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Toward a complexity theory of information systems development

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Abstract

Purpose – Existing literature acknowledges information systems development (ISD) to be a complex activity. This complexity is magnified by the continuous changes in user requirements due to changing organizational needs in changing external competitive environments. Research findings show that, if this increasing complexity is not managed appropriately, information systems fail. The paper thus aims to portray the sources of complexity related to ISD and to suggest the use of complexity theory as a frame of reference, analyzing its implications on information system design and development to deal with the emergent nature of IS.

Design/methodology/approach - Conceptual analysis and review of relevant literature.

Findings – This article provides a conceptual model explaining how top-down "official" and bottom-up "emergent" co-evolutionary adaptations of information systems design with changing user requirements will result in more effective system design and operation. At the heart of this model are seven first principles of adaptive success drawn from foundational biological and social science theory: adaptive tension, requisite complexity, change rate, modular design, positive feedback, causal intricacy, and coordination rhythm. These principles, translated into the ISD context, outline how IS professionals can use them to better enable the co-evolutionary adaptation of ISD projects to changing stakeholder interests and broader environmental changes.

Originality/value – This paper considers and recognizes the different sources of complexity related to ISD before suggesting how they could be better dealt with. It develops a framework for change to deal with the emergent nature of ISD and enable more expeditious co-evolutionary adaptation.

Keywords Information systems, Design and development, Complexity theory, Adaptability, Project management

Paper type Conceptual paper

1. Introduction

Given the aforementioned difficulties, understanding and effectively managing information systems development (ISD) project complexity has become an issue for many organizations that are struggling with resolving new issues that surface very quickly during IS development and that necessitate real-time articulation and resolution. Recent surveys of ISD confirm these challenges: a recent survey by the Boston Consulting Group on IT management practices of more than 20 global companies from a variety of industries reveals that all suffered from excessive IT complexity and, as their businesses expanded, rather than gaining economies of scale, the companies had created "diseconomies of complexity" (Boston Consulting Group, 2004) – what Stuart Kauffman (1993), a founder of the Santa Fe Institute (for the study of complexity sciences) (SFI), terms "complexity catastrophe". Another study involving 250 business and information technology professionals indicates that they are all struggling to reduce the complexity related to their IT (CMP Media, 2001). In addition to these surveys of practitioners, recent academic research acknowledges the growing complexity of IT projects, suggesting complexity and system theories as lenses through which to conceptualize, assess, and then manage this complexity.



Information Technology & People Vol. 19 No. 1, 2006 pp. 12:34 © Emerald Group Publishing Limited 0959:3845 DOI 10.1108/09593840610649952 We use complexity theory as a frame of reference, analyzing its implications on information systems design and development. Complexity science, and especially its research on co-evolution based self-organized emergent behavior and structure, provides important insights for dealing with the emergent nature of IS. We argue that it enables managers to understand and modify complex systems, design new ones for new functions, or enable more rapid IS co-evolutionary adaptation.

We argue first that managers should view ISD projects as what SFI calls "complex adaptive systems" so as to more effectively cope with the challenges of evolutionary complexity in changing environments. We further suggest an adaptation perspective of ISD that rests primarily on co-evolutionary theory, which we believe will be much more useful for managing the emergent nature of most information systems than the prevailing traditional, top-down, engineering focused perspective.

Our article is organized as follows: first, sources of complexity in ISD are discussed, along with some of the limitations of traditional approaches to ISD. This is followed by an overview of complexity science and preliminary research efforts to integrate complexity theory with ISD. We then introduce our co-evolutionary framework of ISD. Our framework is defined primarily by seven first principles of adaptive success:

- (1) adaptive tension;
- (2) requisite complexity;
- (3) change rate;
- (4) modular design;
- (5) positive feedback;
- (6) causal intricacy; and
- (7) coordination rhythm.

2. Problematic complexity in information systems development

2.1 Technological and organizational bases of IS complexity

Information systems development is generally acknowledged to be an intellectually complex activity. This complexity has been traditionally translated into the need for expertise in two disciplinary areas:

- (1) the area of the problem being solved (the application domain); and
- (2) the area of constructing a software solution (the systems and software discipline).

Pressman (2004) describes software design as the process through which requirements are translated into a representation in the form of software. The process of translating user requirements into software also magnifies the complexity inherent in systems development. Thus, system specification, design, and implementation are highly complex and interrelated tasks that greatly complicate the design of custom solutions able to satisfy user requirements.

Initially, the information requirements of an organization are translated into a corresponding physical architecture through a sequence of steps. Then, at each subsequent step, a designer's attention focuses on specific aspects of the overall technical design of the underlying IT architecture, right down to its physical details. At the organizational level, these requirements are described as a collection of information

processes, such as processing intensity, communication intensity, and degree of networking among users. This means that ISD projects are complex not only because they deal with complex technological issues, but also because of organizational factors beyond a project team's control. In other words, the complexity related to ISD is multi-dimensional. Xia and Lee (2004) propose a framework for understanding and measuring the complexity of an ISD project (ISDP). Their framework consists of two dimensions:

- (1) organizational versus technological aspects; and
- (2) structural versus dynamic.

It results in a typology of ISD complexity consisting of four components, as shown in Table I.

