SYNECOLOGICAL SYSTEMS THEORY: AN ALTERNATIVE FOUNDATION FOR ECONOMIC INQUIRY

by

Abigail Devereaux
A Dissertation
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DEDICATION

This manuscript is dedicated to the wide open frontier of social science, and to those who have the courage, curiosity, and creativity to explore its wilds.

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ABSTRACT

SYNECOLOGICAL SYSTEMS THEORY: AN ALTERNATIVE FOUNDATION FOR ECONOMIC INQUIRY

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This thesis introduces an original theory of multiple games called synecological game theory and a concomitant framework for social theorizing called synecological systems theory. Synecological game theory is capable of describing the effects of institutional arrangements on the outcomes of gameplay through time. Synecology is a term borrowed from ecology that treats communities as arenas of interaction among species, in contrast to autecology, which treats individual species like duplicates of one another. Synecological systems theory helps theorists understand, describe, and simulate the evolution of entangled interactions, including the process of entanglement itself. Synecological game theory is the primary tool of synecological systems theory, where the systems in question are envisioned as evolving ecologies of games. Synecological game theory is a new branch of game theoretical analysis that describes how agents are able to solve collective action problems. It complements repeated and multistage game analyses,

rather than replacing them. Like repeated and multistage games, synecological game theory is process-driven. Unlike repeated and multistage games, player knowledge, computational resources, and cognitive ability is strictly limited. Synecological game theory describes an extended system of action where not all players interact, play the same games, or have the same goals. This thesis contends that explicitly modeling the context of a game with suboptimal or perverse outcomes 1) exposes various institutional dependencies enabling perverse outcomes and which might be subverted through evolutionary or other processes, 2) expands the solution space and thus may provide avenues to different outcomes than predicted by traditional game analyses, and 3) endogenizes policy changes to within the system by requiring public interactions to be explicitly modeled and subject to the same computational, epistemological and cognitive limitations on policy makers as on other players in the system. Synecological systems theory fills a gap in current theoretical approaches to economic problems and can be said to be a kind of mesoeconomics, more systems-aware than microeconomics but more rooted in the action of heterogeneous agents than macroeconomics. This thesis builds a basic theoretical framework for synecological systems theory and provides a first evolutionary model to illustrate how synecological gameplay expands the explorable solution space by explicitly modeling traditionally implicit relationships. The thesis concludes by outlining a new frontier of exploration in social science opened up by the mesoeconomics of synecological systems theory: new questions economic theorists may ask, and the potential for new answers to questions long thought to be closed.

CHAPTER ONE:
THE ROADMAP FOR A NEW SOCIAL THEORY

> When the time came to invent economic theory…[t]he procedure of invention was often to accept some such self-suggesting analogy and make the economic questions fit it; not to ask what is peculiar and essential in economic questions, what is the essential nature of the world to which those questions belong. (Shackle 1972: 3)

1.1 The Modeling Problem in Economics

What should economists do?

James Buchanan asked this question of his fellow economists in 1964. If we were to sample the average academic economist in the mid 20th century, they would likely agree that economists study how people allocate scarce resources under constraints by satisfying their preferences over all economic opportunities. In 1964, Buchanan advised economists to understand and design the kinds of institutions that protect and increase choice[1] rather than focus on allocations[2]. Since then, the question of what should economists do pops up frequently in treatises that purport to break new ground in the subject, or in economic fields where the economist's expertise is closely entangled with the design of social programs and the management of economic systems.

Should is a loaded word for a science that isn't closed, whose frontier lays before and not behind it. It smacks of hubris to shackle such a young science with normative chains, as if practitioners of economics' nascent form have the knowledge and ability to design the contours of its mature form. There is a tension between the established mainstream economic theory exemplified by the static neoclassical method, and the frontiers hinted at by process-based mainline economic theory.

The neoclassical method's *ceteris paribii* statements effectively close a problem to outside influences and true movement through time so as to treat it with analytical methods imported from reversible thermodynamics. Closing problems opens doors to apparent predictive power: ignore external influences, ignore open-ended evolution, ignore feedbacks between changes and change-makers, and one can solve for a 'unique' equilibrium emblematic of a desired social state. Resultant rarefied equilibria are more analogy than reality, as they necessarily do not come with a set of processes with which to realize them given a system of many and entangled influences, open-ended evolution, and strong feedbacks between changes and change-makers.

Opening problems to external influences, true novelty and surprise, and entanglements between changes and change-makers closes doors to apparent predictive power. If we do not *know* or cannot *estimate* everything that shall effect the future we are to predict, then we cannot *say* what the contours of the future shall be. Certainly not in a precise-enough manner to satisfy a committee seeking to recommend a policy to realize some desired social state some number of years into the future.

A different question than what should economists do better illuminates this tension in modern economic theory: What can economists say?

If social states are simple, generally static and estimatable, and the feedbacks between changes and changemakers are either known or estimatable, economists can say quite a lot with the neoclassical method. Call these situations *tractable* to the neoclassical method. Scientific disciplines are characterized by many methods, depending on the problem and desired answer in question. Classical mechanics is not suited to quantum-level analysis, but it is sufficient for ballistics. The situations encountered in ballistics are tractable to the methods of classical mechanics. The situations encountered after quantum particle interactions, like the possibility that particles can be in two places at once, are intractable to the methods of classical mechanics. Quantum particle interactions are perfectly logical and rational, they merely appear illogical or irrational in the classical mechanical frame.

Suppose, however, that physicists believe all phenomena *should* be explainable by classical mechanics. Then all quantum mechanical behavior would be misclassified as outside of physics, and alternative foundations for quantum mechanical inquiry would be labeled incorrect at the methodological level, as somehow outside physics. Similarly, neoclassical economists behave as if all economic phenomena *should* be explainable by neoclassical methods. All economic phenomena defying neoclassical explanation, and all methodology used to treat social situations poorly explained by the neoclassical method, is then treated as if it is somehow outside of economics. That is, if the answer to what economists should do includes a particular methodology with which to approach economic inquiry.

By asking instead what economists can say, we necessarily must answer the question of what economists can say *with which method*? The method of explanation becomes an explicit part of the question of what economists are able to explain. Phenomena not explainable by the closed theory of rational expectations, for example, may yet be economic phenomena. The appearance of bias in experimental observations, while outside the theory of rational expectations, may be explainable by a more general economic theory that *admits* heuristics (Gigerenzer and Todd 1999; V. Smith 2003).

Science admits a panoply of methods, and a single question can be investigated in several theoretical frames. Science may seek to illuminate a problem only to discover that in a particular frame the outcome to that problem is undecidable. In the social sciences, phenomena has long been modeled as nonlinear, but still predictable (to protect predictive power). Predictive nonlinearity requires some way of weeding out nonlinear systems that may become unpredictable, or chaotic. Doria and da Costa (1991) proved that no general algorithm exists to tell whether an arbitrary nonlinear system with arbitrary initial conditions will be predictable or chaotic. That is, choosing a frame with nonlinearities representative of observed nonlinearities yet has the predictive power desired by social scientists admits no general method of selection.

The inability to decide which is a suitable frame given some desired characteristics like nonlinearity and predictability is an example of a more general phenomenon plaguing the social sciences rooted in Kurt Gödel's discovery that in any axiom system, there exist true propositions that cannot be proved with the axioms of that system (Doria 2017). Gödel's was one of several mathematical discoveries in the 1930s that challenged Hilbert's program of axiomatizing mathematics, motivated by his belief expressed in his 1900 address to the 2nd International Congress of Mathematicians that all problems are solvable. "This conviction of the solvability of every mathematical problem is a powerful incentive to the worker. We hear within us the perpetual call: There is the problem. Seek its solution. You can find it by pure reason, for in mathematics there is no *ignorabimus*." (Hilbert 1902, as referenced in Feferman 1994).

The inability to decide whether a proposition is true or not true is called *undecidability*. In computable analysis, a solvable problem is a problem for which a Turing machine computing the solution halts (Turing 1936; note that Alonzo Church independently discovered an equivalent formalization the same year). That is, if there exists an effective method of obtaining the value of a function *f*, the *f* can be computed by some Turing machine that halts—finds the solution—in a finite amount of time.

Mathematical economics is struck through with Gödelian undecidability, initially uncovered by Gerard Kramer (1967), who showed that no finite automata could conduct the kind of rational choice embraced by neoclassical economists at the time, a derivative of the theory of value developed by Kenneth Arrow and Gerard Debreu. Alain Lewis, Arrow's protégé, updated Kramer's result for the choice-theoretic mathematical economics of the 1980s, namely, that excess demands were not computable. Lewis (1985) showed that any computable version of choice-theoretic mathematical economics either never halts, fails to converge, or halts at a non-optimal choice. On July 21, 1986, Arrow wrote to Lewis in a letter that "[T]he claim the excess demands are not computable is a much profounder question for economics that the claim that equilibria are not computable. The former challenges economic theory itself; if we assume[3] that human beings have calculating capacities not exceeding those of Turing machines, then the non-computability of optimal demands is a serious challenge to the theory that individuals choose demands optimally."

The problem with uncomputability in mathematical economics hinges on what it means for mathematics to describe reality. Reality consists of pragmatic truths, evident through construction and empirical validation. Mathematics doesn't make sense as tool to study the pragmatic truths of reality if we cannot calculate in it. And theoretically computable functions must be practically computable to be useful in making predictions about or in describing pragmatic reality. Thus, mathematical economists must concern themselves with NP-completeness, where NP constitutes the set of computable problems whose computation time is non-deterministically polynomial. Even though computing machines have gotten much faster since Turing wrote his thesis, P, the set of algorithms known to halt in polynomial time, remain a good heuristic for the feasibility of solving a problem. However, while it is intuitive that P is contained in NP, it is not known if P = NP. Problems proved to be NP-complete are heuristically considered to be infeasible; these problems are called NP-hard.

Think of it this way: a problem is NP-complete if we do not know if there always exists a solution. A well-known example of a problem in NP is the computation of the first Nash equilibrium of any game. As Nash (1951) proved, there exists at least a mixed-strategy equilibrium for any game, though Daskalakis et al (2009) showed that in general there doesn't exist an efficient algorithm for computing it. Knowing whether there is a second equilibrium of a game is NP-hard (Papadimitriou 2011).

Before Lewis's 'profound' discovery about the noncomputability of excess demands, one of the biggest threats to the suitability of equilibrium analysis in economics was posed by the Sonnenschein-Mantel-Debreu (SMD) proof that the functional forms of aggregate demand functions were far less restricted than required for general tractability (Sonnenschein 1973; Mantel 1974; Debreu 1974). Therefore, as was proved in the decades after the result, aggregate demand functions need not have unique equilibria, be stable, or allow for comparative statics and econometric identification (Rizvi 2006). An observation about forcing one equilibrium state to resolve to another may be relevant and explanatory if the phenomenon in question is stationary, or doesn't admit multiple equilibria.

