations span across module boundaries in the prevailing supply-chain for a product or system. They coined the term *systemic innovations* for innovations that “reinforce the existing product but necessitate a change in the process that requires multiple firms to change their practice” (J. E. Taylor, 2005, p. 25). Thus, they are suggesting another dimension of categorization for innovations —the relationship between the product architecture and the prevailing organization of the industry supply chain for those modules. They elaborate Henderson and Clark’s term *architectural innovations* to categorize innovations that also span across multiple firm boundaries in the prevailing supply chain instead of being contained within a single firm as *systemic innovations*.

#### *“Modules” and “Swim Lanes” within Supply Chains*

Our theoretical framework for studying innovations extends prior work through the more precise definition of the concept of “modules” within the product architecture of complex products such as buildings, as well as the concept of “swim lanes” within the supply-chain (Sheffer & Levitt, 2010b).

A *module* is a relatively standard and institutionalized component, prefabricated off-site and brought to the job site to be assembled into the completed product. An example of a “module” within a product is a door, a window, or an air-conditioning unit within a building. The scope of what constitutes a module changes over time, as costly, on-site labor has steadily been extracted from the building process and embodied in prefabricated elements that are more finished. A series of studies conducted by the US Bureau of Labor Statistics in the 1960s and 1970s demonstrated that a steady displacement of on-site construction labor through prefabrication occurs at the rate of about 3% per year compounded. Thus a door that used to be finished and hung on-site within its customized, site-assembled frame by a carpenter using a chisel, screwdriver and wedges, now typically arrives on site already hung within its frame, with locking hardware installed, and often already finished with the appropriate varnish or paint. It may be made of wood, but also steel, vinyl or other materials. Similarly structural steel beams and columns that used to be cut to length and drilled in a fabrication plant, and then riveted or bolted together on site now typically come to the site in larger prefabricated column trees that span multiple stories. And so on.

A module of this type may be produced entirely within an existing firm, but is more typically produced by a set of firms in a well-established and institutionalized “swim lane” within the supply-chain. A *swim lane* includes and bounds the supply chain nodes involved in all phases of producing an individual module, all the way from extraction and refinement of the raw materials through the prefabricated element ready for assembly within the product. For

example, within the building industry supply chain, the swim lane for a window – made up of wood frames, glass sheets, metal latches, neoprene seals, vinyl coverings, electric motors for the actuators, etc. – includes the set of firms that produces the components for the window and assembles them into the prefabricated, ready-to-install window unit. Similarly the firms that produce air-conditioning modules such as chillers or boilers form another swim lane in the prevailing supply-chain together with the suppliers of the compressors, motors, etc., that go into these modules. Thus, there is a one-to-one correspondence between each module and the swim lane within which it is currently produced, allowing for some minor variations that will always exist in the configuration of supply chains across different regions of the country or even within a region.

For each module of an assembled product like a building, such as a door, window or an air-conditioning system, one can observe an established swim lane within the supply-chain through which that module is produced. Within a given swim lane, one or more existing firms employ workers with relatively well defined and institutionalized skills, some of which are enshrined in the professional registrations of different kinds of engineers and in the jurisdictional boundaries of separate craft labor unions.

Thus an innovation that creates a more energy-efficient window assembly or a new, more efficient chiller entirely within its swim lane is a *modular innovation*; but an innovation that requires that this window be electrically actuated and integrated into an intelligent building control system that monitors indoor and outdoor temperatures and humidity, and uses sophisticated software, firmware and relays to activate the chiller, as well as boilers, fans, window actuators, etc., cuts across multiple swim lanes in the prevailing supply-chain and is thus an *integral innovation*.

The mature construction industry's supply-chain has progressively fragmented over time, but the supply-chain can also be deliberately reintegrated to define new and broader scope swim lanes in order to diffuse integral innovations, thereby transforming them into modular innovations (Sheffer & Levitt, 2010b). For example the building industry is currently in the early stages of reorganizing itself to define a new broad-scoped swim lane for “intelligent building control systems.” Initially a single firm such as Johnson Controls might seek to partner with a group of long-term alliance partners in the supply-chain to provide an “integrated intelligent building control systems module” as an integrated package to a builder.

With repeated experience, the integrating firm and its suppliers will discover problems with current modules and their interfaces and will standardize new sub-modules and interface protocols between the sub-modules that comprise this new, higher level module. This will allow the sub-modules to be outsourced within a new configuration of the swim lanes in the supply-chain once the firms within the swim lane have learned how to produce and integrate the newly standardized modules involved in this innovation. This selective debugging and refinement of problematic interfaces between modules eventually allows re-fragmentation of the supply-chain and successive modular innovation of its new set of component modules, as described by Petroski (1994) and Ethiraj and Levinthal (2004).

Thus the boundary between modular vs. integral innovations is a moving target, albeit a very slow-moving one. Innovations such as hollow wall partitions in buildings, using gypsum sheets and 2” x 4” wood—and later sheet metal—studs to replace masonry walls, took as long as 15 years to diffuse through the already fragmented US construction industry.

### *Modular and Integral Innovations*

Put more formally, we define modular innovations as those that affect one or more modules within a single swim lane and have no effect on the way that the modules are integrated with other swim lane modules within a product. By definition, these innovations affect a single swim lane through the supply chain with negligible impacts on product or process attributes of other supply chain nodes (Henderson & Clark, 1990; John E. Taylor & Levitt, 2004). Since there tends to be a one-to-one fit between modules and swim lanes, modular innovations generally affect single modules. A modular innovation can increase the energy-efficiency delivered by the component that emerges from the individual swim lane through which it flows, but tends to have a relatively small effect on overall lifecycle energy use of a built system.