In line with Xia and Lee's (2004) findings, we consider both the organizational and technological dimensions of the complexity related to ISD, with a particular emphasis on user requirements. Indeed, understanding requirements is one of the most critical tasks in the development process (Pressman, 2004). It is generally acknowledged that accumulating requirements are the cause of most problems with IS projects (Potts, 2001). Parnas and Clements (1986) note that "[D]etermining the detailed requirements may well be the most difficult part of the software design process". Brooks (1995) states that "[T]he single hardest part of building a software system is deciding precisely what to build". This situation is even more pronounced if we consider that requirements change as individual and organizational needs change and with them the complexity related to ISD. The question then is how best to deal with the changes of requirements

		Structural	Dynamic
	Organizational	Reflects the nature and strength of the relationships among project elements in an organization's environment, including project resources, support from top management and users, project staffing, and skill proficiency levels of project personnel	Captures the pattern and rate of change in ISDP intraorganizational environments, including changes in user information needs, business processes, and organizational structures; it also reflects the dynamic nature of the project's effect on an organization's external environment
	IT	Captures the complexity of relationships among IT elements: the diversity of user units, software environments, nature of data processing, variety of technology platforms, need for integration, and diversity of external vendors and contractors	Measures the pattern and rate of changes in the ISDP's IT environment, including changes in IT infrastructure, architecture, and software development tools
Table I.Typology of informationsystems developmentcomplexity	Note: Further, the authors provide empirical evidence on the effects of ISDP complexity on poor project performance and suggest that, when it comes to the complexity of an ISDP, the technological aspects are more apparent, but the organizational aspects have more significant effects on ISDP performance and outcomes		

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in ISD. And how should ISD projects be designed to deal with unplanned or unexpected emergent complexity?

2.2 Complexity issues in top-down information systems design

Information systems design is often viewed as a complex top-down process, which identifies the information technology architecture that satisfies performance requirements and at the same time minimizes costs (Blyler and Ray, 1998). This approach considers ISD as a "black box", the form of which is predetermined by decisions as to its role and purpose. This conception of systems relies mainly on the premise of functional simplification and closure introduced by Luhmann (1993). Kallinikos (2005, p. 189) interprets Luhmann's German as follows:

Functional simplification involves the demarcation of an operational domain, within which the complexity of the world is reconstructed as a simplified set of causal or instrumental relations. Functional closure, on the other hand, implies the construction of a protective cocoon that is placed around the selected causal sequences or processes to safeguard undesired interference and ensure their recurrent unfolding.

While these strategies represent a major means for managing complexity, they fall short in dealing with unexpected contingencies and presume a "correct" and complete understanding of organizational requirements up front and of the ongoing fit between requirement and technology (Luhmann, 1993). Traditionally, IS design relied mainly on the systems development life cycle (SDLC), which is viewed as a single stage in defining a detailed physical form for the technical component of an information system. As a guide to the design of organizational information systems, the traditional SDLC has three main limitations:

- it relates to the development of systems to support relatively well-defined, technical goals; it tells us little about how ill-defined and unbounded problems should be defined and resolved (Mathiassen and Stage, 1992);
- (2) it presumes individuals are independent, rational problem solvers, whereas IS design tends to involve collaborative action situated in a socio-political context that is far from rational (Boland and Tenkasi, 1995); and
- (3) it assumes that objective goals and solution requirements are defined early in the design process, whereas empirical research tell us that IS goals emerge helter-skelter through the processes of design, and that these goals are political, subjective, and negotiable (Guindon, 1990).

It is unsurprising, then, that attempts to fix user requirements often end in failure, that developers criticize users for never making up their minds or for not fully understanding the dynamic environment within which they are working, and that a gap between information systems and the requirement appears before implementation is complete. Further, even if the IS is developed to respond to actual user requirements, or even a segment of them, these requirements often change with time, reflecting the evolutionary aspect that IS invariably has to eventually account for. Recent theories explaining the relationship between technology and organization argue that the two are mutually interdependent: each shapes the other through self-reinforcing positive feedback cycles (Orlikowski, 2000; Majchrzak *et al.*, 2001).

Moreover, during the design process it is often true that new purposes and roles for the technology emerge, are debated, and replace the original purposes, as more technically "appropriate" (Gasson, 1999). This results in information systems reflecting intersections between overlapping sets of individual and group perspectives that shift and evolve as the design proceeds. Consequently, there is a need to make IS more flexible and to recognize the need for adaptation via unplanned, emergent IS designs.

The literature shows that preconceived, top-down IS designs will always disappoint in the long term, as they do not allow internal complexity to evolve in line with the imposing resources, limitations, competitors, tensions, and complexity of their environments. They represent temporal "snapshots" that ultimately leave organizations with static systems that they have to live with in a dynamic world. These constraints also sit poorly with the need to design systems that support emerging knowledge processes (Markus *et al.*, 2002). This emergent behavior between co-evolving IS and organizational systems in general and user requirements in particular may be better described and understood through the application of the concepts of complexity theory, and especially its research on co-evolutionary based self-organized emergent behavior and structure. We first introduce the theoretical foundation for this approach by providing an overview of complexity theory and summarizing preliminary research conducted to study its contribution to ISD. Our first-principles framework for improving ISD follows.

3. Complexity science: an overview

3.1 Complexity science

Complexity theory is a relatively new way of thinking about systems of interacting agents such as firms. Unlike mechanistic theories, which assume a centrally controlled governing structure, complexity theory rests on the idea that order emerges through the interactions of organisms or agents. "Agent" is a general term used to designate semi-autonomous entities (i.e. parts of systems), such entities as atoms, molecules, biomolecules, organisms, processes, people, groups, firms, industries, and so on. (Ferber, 1999, p. 9). Analysis shows that systems as diverse as ant colonies, cities, and the stock market provide examples of such "bottom up" development (Johnson, 2001).