In keeping with the Wolfram-Chomsky classification system, I identify four types of system dynamics: static (class 1), periodic (class 2), complex (class 3), and chaotic (class 4). If system behavior is not class 1 but instead falls within classes 2-4, observations about transforming equilibria, particularly when transformations themselves aren't endogenous, are of questionable relevance. As discussed above, many if not most real economic phenomena seem to fall within classes 2 and 3. That is, most economic phenomena are *not* sufficiently explainable by modeling those phenomena as converging to static equilibria.

1.2 The Suitability of Theoretical Frameworks for Modeling Economic Phenomena

The above discussion leads to the obvious question: what theoretical frameworks are most and least suited to economic inquiry, given the nature of social phenomena and the problems and solutions economic science wishes to illuminate?

In order to answer this question, we need to first determine what we mean by economic phenomena. Define an economic phenomenon as some state *S* of an economic system, *E*. (Note that it is unclear to what extent one can scientifically separate a social system at large from its economic system). *S* describes the properties of the economic system of a whole, using some collection of indicators or patterns of agent or industrial transactions. *S* must be some abstraction of *E* in order to be tractably modelable; however, we require at the very least that *S* is able to sufficiently represent all significant properties of *E*. A state of the famous Battle of the Sexes game must include information about each sex, not just one, as censoring one sex misses half the story.

Economic phenomena are characterized by a set of stylized facts: truisms, generalities, observations, experimental results, and psychological insights. A subset of these stylized facts that play well with neoclassical setups is

1) consumers and producers generally prefer more to less;
2) it is rare to see $20 bills lying around on sidewalks; and
3) economies tend to grow at constant rates.

Other of these stylized facts play less well with neoclassical setups, and as such have had much ink spilled on them, like

4) people choose in contexts and form relationships, and that ignoring choice context misses the out-of-model ways in which people interact to exploit gains from trade and sets up models to fail in unpredictable and possibly spectacular ways, and leaves solutions to problems like those associated with negative externalities up to exogenous forces by including the formation of relationships in this model (Farmer 2012; Kirman 2014; Ostrom 1990, 2010; Haldane & May 2011; Helbing & Kirman 2013);
5) decision-making, problem-solving and plan-formation are typically characterized by processes, yet, much of economic theory glosses within-plan choice processes by insisting on a mathematics suitable for reversible thermodynamic systems, what Stuart Kauffman (2000) calls the Newtonian paradigm. The implications of departing from the Newtonian paradigm include, perhaps most importantly, no more "as if" theorizing (as in Friedman 1953), an explicit recognition of the nonstationary "diachronic" nature of complex evolving social systems (Shackle 1972, 1974; Potts 2000; Farmer 2012; Kirman 2010; Axtell 2005), and the explication of constructive processes that tranform current or suboptimal equilibria into more efficient equilibria (Velupillai 2007)
6) knowledge is fundamentally incomplete due to the asymmetry of time and knowledge (Bergson 1908; Knight 1921; Hayek 1945; Shackle 1972; O'Driscoll, Rizzo & Garrison 1996; Koppl et al 2015). The states of socioeconomic systems are fundamentally unknowable at longer timescales, exhibiting what Longo et al (2012) and Zia et al (2014) characterize as "unpredictability and unprestatability";

7) macroeconomic patterns may be irreducible to simple aggregations of agent actions, characteristics, and goals as socioeconomic systems exhibit a high level of complexity in the interactions of individuals, groups, firms, and other social components; economic systems exhibit complex nonlinear behavior like herding, cascades, path dependence, and phase transitions e.g., in financial systems; (Potts 2000; Axtell 2005; Farmer 2012; Miller & Page 2009; Kirman 1992, 2010; Arthur 2013; Beckage et al 2013; Helbing & Kirman 2013).
8) rationality is heterogeneous (Klein 2011), bounded (Simon 1996, 1972; Russell 1997, 2015), heuristic (Gigerenzer & Todd 1999), and when combined with the other points above coheres to form patterns at the macroeconomic level in a way that is a property of the system and not merely the aggregation of agent choice (Smith 2003; Wagner 2012a; Farmer 2012; Kirman 2010). Furthermore, realistic individual decision-making tends to use much less computing power than rational choice theory predicts (Kahneman 2011; Axtell 2005).
9) social systems are made up of agents (choosing individuals, firms, political entities, etc) that are *generally* not fully connected; that is, social systems are typically nonintegral and topologically graph theoretic rather than integral and topologically field theoretic (Potts 2000); in particular, social institutions can be represented as a dynamic structure of interactions, relationships, and commonly-agreed upon rules of interaction; furthermore, information and other asymmetries are the norm in real systems.

1.3 Introduction to Synecological Systems Theory

Suitable economic modeling frameworks must be capable of modeling complex-enough phenomena to sufficiently explain and describe real economic phenomena, while still simplifying reality. I contend that a sufficient modeling framework for economic inquiry is 1) constructive and algorithmic, 2) capable of explaining class 3 complex orders, that is, self-organizing complexity and spontaneous order emergence, 3) sensitive to all kinds of resource constraints, including and perhaps especially computational resource constraints.

In light of those requirements, I introduce *synecological systems theory* as a candidate theoretical framework that is constructive and algorithmic, capable of generating spontaneous or and of modeling self-organization, and is sensitive to computational resource constraints. Synecological systems theory is a theory of multiple games, where a system is modeled as an ecology of games. Call the study of these particular kinds of multiple games, which are defined below, as *synecological game theory*.

In the current literature, multiple games analysis is typically conducted to investigate the formation and influence of institutions like norms and culture by looking at how mental models used to select strategies in one game can influence how strategies are selected in another (Bednar 2018; Bednar & Page 2018; Bednar & Page 2007). The innovation in multiple games analysis described in this thesis comes through considering how games are connected to each other by analogizing games as action arenas.

I characterize synecological action areas such that: (i) the outcome of a particular game furnished inputs to another particular game; that is, games are differentially compatible and synergistically coupled with each other either randomly or specifically; (ii) an agent is required to play a certain sequence of games before attaining some pre-specified goal, that is, the realization of a goal requires the execution of a plan characterized by a sequence of synergistically coupled games and a variety of nonintegrally connected players. Many interacting game sequences with particular interdependencies form an ecology of games (Long 1958; Wagner 2012a; Lubell 2013; Smaldino & Lubell 2014). Define a synecological game as a particular chain of synergistically coupled games such that no player plays all the games in the chain. An ecology of synecological games is a synecological system.

Synecology is a term borrowed from theoretical ecology to mean the study of a group or community of organisms as opposed to *autecology*, which refers to the study of an individual organism. Synecological systems theory is to representative agent theory as the study of a community of organisms is to the study of a sum of individual organisms. Summing up over representative agents leaves unanswered the question of how institutions arise from the interaction of individuals, a question often left to the designer to answer by assumption or by inferring patterns from data. The gold standard of microeconomic theory is to divorce situations from wider contexts (ceteris paribus) to find laws that hold true regardless of context. Such theoretical architecture is suitable for studying simple situations closed off and independent from the greater realm of economic activity. But it is inappropriate for studying economic systems.

Game theory was built to be a language of interdependencies; multiple games analysis can provide a bridge between traditional game theory and a new kind of social theory.

Synecological systems theory possesses the following advantages over current microfounded theories of economic systems: 1) it is capable of describing emergent, spontaneous and polycentric orders (as I show in Chapters 2 and 3), 2) it allows for the endogenization of contextual choice without the need for the theorist to analytically derive a solution space, meaning that contextualizing a prisoner's dilemma is as simple as adding new games and players and relationships in, say, an agent-based simulation where such additions are simple; 3) it blurs the line between "public" and "private" activities and interactions, encouraging theorists to include all relevant interactions in a model of a particular sphere of interest instead of leaving out how public intervention in particular effect private behavior; 4) its knowledge assumptions are weak; 5) it is designed to be mathematically constructive at the system level and to require the use of computational simulations to study system-level characteristics for any reasonably sized system, thus avoiding the computability problems that increasingly plague traditionally microfounded macro theory (Lewis 1985; Velupillai 2007).

In constructing synecological systems theory, I take seriously the contention by Fredrich Hayek (1937, 1945) the importance of understanding the use of knowledge in society for understanding how people do what they do, and the existence and sustainability of the institutions that regulate what people do and how they do it.

Roger Koppl (2018) defines SELECT knowledge as “Synecological, EvoLutionary, Exosomatic, Constitutive and Tacit.” Synecological, in Koppl’s usage, describes knowledge held outside the individual, in groups of other people or in social institutions. Contrast SELECT knowledge to what Koppl calls speculative knowledge. Speculative knowledge consists of the models individuals and groups of experts use to describe the world; it is the attempted concretization of knowledge, not knowledge itself. In the terminology of Henri Bergson (1908), knowledge accumulates and changes with time in an indescribable and continuous way—it has *duration*—while speculative knowledge is an attempt at the static closure of knowledge, a concretization without duration. Synecological knowledge attempts to capture part of the duration of knowledge. Note that synecological knowledge can be and often is developed evolutionarily, but it is a separate category from evolutionary knowledge. This distinction will be made more formal later, when I discuss the differences between how evolutionary game theory expands the one-off solution space, relative to the ways in which synecological game theory expands the one-off solutions space.

Synecological systems are systems whose agents may engage in simpler underlying behavior that, when conjoined with the behavior of other agents, produce complex, unprestatable system states. Synecological implies *synergy*, or what Bob Coecke (2017) calls “togetherness.” The synergy (togetherness) of combining abstractions foo_1 and foo_2 is, a Coecke put it, “the new stuff that emerges when foo_1 and foo_2 get together” (ibid: 63). Synergy is a key and often unexplained feature of socioeconomic systems.

Suppose an agent *i* plays a game with agent *j*, then plays another game with agent *k* such that features of the first game—its payoffs, or perhaps how it is played—determines something about the features of the second game. Suppose then that *k* plays a game with *l* such that features of this game determine something about the features of the game between *k* and *j*. The coupling of the first and last two games results in different gameplay than if each of those pairs had been independent from one another; more importantly, the way *j* and *k* play games with *i* and *l* creates a link of influence between *i* and *l* even though *i* and *l* do not play directly with one another, and presumably, may not even know of the other's existence.

While I introduce synecological game formalism in Chapter 4 and its concepts in Chapters 2 and 3, I'll include its basic definitions here. I start with the definition of an **extended game**, then define a **synecological game** as a special case of an extended game. I further note that other stage and repeated games are themselves special cases of extended games, but that they do not intersect perfectly due to key structural differences between them.

Definition 1: An **extended game** is an *m*-length chain of games γ_i with *N* heterogeneous players, where not all players necessarily play every subgame in sequence, and such that at least 1 player is shared between sequential subgames in the extended game. Extended games are a generalized version of multistage and repeated games, where stages can be of different dimensions, and need not have more than one player in common.

Definition 2: A **synecological game** $\Gamma = \{\gamma_1, \dots, \gamma_m\}$ is an extended game of length *M* where the following conditions hold:

(i). *Weak Connectivity* - At least one player, but not all players, are shared between sequential games. That is, the intersection $\gamma_i^{\text{players}} \cap \gamma_{i+1}^{\text{players}} \neq \emptyset$ in the extended game sequence.

(ii) *No-dictator Condition* - No single player spans the entire extended game. That is, $\bigcap_i^M \gamma_i^{\text{players}} = \emptyset$.

