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When innovations meet chaos: Analyzing the technology development of printers in 1976–2012

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ABSTRACT

This paper applies chaos theory to innovation processes, highlighting nonlinear behavior and temporal dynamics in the process of replacing old and established technologies with the newly created ones. We employed the local Lyapunov exponent (LLE) to develop our model of analysis and define the edge of chaos. To illustrate our ideas, we analyzed the development of printers during the 1976–2012 period using patent application data. The results of the chaotic model were further enriched with a real-world industry review. We discuss the implications for research on chaotic dynamics of change, evolutionary processes of innovation, and managerial practices.

1. Introduction

"You must have chaos within you to give birth to a dancing star."—Friedrich Nietzsche

There is an obscure but deterministic rule that the whole world is moving toward disorder or a chaotic status (Burgelman and Grove, 2007; Kauffman, 1995; Pascale, 1999). Consultants and business gurus routinely highlight temporal complexities and put forward prescriptions for "managing the unexpected" (Weick and Sutcliffe, 2001; p. 21), "competing on the edge of chaos" (Brown and Eisenhardt, 1998; p. 7), and "embracing the complexity" (Mauboussin and Sullivan, 2011; p. 89). Chaos theory has thus entered the spotlight of organization and management studies (e.g., Cheng and Van de Ven, 1996; Dooley and Van de Ven, 1999; Hibbert and Wilkinson, 1994; Hung and Tu, 2014; Jayanthyi and Sinha, 1998; Levy, 1994; Lewin, 1999; McMillan and Carlisle, 2007; Plowman et al., 2007; Samoilenko, 2008), causing us to question predictable models and noncomplex assumptions (e.g., linearity, stability, a buyer-supplier dyad, sparse connectivity, and fixed and non-adaptive individual firm behavior). According to chaos theory, unpredictable consequences usually come from rather modest beginnings; that is, the cause is not linearly proportional to the eventual effect. Sometimes, a subtle error will be dramatically amplified far from equilibrium, as the nonlinear dynamic system behaves across time (Hwarng and Yuan, 2014; Maruyama, 1963; Plowman et al., 2007). Despite increasing interest in and the importance of business, relatively little work has been devoted to identifying and measuring the source of chaos, which is critical to our understanding of the nature and essence of social or industrial dynamics.

In this paper, we apply insights from chaos theory to innovation processes, highlighting nonlinear behavior and temporal dynamics in the course of the structured relationships between order and disorder, stability and disruption, and continuity

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and discontinuity. Chaos theory is one of the most prevailing approaches of complexity science (Mathews et al., 1999), and through the lens of complexity, social systems such as human interconnectedness, economic models, supply chain, and consumer market can be conceptually treated as dynamic, changing, and co-adaptive systems where the cause-effect relationship is not predictably linear, and long-term equilibrium is not expected. Chaos theory is also able to deepen our understanding of the nature of society by means of paradigmatic shift from traditional Newtonism to evolutionism and complexity science.

Innovation is, by and large, an ongoing process of evolutionary change in which new types of technologies or organizations occasionally replace old ones, and order arises out of a disordered realm. In this sense, we contribute to the innovation literature by identifying where, how, and why the phase transition between order and disorder is likely to occur. It is widely accepted that innovation process analogously resembles biological evolution through the continuity-discontinuity or order-disorder loop (Christensen, 1997; Nelson and Winter, 1982; Simon, 1996). The continuity process reveals that, just like the law of inertia, technological performance improves gradually following the evolutionary trajectories of a certain paradigm (i.e., incremental innovation). Correspondingly, the discontinuity side demonstrates the role of substitution between incumbent and emergent technologies in industry (i.e., radical and disruptive innovation), giving birth to a new paradigm or dominant design (Abernathy and Utterback, 1975; Anderson and Tushman, 1990; Chen and Li-Hua, 2011; Christensen, 1997; Dosi, 1982; Lichtenthaler, 2004; Smith, 1992). While the continuity-discontinuity loops undoubtedly underlie the pace of technological change over time, questions remain as to how the loops emerge, reinforce, and make industries work and evolve the way they do.

