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From the Habit of Control to Institutional Enablement: Re-envisioning the Governance of Social-Ecological Systems from the Perspective of Complexity Sciences

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Due to the inherent uncertainty in predicting the evolution of phase-spaces in social-ecological systems (SESs), these systems cannot be “optimally” managed through top-down, command and control type of governance designs. Instead, generalized autocatalytic set theory, a type of network and complexity theory with foundations in mathematical graph theory, may be used as a bottom-up, emergent and co-evolutionary framework to design the governance regimes of SESs. Under this theoretical re-conceptualization, the policy and institutional interventions can at best “enable” the policy-makers to nudge SESs towards socially desirable yet ecologically feasible phase-spaces, which in turn are continually revamped as new elements in phase-spaces emerge.

Keywords: Autocatalytic Sets; Adjacent Possible; Phase-Spaces; Co-evolution; Governance Design; Policy Regimes; Global Governance.

1. Introduction

The persistence of wicked policy problems (Rittel & Webber, 1973), coupled with minor and major instances of market failure, pose particular challenges to those looking to employ complexity science concepts to study and steer social, economic, and environmental systems (broadly defined as Social-Ecological Systems SESs in the tradition of Ostrom, 2007). Since the end of Second World War, the top-down command and

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control style management of global SESs by international organizations has placed human civilization on an un-sustainable path. The unparalleled loss of biodiversity (Sala et al., 2000), growing food insecurity (Bohle, Downing, & Watts, 1994), rising in-equity in global distribution of wealth (Palpacuer, 2008), and runaway human-induced climate change (Stocker et al., 2013) are but few symptoms of this unsustainable pathway.

It could be argued that since the dawn of the industrial revolution, SESs have been mismanaged under the garbs of free market capitalism, benevolent colonialism, and the scientific management of global economic, ecological, and social capitals (Zia, 2013). The current configuration of international organizations, which we define as a global governance regime, further reinforces this unsustainable pathway. Worse, the Newtonian conceptions of political economy (for examples, see Romer, 1990) have incentivized the creation and sustenance of controversial international organizations such as World Trade Organization, World Bank and International Monetary Fund, which perpetuate an "optimization-envy" in the management of inherently complex SESs.

This optimization-envy is predicated on the Newtonian conceptions of equilibrium in dynamic systems, which pivot the design of global governance regimes and international organizational structures to the sustenance of free markets; these conceptions maximize endogenous economic growth while neglecting medium- to long-term response of ecological and natural systems, such as global scale food insecurity induced by anthropogenic climate change and biodiversity loss. Governance of SESs is ultimately a complex game of balancing market values, such as maximizing global social welfare function through the promotion of free trade, with public values, such as ecological conservation.

Promoting short- to medium-term unfettered economic growth over long-term ecological conservation is an example of the "habits of control" that are widely observed in the current global governance and policy regimes. An unintended consequence of this top-down global governance design perspective is that global-scale ecological crises, such as biodiversity loss and climate change, have emerged as existential risks for human civilization; they cannot be effectively mitigated without regulating free markets that cause the ecological crises in the first place. Sociologist Max Weber (1947) observed that with Newton we became disenchanted and entered modernity. The "habit of control" is part of this Newtonian perspective we still live with, and it fails us in a world where we cannot know ahead of time a sufficient understanding of what is probable or what is even possible (e.g. see Kauffman, 1999, for a critique of the Newtonian paradigm).

We argue in this article that complexity science offers some critical insights into understanding the operating dynamics of SESs and intra-societal dynamics shaping economic and political systems. Those readers who are less familiar with the advances in complexity science are encouraged to read some of the major works in the field drawn from physics, biology, and computer science. Recently complexity science has been applied to the study of markets (Axtell, 2001), societies (Epstein, 2006), public policy (Morçöl, 2012), and governance networks (Koliba, Meek, & Zia, 2010; Teisman, van Buuren, & Gerrits, 2009). A variety of trade publications provided essential concepts, computational underpinnings, and major characteristics of complexity science (emergence, self-organization, etc.). Of these essential concepts, we discuss one that became prevalent in recent decades: the theory of generalized autocatalytic sets (GACS). The GACS has been used to better understand the frontiers of certainty in complex systems. Some of the key concepts from GACS theory are phase-spaces, the adjacent possible, co-evolution, and general autocatalytic sets.

According to Longo and Montévil (2013), a “phase-space is the space of the pertinent observables and parameters in which the theoretical determination of the system takes place” (p. 64). Changes in phase-spaces move systems through generative iterations of “adjacent possible.” Kauffman (1999) defines “adjacent possible” as the successive evolutionary pathway in which autonomous agents move through a temporal sequence, reproducing themselves with mutations enabling their adaptation to the changing environments. In this context, some may be disappointed to learn that too little is known about the evolution of phase-spaces in the SESs, primarily due to scientific inability to predict the nature of mutations and adaptations in the adjacent possible. This is a very humbling rebuke to the air of certainty that prevails in much Newtonian science and the habits of control that has evolved with it.