(iii). *Entanglement* - Suppose the shared player *i* plays subgame γ_{j-1} first, and subgame γ_j subsequently. Then, the payoffs v_i^j of subgame γ_j are a function of the payoffs v_i^{j-1} of the previous game γ_{j-1} and of the strategic actions of the nonshared players in γ_j.

Note primarily the differences between multistage and repeated games made evident by the definition of a synecological game above. Unlike the weak connectivity defined by (i), multistage and repeated games are characterized by full connectivity, where all players are shared between sequential games; even if not all players play every stage of the game, all players have access to the gameplay histories, which include the strategy profiles and payoff vectors of all stages. For the same reason, multistage and repeated games cannot satisfy (ii), as *every* player spans the entire extended game. Finally, and most importantly, multistage and repeated games have not been modeled with the outcomes of stages explicitly coupled together. That is, each stage resolves into some numerical payoff, which itself may affect future stages of the game, but is also an independent component of the aggregate payoff at the end of the stage or repeated game (and if the repeated or stage game loops infinitely, the analytical end if the derivation of equilibria are computationally possible). I go into more detail as to these differences in Chapter 4, but as a preview of those later chapters, consider the graph representations of each game below. In order to understand the terminology employed, let's preview another definition of a synecological game:

Definition 3: A synecological game Γ can be specified as a four-tuple in brackets $\Gamma = \langle \mathcal{G}_\Gamma, N_\Gamma, \mathcal{A}_\Gamma, V_\Gamma \rangle$, whose first entry $\mathcal{G}_\Gamma$ is the graph that specifies the topology of Γ, the second entry N_Γ is the ordered membership of each subgame, the third entry $\mathcal{A}_\Gamma$ is the overall strategy space of the synecological game, and the fourth entry V_Γ specifies the payoffs including coupling functions for each game.

Suppose, then, we take the example synecological game Γ with graph $\mathcal{G}_\Gamma = \{\gamma_1 \rightarrow \gamma_2, \gamma_3 \rightarrow \gamma_2\}$ and membership $N_\Gamma = \{\{1,2\}, \{2,3\}, \{3,4\}\}$ (we need not specify the coupling to visualize the game structually). We can visualize Γin Figure 1.1, where solid directed blue lines represent relationships between games, and dotted red lines represent membership in a given game:

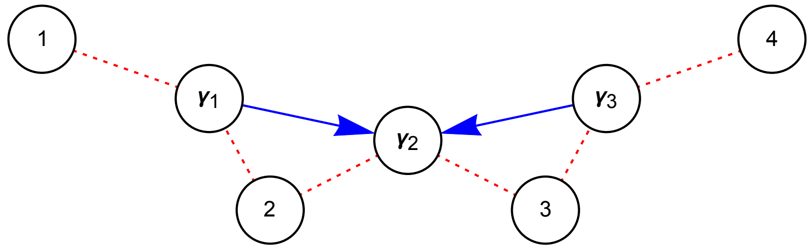

Figure 1 A Synecological Game

Figure 1: The synecological game Γ. Solid directed blue lines represent relationships between games γ_i, and dotted red lines represent membership of player i in a given game.

Contrast the synecological Γ with a typical evolutionary multistage game with the same number of component games and members, as in Figure 2:

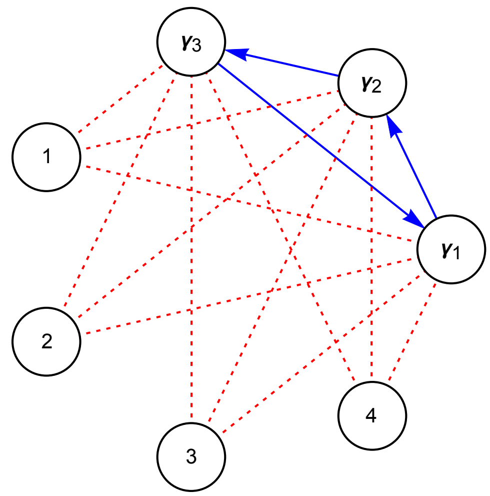

Figure 2 A Multistage Game

Figure 2: An evolutionary multistage game, where solid directed blue lines represent relationships between games γ_i, and dotted red lines represent membership of player i in a given game.

and with a four-member repeated game, as in Figure 3:

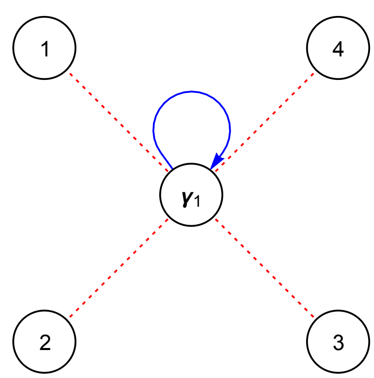

Figure 3 A Repeated Game

Figure 3: A repeated game, where the solid directed blue loop represents the replaying of game γ_1, and the dotted red lines represent the membership of player i in γ_1.

Synecological systems allow agents to utilize system knowledge indirectly by engaging with their own local knowledge sets, and subject agents to the effects of rules-following by distant agents, with whom they may never interact directly. System behavior is no longer a direct reflection of the process of individual decision-making. This means, for any but the smallest synecological games, that the modeler needs to specify all the games and dependencies in an agent-based evolutionary format in order to get a sense for how and whether the system resolves into patterned behavior after a period of time.

For a simple example of the difference between a traditional and a synecological game, consider the tried-and-true prisoner's dilemma. I start with the prisoner's dilemma not only because it is so analytically popular, but because of an observation made by Elinor Ostrom in her Nobel lecture (2010) that you need at least three people to sustain a prisoner's dilemma:

> The classic models have been used to view those who are involved in a Prisoner's Dilemma [PD] game or other social dilemmas as always trapped in the situation without capabilities to change the structure themselves. This analytical step was a retrogressive step in the theories used to analyze the human condition. Whether or not the individuals who are in a situation have capacities to transform the external

variables affecting their own situation varies dramatically from one situation to the next. It is an empirical condition that varies from situation to situation rather than a logical universality. Public investigators purposely keep prisoners separated so they cannot communicate. The users of a common-pool resource are not so limited. (ibid: 648)

As noted in McAdams (2008), there may be a sociology of science reason for why theorists find prisoners' dilemmas so analytically popular: the prisoner's dilemma has a single equilibrium, quite rare in games in general; the prisoner's dilemma seems to imply fundamental interactional failure and thus provides a strong case for third party intervention. What I'm interested in are not the analytical implications of existing prisoners' dilemmas, but how prisoners' dilemmas might arise and why, if they aren't resolved, they remain unresolved.

I start with the classic prisoner's dilemma. The key situational assumption that reinforces the anti-social equilibrium is that prisoners are unable to communicate with each other, as noted by Ostrom above. In a hypothetical synecological prisoner's dilemma game, *confessions* could be a variable input to, say, a **warden's** game with a **district attorney** to obtain more money for the prison in competition with other wardens under the district attorney's jurisdiction. Think of it as the district attorney representing a 'demand for confessions,' and wardens responding to that demand through some self-interested mechanism that transforms greater funds secured for their prisons into funds for themselves, greater prestige or power, greater ability to altruistically improve prison conditions, and so forth. Choose one or several of these incentives per warden, and suddenly you've got a competitive market for confessions.

Let's extend the prisoner's dilemma into a synecological game by considering all the essential players and games required to endogenize the anti-social solution, and the interdependencies between the players and games. First, we add two more players to the original two-player game: the warden and the district attorney. Now, let's consider the games that generate the incentives required for the warden to come upon parallel solitary confinement (SHU) as the best way of generating the anti-social solution we know as the prisoner's dilemma. We start with the district attorney.

Perhaps the district attorney is running for office and is hopeful that more convictions will appeal to their prospective constituents. Suppose the district attorney controls funding to prison system, and promises more funding to prisons which obtain more confessions from prisoners. More funding means more income and prestige for the wardens whose prisons obtain it. Given that the warden is incentivized to produce more confessions and has a large amount of control over the institutional environment in which prisoners find themselves—having control over access to privileges and housing arrangements, for instance—what is the best way for them to obtain more confessions?

In a synecological game, especially an agent-based game with many rounds of play, wardens would not necessarily know ahead of time but could discover that given the choice between keeping prisoners in the general population and putting them in solitary, splitting up collaborators generates a higher percentage of confessions than not. We see once we expand and contextualize the game using multiple games analysis that the prisoner's dilemma *emerges* as a solution due to the specific institutional realities built into the game: (a) the costs of staying mum are relatively low in the general population where behavior prior to interrogation can be coordinated and relatively high in SHU; (b) prisoners have fewer rights and can be subject to solitary confinement; (c) that prison is a dangerous environment, allowing for credible threats of retribution via allies *outside* prison to be made if suspected collaborators remain in the general population before interrogation. In short, prisoners find themselves in an anti-social dilemma because of a lack of agency as prisoners, the existence of SHU, the exigent political and financial incentives to be put into SHU, and an epistemologically myopic view of the game at the system level.

The advantage of specifying the context of choice in the form of interdependent games comes with the disadvantage that we cannot cleanly separate private and public orders in the system. Players instead gain or lose membership in various games, some of which may be publicly ordered, and others privately ordered. Any influence flowing from public to private, or vice-versa, must be specified in terms of game membership and interdependencies between games.

This thesis is organized as follows. Chapter 2, which was co-authored with Richard Wagner and published in *The American Economist* (2018), introduces the main concepts of synecological systems theory as an open-ended evolutionary social systems theory. Chapter 3, also co-authored with Richard Wagner, deepens those concepts and in particular develops an infrastructure for synecological game theory as an ecology of games. Chapter 4 formalizes synecological game theory. Chapter 5 presents an agent-based model of the incentive synecological game, discussed in detail in Chapter 4. Chapter 6, which concludes the thesis, discusses where synecological systems theory might find its best concrete applications.

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[1] While Buchanan used and promoted the rational choice theory of his time, he did not believe being an economist meant working in a particular theoretical frame, and would have likely engaged in process-based computational reasoning to approach certain problems had he access to the kind of computational tools available to economists today.

[2] Buchanan worried that focusing on preferences instead of choice allows normative or ad-hoc declarations of what people want to replace an understanding of how what people choose is associated with their well-being. Robert Sugden (2019) worries that just the ad-hockery with which Buchanan was concerned has found its home in the behavioral prescriptions of modern behavioral economics.

[3] This is a reasonable assumption, given that there is no indication as of yet that humans (or any biologically grounded processes) are capable of hypercomputation. Hayek (1964) himself makes the assumption that humans are at best capable of universal computation, as are some Turing machines.

CHAPTER TWO:
CONTRASTING VISIONS FOR MACROECONOMIC THEORY: OEE AND DSGE

DSGE modeling remains the workhorse of contemporary macroeconomics despite a growing number of critiques of its ability to explain the aggregate properties of an economic system. For the most part, those critiques accept the DSGE presumption that traditional macro data are primitive, causal data. This leads to a stipulative style of analysis where macro variables are explained in terms of one another. In contrast, we set forth an OEE framework for an open-ended evolutionary macroeconomics. Within this framework, systems data are not primitive, but are derived from prior micro-level interactions without any presumption that those macro-level derivations reflect systemic equilibrium among the micro-level primitive sources of action. We explore some contours of an OEE framework by placing coordination games within an ecological setting where there is no agent who has universal knowledge relevant to that ecology of games.