Integral innovations, on the other hand, are those whose implementation requires coordination between nodes in at least two separate swim lanes in the supply chain. These innovations affect the way that modules are integrated rather than just the individual modules. Put another way, they affect the linkages between the subsystems within a larger system, rather than the subsystems themselves. By definition, they cut across swim lane boundaries and require the coordinated efforts of the network of firms involved in the design, construction, and operation phases of a project. As such, they necessitate multiple, interacting changes in the supply chain that require multiple firms to learn and implement changes in their existing work processes, division of labor, division of costs, and division of profits. This generates switching, start-up, and learning costs for some firms, shifts the locus of costs and benefits between firms, and potentially reduces or even eliminates the role of others (John E. Taylor & Levitt, 2004).

Integral innovations such as integrated building control systems are the ones that typically enable the most substantial long term savings in operating costs and attendant energy-efficiency of the resulting product, but they are much more difficult to implement and are therefore slow to diffuse, especially in fragmented industries such as construction (John E. Taylor & Levitt, 2004). In fact, because of the real and perceived risks associated with integral innovations, competitors often “not only resist innovative threats, but actually resist all efforts to understand them, preferring to further entrench their positions in the older products” (Utterback, 1996, p. xxvii).

We have not found an appropriate term in the organizational innovation literature for this type of innovation (Gatignon, Tushman, Smith, & Anderson, 2002; Henderson & Clark, 1990; John E. Taylor & Levitt, 2004). We have therefore coined the term *integral innovations*. Our definition encompasses Henderson and Clark’s (1990) architectural and radical innovations, Taylor and Levitt’s (2004) systemic innovations, and Gatignon and colleagues’ (2002) architectural innovations. Our definition of modular innovations encompasses Henderson and Clark’s (1990) incremental and modular innovations, Taylor and Levitt’s (2004) incremental innovations, and Gatignon and colleagues’ (2002) generational innovations. One of the problems with these prior definitions is that they are inconsistent with one another. For example, Henderson and Clark’s use the term architectural innovation to express both the locus of innovation (linkages between subsystems) and effect size (small), whereas Gatignon and colleagues’ use the term architectural innovation to specify only the locus of innovation (linkages between subsystems). Taylor and Levitt use the term systemic innovation to focus on the locus of innovation (linkages between subsystems) as well as the entities affected (multiple firms). Our term refers only to the locus of innovation (linkages between subsystems), without consideration of effect size (could be small or large) or entities affected (a single or multiple organizations). Further, by importing the terms “modular” and “integral” from operations and

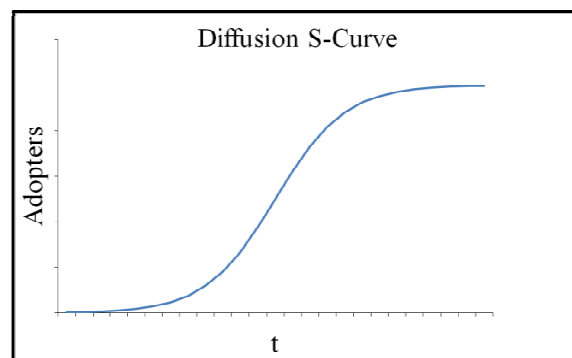
supply chain management, our definitions connect the locus of innovation with their relevant supply chains and thus describe most precisely the constructs that we are studying.

### **Innovation Diffusion Is Never Instantaneous**

Definitions of innovation diffusion vary. Common to all definitions and examinations, however, is the fact that innovation diffusion takes time and is never instantaneous (Dosi, 1991). In fact, “in the history of diffusion of many innovations, one cannot help being struck by two characteristics of the diffusion process: its apparent overall slowness on the one hand, and the wide variation in the rates of acceptance of different inventions, on the other” (Rosenberg, 1976, p. 191). The rate of diffusion varies significantly between firms, industries, and technologies (Dosi, 1991; Nasbeth & Ray, 1974; Ray, 1984; Romeo, 1975).

#### *The Diffusion S-Curve*

For most innovations, when the cumulative number of adopters is plotted over time (cumulative number of adopters on the y-axis and time on the x-axis), the resulting distribution is an S-shaped curve. See Figure 1 below.



**Figure 1: Diffusion S-Curve**

The adopting unit can be at any level of analysis: An individual, a group, an organization, an industry, or a nation. Such a graph depicts the path and rate of innovation diffusion: A slow start with just a few adopters, fast growth as the innovation becomes more mainstream and diffuses more rapidly, and finally stagnation as the curve reaches its asymptote when most potential adopters have already adopted the innovation (Edwin Mansfield, 1968; Moore, 2005; Rogers, 2003). While most innovations follow this pattern, the slope of the curve varies from innovation to innovation. Some innovations have a very steep sloped curve, while others produce a curve with a relatively flat slope.

#### *The Slope of the Diffusion Curve*

Existing research offers many possible factors that affect the slope of the curve depicting the rate of diffusion. Rogers (2003) summarizes the research and argues that there are five types of factors that affect the rate of innovation diffusion. The first set of factors is the perceived attributes of the innovation itself. The critical attributes are relative advantage, compatibility, complexity, trialability, and observability. The second set of factors is the type of innovation-

decision, as optional, collective, or authority. The third set of factors has to do with the communication channels, such as mass media or interpersonal relations. The fourth set of factors is the nature of the social system within which the diffusion takes place. This includes the norms and degree of network interconnectedness. The last set of factors involves the change agent and the extent of their promotion efforts. Rogers further explains that innovations adopted by individuals are faster to diffuse than those adopted by organizations. In a different synthesis of the innovation diffusion literature, Dosi (1991) adds that the characteristics of the original product that will be replaced, the economic incentives to adopt, the characteristics of the potential adopters including technological competence, information availability, and the number of possible adopters are also important factors. Kanter (2000) adds that the coupling between developers and users also affects the rate of diffusion.