Two schools are apparent in complexity science: European and American (McKelvey, 2004b). We highlight the original differences between the two schools so that we can then be more obvious in how we integrate them.

The European group consists of Prigogine (1955), Prigogine and Stengers (1997), Haken (1983), Cramer (1993), and Mainzer (1994), among others. They focus on physical phenomena, phase transitions, and the region of emergent complexity defined by the first and second critical values. Theirs is math intensive. Phase transitions are structural changes that occur at the first and second critical values of R, which is the measure of energy imposing on the system – e.g. in a teapot an emergent structure called a "rolling boil" occurs between the two values. Phase transitions are thus dramatic energy-caused events, far removed from the small instigation events the Americans focus on.

The American group consists largely of researchers such as Lorenz (1963) and those associated with the Santa Fe Institute, such as Gleick (1987), Bak *et al.* (1988), Bak and Chen (1991), Arthur (1990), Kauffman (1993), and Casti (1994). They study heterogeneous agents, the rules that govern agent behavior, and agent interactions

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in search spaces. They focus on the kinds of events or "things" – what Holland (1995) calls "tags" – that initiate positive-feedback mutual causal processes In their vision, positive feedback is the "engine" of complex system adaptation. They emphasize biological and social phenomena and agent-based computational models. They study fractals, power laws, and scale-free theory (Brock, 2000).

The precursor of complexity theory is research into the phenomenon of "chaos". Chaos theory focuses on the discovery of unpredictable behavior from deterministic equations. Chaotic systems are critically dependent on initial conditions that, at some point, result in unpredictable and chaotic behavior. Chaos theory differs from complexity science, which describes order from a system of interconnected agents (e.g. people, group, firms, etc.) - it is mostly concerned with uncertainty and unpredictability and, of course, chaos (Lorenz, 1963; Gleick, 1987; Guastello, 1995). The most cited metaphor of chaos theory is the "butterfly effect": a butterfly flapping its wings in Brazil may cause a storm in Texas (Lorenz, 1972). In contrast, complexity science is quite the opposite. It deals with order and what causes order. It is an order-creation science (Mainzer, 1994; McKelvey, 2004a). This contrasts with most of "normal" science, which is an equilibrium-based science (Mirowski, 1989). In other words, complexity science aims to explain how order emerges from self-organizing agent interactions (Kauffman, 1993; Holland, 1995). It is thus a science that seeks to explain the processes of agent interaction leading to emergent structure rather than the effects of energic forces on objects.

Complexity science recognizes that systems can exist or fluctuate between three states – stable, chaotic, and one in between (Lewin, 1992). The middle state is called the "melting zone" (Kauffman, 1993), "critical complexity" (Cramer, 1993), or "region of emergent complexity" (McKelvey, 1999). Early writing from SFI often talks about this "region" as at "the edge of chaos" (Lewin, 1992; Kauffman, 1995) – at the transition across the second critical value of R. In the "region" at the "edge of chaos", emergent system-level phenomena generate patterns in time and space that have neither too much nor too little form, and are neither static nor chaotic. They are, instead, interesting because of the coupling of individual and global behaviors.

Organizations are defined as complex, dynamic, non-linear systems that do not evolve in a steady, predictable way (Stacey, 1992; Wheatley, 1992; McKelvey, 1997). Many writers applying complexity theory to improve the management of firms argue that complexity theory is a tool that can help managers cope better with rapidly changing non-linear competitive contexts (Goldstein, 1994; Stacey, 1995; Brown and Eisenhardt, 1998; Kelly and Allison, 1999). These ideas are clearly significant for the field of information systems and apply particularly to ISD. In the following section we present the basic features of complexity science.

3.2 Complex adaptive systems

Several authors point to the fact that an IS can be viewed as a complex adaptive system (CAS). Before focusing on the main contributions of these authors, we define CASs and describe their main characteristics.

A CAS not only self-organizes, but can direct its activity towards its own optimization. It is poised between order and chaos. Typical examples of CASs include slime mold, ant colonies, immune systems, brains, markets, and companies (Johnson, 2001). The commonality across the cited examples is that they are composed of a large

number of components (agents) that interact. Holland (1995) defines CASs as exhibiting order creation generated from simple specifications. He defines CASs as systems composed of interacting agents that respond to stimuli, and stimulus-response behavior that can be defined in terms of "simple rules". Agents adapt by changing their rules as experience accumulates. Axelrod and Cohen (1999) define a system as being complex when "there are strong interactions among its elements, so that current events heavily influence the probabilities of many kinds of later events".

Agents' interaction behaviors may result in networks, which then morph into later organizational stages - meta-agents such as groups, hierarchies, complex coordination structures and processes (Lichtenstein and McKelvey, 2004). The emergent behavior of the meta-aggregates cannot be predicted from the behaviors of lower-level agents. The biological definition of the concept of "adaptiveness" is "organic modification by which an organism or species becomes adapted to its environment" (Janzen, 1980). Axelrod and Cohen (1999) refer to adaptiveness as the outcome of a selection process that leads to an improvement according to some measure of success. Boiled down, CASs are adaptive because they accommodate imposing influences from changing environments without disintegrating. The European School defines imposing environmental influences as any kind of energy imposition that creates a phase transition, for example a temperature differential such as the hot surface of the earth versus the cold of outer space, or the fire under a teapot versus normal room temperature. McKelvey (2001, 2005) broadens the energy differential concept to "adaptive tension", which includes any kind of tension imposing on an agent (individual or organization), such as the difference between supply and demand, new technology, changing market tastes, out of control costs, competitor moves, and so on.