2.1 The Problem of Vision in Macroeconomic Theory

Without doubt, DSGE is the predominant vision around which macro theorists orient their work. To be sure, that vision divides into two main branches, depending on whether theorists think economies are better represented as perfectly competitive (for instance, Lucas 1980; Kydland and Prescott 1982; Prescott 1986 and Lucas and Sargent 1979) or imperfectly competitive (for instance, Greenwald and Stiglitz 1986, 1987; De Grauwe 2010; Stiglitz 2017; and Romer forthcoming). Within both branches, theorists are concerned with the entirety of an economic system, as distinct from micro-level observations that pertain to various parts of that system. The key feature of either branch of DSGE is the presumption that an economic system can be apprehended in its entirety at the macro level. Hence, macro variables are primitive variables that can be meaningfully related directly to one another in a causal manner. In contrast, the open-ended evolutionary (OEE) modeling we explore here treats macro variables as derivative from prior micro-level interactions. Macro variables do not act directly upon one another and are not direct objects of choice. Instead, macro variables emerge through micro-level interactions. There are thus no micro-foundations for macro in the standard sense of resting macro theory on some model of rational choice. There are, however, micro-foundations in the emergent sense of a macro whole bearing an emergent relationship to the micro-level interactions that comprise the macro system.

OEE and DSGE both pertain to systems-level observations, but they differ in how they conceptualize human population systems. DSGE modeling starts at the systems level, posits a system in equilibrium, and examines whether the evidence confirms or rejects the postulate of systemic equilibrium. In contrast, the OEE vision starts with individual-level actions and derives system-level observations through interaction among individual entities. This leads to an ecological or emergent style of reasoning, and of conceptualizing the relationship between the parts of an economy and the whole of that economy. So far as we can determine, the first explicit reference to a distinction between micro and macro levels of economic analysis is Eric Lindahl (1919, translated and reprinted in Lindahl (1939)). Our effort to set forth OEE as an alternative vision for macro theory descends from Lindahl (1919) while recognizing that contemporary tools of thought regarding complex systems have made it possible to work analytically with situations where micro-level interaction does not aggregate directly to macro-level outcomes. There are phenomena that emerge through interaction among individuals that do not pertain to individual action. A solitary Crusoe on his island will not have property rights, will not have conflicts with neighbors, will not generate institutions to resolve those conflicts, and will not generate knowledge through interaction. OEE recognizes that a system of interacting agents cannot be reduced reasonably to a representative or average agent because of nonlinearities introduced through interaction among micro entities.

Furthermore, OEE and DSGE differ in the objects or variables that comprise their analytical foregrounds. For DSGE, resource allocations are the objects of prime analytical interest, as reflected in inquiries as to whether observed resource allocations are Pareto efficient. For OEE, by contrast, primacy of analytical interest resides in interactions among action-taking agents, which brings the institutional arrangements governing those interactions into the analytical foreground. Within the DSGE framework, macro theory pertains to a *synchronized* system of economic interaction; observing an economy is equivalent to observing a team of synchronized swimmers. These swimmers might be regarded as either perfectly or imperfectly coordinated, but they are a team of synchronized swimmers in either case.

By contrast, OEE theories make no claim that economies resemble teams of synchronized swimmers. Economic actions will be generally but not universally coordinated, but in no case is societal coordination truly a team activity. To the extent coordination appears to occur, it is a feature of independent actions undertaken by teams of participants inside the economic system, as illustrated by Dopfer et al's (2005) and Potts and Morrison's (2007) insertion of a meso level of analysis between micro and macro levels. Different institutional arrangements governing those interactions can generate different macro-level observations. For instance, unemployment would not be related causally to some such alternative macro variable as government spending. Measured unemployment would emerge out of micro-level interaction, as that interaction is framed by such institutional features as conventions regarding employment contracts, the extent of public support for being unemployed, and entrepreneurial plans and beliefs pertaining to the creation of new enterprises. In any case, the logic of OEE macro proceeds from simpler action to more complex interaction, as befits the micro-macro relation as one of parts to whole. Accordingly, the analytical mode must be generative or emergent, along the lines of the papers that Epstein (2006) collects. Rather than starting macro analysis by stipulating that observations pertain to states of systemic equilibrium, equilibrium would be a possible outcome of a model and not an input into it. Perhaps the network of economic activities is fully synchronized. But if it were, the analytical challenge for OEE modeling would be to explain how this state emerged from some preceding state where those activities were not fully synchronized, and in a setting where no person or office has possession of the knowledge necessary to impose synchronization, as against explaining how synchronization might emerge out of some non-synchronized state when synchronization was not part of any entity's intention or capacity.

To be clear, we recognize that all economists know the economy is complex. Our motivation in setting forth a new tool with which to shine light on the features of the complex economy is to bring certain crucial social phenomena that lie outside the equilibrium method's explanatory ability into a scheme of macro theorizing, along with the infrastructure to explain it. We believe the equilibrium method cannot be expanded in a way to sufficiently capture these phenomena, and therefore find ourselves seeking to develop a new theoretical apparatus with which to explain them. While there are clear points of commonality between OEE theorizing and macro theory in the tradition of Austrian economics, there are also notable points of analytical difference that lead us to emphasize analytical framework over historical heritage. For further elaboration, see Lewis and Wagner (2017).

OEE theorizing recognizes that societies entail turbulence of various forms, and with many economic practices and institutions arising in the process of people dealing with that turbulence (Wagner 2012a,b). Just as some agents each period inject new enterprises into society, other agents disband enterprises they had previously created. Either way, turbulence is injected continually into the ecology of plans as other enterprises and agents must respond to and adapt to the new information that continually is inserted into the economic nexus. OEE accepts the presumption that people seek to execute their plans effectively, for whoever heard of someone trying purposively to be ineffective in whatever he or she sets out to do? It does not, however, impose the presumption that people are seeking to achieve systemic coordination. To the contrary, it entails the presumption that people are seeking to pursue their plans as fully as they can, even though those plans will often conflict with the plans of others. Some enterprises succeed while others fail, and this is a feature of any system of human action. The extent of actual coordination among individual actions and plans is a systemic quality that lies outside individual choice, even the choices of what conventionally are described as "policy-makers."

2.2 Some Problematics in Choosing between Macro Visions

To have a good fit between model and data is important, but so is congruence among model, data, and the purposes a theorist is pursuing in creating models. With respect to purpose, macro-level theories pertain to systems of human interaction. For the most part, macro theorizing seems to have been pursued more for engineering-like purposes of systemic maintenance and repair (Mankiw 2006). There are, however, also significant scientific issues raised by the very conception of an economic or social system, which James Coleman (1990: 28) explained pithily: "the only action takes place at the level of individual actors, and the system level exists solely as emergent properties characterizing the system of action as a whole." Within a framework of systemic interaction, the system is not an object that can be acted on in its entirety, which means that maintenance of the system is a product of congruity among individual actions within the system.

Though individual actions may utilize such system-level information as prices, there is no point at which individual action can be abstracted away in favor of only considering the movements and relationships among system-level variables or properties. The actions of individuals are entangled with the actions of other individuals, and the structure of that entanglement is as important to the emergence of system-level properties as is the plan an individual executes to attain her goals. In this respect, Barkoczi and Galesic (2016) show that group performance is as intimately entwined with the shape of the group's communication network as with the social learning strategies adopted by each individual group member. To understand the group-level properties, it is not sufficient to abstract away from the individual.

The problem the DSGE vision encounters is that resources cannot allocate themselves, for only people can do that. But people don't act within the DSGE model, they merely respond to the allocative imperatives of the equilibrium model. To find loci of action requires a shift of analytical focus to human governance within alternative arrangements, recalling Nathan Rosenberg's (1960) distinction between institutional structure and resource allocation in his explanation that Adam Smith was more concerned with institutions than allocations. Elinor Ostrom (2010) proposed a richer understanding of how institutional arrangements could overcome commons problems without the need to resort to re-allocative policy measures. In similar fashion, OEE modeling is concerned primarily with the systemic properties of different institutional arrangements for human governance, including the comparative properties of private and public ordering of economic interaction.

Imagine, after the spirit of Thomas Schelling (1978), that a homogeneous plane is divided into a large number of squares after the fashion of Schelling's checkerboard.

There are 100 people located on that plane, and they constitute a social economy. Individual action within that society conforms to two rules. First, by the principle of private property no person will move onto a square occupied by someone else. Second, presuming those people comprise a society means that no one will allow more than, say, three squares to arise between themselves and their nearest neighbor. This society can be described in either DSGE or OEE terms, which raises questions of the comparative advantages of the different visions. At any instant, the society can be described as DSGE. Alternative locational patterns at different instants can also be described by DSGE, with the changing patterns of location attributed to exogenous changes in relevant parameters. Parameter changes are *ad hoc* and not determined by properties of the system or its parts. The DSGE model itself gives no guidance relevant for systemic maintenance or repair because those activities, being changes to the system, are exogenous to the model.

In contrast, OEE seeks to explain macro-level properties as unplanned resultants of individual actions. This spontaneous order approach to macro theory does not deny the significance of the planning process to the quality of economic interaction. Quite the contrary, OEE emphasizes that quality in that it attributes planning to all economic agents rather than limiting it an external controller or expert. The overall society itself, however, is not an object that is planned in its entirety. The society is not controlled by Adam Smith's chessmaster, who moves people about as if they had no internal laws of motion (Smith 1759). To the contrary, a society is an ecology of interacting plans, some of those plans complementary with others and some competitive. OEE focuses attention on the governance of interaction among those plans, which provides a position from which questions of systemic maintenance can be raised from *inside* the model.

Suppose during each time period that five members of our grid-like society change location. In consequence of the principles of private property and recognition that these people constitute a society, as against being just a set of randomly located hermits, the movement of the five will induce movement elsewhere within the society. This repeated movement over time in response to five people changing their planned locations can be captured within the DSGE model. The claim that this society is in stationary equilibrium cannot be rejected at the five percent level of significance. DSGE can fit the data this model generates.

But OEE can also fit the data our model generates. Our model has been constructed as an ongoing algorithmic process that reflects movement through time in a potentially open-ended fashion that may or may not come to a state of rest. The prime movers of our model are entrepreneurs seeking new locations in commercial space, recalling Schumpeter's (1934) treatment of entrepreneurship as the locus of leadership in a capitalist society and Kirzner's (1997) treatment of entrepreneurship as the locus of the discovery of new locations in commercial space.

DSGE provides a framework for interpreting our observations, but so does OEE. For DSGE, the primitive observation is the alternative locations at the end of each period. For OEE, the primitive observations pertain to the entrepreneurially creative acts that induce readjustments within the society. The changing locational pattern through time is an emergent response to entrepreneurial action. To be sure, our Schelling-like construction of an OEE model conforms with standard statistical convention of being unable to reject the hypothesis of a stationary state at the 5 percent level of significance. And yet the illustration is constructed so as to portray a society in continual motion.

