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Internet computing as a disruptive information technology innovation: the role of strong order effects[1]

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Abstract. *A cross-sector survey study was conducted between 2004 and 2005 among 121 software firms that adopted internet computing for the presence of strong order effects, which explain how, why and in which order radical innovations in information system (IS) are adopted. The following strong order effects were detected: (1) the amount of base innovations positively and directly influenced the amount of service innovation and the amount of process innovation, while the amount of service innovation partially mediates the impact of base innovation on process innovation; (2) the radicalness of base innovations directly and positively influences the radicalness of service innovation, while the impact of the radicalness of the base innovation on the radicalness of process innovations is fully mediated by the radicalness of service innovation; (3) the predominant sequence of initial adoption of radical information technology innovations is first in base innovations, followed by service innovations and finally by process innovations. Our study helps to better understand how and why radical innovations are adopted in ensembles by software firms. In consequence, software organizations should orchestrate flexible innovation strategies that recognize that radical innovations are interconnected and heterogeneous.*

Keywords: radical IT innovation, strong order effects, technology ecology, software development, computing platforms, internet computing

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INTRODUCTION

The information technology (IT) landscape has occasionally witnessed tectonic shifts as a result of radical innovation in underlying technologies (Grover *et al.*, 1997; Kessler & Chakrabarti, 1999; Adomavicius *et al.*, 2008a,b). For example, inventions in database technology provoked new enterprise-wide system services as well as new development processes. Naturally, these disruptions increase innovation among software firms. Success of these firms depends largely on their capability to adopt and orchestrate *different* types of IT innovations across multiple markets, projects and technologies (Pries-Heje *et al.*, 2004; Cassiman & Veugelers, 2006). Unfortunately, these innovation ecologies are poorly understood (Fichman, 2004a); prior research on innovation in software firms has primarily focused on understanding singular innovation adoptions like, e.g. Computer-Aided Software Engineering (CASE) tools or process improvements (Orlikowski, 1991; Yoo *et al.*, 2006). As a result, we know little of why, how and when IT innovations are adopted in 'ensembles' and how to manage such ensembles effectively. Yet knowledge of how and why heterogeneous IT innovations interact will help software firms to formulate flexible organizational responses to radical changes in underlying technology.

Orchestration of innovation ensembles becomes highly critical when massive changes take place in the deployed computing platforms. This results in disruptive IT innovation (Lyytinen & Rose, 2003a,b) where the contours of the ecology become akin to what Henderson & Clark (1990) call a 'radical innovation'. Recently, Lyytinen & Rose (2003a,b) formulated a disruptive information technology innovation model (DITIM) to describe properties of such innovation ecologies. Their model suggests that adopting a radical platform innovation pushes software firms to adopt other heterogeneous and radical IT innovations. In other words, the radical platform innovation instigates multiple radical IT innovations creating an ensemble where innovations move in 'packs'. Their study, however, does not provide a theoretical rationale for why and how a radical platform innovation spawns other radical IT innovations.

To address this gap, we theoretically extend the DITIM with the concept of a strong order effect (Swanson, 1994). Our extension demonstrates why radical platform innovations become a compelling cause for other IT innovations (Swanson, 1994) and why these other innovations are radical. In more specific terms, we address two research questions.

1 Why, how and in what temporal organization do radical IT platform innovations affect the subsequent amount and radicalness of other IT innovations within software firms?

To answer this first question, we identify the causes and nature of strong order effects, which help explain how and why a radical platform change generates a larger number and more radical innovations 'downstream'. Adopting the framework of Lambe & Spekman (1997), we also investigate whether these effects follow a specific temporal sequence. In this sequence, initial radical platform innovation adoptions precede initial service (application) and (software development) process innovation. Further, initial service innovation adoptions precede initial process innovation adoptions.

2 What are the impacts of adopting internet computing platform on subsequent information system (IS) service and process innovation within software development organizations?

To answer this question, we study the adoption of internet in software firms as a disruptive IT innovation (Lyytinen & Rose, 2003a,b) and measure whether it exhibits the postulated strong order effects. To this end, we validate the proposed model with data collected from 121 software development firms regarding their adoption of internet computing innovations between 1999 and 2005.

Overall, clarifying the order effects within the DITIM advances material theories of IT innovation. Prior research identifies antecedents for innovation in both the material properties of technology and in its social environment (Zaltman *et al.*, 1973; Damanpour, 1991; Prescott & Conger, 1995). We thus take a stand that there is an inherent and mutual relationship between the technical and the social aspects of organizational innovation. As such, research exploring the impact of material features of digital technologies on innovation adoption is a necessary component of the collective research effort (Orlikowski, 2007; Orlikowski & Scott, 2008).

The remainder of the paper is organized as follows. We first lay our theoretical foundations by defining types of IT innovation, radical innovation and disruptive IT innovation. We then define strong order effects and develop an extended DITIM with three sets of hypotheses about strong order effects regarding (1) the amount of innovation; (2) the radicalness of innovation; and (3) the order of innovations. Next, we report on the research design, methodology and findings from a cross-sectional study of the adoption of internet computing to test our hypotheses. We conclude with a discussion of the implications of our findings, noting the limitations and implications for future research in software management.

THEORETICAL FOUNDATIONS

IT innovation

An IT innovation is an 'innovation in the organizational application of digital computer and communication technologies' (Swanson, 1994). IT innovation results from the exponential growth in computing speed, data transmission, and storage and display capability (Messerschmitt & Szyperski, 2003). IT innovation expands IT support of existing organizational tasks and generates new tasks or business processes. Following Lyytinen & Rose (2003a,b) we suggest two ways of categorizing IT innovations: (1) by content – what one is innovating with; and (2) by nature – how the innovator perceives the innovation in terms of its radicalness (i.e. its originality and uniqueness).

Content: three types of IT innovation

By content, we distinguish between three types of IT innovation that are critical for software firms (Swanson, 1994; Lyytinen & Rose, 2003a). The first innovation type is IT *base* innovation (Type 0 in Lyytinen & Rose, 2003a,b). Base innovations are changes in IT platforms (i.e.

technical core of software firms used to develop applications and to support their development). Platforms are defined as general purpose core technologies that enable different families of IS services or development processes (Fichman, 2004b). Platform innovations are founded on new scientific or engineering principles in delivering or developing IS services, which are distinct from those found in other platforms (Sood & Tellis, 2005; Evans *et al.*, 2006). Platforms include, among others, computing platforms (e.g. Wintel, Microsoft Corp, Redmond, Washington, USA; Intel, Santa Clara, CA, USA), infrastructure platforms (e.g. internet computing) or enterprise application platforms (e.g. J2EE, Sun Microsystems Inc, Santa Clara, CA, USA).

The second innovation type involves changes in processes that deliver software denoted as *development processes* (Type I in Lyytinen & Rose, 2003a,b). It covers changes in development tools, methods, teams and their structure. Process innovations cover both technological and administrative process innovations.

The third innovation type encompasses delivering new computing capabilities (i.e. technical and business solutions to clients and users). We refer to them herein as *IS services* (Type II in Lyytinen & Rose, 2003a,b). Here software organizations innovate around new types or more effective uses of IT as to support their clients' technical or administrative cores (e.g. business processes). We recognize that while Lyytinen & Rose call Type II innovations services, Swanson calls them applications. In our view, the term *service* reflects better the new practices of offering application functionality as a 'service' such as through service-oriented architecture (Mathiassen & Sørensen, 2008).

Nature: radical IT innovation

Innovations run on a continuum from incremental to radical. We define radical IT innovation as an innovation with two characteristics. First, it is *unique* in that it departs from other existing alternatives at the time of invention (Zaltman *et al.*, 1973). Consequently, radical IT innovations erect heightened learning barriers (Attewell, 1992). Second, it is *original* in that its use is frame-breaking at the time of adoption (Bijker, 1994; Dahlin & Behrens, 2005). Radical innovations incorporate *different* architectural principles (Henderson & Clark, 1990; Christensen & Bower, 1996; Utterback, 1996) and destroy existing competencies (Dosi, 1982). As a result, radical IT innovations are risky (Dewar & Dutton, 1986), fragile and unclear (Attewell, 1992), and require provisioning of complementary assets (Teece *et al.*, 1997).