While, a uniform definition of what a CAS is remains illusory, several key aspects characterize and distinguish CAS (see Table II).

We summarize the key ideas on CASs as follows:

- They are systems made up of heterogeneous agents that interrelate with each other and with their surroundings, and are unlimited in their capabilities to adapt their behavior, subject to their prior experience. A system's behavior cannot be inferred from that of its agents (Holland, 1995), as there is a possibility of striking emergent diversity within these systems.
- In each system, each agent is different from the others (diversity), and its performance depends on the other agents and the system itself, each of which can

		Holland (1988, 1995)	Axelrod and Cohen (1999)	Markovsky (1998)	Dooley (1997)
	Large number of components				
	Variation		1		
	Self-organization				1
	Diversity				
	Dynamism and liveliness				
	Adaptation to their environment				
teristics of	Interactions				
ptive	Non-linearity				
	Selection				

Table II. Main characteristics or complex adaptive systems

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influence the other's behavior. The agents' environmental context, therefore, takes on a vitally important role. Each agent carries out functions defined by its relationships and rules (Holland, 1995), which result in flows of information, knowledge, etc.

- CASs are capable of anticipating the results of their actions, for which they develop schemas (Holland, 1995; Stacey, 1996; Anderson, 1999). The existence of these shared schemas, together with the agents' individual schemas (diversity), opens up the possibility of changes to these rules, or in other words, evolution and learning. A schema can be defined as a set of rules that reflect regularities in experience or as a cognitive structure that determines what action the agent or the system will take, given its perception of the environment (Stacey, 1996; Anderson, 1999). According to Stacey (1996), the rules are coded in the form of symbols such as mental images, numbers, colors, shapes and so on. In the case of a company, this would depend on the nature of the schemas whether they are concerned with financial policy, strategic posture, product design, etc.
- These systems are self-organized (Stacey, 1995; Anderson, 1999). In other words, new behavior patterns appear as consequences of agent interaction. No single program or agent completely determines the system's behavior, despite the fact that each of the heterogeneous agents holds some common schemata.
- These systems self-organize when they find themselves in the "region of emergent complexity" between the "edge of chaos" (Cramer, 1993; Kauffman, 1993; McKelvey, 1999) and the "edge of order". CASs are able to develop three types of behavior: stable or controlled by negative feedback (order), unstable or continually bifurcating (chaos), and adaptive tension between the first and second critical values, limited instability with positive feedback dynamics (region of emergence). Between the two edges, the system is "complex" in the sense that the degree of a schema's elaboration required to define it is high (Gell-Mann, 1994). This region is a form of emergent "bounded instability" found in the transition phase between the order and disorder zones of CAS behavior (Stacey, 1996).

Kovacs and Ueno (2004) make a general point about the implications of complexity theory and particularly the properties of CASs on the design of an IS. They point to the fact that studying and analyzing CASs in their natural science manifestations has led to the development of genetic algorithms (Holland, 1975, 1995), artificial neural networks (Holland, 1998), artificial life (Sigmund, 1993), and applications to optimization problems. Other researchers have reported additional applications that draw on the common principles responsible for CAS functioning, applying them to analogy making (Mufatto and Faldani, 2003).

Van Aardt (2004) argues that any information system displays the characteristics of a CAS. He characterizes a CAS by the emergence of order as opposed to causal predetermination; a system's history is irreversible, and the system's future is often unpredictable. The only difference, however, is that typically the final functional objective of an IS is mostly predetermined "on paper". In other words, order is predetermined in that how an IS is supposed to appear and behave is first spelled out in the functional specifications, and then the hope is that the system will be developed to achieve these "would-be" goals. The author cites as an example the classic systems

development life cycle (SDLC) and its variants that typically attempt to define what the user requirements are before any development starts. This is in contrast to a CAS, where the final outcome is seldom known. Several authors, including Van Aardt, consider that the best example of IS as a CAS corresponds to open source software (OSS). Indeed, OSS, as opposed to the typical IS, is not designed in a "top-down" manner: instead, OSS evolves over time, with programmers changing, or existing programmers revisiting their previous work to implement improvements. This dynamic variation results in a software tool that is effective, robust, and relatively secure.

While the open source software is considered the "best" example of a CAS according to several authors (Mufatto and Faldani, 2003; Van Aardt, 2004), we consider that all IS act as CASs:

- IS alignment is not an event but a process of continuous adaptation and change;
- IS not only coevolve as whole entities, they also coevolve with respect to their parts; and
- recent research on the relationship between IS and organizations suggests that they are not only mutually interdependent where each shapes the other, but also go through a series of adaptations/re-adaptation cycles.

Despite these recognized parallels to CASs, ISD still relies on traditional, static, top-down design methods that limit its evolution over time.

4. Improving the adaptive development of information systems

The critical factor in all information systems is continual change. This factor is fundamental in the co-evolution of socio-technical systems. Once one recognizes that a pilot system must be built or discarded, and that a redesign with changed ideas is inevitable, it becomes useful to better understand the whole phenomenon of adaptive change. Moreover, as users become competent in using an IS, they often see new ways of doing things and dream up new things to do with the information. Additionally, systems attract new users with different ideas of functionality and consequently new requirements that the designed system cannot accommodate. These new ideas change the organization and its perception of what is required from its IS. If these changes cannot be easily incorporated in the IS, the users become frustrated and dissatisfied with the system. As we noted earlier, despite this reality, ISD still relies on traditional top-down design principles that do not allow easy change (Luhmann, 1993). The reality is that to derive its expected benefits, the IS and its users must continually co-evolve. The key question then is: how can we build information systems that continually co-evolve with changing user needs as users cope with changing competitive environments?