Our comparison of DSGE and OEE modeling relates directly to G. E. P. Box's (1976) observations on why scientists choose some models rather than others, knowing in advance that all models are incomplete or even wrong. If we only care about the average locations of entrepreneurs in commercial space, a no more than 5 percent difference in each period is sufficient to answer the analytical question. Suppose instead we care about why the system grows at *x* percent per period instead of *y* percent per period. In that case, the 5 percent may account for a large portion of that growth. In the first example we need only the locations of the entrepreneurs; a DSGE analysis would suffice. In the second example we require information about entrepreneurial plans that led to the resulting locational pattern; a DSGE analysis would no longer suffice, but an OEE analysis might.

Furthermore, information about the individuals who constitute a macro economy is irrelevant to the DSGE framework, for such information can only clutter the model without offsetting advantage because plans are stipulated as being pre-coordinated without any action having taken place. It matters little why one of the entrepreneurial five percent change their location in commercial space, since every other member of the commercial space has the same information and processes it as relevant or not to their business plan in the same way. Any advantage to be had from exploiting a discovery is symmetrically dissipated through the entire system, meaning that which individuals did what does not matter for our analysis of how the system advanced from its initial to its final state. Recognition that systemic or macro observations are derivative from individual action and interaction has no analytical work to do in DSGE modeling because the only data of relevance for that class of model pertains to aggregate outcomes. The presumption of systemic equilibrium—pre-coordination—renders irrelevant any information pertaining to individual plans or actions. It renders irrelevant how individuals gain and use knowledge to form new models of cause and effect and to update their plans, and how this process ripples through the system to change the models that others use and the failure or success of their plans. All plans are statements of future expectations (Shackle 1972, 1974). Though the DSGE model does not claim that expectations about the future on which present actions are based are invariably accurate, it presumes they will be accurate on average which, in turn, can mean that they are never accurate with respect to particular instances. An estimate can be invariably wrong while being accurate on average all the same. Many people guess the weight of a cow, and there is good basis for thinking that the average of the guesses is an unbiased estimate of the cow's weight. Many people guess what a measure of aggregate output will be at the end of the year, and there is likewise good reason to think that the average of those guesses will be an unbiased expectation of that output.

Economic phenomena, however, illustrate patterns of organized complexity (Weaver 1948). There are discernable patterns to economic activity, with those patterns emerging through the planned activities of numerous people each of whom acts with some degree of independence from other actors. At this point we come to one of those analytical forks in the road. Along one branch of that fork lies the postulation of systemic equilibrium, which enables reduction of that system to simplicity by rendering macro phenomena of the same order of simplicity as micro phenomena. Both micro actions and macro outcomes reflect outcomes of choice. Yet it is surely strange to think that the entirety of an ecology of interactions is reducible to the choices of any single entity within that ecology. At the very least, it is surely unsatisfactory to reduce the entirety of an ecology of interactions to the choices of a single entity through simple stipulation rather than explaining *how* such an outcome might come about, which within OEE requires an explicitly constructed generation of macro-level observations from micro-level interactions. DSGE can make synchronic statements using value theory that start from one timeless pre-reconciled state and move to another, but these statements are not explicitly constructive (Lewis 1985; Velupillai 2008). OEE provides a stage for the unfolding of diachronic processes where situations grow one out of another (Shackle 1972: 89).

Pre-reconciliation implies simultaneity of action, even in the face of shocks to the system. When a shock occurs, the end state of the system is predetermined; furthermore, the path from the initial state to the new state entails a well-behaved transformation from one fixed point to another. With OEE, by contrast, the process of transformation is not necessarily the well-behaved one of individual agents learning of the shock, updating their plans according to their understanding of its implications, and dealing with the ramifications of the corresponding changes in the plans of others. How agents adapt is not of central concern to DSGE. In contrast, how agents adapt is central to the processoriented nature of OEE. The diachronic nature of OEE re-introduces to macro theory the concept of time through the unfolding of un-prereconciled individual actions.

2.3 Generation vs. Stipulation in Systems Modeling

The diachronic theoretical schema we associate with OEE modeling treats a society as an ecology of agents and plans, with ecology taken substantively to denote a locus of interaction among non-identical entities (Scheiner and Willig 2011). This ecological formulation ramifies throughout the domain of macro-theoretic inquiry. Any such effort at theoretical construction must start at the level of parts, with the whole being something to be assembled and with the process of assembly being the object of theoretical inquiry. Within this alternative analytical framework, system variables do not act directly on one another because those variables emerge through interaction among micro-level entities within the system of interaction; moreover, the injection of novelty is continuous as against being discrete, and thereby subject to a theory of punctuated equilibrium.

A simple illustration of this sort of construction follows from recent work on the theory of how the assemblage of work teams relates to the productivity of the team. It is not enough to put five strangers in a room and expect them to successfully complete a project. To whom certain tasks are assigned, and the flow of project steps, matters a great deal to how well and quickly a project is completed. If specialists are assigned tasks that exploit their specialty, perhaps by a coordinator in the team who can assess tasks and assign them to the proper person and then manage the flow of tasks from person to person, the work team works better. It turns out it is not necessary to plan out this structure of connections between agents; it can emerge naturally from repeated interactions (Peltokorpi, 2008). Agent's work teams develop "who knows what" directories that act as instructions as to who best can help them complete a certain type of task. The structure of connections in a mature productive team, where edges represent task-completion chains (1 is connected to 2 if 1 goes to 2 to complete task C) differs substantially and predictably from random networks with the same number of members and edges between them (see Figure 1). Abstracting from the structure of work teams to consider productivity in the form of, say, GDP per capita, leaves out institutional information about the team that is crucial to its capabilities as a social order.

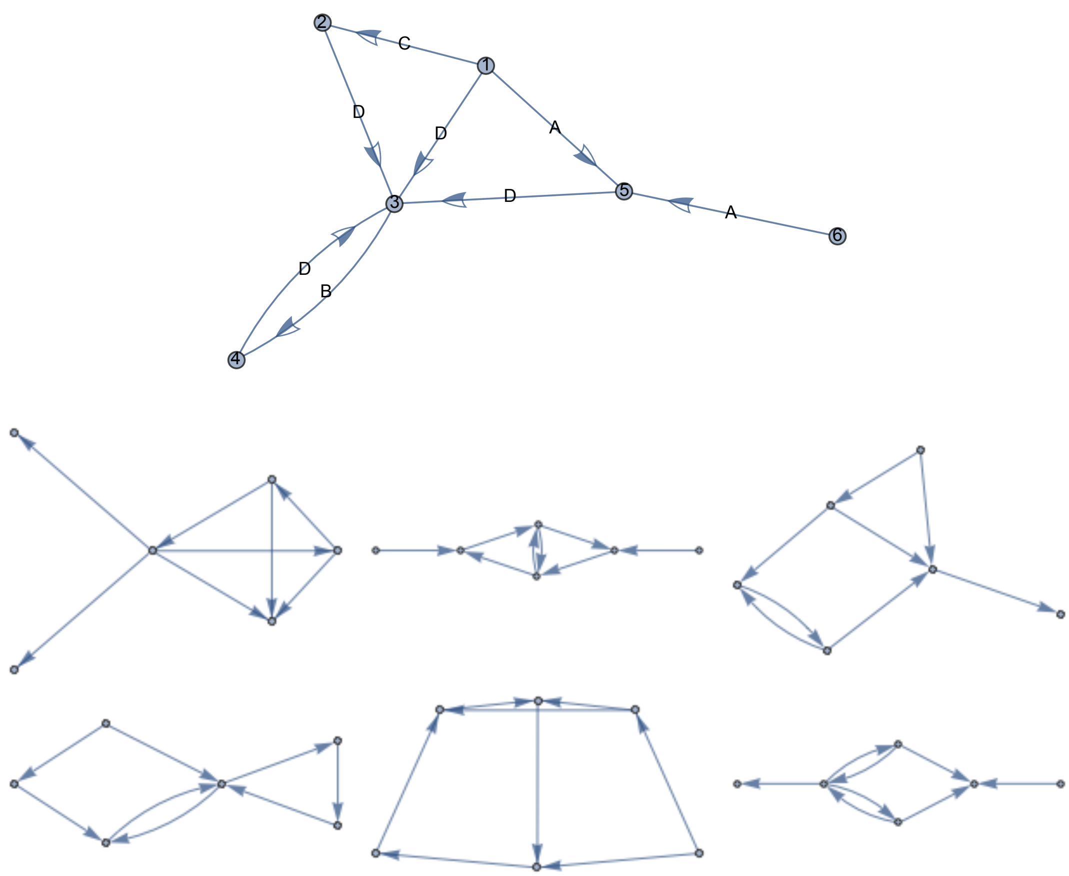

Figure 4 Graphs of work teams

Figure 4: Example of a mature work team network with 6 agents and 8 interactions (top), and a set of six random networks with 6 nodes and 8 edges (bottom)

For the most part, economic theories are formulated within the framework of non-contradiction, where propositions are either true or false. Without doubt, there are domains where the principle of non-contradiction pertains. A philosophy classroom in classical logic is one of them. But there are also domains where it surely does not apply, and where some dialectical principle like yin-and-yang can offer superior insight. At the individual level, this is the world of creative experimentation where utility functions would be described as only partially ordered, as complete ordering requires the non-constructive solution to a fixed-point problem (Lewis 1985). This dialectical setting contrasts with non-contradiction along the lines that Ross Emmett (2006) portrayed Frank Knight's critique of the Stigler-Becker claim on behalf of invariant utility functions. For Knight, a significant part of individual action entailed reflection-induced change. Hayek's theory of the market order placed reflection-induced change within a complex economy (Hayek 1945, 1964). In today's terminology a market constituted by reflective and purposeful individuals would be a complex adaptive system.

We believe that the dialectical framework is best represented by an open-ended evolutionary (OEE) system where changes can enter the system both from recombination of existing resources in the system and from interaction from within the system to a resource space outside of the system (Adams et al 2017a, 2017b). Suppose we have a system with *N* elements and thus 2^N combinations of elements at time t[1]. Each combination represents a possible plan, that is, combinations map to outcomes via a model algorithm constructed by the agent. Advantages are conferred to agents from recombination of system elements and redefinition of the mapping to outcome space. Since agents act as part of a system of other agents, advantages conferred by recombination and the fine-tuning of models dissipate through time (see the discussion by Prigogine (1997) about dissipative emergent structures). Dissipation of advantages within the confines of a fixed combinatorial space is the "yin." This type of theoretical framework, moreover, must entail continual movement through time, in contrast to equilibrium theories where time has no work to do.