There is no doubt that the variables that we reviewed significantly affect the rate of diffusion. To a large degree, however, they all affect the adoption decision, not the implementation phase. Because the implementation process of modular innovations is aligned with industry structure, the diffusion of these innovations can be understood using extant innovation diffusion literature. But for integral innovations that require a re-alignment of work allocation within a network, these factors are insufficient in explaining the rate of diffusion (J. E. Taylor, 2005). This leaves an important gap in the literature.

Taylor (2005) began to fill this gap. He proposed six factors that affect the rate of diffusion of integral innovations: relational stability, interests, boundary strength, the presence of an agent for network-level change, span, and the degree of interdependence between firms. Each of these constructs can mitigate or exacerbate the detrimental effect that misalignment has on the rate of innovation diffusion. However, these propositions have yet to be validated.

Further, and even more critically, no study actually conclusively shows that alignment with industry structure is an important determinant of the rate of diffusion. That is, there is no proof that integral innovations diffuse slower than modular ones. Taylor and Levitt (2004) took a first step in this direction. They cite a US government report (*Technology, Trade, and the U.S. Residential Construction Industry [special report] (OTA-TET-315)*, 1986) that showed that a wall truss modular innovation<sup>1</sup> diffused four times as fast as a prefabricated wall containing lumber, plumbing, electrical, and mechanical components over the same period (1975-1982). The modular innovation achieved a 40% market penetration, whereas the integral<sup>2</sup> one captured only 10% of the market. While this is an excellent first step, this analysis provides inconclusive results. Since Taylor and Levitt only looked at one modular innovation and one integral innovation, they cannot confidently rule out a third variable as a possible explanation for the difference in diffusion rates. Further, since the sample size is one modular innovation and one integral, it is hard to generalize conclusions.

Our initial examination of other innovations within the building industry as well as within other industries suggests that Taylor and Levitt are correct in their proposition. However, more data needs to be collected. This is one of the major gaps in the literature that we are currently working to fill.

*Proposition 1: Modular innovations diffuse more slowly than integral innovations.*

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<sup>1</sup> Taylor and Levitt use the term “incremental” innovation.

<sup>2</sup> Taylor and Levitt use the term “systemic” innovation.

We argue that the primary explanation for the slower diffusion of integral innovations is that these innovations require new architectural knowledge that is difficult to capture, formalize and accumulate since it crosses swim lane boundaries in a fragmented industry where the mix of participants in the implementation process shifts continuously from one implementation to the next. Even if by the end of an implementation process the team of participants has learned the new process, this knowledge is lost when the team disbands. Overall diffusion is thus slow. In the next section, we explore the effects of prior knowledge on implementation and then focus our discussion on architectural knowledge.

### **Competency Trap or Absorptive Capacity?**

Learning any new skill, including the implementation process of a new technology, takes time. This simple insight is another possible explanation for the s-curve pattern of diffusion that has been overlooked by researchers too focused on the adoption decision phase of diffusion and ignored the implementation phase. When an innovation that involves a complicated implementation process is first introduced, few know how to implement it. Some attempts at implementation are successful, while others fail. At this point, diffusion is slow. As successful implementations take place, knowledge slowly starts to accumulate and successes are replicated in more implementations. The rate of diffusion increases. Eventually, the curve asymptotes as fewer and fewer potential implementations remain. Our proposition is essentially about learning by doing.

*Proposition 2A: Experience implementing a particular innovation is positively correlated with the speed of the implementation and negatively correlated with the amount and extent of complications associated with the implementation.*

The “dark” side of learning is that it is difficult to “unlearn” old knowledge. Once experience with a particular innovation is accumulated, the innovation is no longer new. It becomes part of routine process. Then, when a new innovation is introduced, newer knowledge needs to replace the now-old and possibly irrelevant knowledge that already exists. The better an individual, an organization, or a network of organizations know how to perform a certain task, the more difficult it is for them to deviate and do things differently. In writing about research training, Kaplan (1964) termed this phenomenon *trained incapacity*: “the more we know about how to do something, the harder it is to learn how to do it differently” (p. 31). Such trained incapacity is necessary to some degree. Without it, if every task would be new and individuals or organizations could not rely on prior knowledge, the tasks would be daunting and their execution inefficient. This is a sort of competency trap. “A competency trap can occur when favorable performance with an inferior procedure leads an organization to accumulate more experience with it, thus keeping experience with a superior procedure inadequate to make it rewarding to use” (Levitt & March, 1988, p. 322).

We propose that the more experience an organization has in a particular area, the harder it is for that organization to discard irrelevant old knowledge and accumulate new knowledge necessary for implementing an innovation. This is true for all innovations, but much more acute in the case of integral innovations. Organizations with a lot of experience in a particular area are less likely to attempt implementing new innovations that ignore or even defy their old knowledge. Further, in cases that the organizations will attempt to implement the innovation, the implementations are less likely to be successful and the overall rate of diffusion will be lower.