DITIM (Disruptive Information Technology Innovation Model)

Multiple streams in innovation research suggest that innovations often interact. Innovators move in 'packs' (Van de Ven, 2005), are influenced by network effects (West & Dedrick, 2000; Markus & Gelinas, 2006; Zhu *et al.*, 2006) or follow fashions (Newell *et al.*, 2000). These prior studies focus on how social structures and interactions create dependencies between innovations but do not heed to the material aspects of the innovations as a potential source of such dependencies (Orlikowski & Scott, 2008). Yet growing material heterogeneity and new IT capabilities can also act as an effective cause in generating interactions among classes of IT innovations (Swanson, 1994). For example, recent studies on innovation in digital music and wireless technologies reveal mutually reinforcing relationships among IT innovations. In these studies, innovations with unique material features serve specific and new roles in the IT ecology. They provide unforeseen opportunities for the advancement of other technology components (Adomavicius *et al.*, 2007; 2008a,b). Thus, some radical IT innovations can grow disruptive, i.e. their effects are *transformative* and path-breaking in that they start to strongly influence the future IT innovation direction (Henderson & Clark, 1990; Utterback, 1996). Hence, because of their unique and original material properties, occasionally some radical base IT innovations generate transformative effects. When such effects cover all three IT innovation types (Types 0, I and II), Lyytinen & Rose (2003a,b) called the innovation ensemble 'disruptive'. Their DITIM combines the notion of an IT innovation type and its level of radicalness into a specific state of an IT innovation ecology. In this ecology:

1 Three types of IT innovation create an ensemble where innovations move in 'packs'.
2 IT innovation across types is pervasive in that packs of service and process innovations overlap with the adoption of base innovations.
3 Each IT innovation in the ensemble is radical (Lyytinen & Rose, 2003b).

If, and only if, the whole IT innovation ecology embraces both dimensions (pervasiveness and radicalness) is it deemed to be disruptive. Table 1 illustrates how internet computing can be conceived as a disruptive IT innovation.

This formulation of the DITIM views all radical IT innovations across all types to take place roughly at the same time. The model does not explain why and how radical base innovations influence other IT innovations or their radicalness. In addition, no order between innovations in the pack is assumed. A clear rationale is lacking. Specifically, why do radical base innovations instigate other radical IT innovations and create a 'cascade'-like pack form? Likewise, what is the temporal organization of these innovation cascades?

The extended DITIM

To answer the two questions posed above, we adopt Swanson's (1994) notion of strong order effects – the idea that some innovations have second order effects. Drawing upon this concept, we formulate three sets of hypotheses about the order effects' causes, content and temporal organization.

The concept of a strong order effect

For some time, base innovation has been recognized as a critical antecedent for subsequent IT innovation (Somogyi & Galliers, 1987; Tsichritzis, 1997). Similarly, Swanson (1994) posited that IT innovations interact; service or process innovations often 'spawn' other innovations due to the presence of *second order effects*. Thus, he surmised that IT innovations are often mutually dependent, interact and erect an ecology.

Table 1. Internet computing as a disruptive IT innovation

Features of disruptive IT innovation	Internet example
Base innovations are unique and original.	The invention of http protocol (Berners-Lee & Fischetti, 1999) and development of a browser formed the key elements of the radical base innovation. They added new capabilities to transfer and display information, but at the same time reconfigured computing platforms by changing ways in which components could be connected. This changed the way how the platform distributed data, control and computation across resources, and how they were made accessible and integrated. These new features changed design trade-offs through: 1) open and universal access to any computing resource through URL identifiers; 2) a universal browser which changed how control flow and data display was implemented at the user-interface, 3) how an IS service could be configured in terms of speed, richness, and ease of configuration; and 4) how applications could be connected through hyper-linking. Example: Innovations in browsers, hyperlinking and open access which were unique and original (Berners-Lee & Fischetti, 1999).
IS Service innovations are unique and original.	The new principles organized internet-based IS services into loosely coupled systems and offered design rules with a n-tier architecture to build services (Lyytinen & Rose, 2003a). Browsers shaped the user's experience and added design trade-offs (Berners-Lee & Fischetti, 1999) in that applications were approached to be media rich with interactivity and rich representation (Lyytinen & Rose, 2003b). Open access offered new ways to organize and run service through application service provisioning (ASP) like salesforce.com, and offering service integration through service-oriented architectures. Example: Service innovations like portals or e-business web sites and models like portals (Yahoo), e-commerce (Amazon), auctions (E-Bay), ASP (salesforce.com).
Process innovations are unique and original.	Challenging deeply-seated beliefs, new design frames (Bijker, 1994) allowed designers to view their design space from a fresh perspective, enabling them to see original design possibilities. These new opportunities often called for new processes, modelling approaches and tools to build applications, leading to process changes coined in the terms like internet speed and rapid innovation (Pries-Heje *et al.*, 2004). Example: New process forms and speeds (Lyytinen & Rose, 2003b) internet-based development (Pries-Heje *et al.*, 2004).
Base innovations are transformative with respect to services and processes. New services 'compel' new processes.	Base innovations generated ways to radically innovate with services and processes (Lyytinen & Rose, 2003a) in that internet computing generated other radical service and process innovations, and became transformative. Radical new services required organizations to rethink their development process in radical ways. Example: New platforms enabled new IS services which in turn demanded new ways of developing systems through rapid prototypes, marketing-based user needs and new collaboration forms (Kellogg *et al.*, 2006; Lyytinen *et al.*, 2009).

Accordingly, order effects are neither *random* nor *accidental*. Order effects instead are both path creating and dependent, and are influenced by the material features of their 'antecedents'. In such an ecology, when IT innovations provide 'seed(s) for innovation's subsequent origination in a compelling way', Swanson (1994, p. 1077) calls them *strong order effects*. According to Swanson (1994), such strong order effects largely emerge beacause of the new material

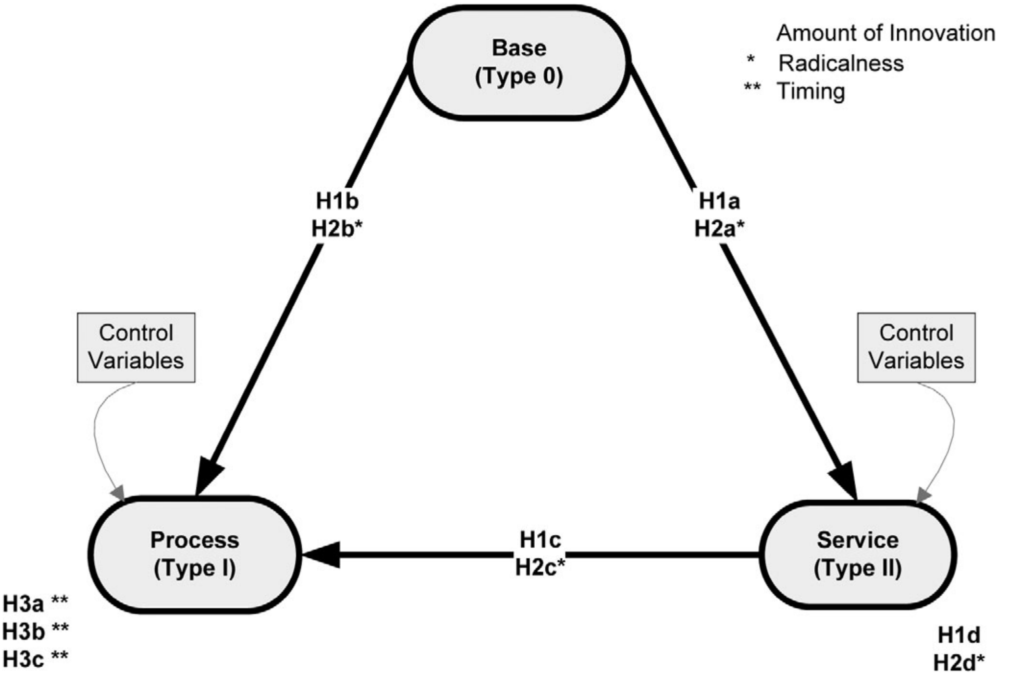

Figure 1. Three IT innovation types and strong order effects (with controls).

and increasingly heterogeneous features of the IS services. Strong order effects are thus akin to the idea of transformative effects of radical IT innovation. Because of the new material features offered by the platform (base innovation), we also argue (based on Lyytinen & Rose, 2003b) that platform innovations can instigate a cascading sequence of service and process innovations. This sequence occurs when the new material features of the platform become compelling 'seeds' for subsequent innovation.

Figure 1 illustrates three types of strong order effects that are present in the context of the DITIM. When produced jointly, it is called a disruptive IT innovation cycle. In particular, we examine how order effects are reflected in the changes in the amount of innovation, the radicalness of innovation and the temporal order of innovations in the ensemble, and why base and service innovations can become 'compelling causes' in such ensembles.

Strong order effects – the amount of innovation

In the IS field, researchers have traditionally attributed causes of IT transformation to individual, social or structural factors such as environmental uncertainty, decision-making decentralization (Grover & Goslar, 1993), IS function power (Grover *et al.*, 2007), knowledge diversity or organizational size (Fichman & Kemerer, 1997). In contrast, a significant body of research on technology innovation has emphasized transformative impacts of material features of platform innovations (Abernathy & Clark, 1985; Anderson & Tushman, 1990; Henderson & Clark, 1990; Utterback, 1994; Christensen & Bower, 1996). In fact, a significant bulk of the recent research around technology systems underscores the criticality of the materiality of technology and its path dependencies and discontinuities in affecting future innovation. These scholars claim that the new material features and their combinations significantly impact the innovations that follow (Funk, 2006). Most of these studies, however, have focused on mass production technologies including automobiles (Abernathy & Clark, 1985) and computers (Abernathy & Clark, 1985; Christensen, 1997; Sood & Tellis, 2005). The presence of such impacts among intangible technologies like software has remained scantily researched, and researchers have mainly investigated the impact of software architectures on the evolution of products categories like MP3 players or mobile phones (Evans *et al.*, 2006; Adomavicius *et al.*, 2008a,b). We know of no research that has looked at similar impacts of platform change in the context of software development.