When the dialectical framework is applied to the social level, what shows itself as contradiction appears. At any moment, a central mass of people might well act as price takers. At the same moment, however, there will be outliers who are inserting new data into the society. It is, however, impossible for everyone to insert new data at the same time. The very ability to insert new data requires that other people accept data. To think dialectically, requires the theorist to think in terms of distributed populations and not in terms of averages or representative agents (Hartley 1997, Kirman 1992). For OEE macro theory, GDP data might serve some useful purposes but those data do not denote the

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[1] Recalling that $\sum_{k=1}^{N} \binom{N}{k} = 2^N$

objects that an OEE theory would seek to explain. Synchronic macro theory conceptualizes a society as an economizing entity, with the GDP accounts summarizing the outcome over some accounting period. In contrast, an OEE macro conceptualizes a society as a vessel that holds numerous economizing entities, with efforts to account for the vessel being distinct from the accountings conducted by the entities inside that vessel.

To carry forward the OEE vision, societies must be treated as ecologies of plans (Wagner 2012a). Each individual owns his or her plan, though there is no Walrasian-like process through which those plans are coordinated in advance of action, as this presumption implicitly requires insertion of a fictive coordinator. Even public actors act on the same playing field as private actors within OEE macro, though their positions may differ in a way that places them in influential locations on the field, as conveyed by Koppl's (2002) theory of Big Players. At any historical instant, some plans are initiated and other plans are abandoned, while many plans created in the past continue to operate. The mere recognition that plans are created and abandoned as time elapses is sufficient for setting a diachronic or ecological research program in motion. At any moment in time, many and perhaps most plans are still in progress, having yet to bear fruit to their creators; at no time can we say the system has come to rest, for rest would imply the end of all plans and the initiation of no new plans. It is unclear how meaningful it would be to ask what would happen if no new plans were initiated after a certain point of time. Such a thought experiment cannot serve to provide much information about some future path of the system compared to some alternate future path, as the economy is no longer a system undergoing a market process but rather more like the staggering of a body without a head.

The economy evolves in an open-ended way, with no state of rest in the mind of its acting individuals or some analogical market coordinator.

To carry forward an open-ended evolutionary conceptualization requires two points of difference from DSGE schemes of thought. First, individual preferences must be only partially ordered to allow space for creative experimentation. Second, there is no Walrasian starting line where all plans are created and enter operation at the same instant. At any instant, some new plans are injected into an existing sea of plans, while some previously created plans are undergoing revision or abandonment. It is perhaps worth noting that Walras (1954: 380-81) offered a brief glimpse of what might be involved in conceptualizing an economy as an ecology of plans that generates turbulence. He did this in contrasting his formulation of an annual market of pre-coordinated activity with what he called a continuous market, which he described as resembling a lake where the water is agitated by the wind, in contrast to the placidity of the water in the annual market. Walras's continual market allowed variable turbulence as a systemic feature of micro-level interaction, only he abandoned this insight in favor of the analytical closure that he thought equilibrium modeling offered.

To pursue a program of OEE macro theory, there must be continual entry and exit of plans, which continually inserts new actions and information into the ecology of plans. A plan that is doing well might turn negative because a new plan attracts away its customers. Alternatively, an input supplier whose product is valuable to someone's plan might abandon business, leading to a weakening of the plan in question. At any instant within the ecology of plans, some plans are being created and others are abandoned, and with those plans located at particular places within abstract enterprise space. The abandonment of plans frees inputs while the creation of plans creates demands for inputs, though there is no reason why these should be offsetting in terms of micro-level detail, nor why they should have a linear effect on resultant system variables. The actions of outliers may drive a large proportion of the changes in various measures of the system's activity. One thing it means in any case is that at each succeeding instant new information and activity is being injected into the ecology of plans. This new information will affect the performance of existing plans within the ecology, which subsequently might lead to revision or abandonment of some plans. The ecology of plans will entail natural turbulence, and with the presence of that turbulence also incorporated into entrepreneurial plans as entrepreneurs recognize the need to abandon plans they own in an economizing manner (Wagner 2012b).

OEE macro theory is a form of spontaneous order theorizing (Aydinonat 2008; Kochugovindan and Vriend 1998). It points to plans and interaction among plans as the prime objects of analytical interest. To do this is to recognize that it is the principles and frameworks of human governance more than resource allocations that are of primary theoretical interest because resource allocations derive from human governance and cannot themselves initiate action. An OEE macro theory would thus have a different analytical agenda from a synchronic macro theory, as illustrated to some extent by Clower and Leijonhufvud (1975), Colander (2006), De Grauwe (2010), Katzner (1998), and Leijonhufvud (1993).

As a simple illustration of this distinction between OEE and DSGE, consider the following two cellular automata evolutions. Cellular automata are simple systems which admit some structure to their output through update rules that instruct each "cell" in a line of cells whether they should turn white or black at the next step (Wolfram 2002). These rules for the most basic or "elementary" cellular automata are based on the states (colors) of a cell's two nearest neighbors. In Figure 5 below, we display the evolutions of two elementary cellular automata, denoted as Rule 70 and Rule 110 in the Wolfram numbering scheme.

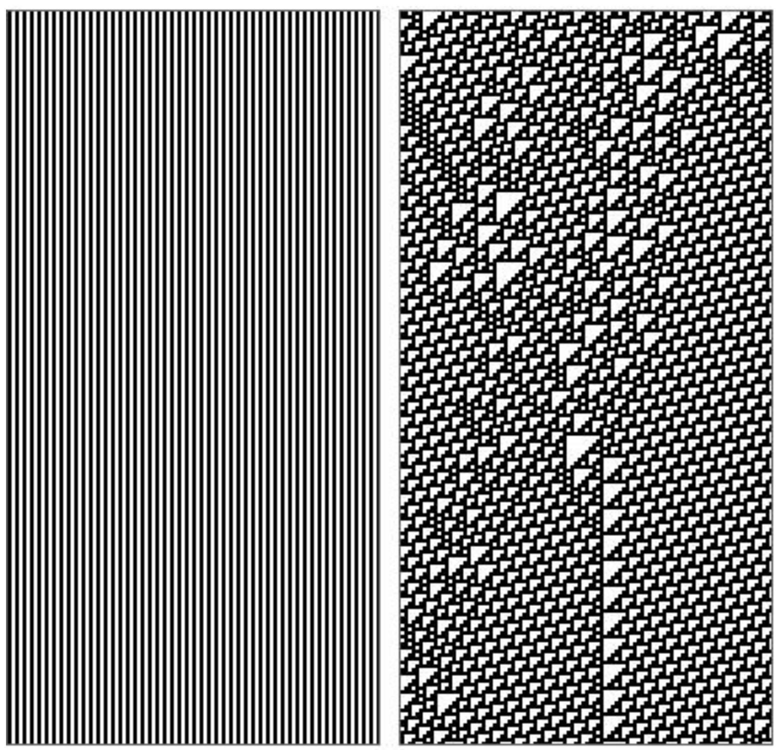


Figure 5 Two elementary cellular automata

Figure 5: Rule 70 (left) and Rule 110 (right) elementary cellular automata.

The density of black cells is exactly 50% for Rule 70; for Rule 110 that density can be described as 50% with 95% confidence. Each rule is evolved from a single central black cell. The width of the evolution is 102 cells for both Rule 70 and Rule 110.

Figure 6 displays the evolution of the cells for both Rules 70 and 110. The outcomes the rules produce differ dramatically, even though their aggregate statistical properties are indistinguishable within a 95% confidence interval. Rule 70 maps readily onto DSGE modeling; for Rule 70 the blue and orange lines coincide, as befits a system continuously in macro equilibrium. OEE modeling maps onto Rule 110, in that OEE modeling illuminates micro-level details that generate macro-level patterns without contesting the macro-level properties of DSGE modeling. The blue and orange lines never coincide and yet their aggregate values are identical within a 95% confidence interval, as befits a market system with self-ordering properties at the macro level.

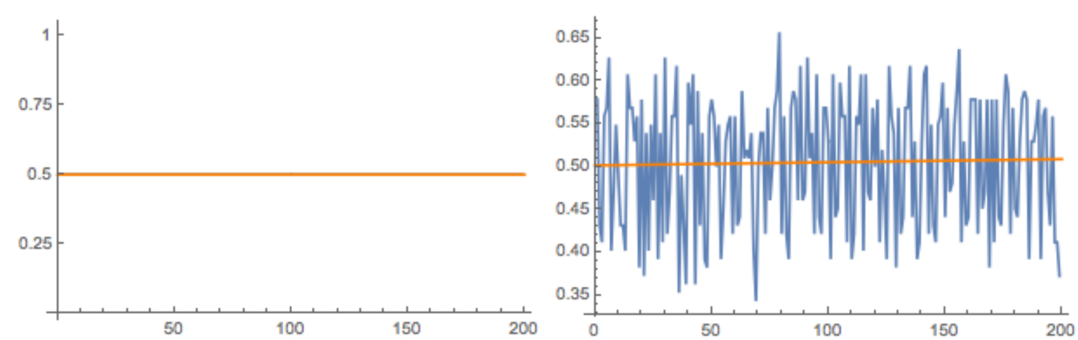


Figure 6 Density of black cells in two cellular automata

Figure 6: The row-by-row density of black cells (blue) and their line of best fit (orange)

Even though Rules 70 and 110 have very similar densities of white and black cells, as the system evolves from top to bottom (Figure 6), they exhibit wildly different structures. The capabilities of each system as it evolves depends on its rules; the first cellular automaton isn't capable of computing anything interesting, while the second cellular automaton is capable of computing *everything* – it is a universal computer (Cook 2004; Reidel and Zenil 2018). That is, the first cellular automaton isn't able (without external intervention) to traverse a path from any one state to any other state, while the second cellular automaton can. For complex evolutions like those embodied by cellular automata or social systems, whether or not intervention is justified is not apparent from looking at the kind of averages embodied by most macro indicators. Neither can we get a sense for how the intervention changes the capabilities of the system to steer its fate by only considering the values of indicators instead of how policy changes percolate through rules and structures of the system.

Macro theorists often work with stylized facts, and seek to explain those facts. Among the facts with which macro theorists seek to explain within the DSGE model are the procyclical behavior of real output and real wages, the acyclical behavior of the real interest rate, and the countercyclical behavior of unemployment. Left out of such examinations are two overwhelming facts that are more than stylized. One fact is that societies work, in the sense that people everywhere are fed, clothed, and housed. This is an observable regularity across time and place. The second fact is that there is continual volatility within societies. Some businesses prosper, others fail. Quarrels among people invariably erupt. Social life has a good deal of roughness and volatility, and by no stretch of the imagination is it placid. Change comes not as exogenous shocks but as eruptions from inside society. That such eruptions occur continually, moreover, meaning that plans are never fully coordinated within a society. Something like Rule 110 more accurately captures the performance characteristics of economic systems than does Rule 70.

Economies have a generally coordinated quality, in that the quantity of grain converted into flour generally matches the amount of bread that bakers want to bake and consumers want to buy. Another such fact is that such coordination is never complete. The production of grain is subject to variability in the weather. Bread that is baked might not reach the store where it was scheduled to be sold because the truck carrying the bread was destroyed in a collision with a train. Alternatively, bakers or truck drivers might be unionized and go on strike. Bread as a staple depends on where you live, as communities where people favor rice and noodles are gaining influence in many traditionally bread-dominant areas. Furthermore, a good number of consumers might think they should reduce their consumption of bread and other products made from grain. Things like this happen continually, which means that fluidity and change are likewise a stylized fact of economic life, as are the failures of commercial enterprises and the economic dislocations that result (Wagner 2012b).