*Proposition 2B: The more experience an organization has in a particular area, the lower the rate of diffusion for innovations that require new knowledge. This is more acute for integral innovations.*

Related to the amount of prior knowledge an organization has is the organization's age. Young organizations might have an easier time innovating because they are less invested in old knowledge and are less entrenched in it.

*Proposition 2C: Younger firms will experience a higher rate of implementation of integral innovations than mature firms.*

However, it is plausible that the opposite is true, as the theory of absorptive capacity (Cohen & Levinthal, 1990) would predict. Absorptive capacity is "the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends... it is largely a function of the firm's level of prior related knowledge... The premise of the notion of absorptive capacity is that the organization needs prior related knowledge to assimilate and use new knowledge" (Cohen & Levinthal, 1990, pp. 128-129). They argue that "prior knowledge permits the assimilation and exploitation of new knowledge" (Cohen & Levinthal, 1990, pp. 135-136).

*Proposition 2D: The more experience an organization has in a particular area, the higher the rate of diffusion for innovations that requires new knowledge.*

A way to reconcile these two discrepant ideas is perhaps to recognize that the relationship between prior knowledge and ability to implement innovations is nonlinear. General background knowledge is helpful and increases the rate of diffusion, but too much knowledge that is very specific to an old technology leads to rigidity and is detrimental to innovation diffusion. Understanding the bounds and types of knowledge are thus critical in resolving this conflict. This represents another gap in knowledge that we are working to address.

### **Architectural Knowledge**

Beyond the amount of prior knowledge and what firms choose to do with it (search behavior), it is important to distinguish between types of knowledge. An important insight that Henderson and Clark (1990) bring is that two types of knowledge are involved in successful product development: component knowledge and architectural knowledge. *Component knowledge* is knowledge about individual modules, their core design concepts, and the way in which they are implemented individually. *Architectural knowledge* is knowledge about the way that the components, or modules, are integrated and put together to make a coherent product. Once a dominant design has emerged in an industry, architectural knowledge "tends to become embedded in the practices and procedures of the organization" (p. 15). Institutional mechanisms include routines (Galbraith, 1973; Nelson & Winter, 1982), communication channels, information filters, and problem-solving strategies (Henderson & Clark, 1990). Also sequential bug fixes for problematic interfaces eventually eliminate the most problematic interface challenges (Petroski, 1994).

Component and architectural knowledge are managed differently in organizations. While component knowledge is managed explicitly, architectural knowledge is managed implicitly and becomes embedded in the institutional mechanisms mentioned above (Henderson & Clark, 1990). This distinction suggests that architectural knowledge is harder to accumulate and change than component knowledge (Nissen, 2005; Nonaka, 1994). Henderson and Clark argue that not only is it difficult for firms to recognize that a particular innovation is indeed integral and not

modular<sup>3</sup>, it then has difficulties acquiring the necessary architectural knowledge. Replacing old architectural knowledge with new knowledge involves reorienting the organization and essentially switching from a mode of exploitation of old knowledge to an active search mode of exploration of new knowledge (Louis & Sutton, 1991; March, 1991).

*Proposition 2H: Architectural knowledge is more difficult and thus slower to acquire than component knowledge.*

Given the difficulty associated with acquiring architectural knowledge, it is not surprising that architectural (Henderson & Clark, 1990), systemic (John E. Taylor & Levitt, 2004), and disruptive (Christensen, Suarez, & Utterback, 1999) or discontinuous (Robertson, 1971; Robertson & Gatignon, 1986) innovations are associated with delayed and incomplete innovations in several industries, including photolithography, automobile, disk drives, and construction (Gatignon, et al., 2002).

Thus far, we have described our main theory (that alignment with industry structure affects an innovation's rate of diffusion) and the main mechanism that we propose to explain this theory (that architectural knowledge is difficult to replace). Now, we turn to the important influence that the context within which the diffusion process takes place has, namely the stage in a product's life cycle and the resulting level of fragmentation in the industry.

### **Product Life Cycle and Industry Fragmentation**

Innovation activity depends strongly on time in an industry's life cycle (Abernathy & Utterback, 1978; Eccles, 1981; Klepper, 1996; Williamson, 1975). A common view of the relationship between product life cycle (PLC) and innovation has emerged in multiple disciplines, including economics (Klepper, 1996), strategy (Moore, 2005), and management (Abernathy & Utterback, 1978). That is, early on in an industry's lifecycle, the rate of product innovation is high. When a dominant design emerges or a shakeout in the number of producers takes place, the rate of product innovation decreases and that of process innovation increases. As the industry matures, innovations become incremental in nature and affect productivity and quality. In mature industries, "significant innovations tend to be fewer and are mainly of an improvement variety" (Williamson, 1975, p. 216). The mechanism for this pattern, however, is still disputed. Abernathy and Utterback argue that the emergence of a dominant design is the critical factor to explain the PLC. Klepper highlights the role of incentives in shaping the PLC. Moore focuses on consumer preferences.

We propose an alternative, supply chain-based explanation to the PLC. The basic idea is that as products mature, their supply chains tend to fragment, making the implementation of integral innovations very challenging and the resultant diffusion rate is low. We shall explain. Early on in an industry's life cycle, the supply chain tends to be integrated and the activities involved in the design, production, marketing, and implementation of products are performed by a single firm. That is, firms tend to design and produce their products in-house. As industries mature, their supply chains tend to become fragmented, as organizations become more and more specialized (Stigler, 1951). This signifies a transition from complex systems into volume operations (Moore, 2005). In this network production mode, multiple firms participate in the design, engineering, manufacturing, and installation of a product. Increasing aspects of design and production are thus outsourced to specialized firms that perform those tasks better and

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<sup>3</sup> Henderson and Clark refer to these as architectural and incremental, respectively.

cheaper with an “orchestrating” system integrating firm that coordinates the efforts of multiple firms.