For software firms, a computing platform (also known as set of base innovations) forms a key element of their technological core, which they deploy in delivering IS services. The platform can be conceived of as a layered and nested component/service hierarchy (Adomavicius *et al.*, 2007; 2008a,b). This hierarchy combines heterogeneous complements like alternative computational capabilities with component features (e.g. speed, cost, size, reliability, power demands, scalability) and associated design capabilities (configuration ease and cost, flexibility, portability, scalability) (Messerschmitt & Szyperski, 2003). Any of these components can be further decomposed into lower level options. Each such option offers an alternative to build up a higher level component or a service with a different trade-off like cost or speed. These sub-options, again, can be decomposed, generating a tree of design choices called a product/service hierarchy (Funk, 2006).

When critical components and/or their relationships in the hierarchy change significantly, this generates upward and sideways cascades of innovation for both how to configure base capabilities and how to deliver services. It can be visualized as a kind of domino effect (a wake of change) in the hierarchy that adds new components and relationships and/or expands the scope of the product tree (Funk, 2006; Adomavicius *et al.*, 2007; 2008a,b). From an IS designer's viewpoint, the changes generate alternative *design spaces*, which involve fundamentally different design trade-offs for delivering IS services (Henderson & Clark, 1990). This can significantly redirect the design activity that follows. Redirection can occur not only in other parts of the computing platform but also in IS services that rely on those capabilities, if and when designers seize those new opportunities.

Consider, for example, the following. If the computing speed/cost ratio goes up 10 times or if the cost of configuring a similar IS service decreases by 80%, then designers surely will reconsider how their design spaces are being re-formed and what new design decisions they can now imagine. Such a growing cascade of trade-offs created by upward and sideways innovation movements in the base – when cleverly utilized and adopted by IS designers – will thus yield second order effects on IS services. It will also change design processes, because received software methodologies and processes and practices become incompatible with radically new services and computing platforms (Lyytinen & Rose, 2003a,b). This urges radical

Table 2. Strong order effect hypotheses: the amount of IT innovation

H1a.	The amount of base innovations positively affects the amount of service innovations.
H1b.	The amount of base innovations positively affects the amount of process innovations.
H1c.	The amount of service innovations positively affects the amount of process innovations.
H1d.	The amount of service innovations partially mediates the impact of the amount of base innovations on the amount of process innovations.

new processes to be invented, thus continuing the movement upwards in the innovation 'hierarchy'.

Ostensibly, the more software developers adopt radical base innovations, the more new design trade-offs they will opt for. It follows that developers are also more likely to generate an increasing amount of radical service and process innovations, thereby creating the 'pack form'. We posit that the amount of service and process innovation will be positively influenced by a cumulative increase in the amount of radical base innovations **(H1a** and **H1b)** (Funk, 2006; Adomavicius *et al.*, 2007). For example, the adoption of an multi-tier (n-tier) architecture and universal browser will increase the amount of new services a software firm builds and what types of process methods it uses. If it also adds multimedia features into the platforms, this will change more services and also introduce more process changes. These strong order effects will also set the stage for accelerated process innovations (e.g. the cumulative increased amount of service innovations will positively affect the amount of process innovation) (Lambe & Spekman, 1997) **(H1c)**. These influences are direct in that the amount of base innovation directly influences the amount of service and process innovation, and the amount of service innovations directly influences the amount of process innovation.

Finally, our analysis (Figure 1) suggests that the amount of service innovations can partially mediate the impact of the amount of base innovations on the amount of process innovations **(H1d)**. Adopting units often can see the implications of new base technologies immediately and turn them into direct changes in their processes. But many times they have to apply new base innovations to generate services before they can see how their development processes are being impacted. As an early study of internet computing, Lyytinen & Rose (2003b) observed software organizations often did not notice that their traditional processes no longer worked until they had started to build new internet-based services. Firms had to experiment with novel services that triggered a swift and pervasive process change. The amount of service innovation therefore serves as a *mediator* that transmits the (positive) effect of the base innovation on process innovation (Mathieu & Taylor, 2006). The hypotheses in Table 2 test for the transformative effects of radical, base-innovation adoption on the amount of radical process and service innovation during the disruptive innovation cycle.

Strong order effects: the radicalness of innovation

Service and process innovations become increasingly ambiguous, risky and contested as innovations propagate in design hierarchies and rescope design spaces (Henderson & Clark, 1990; Bijker, 1994; Funk, 2006; Adomavicius *et al.*, 2007). Therefore, designers will perceive

Table 3. Strong order effect hypotheses: radicalness of IT innovation

H2a.	The radicalness of base innovations positively affects the radicalness of service innovations.
H2b.	The radicalness of base innovations positively affects the radicalness of process innovations.
H2c.	The radicalness of service innovations positively affects the radicalness of process innovations.
H2d.	The radicalness of service innovations partially mediates the impact of the radicalness of base innovations on the radicalness of process innovations.

new service and process innovations as increasingly original (see e.g. Ihlsoon & Young-Gul, 2001). The services will also become more unique as designers can now imagine services and processes that depart significantly from contemporary ones (Lyytinen & Rose, 2003a; Pries-Heje *et al.*, 2004). These new possibilities lead to the generation of services that could not have been imagined earlier (Bijker, 1994).

As shown in Figure 1, we propose that during the disruptive innovation cycle that base-innovation radicalness forms an antecedent for service-innovation and process-innovation radicalness. In particular, the increased level of radicalness of the base will positively influence the radicalness of service and process innovation (**H2a** and **H2b**) (Henderson & Clark, 1990; Bijker, 1994; Funk, 2006; Adomavicius *et al.*, 2007) (see Table 3). For example, a software firm that finds its new internet platform to be radical will also likely perceive subsequent service innovations and process innovations to be radical. Likewise, the increased radicalness of service innovation will positively impact the radicalness of process innovation: new radical services lead to the development of significantly original software services (Lambe & Spekman, 1997) (**H2c**). Finally, we include a mediation hypothesis (**H2d**) for the same reasons as we included H1d. Changes in the radicalness of service innovation may be required before developers can see how changes to the base radicalness impact the radicalness of the process innovations. The hypotheses in Table 3 test for the transformative effects of radical base-innovation adoption on the level of radicalness in process and service innovation during the disruptive innovation cycle.

Temporal organization of strong order effects

A temporal organization has been postulated among innovations in recent analyses of IT innovation (Funk, 2006; Adomavicius *et al.*, 2007). This temporal organization is seen to ‘follow’ from the material features of the technology (i.e. in which parts of the ecology the new innovations are entered, what their properties are and how they subsequently influence future innovation). Lambe & Spekman (1997) also noted that after architectural innovation, radical service innovations dominate until designers agree on the ‘stability of product parameters’ (Clark, 1985). Continued experimentation with services is needed to shake out viable services before the locus of innovation can shift to processes. At that point in a disruption cycle, new imperatives will drive down cost and improve quality. Accordingly, we posit that base innovations become a compelling ‘cause’ for subsequent radical service innovation, while service and base innovation together become a subsequent compelling cause for process innovation (Figure 1).

Table 4. Strong order effect: temporal organization between IT innovation types

H3a.	In most cases, the adoption of initial base innovations comes before or simultaneously with the first service innovations.
H3b.	In most cases, the adoption of initial base innovations comes before or simultaneously with the first process innovations.
H3c.	In most cases, the adoption of initial service innovations comes before or simultaneously with the first process innovations.

During a disruptive IT innovation cycle, in most cases, radical base-innovation adoption starts before service innovation; i.e. software developers can carve out the implications of radical changes in base for IS services *only* after adopting some base innovations. One reason for the delay is that the heightened level of base and service innovation radicalness will introduce adoption lags: it will take time for designers to learn new ideas, unlearn old ideas and invent routines that effectively deploy radical base or service innovations (Evan, 1966; Damanpour & Evan, 1984). We posit therefore that during a disruptive IT innovation cycle, most software firms will adopt radical base innovations first, followed by the initiation of radical service innovation, which will precede the initiation of radical process innovation. We hypothesize that, primarily, base innovation adoption will come earlier than, or simultaneously with, service innovation adoption (**H3a**) and process innovation adoption (**H3b**), while process innovation adoption will most commonly start simultaneously or after service innovations (**H3c**) (Table 4). The hypotheses in Table 4 test for the primary temporal order of IT innovation during the disruptive innovation cycle (Base→Service, Base→Process, Service→Process).