Under the Newtonian paradigm, the chains of causality, such as that C follows from B which follows from A, have been used to predict future phase-spaces of a system. In contrast, biological systems, including natural ecosystems, and social systems are relatively less predictable than physics-based systems, a case that has been made extensively elsewhere (Beckage, Gross, & Kauffman, 2011; Beckage, Kauffman, Zia, Koliba, & Gross, 2013; Longo & Montévil, 2011, 2013; Zia, Kauffman, & Niiranen, 2012). The capacity of researchers to predict the future states of biological systems, or their sub-components, is diminished. This is because the nested hierarchical structure of biological functions—nucleotides forming DNA, which form genes, which form cells, and so on—provides a virtually endless combinatorial variations that are sensitive to environmental conditions and respond to autonomous decision making by higher order organisms in the nested hierarchies of ecological systems.

In social systems, the behaviors of autonomous agents, individual members of societies, are governed by constellations of rules, norms and shared strategies, which evolve over time (Ostrom, 2005). We call this system of explicit and tacit rules, norms, and strategies that forge and sustain the material bonds that form families, communities, and organizations over multiple generations “institutions.” In modern societies, economic markets are examples of established institutions that govern the exchanges of goods, services, and resources.

Institutions evolve and the evolutionary patterns of the phase-spaces in these social systems are essentially stochastic and often unpredictable. In other words, they are “unprestatable” at longer timescales (Longo, Montévil, & Kauffman, 2012). The unprestatability here refers to the theoretical inability to accurately identify the elements (observables and parameters) of future phase-spaces. The unpredictability and unprestatability in social systems arises not just from the internal dynamics of social systems (e.g. revolutions and technological advances), but also from the mutual interdependence of social systems with ecological systems (e.g. provision and regulation of food, air, and water based ecosystem services from ecosystems to sustain the populations, as defined in Millennium Ecosystem Assessment (2005)). Predicting the evolution of phase-spaces in SESs is inherently beyond the capacity of the Newtonian paradigm.

In this article, we argue that the habit of top-down control in governing SESs often fails because top-down management is predicated on the assumption of complete knowledge of phase-spaces. We posit that governance theorists need to look for bottom-up emergence; they should acknowledge the unpredictability in governance systems because of their co-evolutionary nature (Kauffman, 1993; Morçöl, 2012). Co-evolution in complex systems typically involves mutual interdependence among their elements. A complexity science inspired form of governance could aim at enabling and coordinating generative co-evolutionary processes in SESs, bearing in mind that when we enable by laws and institutional mechanisms, we cannot entirely pre-state the evolution of phase-spaces in social systems. Hence, as new phase-spaces emerge, adaptive interventions to continuously refine and revise institutional mechanisms are always needed by societies.

In this paper, we present a framework that is informed by complexity science. In this framework, we utilize the generalized autocatalytic set (GACS) theory to model the co-evolution of phase-spaces in complex SESs (Kauffman, 1986). Within the GACS conceptualization, SESs cannot be "optimally" managed due to the lack of determinism in predicting the evolution of their phase-spaces; instead, the policy and governance interventions can at best "enable" the policy-makers in SESs to nudge the system towards socially desirable, yet ecologically feasible phase-spaces, which in turn are continually revamped as new elements emerge in phase-spaces.

In the next section we briefly describe formal GACS theory. In the following section, we review recent studies and modeling efforts in applying GACS to model the evolution of phase-spaces in social, economic, and political systems. We conclude the paper by exploring the potential role of GACS theory in investigating the design and structure of governance regimes of SESs from a complexity science perspective.

2. Formal GACS Theory

Arguably, GACS has played an important role in understanding the origin of life in this universe (see Kauffman, 1993). GACS has its critics in the fields of molecular biology and genetics (e.g. Lifson, 1997; Maynard Smith & Szathmary, 1995). The critics did not accept the hypothesis that GACS can sufficiently solve the origin of life problem in the physical universe. This origin of life problem might not be resolved conclusively anytime soon; we leave it to biologists to debate.

Our interest in GACS is to apply it explaining the "emergence" of phase-spaces in the "adjacent possible" in SESs. The formal mathematical and graph-theoretical concepts of GACS were developed by Hordijk and Steel (2004), Hordijk, Kauffman and Steel (2011), Kauffman (1986, 1993), Mossel and Steel (2005), and Steel (2000). Here we will present the formal definition of GACS from a biochemistry perspective (adapted from Steel, 2000) and then describe the adaptations of GACS methodology in SES modeling applications.