We argue that this transition exacerbates the difficulties associated with acquiring – and replacing – architectural knowledge. Thus, innovations that affect only modular components are relatively easy to implement and can result in dramatic performance improvements. However, innovations that affect more than one node in the supply chain and generally more difficult to implement and consequently slow to diffuse.

*Proposition 3A: As industries mature, their supply chains tend to fragment, which in turn make the acquisition of new architectural knowledge more difficult. This results in a decrease in the rate of diffusion for integral innovations, but not for modular innovations.*

We further propose that it is more difficult to acquire new architectural knowledge at the network level than at the organizational level. The reason is that architectural knowledge involves the way the entire system is integrated. Thus, in order for architectural knowledge to be useful, all relevant parties must acquire it. When those parties are separated by organizational boundaries, it is more difficult for them to coordinate, learn from one another, and mutually adjust their roles to the new process.

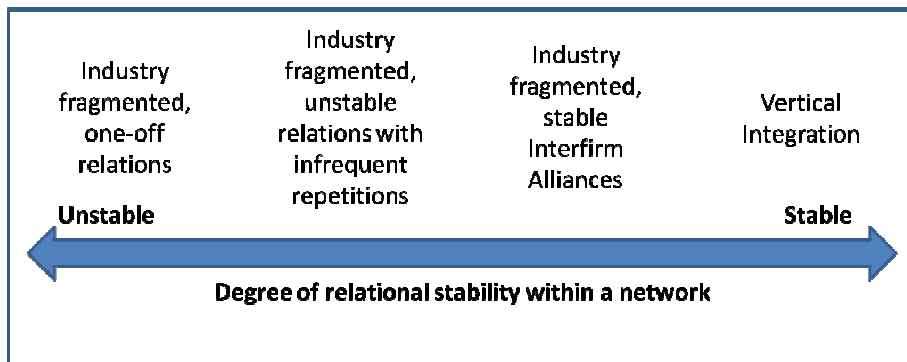
*Proposition 3B: Architectural knowledge that crosses firm boundaries (knowledge about processes that involve multiple firms) is more difficult to acquire and reacquire than architectural knowledge within the boundaries of a single firm.*

The detrimental effect that supply chain fragmentation has on the diffusion of integral innovations is more pertinent today than ever, as more and more industries become fragmented. Examples of this phenomenon are the construction, automobile, PC, mobile phones, pharmaceuticals, and the movie industries. Early construction was done by “master builders” who mastered all aspects of the building craft. These master builders played the roles of architects, engineers, and superintendents. As technologies advanced, a need for specialized training arose, and the construction industry began to fragment (Yates & Battersby, 2003). The first step was to fragment into design and construction specialties, but over time these specialties were further separated into the narrower specializations we see today. Early automobiles were handmade custom products. The unique components made by a single firm were assembled by fitters. Henry Ford’s assembly-line process changed all this and turned the automobile into a platform with standardized parts that are manufactured by vendors and assembled by unskilled workers (Davidow & Malone, 1993). In both the PC and mobile phone industries, early machines were produced from custom parts and software and sold by single vendors. After IBM published its IBM PC specifications in 1981, PCs became platforms with standardized parts that are outsourced, assembled, and sold through channels. The same holds true of mobile phones. Nokia, Motorola and Ericsson originally produced most of the hardware and software involved in cellular phone and cellular phone networks. Today firms like Qualcomm write software and make the microprocessors, Taiwanese and Korean firms make the touch screens and keyboards, Flextronics and others assemble the phones in China, etc. In the pharmaceutical industry, drugs were developed, tested, marketed, and sold by large pharmaceutical companies until their patents ran out. Today, drugs are invented or discovered by biotechnology firms, drug testing is outsourced, and the drugs are licensed for manufacturing and distribution to, or acquired by, the

big pharmaceutical companies. The same trend can even be observed in the movie industry, in its transition from movie houses that do all the writing, casting, producing, and other functions in-house, to a very specialized, segmented industry with separate organizations for each aspect of the movie production process.

### Relational Stability

We have argued thus far that fragmented supply chains negatively affect the rate of diffusion of integral innovations because they require that new architectural knowledge be accumulated at the network level which is very difficult. However, integration and fragmentation can be thought of as two polar extremes on a scale of relational stability within a network. *Relational stability* is defined as the degree to which relations between individual firms within a network persist over time. At one extreme, when relational stability is highest, the firms are vertically integrated and always work together. At the other extreme, the industry is highly fragmented and relations between firms are one-off. That is, on every project or production task, a focal firm works with a different set of firms. In between these two extremes can be distant relations that repeat themselves infrequently or stable partnerships that do not represent full and legal integration. Figure 3 provides a graphical representation.



**Figure 2: Relational Stability and Industry Fragmentation**

Taylor (2005) proposed that high relational stability can mediate the detrimental effect that misalignment with industry structure has on integral innovations. The reason, we argue, is that relational stability affects the rate with which architectural knowledge can be accumulated. Relational stability allows the firms that work together on successive projects to accumulate architectural knowledge and retain it within the network. This form of organization is the closest relative to vertical integration. These separate firms essentially become more like separate departments within a single vertically integrated organization. In contrast, if relations within the network are unstable, it is more difficult to acquire and accumulate new architectural knowledge. Firms that change the mix of firms in their supply chain network frequently may find themselves in situations in which even though they know and understand the new process, their new partners do not, since they may still hold the old architectural knowledge.