Note two key characteristics in these three hypotheses. First, we hypothesize the possibility of simultaneity. This recognizes an inherent challenge in empirically measuring the precise timing of adoption – especially with the granular level necessary to delineate between a short sequence of adopting vs. assimilation. It also recognizes that some innovations could indeed be simultaneous yet still support the rationale for the proposed hypotheses. Second, our hypotheses and rationale for them are only intended to explain the majority-sequence pattern. The hypotheses are not expected to explain strict causation or predict the sequences for all innovation adoption. This allowance for exceptions to the majority pattern is consistent with the findings of prior research. Notably, Clark (1985) and Lambe & Spekman (1997) both recognize that a minority of exceptions to the majority-sequence pattern do occur within a cycle.

RESEARCH METHODOLOGY

To validate our hypotheses, we carried out a survey in late 2005–early 2006 among software firms that had adopted *internet computing* – a radical innovation par excellence (Lyytinen & Rose, 2003a,b; Carlo *et al.*, 2005) (cf. Table 1). While internet computing is by no means the only radical IT innovation (see e.g. Lambe & Spekman, 1997), it has the advantage of being both analytically and empirically identifiable (Lyytinen & Rose, 2003a). It was also a recent enough phenomenon at the time of the data collection and reduced the threat of hindsight and recall biases. Indeed, professionals participating in instrument validation confirmed that internet computing was sufficiently recent for them to easily provide the data being collected.

Construct development

Dependent and independent variables

Amount of innovation. We measured the amount of innovation by the number of distinct innovations adopted for each IT innovation type within an organization during the period of the study (1995–2005). This single absolute-scale measure in each type tapped into the number of internet-related innovations a software firm had adopted in base innovations, process innovations and service innovations (Lyytinen & Rose, 2003b). Although there are specific validity threats to using this measure, including granularity (i.e. what counts as a separate innovation) and response interpretation (i.e. what does each innovation mean since the terminology is not fixed), our pilot study with experienced software developers (see Appendix A) suggested that this measure was the best available measure. Two additional reasons motivated this choice: (1) other studies have used similar measures (Zmud, 1982; Grover & Goslar, 1993; Rogers, 1995); and (2) aggregated measures are more robust and generalizable and thus promote stronger predictive validity and reduce Type II errors (Fichman, 2001).

Level of radicalness. We measured the level of perceived radicalness for each of the three types of IT innovation. Overall, the measure reflects the combined, cumulative effect of all adopted items within each innovation type. The measure taps into both the cumulative perception of uniqueness and originality of all IT innovations in a given type. We customized Gatignon *et al.*'s (2002) five-item instrument of perceived radicalness to measure this construct.

Control variables

We controlled for the influence of: (a) organizational size; (b) the extent of adoption; and (c) timing of adoption. ***Organizational size*** can either positively or negatively influence radical innovation (Damanpour, 1992). Large organizations are better positioned to innovate radically because they have more diversified knowledge and slack (Grover *et al.*, 1997). They can also better buffer against financial risks and amortize learning costs (Fichman & Kemerer, 1997). At the same time, larger organizations perceive radical innovations to be more radical (Christensen, 1997) because such firms suffer from increased formalization, complexity and structural inertia (Damanpour, 1992; Grover *et al.*, 2007). Without taking sides on the direction of the impact of the organization size, we treated the size as an important control affecting the amount and radicalness of innovations. Following prior research (Blau & McKinley, 1979; Grover *et al.*, 1997; Ettlie, 1998; Zhu *et al.*, 2006), we measured organizational size by the number of employees (log transformed).

Based on Zhu *et al.* (2006), we define ***the extent of adoption*** as the percentage of development projects in a software firm that use new radical IT innovation types (i.e. the level of infusion of the new innovations in the projects that organizations delivered to their clients). The construct captures the potential impact of the increased scope of assimilating radical innovations across the organization. We suspect that higher levels of assimilation will promote faster learning and lower the adoption threshold for similar technologies. Likewise, an increased extent of adoption should influence the organization's absorptive capacity (Cohen & Levinthal, 1990) by expanding its knowledge base. Finally, it is more likely that the organization will find a fit between its existing knowledge and any novel knowledge embedded in radical innovations it adopts. Therefore, an increased extent of adoption will decrease the level of radicalness of innovations. The three-scale construct captured for each IT innovation type the percentage (<10%; 10–50%; >50%) of all the organization's projects that used the adopted innovation (Fichman & Kemerer, 1997; Zhu *et al.*, 2006).

Timing of adoption was critical in measuring the adoption lags and order. Following Lambe & Spekman (1997) and Damanpour (1991), we expected that the timing of innovation adoption would affect both the radicalness of the innovation and its adoption rate. Early innovation stages involve increased turbulence (Tushman & Anderson, 1986; Anderson & Tushman, 1990; Henderson & Clark, 1990; Sood & Tellis, 2005). Therefore, early adopters are likely to perceive innovations to be more radical than late adopters. Likewise, later adopters are more likely to adopt more innovations because of the presence of vicarious learning, maturing of the technology and the increased availability of 'standardized' innovations. Because we introduce the timing of adoption as a control variable, we did not explicitly assume a specific direction of the impact. The timing of adoption is captured for each of the three innovation types by a single measure: the first year of adoption of any innovation within each type.

Data collection

All participating software firms developed either tailored software or software products for external clients. Such firms were deemed most appropriate for our study for several reasons. First, they have extensive knowledge of all three types of IT innovations: they have to adopt base innovations from the outside; imitate process innovations from their competitors; or internally generate process innovations through trial and learning in order to create novel IS services for their clients. Second, they are more likely to adopt new and radical technologies because they are able to distribute learning costs more evenly than most other types of firms (Fichman & Kemerer, 1997). Third, they need to continuously innovate in base technologies, in services and in processes to remain competitive. Therefore, these firms have a greater propensity to initiate and assimilate radical IT innovations (Fichman & Kemerer, 1997).

With the help from two software associations, BETA and SIGMA, we conducted a survey in their member firms. BETA and SIGMA are membership-based trade organizations of more than 1400 companies representing a broad spectrum of information technology. To improve the response rate, both organizations granted us the use of their logos and helped in sending out soliciting emails. A summary of the findings and a research seminar sponsored by the researchers' university and BETA/SIGMA were offered to participants as incentives. We selected 710 relevant companies. To be included, a firm had to develop software or provide associated development services. For example, a company that developed information-focused web sites was deemed relevant, whereas companies that specialized in hardware design, graphics design or designing embedded software were not included.

We mailed two rounds of paper-based survey to people with such titles as Chief Executive Officer (CEO), Chief Information Officer (CIO), Chief Technology Officer (CTO), president, chairman, owner, principal, or Vice President (VP) of research and development. Based on feedback in our pilot studies, it was determined that these respondents were best qualified to speak about their firm's experience with internet computing. People in these positions were in charge of their firms' technology development and technology strategy. They also were responsible for decisions about technology adoption and market selection. As the vast majority of respondent firms were entrepreneurial companies with fewer than 40 employees, the respondents were very knowledgeable about their technology choices, and, as revealed in follow-up interviews, they could easily find information about or recall when major innovations in internet computing took place. Respondents in these positions were also deemed well qualified and well positioned within the firm to evaluate the relative radicalness of each innovation on their firm. Participants in our pilot study indicated they were quite capable of making these evaluations.

After three follow-up rounds, we received 139 replies out of the 710 relevant companies. The final response rate of 20% is reasonable, especially given that our survey was voluntary and involved top management (Stimpert, 1992). Of the replying companies, only 11 had more than 100 employees with a wide range of size from 132 to 75 000 employees. These 11 firms were omitted as outliers to avoid potential confounders. As a result, our study only focused on small entrepreneurial software firms. Eventually, we ended up with 121 valid responses. Most of the companies in the sample developed customized software for their clients. The remaining firms developed specialized products for vertical markets. Table 5 summarized the sample characteristics.

We also checked for response accuracy, respondent bias and method bias. Appendix B provides the details regarding these procedures.

Measurement validation

To establish the construct validity of the latent variable in our model – innovation radicalness – we conducted Exploratory Factor Analysis (EFA) in SPSS (SPSS Inc., Chicago, IL, USA) and then Confirmatory Factor Analysis (CFA) using structural equation modeling [Partial Least Squares (PLS)]. The analysis led us to drop two items from base-innovation radicalness (b_rad4 and b_rad5), two items from process innovation radicalness (p_rad2, p_rad3) and one item from service innovation radicalness (s_rad5) (see Appendix A for the details of the dropped items). Differences in the items were expected: the definition of IT innovation types implies that these innovations are different and have different characteristics. These analyses yielded three-item measures for both process and base-innovation radicalness, and a

Table 5. Sample characteristics (n = 121)

	Observations	%
No. of employees		
1–20	95	78.5%
20–40	15	12.4%
40–60	8	6.6%
60–80	2	1.7%
80–100	1	0.8%
Total	**121**	
Respondent title		
President, CEO, partner, principle, owner, managing director, executive VP	86	71.1%
CIO/CTO/VP of IS, VP of product development	9	7.4%
IS manager, technology manager, software development manager, director	7	5.8%
Other managers in IS department	2	1.7%
Business operations manager, COO	3	2.5%
Other VP (marketing, finance, etc.), CFO	7	5.8%
Others	7	5.8%

COO, Chief Operating Officer; CFO, Chief Financial Officer.