Economic life is generally orderly, but the associated orderliness is not that of a parade. It is rather that of a surging crowd of spectators leaving a stadium after an event. Unlike the members of a parade, the members of a pedestrian crowd will not know the exact path of exit they will take until they start their movement from the stadium. The path they discover might require them to walk around a crowd of slow moving pedestrians, or run to catch a bus that is just now pulling into the curb. Rule 110 reflects this form of orderliness, while reducing that orderliness to Rule 70 eliminates from analytical attention the self-ordering properties of alternative economic systems.

The pedestrian crowd is clearly a different species of societal configuration than the parade, and requires a different conceptual foundation to explain its coherence. Both configurations are orderly, but the principles that govern that orderliness differ between the configurations. The orderliness of the parade is governed by the musical and marching talents of the members of the parade, as well as of the directional and supervisory talents of the parade marshal. These features have nothing to do with the orderliness of the pedestrian crowd. The orderliness of the crowd depends on such things as the ability of people to read minds as it were, by anticipating other people's speed and direction of movement to avoid collisions. The pedestrian crowd is a self-organized social configuration; it is an order of independently acting pedestrians. In contrast, the parade is an organization under the direction of a parade marshal.

For OEE macro theory, the relationships of governance among economizing entities acquires central significance. For synchronic macro theories, governance is irrelevant because it has no place within the conceptual framework. For OEE macro, relationships of governance are of central significance. The principles of property and contract that govern market interaction mean that all participants speak the same language of profit and loss. Among other things, this means that participants will abandon failed plans in an economically efficient manner, thereby promoting efficient redeployment of released resources (Wagner 2012b). Political entities, however, do not speak the language of profit and loss, as Roger Koppl (2002) explains. Big Players lack the budget constraints that ordinary players have, and this absence renders such players less predictable than ordinary players. A central bank, for instance, can buy assets without being concerned about how to pay for those assets or about the returns they expect to receive.

2.4 Competition and Coordination within an Ecology of Plans and Games

Macro theories typically treat macro variables as acting directly on one another, as when monetary or fiscal expansion is modeled as increasing aggregate output. Macro policy, in turn, is treated as an instrument to control the state of macro variables, typically to smooth variability through time in macro variables. This type of analysis treats macro variables as scaled-up versions of micro variables. A number of scholars have pointed to some problematical features of this treatment, as illustrated by Kirman's (1992) and Hartley's (1997) critical analyses of representative agent modeling, Janssen's (1993) analysis of the effort to erect macro on secure microfoundations, Smithin's (2004) effort to point out that the macrofoundation for micro theory is as much an open question as is the microfoundation for macro theory, and the several efforts in Colander (2006) to move away from Walrasian-style macro theorizing.

This paper embraces the general theme conveyed in these critical efforts, and seeks to place the micro-macro relationship within an ecological orientation wherein the relationship between micro and macro is one of parts to whole. This scheme of thought entails no presumption that macro observations pertain to states of equilibrium, and rather proceeds within a non-equilibrium framework where macro phenomena emerge out of interaction among micro entities within an evolving ecology of plans (Wagner 2012a). An ecology of plans entails turbulence because plans can interfere with one another, as when a new product takes away customers from an established business (Louçã 1997). This turbulence arises because there is no presumption that there exists some pre-established coordination among plans. Instead, some plans fail while others do far better than their creators anticipated, injecting turbulence into the ecology in either case. The generally modest character of this turbulence can plausibly be attributed to the conventions of private property which operate to facilitate the efficient abandonment as well as revision of plans, as Wagner (2012b) explains. Within this ecology, state policy might operate to increase turbulence, due to the inability of policy truly to mirror the pattern of transactions that otherwise would take place within the ecology. Macro variables are not primitive variables that connect directly with the agents whose actions those variables reflect.

Peyton Young (1998) uses a series of simple coordination games to illustrate the emergence of coordinated patterns of economic interaction, as do the essays collected in Friedman (1994). Among the simple illustrations of systems-level phenomena are convergence to a single means of payment, convergence to a single rule for driving on a road, and convergence for a single standard of etiquette. Much of the analytical work done with these formulations comes through the analysis of evolutionary stability, wherein deviations from some established standard are either suffocated or give way abruptly to some alternative standard. Consider the use of the stag hunt game in Figure 4 to illustrate the possibility of an underemployment equilibrium. Two people are assumed to hunt a game animal, which they will consume in common. If each expends great effort, they will catch a deer, yielding the net payoffs (5,5) in Figure 4. Should both slack off in expending effort, they will have to settle for rabbit, with the associated net payoffs being (2,2). Should one slack while the other hunts energetically, only a rabbit will be caught. The slacker will have a net yield of 2, but the vigorous hunter will have a net yield of zero to indicate the disutility of effort offsets the gain from consuming half the rabbit.

The stag hunt game can be and has been interpreted macroeconomically as illustrating underemployment equilibrium. Which of the two equilibriums in Figure 4 occurs is accidental, unless some outside authority intervenes to promote jointly high effort. To interpret the stag hunt as representing a macro economy raises issues about what constitutes reasonable reduction of complex realities to simpler representations of that reality. In this regard, the stag hunt surely fails. Such simple games as the stag hunt can only reasonably represent relationships and interactions in isolated settings that encase the participants and hold their exclusive attention. Otherwise, we must recognize that any particular interaction occurs within an ecology of overlapping interactions.

Table 1 Stag Hunt and Macro Equilibrium

	Low effort	*High effort*
Low effort	2,2	2,0
High effort	0,2	5,5

An ecological style of OEE analysis would seek to explain social coordination as an emergent product of a set of interactions within *an ecology of games* or interactions, as against reducing reality to one universal game. Individuals participate in multiple interactions, and with the identities of the other participants varying among individuals. In classical game theory, payoffs to players participating in any game are deduced from the situation by a theorist or expert and inserted into the payoff matrix. The theorist then searches through a menu of pre-solved one-shot and repeated games to find which abstract ordered payoff scheme matches his setup, as if these are the only trajectories a system of rational agents with coupled outcomes could ever traverse. In practice, game parametrizations are externally derived assertions crafted in a way to represent a recognizable set of attainable equilibria rather than to *discover* a macro trajectory for the system. There is no *discovery* in comparing the use of common-pool resources to a Prisoner's Dilemma. The lack of institutional substructure required for self-management of CPRs is built into the payoffs by the theorist. No wonder theorists then conclude there exists no endogenous institutional substructure to assist agent coordination. The Prisoner's Dilemma is not truly a two-person game because it requires a third person—the warden—who prevents the two prisoners from communicating with each other, as deftly pointed out by Elinor Ostrom in response to the widespread use of Prisoner's Dilemma games in CPR analyses (Ostrom 2010).

Market prices are endogenously attained through the competition among firms in their production-cost method in coordination with (local) demand. Market prices for goods are not simply asserted to equal such-and-such by an expert or theorist. Similarly, it would make sense to ask how we could obtain a plausible parametrization of a game by including the belief-formation process in the model. A macro game would then take into account the belief-formation processes of many player types. Belief formation relevant to a macro game may—and, we believe, often—require playing *different* games with other players. For game theory to shed insight into macro or systemic questions, it must have ecological character. A model of an ecology is necessarily a reduction from any actual ecology; however, within that representation ecological characteristics will remain apparent, as against being reduced out of sight. By treating a macro economy as an ecology of games, we have in mind a model in which systemic outcomes emerge out of interaction among participants across several localized games with overlapping participation among the games.

To use game theory to illustrate systemic coordination, we must work with an ecology of games and not a representative game if we are to avoid embracing a model where one agent can apprehend and act on the entire system of economic interaction. Within the spirit of the stag hunt, suppose the economy entails three sets of interactions: 1) a hunting game, 2) a butchering-and-packing game, and 3) a retailing game. Two hunters search for game, one of whom sells the game to be butchered and packaged, and with one of the butchers distributing the meat to a retail outlet. Within this analytical setup, no player spans the entire set of games that constitutes the economic ecology, though there are at least two players who participate in two games: one hunter makes contact with a player in the meat game while one player in the meat game makes contract with one player in the retail game. Within this setup, information is spread across markets through exchange, yet no participant is able truly to apprehend the entire system. Societal coordination is thus not something imposed or assured by a coordinating agent who stands apart from market interactions, but rather is an emergent quality of societal interaction; moreover, the quality of those interactions is likely to vary among possible institutional arrangements. The stag hunt macro game is now broken into a series of three overlapping games with not all the same players in every stage, to provide a reasonable framework to illustrate systemic coordination without a coordinating agent.

A simple example can show how payoffs in one game can determine the payoffs in another game. A parametrization of the game facing hunters, for example, can be obtained from considering the relationships between agents across the chain of games starting with extracting the raw material to selling the final product to consumers. Suppose there are three games: 1) hunt game, 2) butcher game, 3) retail game. Refer to these games as $\Gamma = 1,2,3$ respectively.

The payoffs attained by hunters depend on the profits attained by the butcher game, which depend on the profit attainable in the retail game, which itself depends on consumer demand. Games are played pairwise, meaning that players form expectations based on beliefs formed about their direct interactions with players in other games. These beliefs may contain some knowledge about upstream games, like a knowledge of market price for the good, but they do not explicitly take into account the details of other games. Games are played locally, which is why players who play more than one game in the chain of games that underlay a "macro" game are so important: they have knowledge of the details of two different games, and may be able to use that knowledge to alter the payoff structure of each. Let's express this formally.

There are five total players in the ecological game: $N = 5$. Players 2 and 5 only play one game each. The rest of the players play two games each. Players 1 and 2 play the hunter game ($\Gamma = 1$). Suppose we denote the price at which hunters are willing to sell whole animals to butchers n_S for stags, and n_H for hares. Then, without knowing what the parametrization of the matrix is, we can write the game as:

$$\begin{array}{ccc} & S & H \\ S & (n_S, n_S) & (0, n_H) \\ H & (n_H, 0) & (n_H, n_H) \end{array}$$

The formal expression of game 1 as a tuple is:

$$\Gamma_1 = \langle N = \{1,2\}, \mathcal{S}_1 = \{S, H\}, \{v_1, v_2\} \rangle$$

In the butcher game, one of the hunters (it doesn't matter which) sells a whole rabbit/stag to a butcher ($N = 3$), who then processes it and sells the butchered meat to a retailer ($N = 4$). If the hunter shows up with a hare and the butcher wanted a stag, both players get nothing. Otherwise, the payoff to the hunter is the input price the butcher negotiates with the hunter. Only then can the hunter realize the payoff for his hunt. The payoff to the butcher is the difference between the price he expects to get from retailers, c_S for butchered stag or c_H for butchered hare, and the input price (suppose there is no marginal cost to butcher meat, for simplicity).