In sum, the higher the degree of relational stability within a network, the faster that knowledge can accumulate at the network level. This essentially mediates the negative effects of misalignment with industry structure on the rate of diffusion for integral innovations.

*Proposition 3D: The higher the degree of relational stability within a network, the faster that knowledge can accumulate at the network level and the higher the rate of diffusion of integral innovations.*

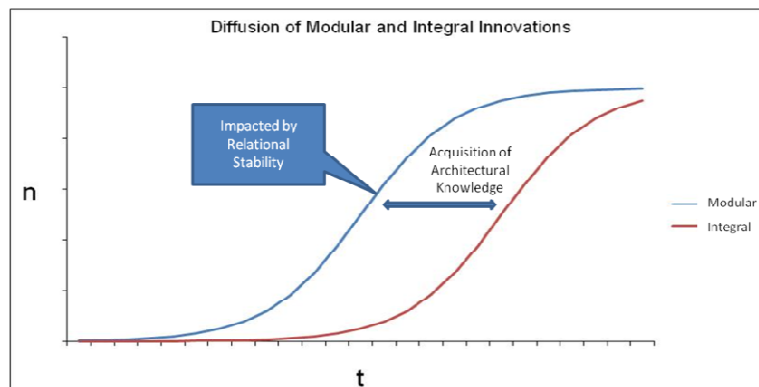
*Proposition 3E: Relational stability is uncorrelated with the rate of diffusion of a modular innovation.*

In the liberal market economy of the United States, relational stability is very low in comparison to more coordinated market economies like Finland or Japan tends to be high (Hall & Soskice, 2001; John E. Taylor & Levitt, 2004). Relations between clients and contractors, and between contractors and subcontractors, tend to be one-off and arms-length. Many clients, including virtually all public construction buyers, require general contractors to submit lump-sum bids and then choose the “lowest qualified bidder”<sup>4</sup>. General contractors, in turn then solicit lump-sum bids from multiple specialized subcontractors, either at large, or from a list of approved prequalified subcontractors.

Thus, individuals and firms at every node in the supply chain tend to select the bidder with the lowest price for each component’s materials and subsystems rather than working with the same set of players across industry swim lanes from project to project (J. E. Taylor, 2006). As a result, the makeup of the core team of architects, engineers, building contractors, subcontractors, and component suppliers required to deliver significant building projects tends to change significantly from project to project, even in the same metropolitan area. Therefore, much of the architectural and tacit knowledge gained from installing an innovative integral energy-saving building technology—or any other integral innovation—on a given project is lost when teams disband, so the learning cannot be transferred to future projects.

### **Proof-of-Concept Model**

The main insight that we are bringing forth is that a need for new network-level architectural knowledge decreases the rate of diffusion of integral innovations and is the main mechanism to explain the differing rates of diffusion. Further, the difference in the rates of diffusion of modular and integral innovations is inversely proportional to the degree of relational stability. Our analyses and propositions culminate in the proof-of-concept model depicted in Figure 4.



**Figure 3: Proof-of-Concept Model for the Diffusion of Modular and Integral Innovations**

<sup>4</sup> “Qualified bidder”, in this context, means simply a contractor that can secure a surety bond guaranteeing completion of its work and payment of its subcontractors and vendors on the project.

This can be expressed mathematically using a mixed-influence diffusion model (Lave & March, 1993):

$$\frac{\Delta n}{\Delta t} = \beta a_1 n(N - n) + a_2(N - n)$$

Where,  $N$ =the total number of people in the population of possible adopters  
 $n$ =the number of people who have already adopted the innovation  
 $a_1$ =constant representing the net effect of the internal influence  
 $a_2$ =constant representing the net effect of the external influence  
 $\beta$ =coefficient representing the acquisition of new network-level architectural knowledge

The mixed-influence model is appropriate for social systems because it takes into account the influence of both internal as well as external factors. It includes two coefficients instead of one, the first for the influence of internal factors and the second for external factors. It is widely used to depict diffusion processes in social systems. Further, we have added an additional coefficient ( $\beta$ ) to capture the effect of the acquisition of new network-level architectural knowledge. Since the implementation of modular innovations does not involve the acquisition of new network-level architectural knowledge,  $\beta=1$ . For integral innovations, the size of the coefficient is impacted by relational stability within the network.

### **Innovation in the Building Industry**

Thus far, we have argued that integral innovations diffuse slower than modular innovations in industries with fragmented supply chains. The extreme fragmentation of the building industry makes this analysis incredibly pertinent in its context. This project-based industry is fragmented both “horizontally” in terms of discipline/trade (i.e., mechanical, electrical, structural) and “vertically” in terms of project life cycle (i.e., project shaping, design, construction, commissioning and operation). The top 400 construction firms in the US account for less than 15% of industry volume (ENR, 2009). The US construction industry includes close to two million small, specialized local firms, fifty percent of which have zero employees (Census, 2004) and are thus “mom *or* pop” firms.

The horizontal fragmentation in the building industry, coupled with a very low relational stability that results from a culture of low cost competitive bidding, results in a severe case of “learning disability” at the network level. Implementing modular innovations that align with existing industry structure and work processes is relatively straightforward. However, deviating from existing processes requires the accumulation of architectural knowledge, which is very difficult to do in a context with such low relational stability.