Steel’s (2000, p. 92) version of GACS can be summarized as follows.

Let X denote a set of molecules. A reaction r will denote a pair $r = (\{a,b\}, c), a,b,c \in X)$ which represents an allowable chemical reaction in both forward and backward directions: $a+b \leftrightarrow c$.

Let F (for “food”) denote a distinguished subset of X.

Let R be the set of allowable reactions. A catalyzation is a pair (x, r) where $x \in X$, $r \in R$, denoting that molecule x catalyzes reaction r. Let $C \subseteq X \text{ x } R$ be a set of catalyzations.

Given the quadruple (X, F, R, C), a subset R\` of R is reflexively autocatalytic (RA), if for all r ∈ R\`, there exists an s ∈ supp (R\`): (s, r) ∈ C, connected to F if supp (R\`) = clR\`(F), and connected, reflexively autocatalytic (CRA) if R\` is both RA and connected to F. The clR\`(F) represents the closure of X\`(a subset of X) with respect to R\` that satisfies the condition that for each reaction $a+b \leftrightarrow c$ in R\`: a,b ∈ X\` U W ⇒ c ∈ W, and c ∈ W ⇒ a, b ∈ W, where W is a unique minimal subset of X.

The formal GACS system described above captures “the abstract idea of “life” as a self-catalyzing system that is able to sustain itself by using a stable food source” (Steel, 2000, p. 92). Hordijk et al. (2011, p. 3) present a visual representation (reproduced here as Figure 1) of the formal GACS system defined above for a simple example of GACS with seven molecule types {a, b, c, d, e, f, g} (solid nodes) and four reactions {r1, r2, r3, r4} (open nodes). The food set is F = {a, b}. Solid arrows represent reactants going into and products coming out of a reaction, and dashed arrows represent catalysis. The subset R = {r1, r2}, shown with bold arrows in Figure 1, is a CRA (connected, reflexively autocatalytic) set.

A generalized autocatalytic set (GACS) is a whole system that “gets to exist” in the emergent universe above the level of atoms, precisely because it is a *self-reproducing* whole. In self-reproduction processes, the generalized autocatalytic sets exhibit an important dynamic property. If we consider catalyzing a reaction a “catalytic task,” then the set as a whole achieves “task closure,” as formally defined above, which in turn enables the emergence of new properties of the system’s phase-space in the adjacent possible. This dynamic property of the GACS has been reproduced in earlier applications, such as Caminati and Stabile (2010) and Padgett, Lee and Collier (2003)in social and economic systems, Dittrich and Winter (2008) in political systems, Gabora (2004, 2011) in anthropology, and Marion and Uhl-Bien (2001, 2003), and Reschke and Kraus (2009) in management sciences.

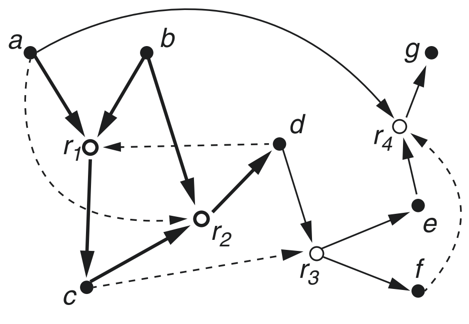

Figure 1. A simple example of a GACS (reproduced from Hordijk et al. (2011, p. 3)).

3. Applications of GACS in Social Ecological Systems

Padgett et al. (2003) developed an agent-based model (ABM) called “Hypercycle,” which used GACS to model the emergence of complex market structures from simple firm interactions, representing market competition, and their coevolution in the technology sector. The Hypercycle ABM has three components: rules (“skills”), balls (“products”), and bins (“firms”). Inside the model, the rules/firms transform balls/products into other balls/products. While the rules/skills are contained in bins/firms, they learn from each other the set of “transformative” rules/skills, also known as “technologies” in the Hypercycle ABM. Products successfully transformed within the firm are passed randomly to one of the firm’s eight possible trading partners. If that firm possesses a compatible skill, it transforms the product further and passes that along in a random direction. Firms continue passing around transformed products among themselves until the product lands on a firm that does not possess a compatible skill to transform it further. At that point, the product is ejected further into the environment, and a new iterative ball is selected to begin the iterative process again, representing the autocatalytic process of economic production and trading of goods, enabled by the coevolution of technologies and firms. This simple model reproduces some interesting properties of the complexity observed in real-world economic evolution of goods and services over time; however, the model has not been applied or calibrated to a specific market evolution yet.