In the following subsections we develop a generalized adaptation framework applicable to ISD. It builds from the seven "first principles" of biological and/or social system adaptation. These principles build from theories aimed at explaining mass extinctions and explosions of species over the eons of biological evolution. It is composed of seven jointly probable elements, any one of which gives an organism, species, or organization adaptive advantage. Having none is a disaster; having all greatly fosters adaptive success. These principles are said to be "interdependent" in the sense that they should not be applied in isolation if one wants to reach valid

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conclusions regarding co-evolutionary adaptations. In fact, their use in isolation from one another could arguably lead to inertia. Indeed, some of these principles have been suggested and used in ISD – mainly the ones related to IS adaptation, modularity and spiral development. However, their use in isolation from one another does not foster efficacious adaptation with respect to the dynamic and social environment in which the system is embedded. These "first principles" are one logic step above self-evident foundational axioms, such as F = ma. They are:

- *adaptive tension*: environmentally imposed tensions (energy differentials) stimulate adaptive order creation Prigogine's (1955) dissipative structures theory;
- *requisite complexity*: adaptive order creation occurs if internal complexity exceeds external complexity Ashby's (1956) law of requisite variety updated from variety to degrees of freedom to complexity;
- *change rate*: higher internal rates of change offer adaptive advantage in a changing environment Fisher's (1930) genetic variance theorem;
- *modular design*: nearly autonomous subunits increase complexity and rate of adaptive response Simon's (1962) near decomposability principle;
- *positive feedback*: insignificant instigating events among agents or modules may result in significant order creation – Maruyama's (1963) deviation amplification theory;
- *causal intricacy*: complexity requires advantageously coping with multiple causes (bottom-up, top-down, horizontal, diagonal, intermittent, and Aristotelian) Lindblom's (1959) science of muddling through; and
- coordination rhythms: rhythmic alternation of causal dominance offers more functional adaptive response than balance – Dumont's (1966) entangled hierarchy theory.

We apply these principles to ISD in the next section.

4.1 Principle of adaptive tension

The first – adaptive tension – already appears in our brief description of the European School: tensions caused by differences in energy (heat) cause phase transitions, which in turn cause new kinds of ordered structures, such as the rolling boil in a teapot. In the organizational world, the best statement of adaptive tension comes from Jack Welch, 20-year CEO of GE and named "Manager of the Century". His "tension" statement is: "Be #1 or 2 in your industry or you will be fixed, sold, or closed" (Tichy and Sherman, 1994, p. 108; slightly paraphrased; our italics). While Welch's "tension" applied to inadequate market share, it could easily apply to being uncompetitive in innovation, product design, costs, production, or IS design and use.

It is largely acknowledged that ISD is not an event where "the one true set of requirements" is translated into technological artifacts, but rather it is a dynamic process full of contradictions (Chiasson and Dexter, 2001; Peppard and Breu, 2003). Indeed, instead of a singular organizational "reality", ISD is characterized by multiple and conflicting realities that surface as the project develops and progresses, reflecting the different "worlds" of the main stakeholders (users, organization, IS team, etc.). This expansion in diverse requirements results in not one but several development spirals,

each instigated by the initial conceptions and interests of the various stakeholder groups, who eventually may insist on full inclusion of its systems components. As a consequence, the resulting IS reflects an adaptive tension between intersections of overlapping sets of individual and group perspectives that shifts and evolves as the design proceeds. Furthermore, as the broader environment and the intersecting stakeholder "worlds" continue to change (slowly or rapidly), adaptive tension increases: changes that the system has to address if it is to remain effective become evident, as do tensions calling for aligning IS to a new set of organizational needs. Using a co-evolutionary perspective allows us to frame this process of adaptive tension not just as a matter of alignment facilitating short-term success – which leads to inertia, which in turn leads to failure when the environment suddenly shifts (Greenwood and Hinings, 1996) – but as a dynamic interplay of co-evolving interactions, mechanisms and effects, all of which are set in motion by adaptive tensions (McKelvey, 2001, 2004a).

4.2 Principle of requisite complexity – appropriate evolving IS complexity

The second characteristic that defines our co-evolutionary framework of ISD is *evolved complexity*. This builds from Ashby's "law of requisite variety", which Boisot and McKelvey (2005) update to the "law of requisite complexity". Ashby's (1956) path-breaking work on cybernetics identified a key principle of system "complexity", namely that in order to remain viable, a system needs to generate the same degree of internal complexity as the external complexity it faces in its environment. Essentially, external complexity – including "disturbances" or uncertainty – can be managed or "destroyed" by matching it with a similar degree of internal complexity: "Only *complexity can destroy complexity*" (p. 207; our italics).

Lycett and Paul (1999) argue that it is more realistic to postulate a "reality" of systems continuously adapting to compensate for environmental perturbations. Indeed, an environment cannot be taken as stable or an a priori given. It may be more realistic to characterize the environment itself as consisting of many systems evolving toward "trade-off" points. The larger the available counteractions available to an IS, the larger the set of perturbations it can compensate for, and the larger the number of different environmental situations to which it can successfully adapt. The latter point above provides an illustration of Van Valen's (1973) Red Queen Paradox, which proposes that a system must continuously develop faster just to stay even with the fitness of the changing systems with which it competes and co-evolves.