There are surprisingly few studies that have examined structural, market-level variables in the building industry. However, the few studies that consider market-level variables have found that almost all the innovations that have successfully diffused in the building industry are modular in nature (Arditi & Tangkar, 1997; Lutzenhiser & N., 2003; John E. Taylor & Levitt, 2004). In contrast, integral innovations diffuse very slowly through the industry (John E. Taylor & Levitt, 2004).

It is important to note that although modular innovations diffuse much faster than integral innovations in the building industry, they also are rather slow to diffuse. That is, relative to other

industries, *all* innovations diffuse slowly in the building industry. In this section, we describe our theoretical framework of the structural features unique to the building industry that pose obstacles to the diffusion of any kind of innovation. In addition to the network-level learning disability that we already described, we propose four additional factors that retard the diffusion of all innovations in the building industry (Sheffer & Levitt, 2010a). The first is a culture of low cost competitive bidding. The second is decision making plagued by "broken agency" between building design and construction vs. operations. The third is the high level of demand fluctuation that strands capital and provides a disincentive to make capital investments. The fourth is a technological risk aversion that results from long time horizons and high capital costs. These five factors play important and interconnected roles in inhibiting the diffusion of any kind of energy-saving building technologies.

### *Culture of Competitive Bidding*

Bidding for a building project is typically done separately by component/sub-trade—i.e., the lowest bidder for each building component on a typical project is chosen to supply and install that component. This fragmented competitive bidding process blocks any inter-component cross-subsidies that might be positive in the aggregate, so the best overall solution may not be chosen. For example, ConXTech's innovative steel structural system has a higher cost than traditional structural systems, but can be installed at the rate of one floor per day (vs. about one floor per week) and allows for significant savings on mechanical and electrical systems. It thus provides a substantial reduction in overall project cost and time. However, when bids are awarded separately by subtrade/component, contractors using lower cost traditional structural systems can underbid ConXTech and displace the innovative, and globally more optimal, integral structural system (ConXTech).

*Proposition 5: Projects that employ a competitive bidding system will have fewer integral innovations than projects that do not.*

### *Broken Agency*

Separate individuals, different departments within an organization, or different companies incur the risks and benefits associated with each phase of a building project's life cycle, so no individual or firm on the project has a truly multidisciplinary, life cycle perspective. In particular, the individual or firm that bears capital costs does not usually bear the full lifecycle operating costs. Overall project benefits may conflict with individual participants' self interests and so tend to be ignored. This "broken agency" is present in each phase of a building's life cycle as a result of vertical fragmentation of the industry (Henisz & Levitt, 2009). A Lawrence Berkeley National Laboratory study that measured differences in implementation of energy-efficient technologies by principals and agents (sellers and purchasers, owners and users) found that in just four of the major energy end uses in the US residential sector alone, the magnitude of this broken agency problem totaled over 3,400 trillion BTUs in 2003, which equaled 35% of site energy consumed (Martishaw & Sathaye, 2006).

*Proposition 6: When the entity that bears the capital costs is not the one that will bear the operating cost of a project, innovations that have a positive net present value, but cause a significant capital cost increase are less likely to be implemented.*

### *Stranded Capital*

An exceptionally high level of demand fluctuation—several times greater than the overall business cycle—plagues the building industry. This is an additional constraint to diffusing innovative building technologies, because investments become *stranded capital* when demand turns down, as it did so viciously in 2009. This severe demand fluctuation renders building industry firms unable to service large amounts of long term debt or to justify external investment<sup>5</sup>. This forces them to finance their growth out of retained earnings and operate with extremely low fixed overheads. Even modest investments in equipment or training needed to implement integral energy-saving innovations are difficult for building firms to justify. Moreover, horizontal integration to address the learning disability described above can be risky, as firms must then bear a larger percentage of overall costs and must struggle to balance workloads for multiple disciplines or trades in the face of these severe demand fluctuations. George Romney, an ex-auto industry executive who was US HUD Administrator under President Nixon, launched “Operation Breakthrough” in the early 1970s to encourage investment in producing modular housing units. When demand turned down after the end of the Vietnam War, the newly formed modular housing component manufacturers failed, in large part, due to *stranded capital*. “Project Hus” in Denmark met a similar fate in the early 2000s.

*Proposition 7: Projects that are less affected by demand fluctuation, such as government or institutional buildings, will invest more in innovations and consequently have more innovations than projects that are more affected by demand fluctuation, like residential or commercial buildings.*

### *Technological Risk Aversion*

Relative to other products, buildings are meant to last a long time. Mistakes in design or execution are likely to be long-lasting. Further, not only will mistakes last a long time, but they are also likely to be costly, as most U.S. States hold developers and contractors responsible for “latent defects” in buildings for up to 15 years after completion of construction, and repairing or replacing building components is expensive. Moreover, engineers who specify innovative materials or components can incur claims against their professional liability “errors and omissions” insurance. Thus, decision-makers in building development, design and construction firms all tend to be averse to adopting risky technologies that have not been proven conclusively to be durable, and to be able to pay back their incremental capital cost in a relatively short time frame. In an interview with a senior executive at a large US General Contractor, he explained his sentiments about PV panels,

*“We just don’t know what will happen to the [PV panels] after 20 years and how much maintenance will cost. Have you seen what happens to plastic when it lays out in the sun? It gets yellow and starts to crack. And yes, I am sure that those who designed it know what they are doing and have thought about these things, but how can we be certain? We haven’t seen it work anywhere for twenty years.”*

Unsurprisingly, the company eventually decided not to implement the PV panels.