Caminati and Stabile (2010) took a data-mining approach to explore the notion of “modularity” and autocatalytic sets and “to identify the functional and structural units of an empirical knowledge pattern that defines the strongest systematic and self-sustaining mechanisms of knowledge transfer and accumulation within the network” (p. 365). Caminati and Stabile (2010) reconstructed the architecture of the empirical knowledge pattern based on USPTO patent citation data from 1975-1999 and discovered that the recent progress towards catalyzing the information and communication technology revolution is marked by innovative solutions to “complementarities based on strong and *mutual* knowledge interactions between the different application-oriented and base components of the technology” (p. 394).

Dittrich and Winter (2008) developed a toy model to simulate a hypothetical political system that is driven by autocatalytic set theoretical dynamics, as formally described in the previous section. The political system “consists of a list of molecules and a list of reaction rules (i.e. production rules). A molecule represents a specific communication, which in the political system is a decision” (p. 620). In Dittrich and Winter’s toy model, there are 13 different decisions and 20 reaction rules. The simulation model reproduces the evolving network of political organizations given the assumed decisions and reaction rules. They argue that the simulation methodology they propose permits mapping of real data to the set of political organizations and can help us understand the dynamic properties of the evolving political networks in future applications of GACS.

Gabora (2004) argues that ideas are not replicators in human cultural evolution, but minds are. She further argues that human culture is an “associatively-structured network” of ideas that together form an internal model of the world, or “world-view.” A world-view is a “primitive uncoded replicator, like the autocatalytic sets of polymers widely believed to be the earliest form of life” (p. 128). Building on this work, Gabora (2011) suggests that cultural evolution cannot be strictly explained by Darwinian principles of natural selection and replicators, as Dawkins (1976, 1982) did. Instead, “what evolves through culture is *worldviews* [original italics], the integrated web of ideas, beliefs and so forth, that constitute our internal models of the world, and they evolve, as did early life, not through competition and survival of the *fittest* but through transformation of *all”* (p. 16).

According to Marion and Uhl-Bien (2001), autocatalytic interaction is the key to understanding effective complex organizational behavior, because “autocatalysis depends upon emergent distributed intelligence. . . . which cannot be directed but can be enabled by leaders” (p. 398). Marion and Uhl-Bien (2003) applied the insights from the GACS theory to describe the emergence of al-Qaeda leadership as an outcome of social dynamics in Muslim societies.

Reschke and Kraus (2009) apply GACS theory to analyze stability and change in social and cultural systems. For Reschke and Kraus (2009, p. 263), the relations in autocatalytic networks lead to “constrained probabilities” of interactions, which are more probable than the average unconstrained probability over all possible interactions. According to Reschke and Kraus (2009) “institutions came to be seen as sets of habits which form as autocatalytic sets of functional interactions. Those elements that perform relatively better will be selected by inclusion, while others will fade into relative or absolute oblivion. Stability and change depend on the network connections among entities in social systems, such as peer groups, organizations, and societies” (p. 266).

4. Implications and Conclusions

The underlying graph theoretical and mathematical foundations of GACS theory provide powerful tools to formally study the governance of SESs from the perspective of complexity science. If the governance of market and societal conflicts is mediated by nested hierarchies of institutionalized action arenas, also known as “polycentric governance regimes” (Ostrom, 2005), a tweak in institutional rules in any node of this vast network of action arenas essentially catalyzes and enables new set of constraints and opportunities that ultimately affect the autocatalytic cycles of evolution in nested social ecological complexity of our planet. In the context of global governance of SESs, the prevailing habits of control observed in the strategic and tactical behaviors of international organizations need to be re-considered. This reconsideration of the global governance regime from a complexity science perspective can potentially provide an alternative bottom-up pathway for enabling coevolution among various components of SESs as new phase-spaces emerge over time.

In the broad complexity science-informed context of governing SESs, we propose articulation of a new research program to study institutional enablement that is predicated on an institutional framework facilitated by a GACS theoretical perspective on designing governance regimes. Institutional enablement applies a complexity science approach to innovation and systems change. By viewing global SESs as coupled human, biological and physical systems, we plan to explore the opportunities that complexity science and GACS theory could potentially contribute to the reconceptualization of a vision for understanding and steering governance regimes of SESs. With this view, we seek to explore how policy and governance design changes could be treated as *triggers*. These triggers can in turn *enable or disable* the emergence of innovation in societies by affecting the enabling or governing variables that drive a system to stability or instability. The GACS theoretical perspective, with continual refinement, can open up new vistas of understanding in public management and policy sciences. It will require a sustained research program for many years and decades to test and demonstrate the viability of this theoretical perspective. The new journal, *Complexity, Governance and Networks,* can be a great venue to advance the proposed research program, generating novel ways to understand governance networks from GACS and other generative theories of complexity science.

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