Table 6. Measurement model: factor loadings, reliability and convergent validity

Construct (reliability)	Indicator	Indicator descriptions	Loadings*	Convergent validity (t-stat)
Base radicalness (0.90)	b_rad1	These technologies were major improvements over previous technologies.	0.81	17.08
	b_rad2	These technologies were based on revolutionary changes in technology.	0.88	27.58
	b_rad3	These technologies were breakthrough innovations.	0.92	56.85
Process radicalness (0.89)	p_rad1	These techniques/methods/approaches were major improvements over previous development practices.	0.83	14.70
	p_rad4	These techniques/methods/approaches have led to development outcomes that were difficult to replace or substitute using older methods/ techniques/approaches.	0.88	35.19
	p_rad5	These techniques/methods/approaches represented major methodological advance(s) within the local contexts in which they were applied.	0.85	16.17
Service radicalness (0.92)	s_rad1	These applications were major improvements over previous technologies.	0.84	19.79
	s_rad2	These applications were based on revolutionary changes in technology.	0.90	37.28
	s_rad3	These applications were breakthrough innovations.	0.89	40.48
	s_rad4	These applications have led to products that were difficult to replace or substitute using older technologies.	0.81	16.94

*All standardized loadings are significant at $P \leq 0.01$. Insignificant items are dropped.

Table 7. Correlations among latent variables (diagonal SQRT of AVE)

	Base radicalness	Process radicalness	Service radicalness
Base radicalness	**0.87**		
Process radicalness	0.24	**0.85**	
Service radicalness	0.63	0.32	**0.86**

SQRT, square root of.

four-item measure for the service innovation radicalness. These were deemed semantically acceptable and had good statistical properties. As shown in Table 6, all constructs have an acceptable *composite reliability* over the cut-off of 0.70 (Straub, 1989).

The items also have good internal consistency and can be conceived of as good indicators for their common latent construct. The significant estimated standard loadings ($P < 0.01$) also suggest good *convergent validity*. As shown in Table 7, these items exhibit good *discriminant validity*. The square root of the average variance extracted (AVE) for each construct is highest for its assigned construct (Fornell & Larcker, 1981). Therefore, the items share more common variance with their assigned constructs than with other constructs.

Hypothesis testing

To test for the presence of transformative order effects (**H1a–H2d**), two separate structural models were run using PLS-Graph (version 3.00, Soft Modeling Inc., Houston, Texas, USA). The first model tests for the amount of innovations. The second model tests for the level of radicalness. To detect the mediation effects in the paths (Base→Service→Process) (**H1d, H2d**), we applied Baron & Kenny's (1986) test. The sample size met the suggested guidelines for running both PLS tests (Chin, 1998b; Zhu & Kraemer, 2005). Descriptive statistics and chi-square tests were applied to analyse the presence of sequential or simultaneous innovation (**H3a–H3c**). The significance level was set at $\alpha = 0.05$ for these tests. A post hoc analysis indicates that the power of analysis with the smallest sample was 0.87 for detecting medium effect size (close fit) at the significance level of 0.05 (MacCallum *et al.*, 1996). This exceeds the accepted level of $\beta = 0.8$ for statistical power.

The model was built by first introducing the control variables associated with each dependent variables: organizational size; extent of base adoption; time of base adoption (for both service and process innovation); extent of service adoption; and time of service innovation (for process innovation only). Then the main independent variables were added for each dependent variable in the model. A bootstrapping of 500 samples with the construct level change was conducted to estimate standard errors, t-statistics and AVE. Because the final data set was pooled from two subsamples, we also ran our models using separate samples:

one with only BETA, and another with both BETA and SIGMA. No significant differences were found between the two subsamples. Accordingly, analyses from the pooled data are reported below.

FINDINGS

Descriptive analysis: internet innovations run in packs and are radical

Initial tests were conducted to confirm the original DITIM (Lyytinen & Rose, 2003b) with quantitative data. Indeed, internet computing innovations were found to be adopted pervasively and to be deemed radical across each innovation type for the clear majority of firms. Pervasiveness was seen in that adoption of more than one type of innovation occurred in 95% of firms that adopted any internet innovations. More importantly, 79% of firms adopted innovations in all three sets (Table 8). A statistically significant chi-square result ($\chi^2 = 506.24$, $P = 0.00$) (7, $n = 121$) rejects the null hypothesis that each group membership was equally likely. The largest absolute value of the residuals (80.88) was associated with the group innovating with all three sets, indicating that adopting all sets simultaneously was the most prominent and organizations adopted all three sets far more often than they adopted any type of IT innovation at random. Organizations adopted on average 5.28 out of 10 base innovations (53%) and 4.53 out of 10 process innovations (45%) and generated 5.89 out of 14 service innovations (42%).

Finally, we analysed average ratings of the radicalness for each innovation type. The means ranged from 3.45 to 4.04 on the 1–5 scale, where 5 indicates a strong agreement with a statement like 'these technologies were breakthrough innovations'. Thus, the firms fairly strongly agreed that each innovation type was radical. Collectively, these results triangulate the original DITIM (Lyytinen & Rose, 2003b): adoption of internet computing was radical and pervasive and therefore internet computing was a disruptive innovation.

Strong order effects – the amount of innovation

We found significant **support** for **H1a, H1b, H1c** and **H1d** (Figure 2). The amounts of base innovations are positively correlated with and significantly predict the amount of service

Table 8. Frequencies of IT innovation adoption

Innovation types	Observed *n*	%	cumulative %	Expected *n*	Residual
None	1	0.83	0.83	15.13	–14.13
Base only	2	1.65	2.48	15.13	–13.13
Process only	2	1.65	4.13	15.13	–13.13
Service only	1	0.83	4.96	15.13	–14.13
Base, process	16	13.22	18.18	15.13	0.88
Process, service	1	0.83	19.01	15.13	–14.13
Base, service	2	1.65	20.66	15.13	–13.13
Base, process, service	96	79.34	100	15.13	80.88

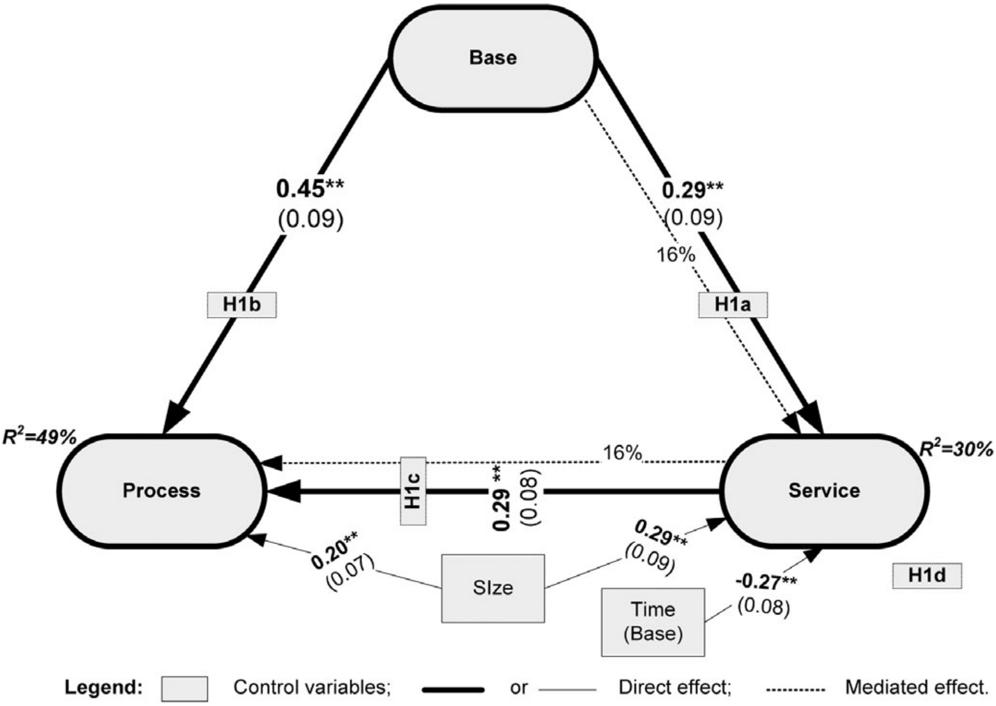

Figure 2. *$P < 0.05$; **$P < 0.01$. Strong order effects: amount of innovation. Standardized estimates (standard error). Only significant control variables are shown. Hypothesis: bold font, supported; regular font, not supported.

innovations ($\beta = 0.29$, $P < 0.01$) (**H1a**). Base-innovation amounts also positively and significantly predict the amount of process innovation ($\beta = 0.45$, $P < 0.01$) (**H1b**). We also found support for the strong order effect from services to processes (**H1c**): the amount of service innovation positively correlates with the amount of process innovation ($\beta = 0.29$, $P < 0.01$). As hypothesized, for **H1d**, we found a significant partial mediation effect: the amount of base innovations directly impacts the amount of process innovations (C = 0.54, $P < 0.01$). However, the influence decreased but still remained significant (c′ = 0.45, $P < 0.01$) after the amount of service innovation entered the model. Overall, 16% of the total effect of the amount of base innovation upon the amount of process innovations is mediated through services.