We propose that the technological risk aversion that is present in the building industry has to do with the combination of high costs and long time horizons. Decreases in either of these

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<sup>5</sup> Note the very low number of publicly listed construction companies among the scores of US construction firms with annual revenues over \$1 billion.

two variables, or an interaction of both, is expected to result in increased willingness to implement new innovations.

*Proposition 8: Decreased time horizons for liability or reduced capital costs are likely to mitigate technological risk aversion and lead to an increase in the rate of innovation diffusion.*

### *Potential Interventions*

Three possible types of interventions can help overcome the critical market failure of the slow diffusion of both modular and integral innovations: (1) Legislation and incentives; (2) Corporate strategic actions; and (3) Consumer education.

Intervention by government – through regulations, codes, incentives, or other policies – is generally justified in circumstances in which market failures result in outcomes that are less than optimal for society. In some cases, regulation can be quite effective; in fact, codes are a standard solution to deal with the problem of broken agency. And a voluntary standard such as LEED, even if not always as effective as it hopes to be (Newsham, Mancini, & Birt, 2009), does increase public awareness of environmental issues and is likely to have a positive long-term effect.

However, codes and voluntary standards alone are not enough and do not necessarily increase the rate of diffusion of innovations (Gann, Wang, & Hawlins, 1998). Even states like California with aggressive green energy codes see relatively slow implementation of integral energy-saving building technologies. Moreover, in some cases, codes can even decrease the rate of innovation diffusion (Oster & Quigley, 1977). For example, building owners may decide not to retrofit existing buildings – an area that holds the greatest opportunity for energy saving – if doing so will require them to comply with costly new building codes. Finally, codes do not solve the learning disability that we described; while codes and voluntary assessment regimes like LEED may require or induce firms to implement energy-saving technologies, they do not guarantee that the technologies will be implemented correctly to achieve their energy saving potential.

There are several strategic actions that building industry firms can take to increase the rate and magnitude of diffusion of energy-saving innovations. For example, to counter the learning disability caused by fragmentation, firms could reconfigure their supply chain by horizontally or vertically integrating the interdependent nodes required for the implementation of an integral innovation. In fact, integration is a standard way to buffer environmental uncertainty (Pfeffer & Salancik, 1978; Thompson, 1967). In our interviews at a green “start up” that produces extremely energy efficient homes, we learned that they are employing this strategy of bringing many of the key design and construction steps in-house to reduce uncertainties and learning costs by retaining important knowledge within the firm.

*Proposition 9A: Vertical integration is positively associated with the rate of diffusion of an integral innovation.*

In dynamic environments, however, vertical integration is suboptimal as it reduces flexibility and increases inertia (Achrol, 1997). Further, integrating the supply chain can increase the risk of stranded capital when demand turns down, as we previously explained. A strategy that addresses the learning disability but takes into account the possibility of demand fluctuation is creating multi-project joint ventures or alliances. This is another strategy that the green start-up is attempting to employ. They are trying to create a network of professionals for processes that

cannot be internalized. To counter the dangers caused by demand fluctuation head on, firms could employ innovative finance strategies, as Ryan Homes did in the 1970s.

*Proposition 9B: Stable alliances or joint ventures are positively associated with the rate of diffusion of integral innovations.*

*Proposition 9C: Stable alliances or joint ventures could replace vertical integration as the best strategy to accumulate learning while reducing the risks associated with demand fluctuation.*

Increased interest in and understanding of the benefits of building energy saving technologies by consumers will incentivize firms to overcome the market barriers and implement these new technologies. Consumer interest is rising due to several factors, including a general increase in consumer awareness of global warming; higher energy costs that begin to become significant even for commercial office tenants; LEED certification; and other factors.

*Proposition 10: Consumer interest is associated with the rate of diffusion of both modular and integral innovations.*

If the McKinsey (Choi Granade, et al., 2009) study is correct and there exist multiple energy-saving opportunities with positive net present values and reasonable payback periods, financial arbitrageurs should see opportunities to step in and arbitrage the opportunities created by broken agency. Indeed we can begin to see the emergence of energy-savings entrepreneurs such as GreenCampusPartners (<http://greencampuspartners.com/>) that offer to finance energy-saving upgrades for universities and operate the upgraded energy systems at no up-front charge, and be compensated through the long term energy savings thus achieved. Similar business models have arisen to address this need for residential solar systems. On the governmental side, Berkeley's Property-Assessed Clean Energy (PACE) system uses property-tax-based repayment of residential energy-saving to arbitrage the broken agency of short term homeowners making long payback investments in energy upgrades. PACE experienced rapid uptake and been widely emulated, although this financing approach is now running into organized opposition from utilities, commercial banks and other stakeholders in the status quo of broken agency.

*Proposition 11: Broken agency in the presence of opportunities for medium-term or long-term positive returns should give rise to arbitrage opportunities for financial intermediaries to exploit.*

## DISCUSSION

In this paper, we have described the concepts of *modules* and *swim lanes* to distinguish between modular and integral innovations. Further, we have developed a proof-of-concept model that describes and explains a type of network-level learning disability that is common for integral innovations in fragmented industries. Our model argues that in fragmented industries with low relational stability, integral innovations diffuse more slowly than modular ones. The underlying mechanism is the difficulty associated with accumulating the necessary network-level architectural knowledge. Finally, in addition to the learning disability that affects integral innovations, we have outlined four additional structural characteristics of the building industry that pose obstacles to the diffusion of any type of innovation. These are competitive bidding, broken agency, demand fluctuation, and technological risk aversion. We have suggested three

types of possible solutions to these obstacles. Our ongoing research aims to extend and validate the model presented in this paper.

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