However, as one cannot easily design IS with sufficient up-front complexity to respond to dynamic complex environments, because of the emergent and unpredictable nature of future IS requirements and their environments, it is essential to develop IS able to evolve and generate sufficient complexity as needed. In other words, where feedback derived from social complexity is positive, change and/or growth to the structural assembly of components allows the system to regulate the divergences of positive feedback and stabilize itself. This aspect provides a more dynamic mechanism for dealing with evolutionary complexity than current development approaches.

Mansfield and Kaplan (2001) propose an iterative process in which, given a high-level prototype being criticized by users, a more refined prototype is constructed that is used and then is again critiqued by users, and so on, iteratively. This process is

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continued until the users are satisfied that they have a useable system. The result of this process is an IS that responds to problems posed by its current environment, as seen by current users. This is an improvement over previous methods that froze the design before the implementation started. Even so, this approach still does not account for changes in the external environment over time.

Mansfield and Kaplan (2001), reporting on Brand's vision of co-evolutionary architectural design, suggest the technique of scenario planning, used in the military to apply in an information system's design to predict some of the changes that may account in the future.

They suggest the following steps in IS design:

- (1) identify the issue that makes it necessary to build a new information system;
- (2) explore the driving forces that will shape the environment the system will run in;
- (3) identify a set of possible scenarios or basic plot lines (including the scenario the system is expected to operate in) and work out the basic uncertainties;
- (4) think the unthinkable identify events that might happen and that would have a catastrophic effect;
- (5) revise the basic scenarios and flesh them out, name them with an overstated, caricature quality, name; live through a "day in the life of a scenario";
- (6) cull them to no more than five, but leave in one or more "wild card" scenarios;
- (7) devise a strategy that will accommodate all the scenarios;
- (8) in the light of the strategy revisit the scenarios; and
- (9) revisit the strategy.

They also suggest the inclusion of participants from different backgrounds in this process, i.e. heterogeneous agents.

We consider that this perspective of attempting to predict and/or control change is a useful way of accounting for the complexity necessary for the system to co-evolve with user requirements. This perspective should, however, be integrated with a dynamic conception of IS maintenance over time, that is, of incremental release of new components (or evolutionary development). This sets up the need for our third principle of co-evolutionary ISD, which focuses on quickened learning action loops.

4.3 Principle of change rate – quickened learning action loops

Fisher's (1930) work made a key link between variation and adaptation, a link that is now all but axiomatic in the biological and social sciences. His basic theorem stated: *"The rate of evolution of a character at any time is proportional to its additive genetic variance at that time"* (quoted in Depew and Weber, 1995, p. 251; our italics). In other words, adaptation can proceed no faster than the rate that usable variation (i.e. in new knowledge, learning, innovation, networking, agent skills, etc.) becomes available. El Sawy and Majchrzak (2004) refer to this process as "quickened action loops" in the context of real-time knowledge management. This occurs when new issues surface that were unknown in advance and necessitate identification, interpretation, articulation and resolution in real time.

The best example of a conceptual framework developed for quickening the learning-action loops, according to these authors, is the concept of OODA loops that

ITPwas originated in the US Air Force by Colonel John Boyd. He wanted to understand
how fighter pilots won air combat engagements (dog fights) against other pilots
despite aircraft with inferior maneuverability. Boyd found that winning pilots were
able to compress the whole cycle of activities that happen in a dogfight and complete
them quicker than their adversaries. Boyd's OODA loop of activities (the Observe \rightarrow
Orient \rightarrow Decide \rightarrow Act loop), which was popularized into business use by Stalk and
Hout (1990), includes:

- *observation* (seeing situation and adversary);
- orientation (sizing up vulnerabilities and opportunities);
- · decision (deciding which combat maneuver to take); and
- *action* (executing the maneuver).

OODA loops should not only be executed rapidly, but they should also be flexible and responsive to requisite changes triggered by the environment. We suggest that OODA loop activities could apply to ISD as it is characterized by the emergence of new issues that surface very quickly during the process and after the implementation of the system and that necessitate real-time articulation and resolution. Indeed, requirements change along the development process and after the system is implemented, as users request additional requirements. This process necessitates effective users to identify changes required in the system and designers able to initiate and implement the changes required through a continuous interaction process (Boland, 1978; Davis, 1982). Thus, an ISD team's use of the OODA loops and its acting on their feedback loops has the potential of reducing the gap between the changing requirements of users and an IS being used and implemented effectively.

4.4 Principle of modular design – toward agile design spaces

Simon's (1962) classic essay on the "architecture of complexity" articulates the general design principles for modular systems. He argued that complex systems that are hierarchical – but which consist of "nearly decomposable" subunits (meaning that they are almost totally independent from top-down control or interdependencies with other subunits) – tend to evolve faster and toward stable, self-generating configurations, have been influential in the way modularity has been conceived. Simon's idea re-emerged as Weick's (1976) "loose coupling" concept and more recently as modular production and product design (Sanchez and Mahoney, 1996; Schilling, 2000). A modular system is thus represented as a complex of components or sub-systems, where designers try to minimize interdependencies among modules. Modular design has been suggested as a mechanism for improving the flexibility and comprehensibility of a system while allowing the shortening of its development time (Parnas, 1972). He suggests the following benefits of modularization:

- *managerial development time* it is shortened because separate groups can work on each module with little need for communication;
- *product flexibility* it is possible to make drastic changes to one module without a need to change others; and
- *comprehensibility* it is possible to study the system one module at a time: the whole system can therefore be better designed because it is better understood.