Empirically, we chose to study the technology development of printers during 1976–2012 to illustrate our ideas. Changes in printer technology are rich, dynamic, and characterized by a long period of stability-disruption linkages (Christensen, 1997; Clymer and Asaba, 2008; Fleming, 2002; Sood and Tellis, 2005). To illustrate our ideas, we draw on one of the most prevailing mathematical quantifiers, local Lyapunov exponent (LLE), to measure the chaos in the printer industry. Our research is thus quantitative, and has the potential to extend complex analysis of management from the confines of metaphors and analogies into the mathematic and instrumental analysis of change for innovation processes (cf. Davis et al., 2009). We also aim to add to the evolutionary process of innovation by developing an alternative view on punctuated change or paradigm shift (Eisenman, 2013; Roepke and Moehrle, 2014; Ziman, 2000). Standard evolutionary explanations already have a strong stabilizing negative feedback loop built into them. We propose to make more of the evolutionary context, emphasizing the role of positive feedback loops that amplify deviation and cause chaos. This, in turn, accounts for how small initial differences between technologies can turn into large differences given sufficient time.

This paper is divided into six main sections. First is the introduction, noting our research motivations and the contributions to innovation studies using complexity and evolutionary approaches. Second, we provide a theoretical background about chaos theory and innovation processes, upon which we develop a chaotic model of evolutionary innovation process. Third, we detail the design of our research method and the data collection processes. Fourth, we present the results of the quantitative analysis. Fifth, we move to discuss the implications of our study as it applies to chaotic dynamics of change, evolutionary processes of innovation, and managerial practices. We conclude the paper by describing the research limitations and suggestions for further research.

2. Theory

2.1. Chaos theory and its applications

Chaos theory can be traced back to the meteorological observation and experiment conducted by Edward Lorenz in the 1960s. He surprisingly discovered that a subtle initial computational error is most likely to result in dramatic variation and deviation. This concept of sensitivity to initial condition has since become known as the butterfly effect (Lorenz, 1972). Even though such a dynamic system as meteorological behavior seems to be differently stochastic and unpredictable, Lorenz (1963) argued that there are actually hidden underlying orders and a macroscopic simple structure, just like the orbits of motion exhibited by a double pendulum. In this sense, a nonlinear dynamic system might be influentially pulled or attracted by some kind of force – an “attractor” – that directly or indirectly governs the complete system across time (Ruelle and Takens, 1971). An attractor is the spatial structure constructed by evolutionary trajectories of a dynamic system in the long run, and could be seen as the measurement of predictability in a system’s evolution. Consider the Lorenz attractor as an example. The orbital graph of the Lorenz system in the limited phase space from three simple logistic difference equations represents a simplified model of forecasting dynamic systems. Furthermore, through the mechanism of tuning endogenous parameters within a specific interval, the trajectory of the Lorenz system is difficult to predict, but the exterior appearance is like an elegant butterfly flapping with nearly, but not quite, perfectly symmetrical wings. The periodic patterns shaped by Lorenz attractors, a kind of “strange” attractor that is unpredictable in the short run but weakly predictable in the long run, have been referred to as chaos (Li and Yorke, 1975; Ruelle and Takens, 1971; Ruelle, 1989, 2006).

In terms of application, chaos theory was initially used in physics, mathematics, topology, and other fields to forecast the behavior of nonlinear dynamic systems through mathematical or computational modeling (Kauffman, 1995). It challenged the predominant idea established by Newtonism of how our world actually operates. As time went by, the application of chaos theory was extended to the analysis of complex social issues or phenomena, particularly economic systems, industry dynamics, and strategic management (Loye and Eisler, 1987). In economics, the 1980s brought about the study of economic