As expected, some of the control variables were also significant. Larger organizational size increases a software firm's propensity to radically innovate with novel services ($\beta = 0.29$, $P < 0.01$) and development processes ($\beta = 0.20$, $P < 0.01$). Meanwhile, the earlier a software firm adopts radical base innovations, the less likely it will innovate with radical service innovations ($\beta = -0.27$, $P < 0.01$).

The overall model demonstrates good predictive values for our hypotheses. It explains 30% of the total variance in the amount of service innovations and 49% of the amount of process innovation. This pattern is also expected because the amount of both base and process innovations significantly impact, both directly and indirectly, the amount of process innovations (β = 0.45, $P < 0.01$ for base; β = 0.29, $P < 0.01$ for service), while only base innovation directly influences service innovations (β = 0.29, $P < 0.01$). In terms of the amount of innovation, base innovations influence more significantly process than service innovations.

Strong order effects: the radicalness of innovation

Tests for strong order effects on radicalness of innovation **support H2a, H2c** and **H2d** (Figure 3). Per **H2a**, the radicalness of base innovations has a direct positive effect on the radicalness of service innovations (β = 0.62, $P < 0.01$). This supports the foundation of our theoretical argument for disruptive IT innovation that the radicalness of service innovation is driven by increased originality and uniqueness of base innovations. As also hypothesized, the radicalness of service innovation positively and significantly predicts the radicalness of process innovations (β = 0.45, $P < 0.01$) (**supporting H2c**).

Surprisingly, increased radicalness of base innovations did not directly correlate with radicalness of process innovations (**Rejecting 2b**). However, Baron & Kenny's (1986) test dem-

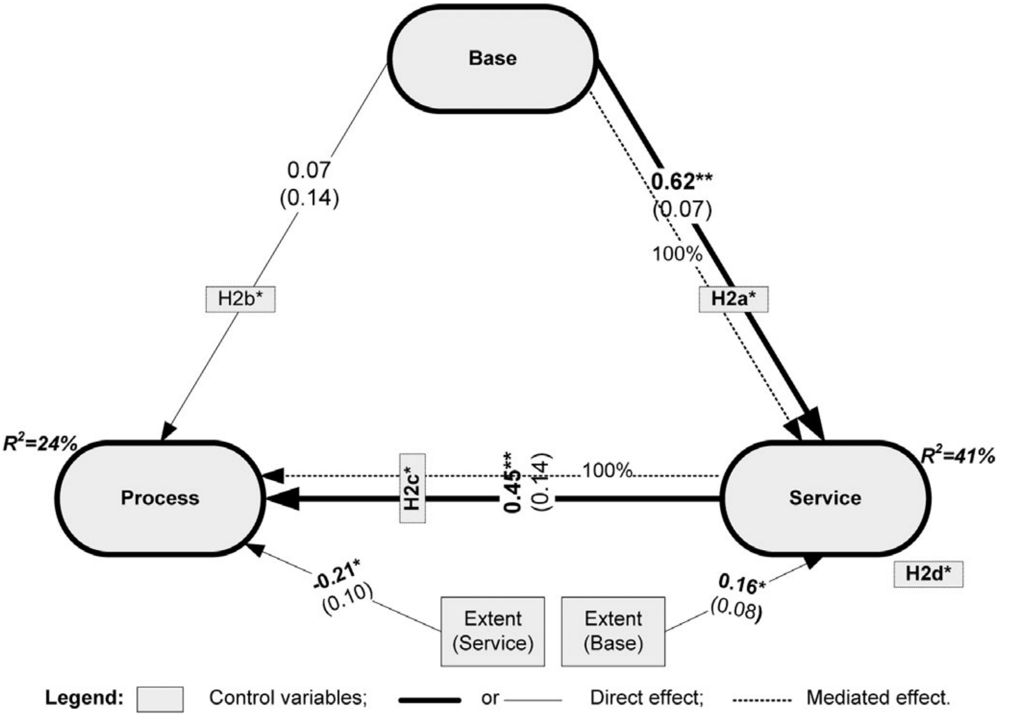

Figure 3. *$P < 0.05$; **$P < 0.01$. Strong order effects: radicalness of innovation. Standardized estimates (standard error). Only significant control variables are shown. Hypothesis: bold font, supported; regular font, not supported.

onstrates the presence of a full mediation. The radicalness of base innovations significantly impacted directly the radicalness of process innovation (C = 0.40, $P < 0.01$). This influence, however, diminished to a non-significant level when the radicalness of service innovations entered the model ($c' = 0.07$, $P > 0.1$). In other words, 100% of the effect of the radicalness of base innovation upon the radicalness of process innovations is mediated through radicalness of service innovation. This result supports **H2d** with **full mediation**.

As expected, the extent control variable was significant. Extent of base innovation positively and significantly correlated with increased radical service innovation ($\beta = 0.16$, $P < 0.05$). Meanwhile, a significant, but negative, correlation was found with the extent of adoption of services. As the extent of the adoption of services increased, processes were deemed less radical ($\beta = -0.21$, $P < 0.05$).

Overall, the model has a good predictive value. It explains 41% of the total variance in the radicalness of service innovations and 24% of the total variance in the radicalness of process innovations. This pattern is expected because radicalness of base innovations significantly drives radicalness of service innovations ($\beta = 0.62$, $P < 0.01$), while radicalness of base innovations only indirectly influences radicalness of process innovations through radicalness of service innovations. At the same time, the impact of radicalness of service innovations on radicalness of process innovations is relatively small ($\beta = 0.45$, $P < 0.01$). In terms of radicalness, service innovations are more intimately connected with base innovations than process innovations.

Temporal organization of strong order effects

To test for the temporal organization of strong order effects (**H3a, H3b** and **H3c**), timing of the adoption of the initial innovation within each IT innovation type was examined. As proposed by **H3a**, the companies generally adopted their first-base innovation at the same time or before innovating with services. Eighty five of the 97 companies (88%) that had engaged in both innovations adopted a base innovation concurrently or first. The average adoption year for base and service innovations was 1998.78 and 1999.65, respectively. A statistically significant chi-square result ($\chi^2 = 54.94$, $P = 0.00$) (1, $n = 97$) indicates that the vast majority of firms fall into the group that adopted base innovations prior to, or in the same year, as service innovations.

We also found that 97 of the 112 companies (87%) that had adopted both base and process innovations had adopted a base innovation concurrently or first (**H3b**). The average adoption year for base and process innovations was 1998.99 and 1999.95, respectively. A statistically significant chi-square result ($\chi^2 = 60.04$, $P = 0.00$) (1, $n = 112$) suggests that the vast majority of firms fall into the group that adopted a base innovation prior to, or in the same year, as the first process innovation.

Finally, **H3c** states that most companies engaged in service innovations concurrently or prior to process innovations. Sixty-eight of the 95 companies (72%) that had engaged in both innovations had innovated with a service first or in the same year. The average adoption year for service and process innovations was 1999.10 and 1999.97, respectively. A statistically significant chi-square result ($\chi^2 = 17.69$, $P = 0.00$) (1, $n = 95$) suggests that the large majority of the firms adopted a service innovation prior to or in the same year as a process innovation.

Finally, an omnibus test for **H3a, H3b** and **H3c** was run. To identify the majority temporal pattern of the adoption sequence, we created three Boolean variables for each firm that had adopted all three innovation types. These variables represented a collective test of the three order hypotheses shown in Table 4: (1) base is adopted before or at the same time as process (Base ≤ Process); (2) base is adopted before or at the same time as service (Base ≤ Service); and (3) service is adopted before or at the same time as process (Service ≤ Process). This analysis sorts out the frequency of alternative sequences of types of innovations. Based on the value of these binary triplets, we sorted the data into six disjoint groups. Overall, there are eight possible adoption order profiles, although our data included only six patterns. Forms ⟨0, 1, 1⟩ and ⟨1, 0, 0⟩ were absent from the data received. If the adoptions among all IT innovations were to occur randomly, each group would be expected to have 16 companies (17%). Instead, we found that 58 out of the 94 companies (62%) clustered into the one profile group hypothesized to be most likely (Base ≤ Process; Base ≤ Service; and Service ≤ Process). This group has the highest residual (42.33) and a significant chi-square result ($\chi^2 = 150.72$, $P = 0.00$) (5, $n = 94$). Collectively, support for **H3a, H3b** and **H3c** was demonstrated.