From an evolutionary point of view, design can be understood from the viewpoint that large, complex socio-technical systems, such as IS, consist of co-evolving, interacting subsystems that exist in some environment, where perturbations to one subsystem or to the environment create the possibility for evolution elsewhere in the system. "Design" in this approach is the series of co-evolutionary moves that IS make over time. Quite frequently, "useful moves" turn out either to be unanticipated a priori, or have unexpected and unintended user consequences.

The parts of many early IS were so tightly coupled that it was impossible to continually evolve. Hence when a major change was required the system had to be discarded. Modular design has been proposed as a useful means to manage IS complexity (Homann *et al.*, 2004). Modular and agile ISD can only be achieved through a modular architecture that allows components to be removed, replaced and reconfigured in a more dynamic fashion than current tightly coupled designs allow.

4.5 Principle of positive feedback – development spirals

This principle is founded on Maruyama's (1963) classic paper on deviation amplifying mutual causal processes. Earlier we noted that co-evolution could be a negative or positive feedback process. Here we focus on positive feedback. In the American School's perspective, order stems from the interactions of heterogeneous agents. If negative feedback processes prevailed at the outset of agent interactions, they would simply revert to the initial "square one" state of existing order, if any. Clearly, co-evolution in bottom-up science is a positive feedback process that proceeds toward more and more complex structures, probabilities permitting (Arthur, 1988; Holland, 1988; Kauffman, 1993).

In the face of failing top-down IS design and implementation, much of the IS literature we have mentioned, and most of our discussion about user responses to unmet IS requirements, focuses on positive-feedback co-evolution. Our intent in applying the bottom-up thinking of complexity science is to push the idea that self-organizing agents can (at some probability) create significant new structures and processes apt to create better functioning IS. Thus, we have already mentioned "development spirals", in which the initial conceptions (insignificant instigation events) spiral into dramatic new structures as stakeholder groups attempt to see their views about system components embedded in the IS. Boehm (1988) argues that this approach:

- fosters the development of specifications that are not necessarily uniform, exhaustive or formal;
- incorporates prototyping as a risk reduction option at any stage of development; and
- accommodates reworks or go-backs to earlier stages as more attractive alternatives are identified or as new risk issues need resolution.

4.6 Principle of causal intricacy – causes of IS misalignments

In his "science of muddling through" paper, Lindblom (1959) shows that in a bureaucracy an *end* for one person may be the means to an end for another person. To expand on this, we note that in an hierarchical organization causal influences may be downward, upward, horizontal, diagonal, and intermittent. Lindblom's means and ends analysis also brings to the fore the four Aristotelian causes:

- (1) final cause (ends);
 - (2) *formal* cause (means);
 - (3) material cause (environmental constraints and resources); and
 - (4) *efficient* cause (the energy force of our first principle) (see Barnes, 1995, for further definition).

Despite the recognition that IS design, development and alignment is not an event but a co-evolutionary process where several mechanisms interact, its conception is still overly deterministic and little insight is available on how to sustain this dynamic process of adaptation and change. Bergman et al. (2002) outline that the failure to recognize and understand how technological, organizational and institutional changes are inherently intervoven in ISD is behind many of the failures of IS. They cite the example of Taurus project – an IS designed to automate settlement in the London Stock Exchange – that failed because the political, business and technical issues on which success depended could not be clearly apprehended during requirements capture, and the unforeseen interactions among these issues created cascades of new requirements and continuous shifts in the focus of the project. Indeed, a classical problem in IS implementations is the study of the causal mechanisms of IS alignment; these mechanisms range, for example, from cultural and structural to Institutional (Benbya et al., 2004; Benbya and Belbaly, 2005). While several studies focus on how these mechanisms shape ISD, they consider them as "static ingredients" and miss the fact that:

- these causalities are multidirectional;
- · change in one variable has multilevel effects on other variables; and
- · forces of change are non-linear.

Taking a co-evolutionary stance, however, allows us to frame the process of mutual adaptation not just as a matter of alignment but as a dynamic interplay of co-evolving interactions, relationships and effects.

Benbya (2005), studying the mechanisms that influence knowledge management systems (KMS) implementations, based on a multiple case studies, finds that top-down institutional structure (i.e. management and knowledge support structures), and bottom-up cultural development (mainly identification, trust and socialization), not only need to be interdependent for the effectiveness of KMS, but are also simultaneous co-evolving forces where each causal influence is influenced by another. The literature, however, has treated these mechanisms using a static perspective focusing on a specific factor or proposing a universal checklist that is supposed to apply in all organizations with very little emphasis on the dynamic interaction between them. Only through recognizing that ISD depends on the dynamic interaction of technical, business and institutional requirements that continually shifts and changes that we can expect to make progress in understanding how systems developers might successfully state and manage requirements for such systems.

4.7 Principle of coordination rhythm – IS design versus user inputs

The "rhythm" principle stems from Dumont's (1966) initiating study of Hindu society, where he finds oscillation between the dominance of *Brahmins* and *Rajahs* –

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domination of religion versus secular forces. Dominance inverts to the *Rajahs* during times of war or economic upheaval and then reverts back to the *Brahmins* during stable periods. In Dumont's view, top-down control and bottom-up autonomy influences – and other dualities such as Roethlisberger and Dixon's (1939) formal and informal authority – are "entangled" in a twisted, confusing mess, as the word implies. The dynamic rhythm idea, termed "circular organizing", also appears in early studies by Ackoff (1981, 1989), Endenburg (1988), Nonaka (1988), then Romme (1995), and most recently as "irregular oscillation dynamics" in Thomas *et al.* (2005a, b) and Benbya (2005).

The top-down control versus bottom-up autonomy duality shows up in IS as a tension between the IS design experts versus co-evolving user initiatives. So far we have emphasized all of the emergent dynamics associated with heterogeneous. self-organization, bottom-up influence dynamics, and emergent structure. This is all well and good, but this could also simply be the blind leading the blind. Organizations that have high-quality IS design experts on the payroll or available as consultants would be silly to ignore their inputs. The result is a constant duality of influence between IS design experts versus the co-evolving experience and influences of user stakeholders. The "irregular oscillation" principle (analogous to the irregular movements needed to balance a bicycle) argues that both poles of a duality have to be legitimized and brought to bear on a timely, irregular basis for adaptive effectiveness – some changes external to the IS are seldom, if ever, "regular" in timing (Thomas et al., 2005a). IS professionals' interactions with users are thus viewed as a series of learning, analyzing, and suggesting protocols. This mutual interaction between IS developers and users makes possible informed decision and decrease of power domination (Lyytinen, 1987).

It is also largely acknowledged that ISD is not solely a technical process. It incorporates a variety of interrelated mechanisms of alignment that lead to a sustainable competitive advantage (Henderson and Venkatraman, 1999). This approach, however, argues that alignment should involve strategic and structural mechanisms (i.e. the following domains: business strategy, organizational infrastructure/processes, IS strategy, and IS infrastructure/processes), and that effective management requires balancing choices made across all four domains. While this approach stresses the importance of the presence of mechanisms for alignment it does not account for the dynamic interactions between them. But, balancing these domains – even when they are complementary – is a dilemma that managers have faced for more that 50 years (Thomas *et al.*, 2005a, b). Dualities consisting of opposing forces cannot be easily compartmentalized, balanced, or designed toward some static optimal configuration. In referring to one of them (exploitation/exploration), for example, March (1999) says it is "impossible".

5. Conclusion

Though there has been considerable recent progress in understanding information systems (IS) development and design, the systems themselves, however, continue to disappoint. Our review of the literature shows that preconceived, top-down IS designs will always disappoint in the long term, as they do not allow internal complexity to evolve in line with the imposing resources, limitations, competitors, tensions, and complexity of their environments. They result in temporal "snapshots" that ultimately

leave organizations with static systems that they have to suffer with in a dynamic world.

We argue that current top-down methods of IS design are unable to deal with the challenge of evolutionary complexity resulting from the evolution of user requirements and needs. We suggest, consequently, that a system should not be designed with the up-front view that it will be right or correct. Rather, it should be designed so that its components are structurally coupled in the short term and to provide it with a design framework allowing for flexibility. This will allow its emergent structures to remain effective in the face of changing long-run conditions. In other words, we suggest a shift in system design from a prepensive "top-down" approach to one enabling a co-evolutionary approach, where design is viewed as an ongoing process (Uhl-Bien *et al.*, 2004).

Our framework is defined by seven first principles of adaptive success drawn from foundational biological and social science theory. We summarize these principles in terms that bear on ISD problems:

- Adaptive tension. Framing the process of adaptive tension between intersections
 of overlapping sets of individuals and group perspectives so that adaptive
 tension motivators shift and evolve as the IS design process proceeds. IS
 designers should not focus only on realigning to facilitate short-term success, but
 need to also recognize that the dynamic interplay of coevolving interactions,
 mechanisms and effects, is set in motion by adaptive tensions.
- *Requisite complexity*. Enabling self-organized emergent complexity by the various agents (employees or groups, departments, etc.) so as to develop internal complexity capabilities capable of matching the variation and complexity of both internal organizational, IS, and external environments.
- *Change rate*. Speeding up the rate of gap reduction between IS effectiveness and changing requirements of users via quickened learning action loops and "real time" action on their feedback as the iterative process continues.
- Modular design. Using modular architecture so as to allow components to be removed, replaced and reconfigured in ongoing dynamic fashion with less damage to adjacent IS components than current tightly coupled designs allow.
- *Positive feedback.* Enabling vague initial redesign ideas (insignificant instigation events) to more easily spiral into dramatic new structures by using an iterative design approach that more readily fosters the emergence of new IS architecture.
- *Causal intricacy*. Framing the process of mutual adaptation not just as a matter of alignment but as a dynamic interplay over time of co-evolving interactions, relationships and effects.
- *Coordination rhythm.* Taking advantage of the irregular oscillation principle or dynamic oscillation to legitimate not only top-down control versus bottom-up autonomy, but also the irregular influence of IS design experts and co-evolving user initiatives, and the different forces or mechanisms that may be contradictorily involved in the realignment process as the broader environment changes.

Information systems should not be developed as static entities, but should be allowed to grow and adapt to emergent user requirements. Our seven first principles

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framework provides important insights not only for dealing with the emergent nature of IS, but also for designing and enabling more expeditious co-evolutionary adaptation. These principles contribute significantly to IS designer and user:

- · understanding of complex systems; and from this their
- modification and design of IS systems capable of altered and more effective new functions; and their
- enabling more effective adaptation of ISD in changing environments.

Future studies may benefit from our attempt to advance the IS community's understanding of how most effectively and expeditiously to deal with the complexity dynamics related to ISD. Admittedly, our contribution is a first step towards designing more adaptive ISD; it remains conceptual in nature. A further step and natural direction towards developing a complexity theory of ISD would be to apply our suggested framework to a longitudinal case study analysis. Then, the tentative conclusions and theory ideas stemming from the case can be subjected to experimental analysis with the use of agent-based computational experiments.

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