Alternate model tests

As Mathieu & Taylor (2006) recommend, in the presence of hypothesized mediated effects, it is advisable to run alternative models to confirm the validity of the hypothesized directions of the model. To this end, we ran alternative models where the amount and radicalness of base innovation is affected by the amount of service and process innovation (Table 9). In other words, we tested for alternative order effects, e.g. weak order effects per Swanson (1994). The comparison of R-squares indicates that the hypothesized model explains more combined variance in both of the dependent variables: 79% (our model) vs. 67% (alternative model). In short, it fits the data better than the alternative model (Chin, 1998a). The alternative model test

Table 9. Comparison with alternative models

Order effect type	Tested path	Final model β	Final model T statistics	Tested Path	Alternative model β	Alternative model T statistics
Amount of innovation	**Base→Process**	0.45*	5.00	**Process→Base**	0.57*	5.71
	Base→Service	0.29*	3.38	**Service→Base**	0.10	0.90
	Service→Process	0.29*	3.70	**Service→Process**	0.45*	5.00
	R2	49% (process), 30% (service)			36% (base), 31% (service)	
Level of radicalness	**Base→Process**	0.07	0.49	**Process→Base**	0.04	0.39
	Base→Service	0.62*	9.25	**Service→Base**	0.60*	7.59
	Service→Process	0.45*	3.24	**Service→Process**	0.44*	3.70
	R2	24% (process), 41% (service)			39% (base), 20% (service)	

*Significant at $P < 0.01$.

also yielded a non-significant path estimate for the path from service innovation to base innovation (β = 0.10, t = 0.90), suggesting that the amount of service innovation does not influence the amount of base innovation (while the reverse direction is significant). While the impact of process innovations on service innovations was significant (β = 0.45, t = 5.00), this result goes against tested temporal conditions, which need to be assumed in mediations (Mathieu & Taylor, 2006). As service innovation origination preceded process innovation origination, the amount of process innovation cannot be the main causes for this correlation. Rather, as expected, service and process innovations are highly correlated (i.e. they move in packs).

We also ran an alternative model with reversed paths for the level of radicalness (Table 9). Again, our model explains more combined variance in the dependent variables 65% (our model) vs. 59% (alternative model). The alternative model also has theoretically weak support. Temporally, it is difficult to conceive of how radical process innovations could precede radical base technologies, and should thus be rejected (Mathieu & Taylor, 2006).

DISCUSSION AND CONCLUSIONS

The IS field needs to better understand its technology ecologies. This understanding will enable software firms to craft effective strategies for the adoption and orchestration of ensembles of innovations and to understand when this is necessary. To this end, we formulated an extension of the DITIM with strong order effects. The model articulates how radical IT platform innovations influence other IT innovations in a compelling way and in a specific order that generates a disruptive IT innovation. We provide theoretical explanation for both the direction of these influences and their temporal order. Our theory is drawn from prior research on IT platforms (Funk, 2006; Adomavicius *et al.*, 2007) and radical innovation (Clark, 1985; Lambe & Spekman, 1997). The model contributes to prior research about specific classes of radical IT platform innovations by showing how disruptive IT innovation ecologies can grow (Henderson & Clark, 1990; Christensen & Bower, 1996; Utterback, 1996). To our knowledge, our study is one of the first to empirically investigate transformative interactions between *multiple types* of *ordered* and *radical* IT innovations. It augments research on platform changes among computing products (Clark, 1985; Funk, 2006; Adomavicius *et al.*, 2007) and radical software *process* innovation (Fichman & Kemerer, 1997; Sircar *et al.*, 2001). In doing so, it responds to Fichman's (2004a) invitation to investigate multiple types of IT innovations – both as independent and as dependent variables.

Our study differs from earlier innovation research of software organizations that have focused primarily on singular process innovations like CASE tools (Orlikowski, 1991), programming paradigms (Fichman & Kemerer, 1997; Ihlsoon & Young-Gul, 2001) or process improvements [Capability Maturity Model (CMM)] (Yoo *et al.*, 2006) but neglected their technological antecedents and interactions with other innovations. Our study expands this research by showing that software organizations occasionally need to come to grips with 'big' innovation challenges when their 'core technology' (i.e. their computing platform) changes. Such wakes of innovation have previously been examined in relation to market and product innovations (Henderson & Clark, 1990; Christensen & Bower, 1996; Utterback, 1996; Lambe & Spekman, 1997; Funk, 2006; Adomavicius *et al.*, 2007). However, no such studies have been conducted in software firms. Our study shows that similar wakes take place internally among software organizations when the material features of their computing platforms change.

We developed hypotheses regarding positive, direct and mediated influences between three IT innovation types in terms of: (1) their amount of innovation; (2) the levels of radicalness; and (3) the order of innovations. The presence of these hypothesized effects, although assumed in earlier studies (Somogyi & Galliers, 1987; Swanson, 1994; Tsichritzis, 1997), had not been empirically validated. Indeed, internet computing affected subsequent IT innovation because of the presence of strong order effects: the amount of base innovation positively influenced the subsequent amount of service innovation; and the amount of base innovations and service innovation together positively influenced the amount of process innovation. Results also suggest the hectic spurt of innovation during the dot-com boom was partially driven by extended material features afforded by the new computing platform. In addition, internet computing became 'frame-breaking' in that its radicalness influenced the radicalness of both subsequent service and process innovation. Internet computing brought along novel frames that fundamentally shaped sense-making around design and process spaces (Lyytinen & Rose, 2003a,b). Finally, because of the radicalness and the nature of the order effects, the innovations introduced adoption lags and were adopted primarily in the specified temporal order.

Our study emphasizes the importance of identifying and picking up platform innovations carefully and in a timely fashion, as this change shapes fundamentally the software firm's future application portfolios and development patterns. Accordingly, software firms need to approach platform innovations as being rife with strong order effects that will amplify the pivotal effect of prior base technology decisions. Therefore, managers need to consider carefully when they jump on new technology bandwagons. Second, these effects generate high levels of ambiguity in their task environment as base radicalness increases the radicalness of both services and processes. As a result, given the fast pace of disruptive innovation cycles, high-velocity decision-making is required (Pries-Heje *et al.*, 2004; Cassiman & Veugelers, 2006). Organizations need to be prepared for significant and swift changes in their development organization, management style and the necessity to learn fast and flexibly (Lyytinen *et al.*, 2009).

Second, we show that disruptive IT innovations run in 'packs'. Accordingly, the software organization's success depends largely on how smoothly it orchestrates together *different* types of IT innovations, while it balances its innovation portfolios across markets, projects and technologies (Pries-Heje *et al.*, 2004; Cassiman & Veugelers, 2006). This can only be achieved by managing innovation portfolios through options and related risks and by avoiding too high levels of systemic risk. This balancing act can be improved if the organization manages better the direction and timing of its innovations. For example, our findings suggest that organizations will engage in deeper and extensive process innovation after the initial base innovation adoption. Therefore, firms should start with localized base innovations and manage increased base-innovation radicalness through experimentation. Thereafter, they should address challenges in services and processes. Overall, disruptive innovation cycles demand that software organizations replace their current models for process improvement with organic project strategies, ongoing experimentation, and flexible hiring and training policies.

The study has three limitations: (1) the sample with mainly small firms; (2) an examination of one platform change; and (3) data reliability threats due to the use of recall data. Our data were from small software organizations that had, on average, fewer than 40 employees. Unlike larger firms, small firms have more limited resources, lower structural complexity and lower levels of routinization. As a result, it was not possible to control some structural factors such as resource slack or structural complexity. Larger firms are also more likely to be older than small firms and therefore posed another potential confounders. To test for this factor, alternate models were run with 'organizational age' as a control variable. No significant differences were found. Our second limitation is that our data measure only a single disruptive innovation. It is possible that the radicalness of change associated with internet computing was exceptional. If that is the case, our observed effects may be more pronounced than what might be found in other innovation cycles. Finally, the retrospective, one single respondent approach makes our study vulnerable to the threats of feedback problems and method biases inherent in most IT innovation research. Because of the size of the organizations and the nature of data collection, using one single respondent approach was the best workable option. In our context, foresight bias poses a greater threat than hindsight bias (Dahlin & Behrens, 2005). The respondents' assessment of radicalness was, as noted, based on the cumulative impact of the innovations adopted within each innovation type as the respondents saw them *at the time of their response* – not how these innovations were perceived at the time of adoption. However, radicalness can only be seen after the adopters have had the time to observe the magnitude of its transformative impact and its uniqueness. Finally, accuracy of recall of which innovations were adopted and when, could have posed a problem. Fortunately, participants noted that the importance of these innovations made them easy to recall.

Our study suggests at least four directions for future research. First, as noted above, larger firms have known characteristics that differ from those in smaller firms. It would be worthwhile to comprehensively review the literature to identify what these differences are. The hypotheses herein could then be re-evaluated, modified and tested accordingly. Second, we analysed the impact of the increased *amount* of innovations that is amenable for regression-based analysis. An interesting additional question is: what is the impact of each base innovation, separately or in different combinations, on subsequent innovation behaviours, and do firms organize themselves into path dependent 'clusters' of innovations? Third, our study measured the initial year of adoption within each type of IT innovation. Future research could adopt methods that capture the timing of each IT innovation in each type separately and with finer granularity. While this would likely provide new insights of how innovations interact over time, such data would be difficult to obtain for a variety of reasons and may be impractical to collect. Fourth, we did not analyse the moderating effects of organizational design routines on strong order effects. Our study shows the significance and occasional radical impact of new material features of IT on how computing advances in organizations. We hope future studies will shed additional light to the dynamic, interdependent nature of innovations, and the multiple ways in which they continue to shape realities of software development.

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APPENDIX A: MEASUREMENT ITEMS FOR KEY RESEARCH VARIABLES

In operationalizing the construct of ‘amount of innovations’, we adopted multiple techniques followed in prior studies (Damanpour & Evan, 1984; Fichman & Kemerer, 1997; Grover *et al.*, 1997). First, based on an extensive literature review, we compiled a large pool of innovations that had occurred since the widespread use of internet computing (1995–2005). To avoid tautology, we worked with IS development professionals to eliminate any innovations which they felt would likely have occurred without internet computing (e.g. client-/server-based enterprise resource planning).

We validated the list of innovations for face and content validity with a pilot study. We conducted 19 tape-recorded interviews of top development experts in seven software firms with a combined experience of over 100 years in developing software, as well as four *PhD* students with extensive IT industry background. Three additional IS faculty members with industry background were also consulted. These experts did not belong to our final survey sample. The separation between the pilot study and the final survey helped in eliminating possible contamination of our findings.

Talk-aloud protocols (Lyytinen & Rose, 2003b) were used during the validation interviews. Participants talked aloud when filling out the questionnaire, and we observed their reactions to the questions and took notes. We also probed the participants for additional comments when they experienced information processing difficulties identified in Bolton (1993), such as difficulty in understanding a question or retrieving answers. Items were continuously revised until participants made no additional requests for revisions and exhibited minimum information processing difficulties. To render the list complete, we added new types of innovations when interviewees mentioned some innovations that we had not included in the original list. We also deleted some items from the list, if the interviewees indicated that they were not associated with the range of base technologies we were studying. For example, we excluded all service and process innovations that had been adopted before 1995 and could not be connected necessarily with adopting internet computing. We continued with this process until the list was saturated and no new innovations emerged. The cut-off point for inclusion was whether more than 50% of the interviewees said they had started to use the innovation after adopting internet computing. By setting the cut-off point so high, we applied a conservative criterion in compiling the final list, which guaranteed that we examined interactions between widely adopted and commonly known innovations. The final list, as shown below, consists of 10 base innovations, nine process innovations and 14 service innovations.

Amount of Innovation:

Base: Has your organization adopted the following internet-based technologies? Check all that apply.

- ☐ Uniform and ubiquitous clients (e.g. HTML browser) with multimedia capability that are platform independent
- ☐ Use of three-tier or higher level architecture
- ☐ Web services based on interoperability standards (e.g. XML, SOAP, UDDI or WSDL)
- ☐ Peer-to-peer applications and protocols (e.g. groupware or contentware)
- ☐ Application server middleware (e.g. Java Beans, CORBA,.Net, Java J2EE)
- ☐ Middleware (e.g. CGI, ASP, JSP)
- ☐ Software patterns (e.g. broker and observer patterns)
- ☐ Ubiquitous services available at any terminal, anytime and anywhere across a multitude of often ‘unknown’ client types (e.g. mobile or multi-channel web applications, WAP)
- ☐ Media-oriented services (e.g. video and graphics in web applications or voice recognition and generation, VOIP)
- ☐ Open telecommunication services (e.g. wireless broadband services, 802.11.x, or TCP/IP v6)

Process: Has your organization. . . . Check all that apply.

- ☐ Hired specialists in graphic design or required existing staff to acquire such competencies
- ☐ Hired specialists in site branding or required existing staff to acquire such competencies
- ☐ Hired specialists in telecommunications design or required existing staff to acquire such competencies
- ☐ Used open source development
- ☐ Incorporated clients and other stakeholders into the development process (e.g. JAD sessions)
- ☐ Used external sources for developing solutions or carrying out development tasks (e.g. outsourcing / offshoring)
- ☐ Used new specification models and techniques (e.g. agile development, extreme programming, UML variants for web services, RUP)
- ☐ Bought software component libraries or frameworks in the market, instead of developing them in-house
- ☐ Adopted **significantly** faster development times (e.g. Extreme Programming, Agile development, RAD systems)

Services: Has your organization developed the following **e-business** applications for your clients (either internal or external clients)? Check all that apply.

- ☐ Intranet
- ☐ Web-based transaction-based data delivery
- ☐ Web-based periodic information delivery
- ☐ Web-based enterprise-wide document management and sharing
- ☐ Web-based R&D related knowledge management
- ☐ Business intelligence using internet
- ☐ Public web (e.g. external web presence)
- ☐ One-to-one marketing (e.g. rule-based and collaborative filtering, CRM)
- ☐ B2C order entry and customer management (e.g. ERP)
- ☐ Extranet with business partners
- ☐ Electronic marketplace and exchange applications (e.g. internet 2 or Manugistics)
- ☐ Electronic auctions
- ☐ Web-based supply chain management (e.g. eCollaboration)
- ☐ Web-based logistic management systems

Level of Radicalness: (* indicates dropped items)

Base: (1- strongly disagree, 5-strongly agree; NA)

1. These technologies were **major** improvements over previous technologies.
2. These technologies were based on **revolutionary** changes in technology.
3. These technologies were **breakthrough** innovations.
4. These technologies have led to products that were difficult to replace or substitute using older technologies.*
5. These technologies represented major technological advance(s) **within** the local contexts in which they were applied.*

Process: (1- strongly disagree, 5-strongly agree; NA)

1. These techniques / methods / approaches were **major** improvements over previous development practices.
2. These techniques / methods / approaches were based on **revolutionary** changes.*
3. These techniques / methods / approaches were **breakthrough** innovations.*

4. These techniques / methods/ approaches have led to development outcomes that were difficult to replace or substitute using older methods / techniques / approaches.
5. These techniques / methods/ approaches represented major methodological advance(s) **within** the local contexts in which they were applied.

Services: (1- strongly disagree, 5-strongly agree; NA)

1. These applications were **major** improvements over previous technologies.
2. These applications were based on **revolutionary** changes in technology.
3. These applications were **breakthrough** innovations.
4. These applications have led to products that were difficult to replace or substitute using older technologies.
5. These applications represented major technological advance(s) **within** the local contexts in which they were applied.*

Timing of Adoption:

Base: What is the year your organization **first** began to adopt **any** of these technologies?
Process: What year did your organization **first** began to adopt **any** of these techniques /methods/ approaches?
Services: What year did your organization **first** began to develop **any** of these applications?

Extent of Adoption:

Base: How many projects are using these technologies **today**? (in % total number of projects)
Process: How many projects are using these techniques /methods / approaches **today**? (in % total number of projects)
Services: How many projects are developing these applications **today**? (in % total number of projects)

Organizational Size: Number of employees.

APPENDIX B: RESPONSE ACCURACY, RESPONDENT BIAS AND METHOD BIAS

The *response accuracy* was checked. If there was missing information, we sent a copy of the page(s) with missing items requesting respondents to complete the data set. To ensure consistency, we sent not only the information about the missing items but also their answers to other questions. We also made follow-up calls to verify some of their comments or suspicious answers. For instance, one respondent indicated that his company had adopted a few process innovations but none of the base or service innovations. We called him and found out this company is a pure graphic design firm. As a result, we excluded this data point.

Non-response bias was assessed by verifying that early and late respondents were not significantly different (Armstrong & Overton, 1977). Following Pavlou & El Sawy (2006), we compared the earliest 25 respondents and the latest 25 respondents in terms of the company demographics and their responses on key constructs. All t-tests between the means of the two groups were insignificant ($P < 0.1$) indicating there was virtually no difference between the two groups. Random follow up calls to 20 non-respondents found three main reasons for not participating in the study: they were too busy, not interested or had a ‘no survey’ policy. We concluded that there were no significant threats due to non-response bias.

Because we carried out a cross-sectional survey, we analysed two sources for *common method* bias: (1) a single instrument of data collection; and (2) repeated use of identical wordings of perceived radicalness for three IT innovation types. Regarding the first source, we used Harman’s single-factor test. We found that the majority of data variance cannot be accounted for by one general factor, indicating that the common method bias due to the single instrument of data collection is not significant. To control for the second source, we deliberately asked participants about their perceptions about each IT innovation type right after requesting them to identify specific innovations they have adopted within each corresponding innovation type. In this way, we tried to proximally, temporally and psychologically separate the measures by having participants complete their answers about their perceptions after mentally focusing their attention on the corresponding IT innovations (Podsakoff *et al.*, 2003). To test the effectiveness of this strategy, we used the multi-trait–multi-method (MTMM) model decomposing the data variance into *trait* (base, process and service), *method* (improvement, revolutionary, breakthrough, replace, local) and *random error* components (Campbell & Fiske, 1959; Bagozzi & Yi, 1990). We found that the loadings upon the traits were higher than the loadings upon the methods for the successful 10 items that ended up in our final constructs, while all the trait loadings for these 10 items were greater than 0.30. This indicates that there is no significant common method bias due to repeated measures of perceived radicalness using identical wordings.