We can express game 2 as:

$$\begin{array}{ccc} & S & H \\ S & (n_S, c_S - n_S) & (0,0) \\ H & (0,0) & (n_H, c_H - n_H) \end{array}$$

which is a simple coordination game. The formal expression of game 2 as a tuple is:

$$\Gamma_2 = \langle N = \{1,3\}, \mathcal{S}_2 = \{S, H\}, \{v_1, v_3\} \rangle$$

The payoffs to hunters in game 2 determine the payoffs in game 1. To make that relationship explicit, assume that player 2 in game 1 obtains his payoffs in the same way as player 1 and note that the payoffs to player 1 (the hunter) in game 2 can be written as:

$$n_S = v_1(\Gamma_2, (s_1^1, s_1^3))$$

where $(s_1^1, s_1^3) = (S, S)$ in game 2. We can then rewrite the payoff matrix for game 1 as:

$$\begin{array}{ccc} & S & H \\ S & \left(v_1\left(\Gamma_2, (s_1^1, s_1^3)\right), v_2(\Gamma_2, (s_1^2, s_1^3))\right) & (0, v_2(\Gamma_2, (s_2^2, s_2^3))) \\ H & (v_1(\Gamma_2, (s_2^1, s_2^3)), 0) & (v_1(\Gamma_2, (s_2^1, s_2^3)), v_2(\Gamma_2, (s_2^2, s_2^3))) \end{array}$$

where $\left(s_1^k, s_1^3\right) = (S, S), \left(s_2^k, s_2^3\right) = (H, H)$ in game 2, for $k \in \{1,2\}$. The above matrix is an *unparametrized* version of the game faced by the hunters. It explicitly takes into account the relationship between the hunt game and the butcher game without assigning values to those payoffs.

To analyze the retail game and show how it is interrelated with the hunt and butcher games, suppose for the sake of simplicity that *N* = 4 buys from *N* = 3 at a cost c_3. Retailers *N* = 4,5 must then compete with each other for the business of consumers. In this part of the game, we only consider the sale of stag as its greater profit margin compared to the sale of hare will be reflected in the payoffs of game 2 and therefore need not explicitly be taken into account in game 3.

Suppose that players 4 and 5 play a Cournot game of quantity-setting, given some abstract linear demand for stag meat $p_S = a - b\ q_S$, where $q_S = q_4 + q_5$. Suppose retailers face a constant marginal cost function $c(q_i) = c_j q_i$ for retailer *i* and butcher *j*. Then it is simple to show that the solution q_i to the maximization problem

$$\max_{q_i}\{\pi_i = (a - b\ q_S)q_i - c_j q_i\}$$

is

$$q_i = \frac{a - b\ q_{-i} - c_j}{2b}, i \in \{4,5\}$$

where q_{-i} is the quantity chosen by the retailer against which retailer *i* is playing.

Consider the strategy profile where players 1 and 3 are both playing stag in game 2. Then, for player 3, her profits are the same as her payoff:

$$\pi_3\big(\Gamma_2, (s_1^1, s_1^3)\big) = v_3\big(\Gamma_2, (s_1^1, s_1^3)\big)$$

and her input cost is the same as the payoff to player 1:

$$n_S = v_1\big(\Gamma_1, \Gamma_2, (s_1^1, s_1^3)\big)$$

where we include Γ_1 to signify that the strategy chosen in Γ_1 determines the strategy chosen in Γ_2. Then the "cost" faced by the retailer, $N = 4$, will be the difference between player 3's profits and input costs, or

$$c_3 = v_3\big(\Gamma_2, (s_1^1, s_1^3)\big) - v_1\big(\Gamma_1, \Gamma_2, (s_1^1, s_1^3)\big)$$

Since we're only considering the stag strategy profile at the moment, let's abbreviate:

$$v_3\big(\Gamma_2, (s_1^1, s_1^3)\big) = v_3(\Gamma_2)$$
$$v_1\big(\Gamma_1, \Gamma_2, (s_1^1, s_1^3)\big) = v_1(\Gamma_1, \Gamma_2)$$

The choice of $N = 4$ that maximizes his payoff is therefore

$$q_4 = \frac{a - b\, q_5 - v_3(\Gamma_2) + v_1(\Gamma_1, \Gamma_2)}{2b}$$

The maximum payoff to the retailer is then

$$v_4\big(\Gamma_3,(q_4,q_5)\big) = p_S q_4 - c(q_4)$$

$$= \frac{1}{2b}\left[p_S(a - b\, q_5) - \big(v_3(\Gamma_2) - v_1(\Gamma_1,\Gamma_2)\big)(p_S + a - b\, q_5) + v_3(\Gamma_2)^2 + v_1(\Gamma_1,\Gamma_2)^2\right]$$

So we see that the payoff to player 4 in game 3 is nonlinear in the payoffs to players 1 and 3 as determined in games 1 and 2. Information concerning strategies of a game downstream from player 4, concerning players of a game in which he is not directly involved, become part of the determination of his payoff. It should be noted that we do not expect player 4 to be explicitly aware of the payoffs to player 3 and 1, all he needs to know is the cost of buying butchered stag which encodes information about the payoffs to player 3 and 1.

Notice that the interconnection between games forms a bipartite network of relationships between games, where games which share participants are connected with a directed edge from more to less primary stages of the production process, and participants are indicated by undirected connections to the games they play. Figure 7 represents the preceding stag hunt example by such a network, where the game nodes are indicated in red and the player nodes are indicated in blue. Note that there is one game stage in which the retailer and butcher exchange that isn't included explicitly in the example above.

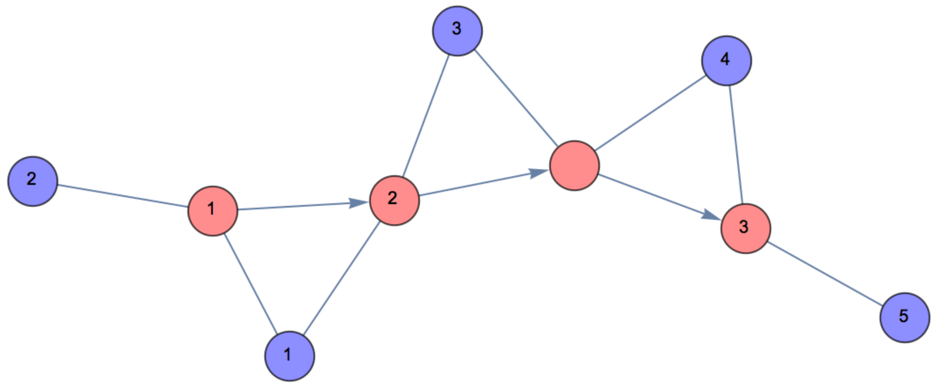


Figure 7 The graph of the stag hunt ecology of games

Figure 7: The bipartite network representing the stag hunt ecology of games. Note that there is one game stage in which the retailer and butcher exchange that isn't included explicitly in the example above.

What interconnection among some subset of players across the games accomplishes is some spread of knowledge beyond what is contained within any particular game. This spread of knowledge breaks down the structure of any single stipulated game. Suppose hunters sold their meat directly to consumers of the meat. If there are only two hunters in society and they distrust each other, then consumers may be stuck in a situation where they are only ever supplied hare even though they exhibit a positive demand for stag. But once there is more than one pair of hunters, they compete with each other not just with credibility but by choosing to play variations of the hunting game that may better survive competition by providing a high-valued item to the market.

Or, institutions--like assurance--may be selected for, which enables hunters to change the payoff structure they face. For instance, a participant in the hunter game might deal regularly with a participant in the butcher game. In the course of those transactions, conversations will lead to some sharing of experiences and stories. The butcher player might report his experience that in the majority of cases the other hunters return with rabbits. This exchange of information might inspire the hunter, who knows that he is not a slacker, to spy on some other hunter during one excursion. Suppose that hunter observes the other party to swim in a pond rather than chase deer. At that point the hunter faces several options, other than also becoming a slacker. He could kill the slacker, thereby hoping to secure a more energetic replacement. He could accost the slacker, hoping to induce a change in behavior. He could report the slacker to the Chief, along with perhaps suggesting a remedy whereby communal consumption is abandoned in some fashion. Since the hunter benefits if he can be confident other hunters will hunt stag with him instead of slack, he may offer effort or payment to help ensure that other hunters do not slack. Since both he and the butcher benefit from the higher profit margins on stags, the hunter may simply relay to the butcher information about other hunters slacking, and the butcher may then decide to offer effort or payment to help ensure hunters do not slack. Retailers all the way upstream may get word from butchers that hunters are slacking, and decide to do something to change the payoff structure faced by the hunters in a way so that stag is selected for.

Our point in raising such a menu of options is to move in the direction of a generative or emergent style of macro analysis where systemic outcomes emerge out of micro-level interactions. By allowing games to compete, and explicitly expressing payoffs as a function of demand and/or expected profits from a producer upstream, we can expose the process of payoff parametrization in such a way that enables us to investigate the ways in which markets operating as usual deal with the kinds of perverse social situations indicated by the stag hunt and prisoner's dilemma games.

Generally, an ecology of games framework is one in which

1. Payoffs are coupled between different games
2. Games are allowed to compete, i.e., games are objects of choice by virtue of endogenized payoffs

The standard approach of game theory is to stipulate a set of rules and payoffs the players face, which determines the game’s properties. Our suggested ecological framework, however, starts with individuals who interact among other people in a variety of settings, with conventions, practices, and payoffs emerging through those interactions. Where the stag hunt game posits a rule of communal consumption, the ecological formulation is one were rules of consumption and ownership emerge through interactions among the participants. In this respect, we would note the presence of a good deal of anthropological literature that situations of common consumption of game where tribal customs have rules for attributing ownership of game all the same. Whoever receives the attribution of ownership is able to host the meal where the game is served, thus harnessing an interest in status to offset what might otherwise be tendencies toward lassitude.

To put game theory into an ecological framework means that the aggregate or systemic properties of that game cannot be inferred from the solution to a representative game. To the contrary, there must be interaction among games, with the systemic properties stemming from that interaction. At every node in this supply chain, there will be multiple participants connected with one another through webs of expectations and contracts. Performance within the system can't be reduced to performance at one node within the system, nor can a system of independent nodes be reduced to a representative node.

DSGE highlights a system that is well coordinated, accompanied by a presumption that failures of coordination might be overcome with appropriate actions by a political authority. This recourse to political authority appears reasonable, even necessary, when the macro economy is modeled as a representative game. When it is modeled as an ecology of games, however, the macro economy entails internal sources for replacement of lower-valued with higher-valued practices. Disaster is invariably followed by recovery, though with differences in the speed and quality of recovery across time and place. DSGE provides no insight into processes of recovery, as against asserting that recovery from failure does occur, and might be facilitated by political effort, though possibly not. Where OEE comes into play is in probing the processes and institutions that undergird recovery, facilitating recovery or hindering it. OEE shifts the analytical focus from resource allocation to the institutional arrangements that govern social interactions, and with the macro or systemic properties emerging out of those institutionally-governed interactions.

We close this section by summarizing the qualities of an OEE macro theory as a series of “stylized facts” to guide our construction of an OEE theoretical apparatus.

Table 2 Stylized Facts of OEE Macro Theory

Stylized Fact	Description	Tools	Insights	Primary Referential Works
Rationality is bounded and ecological	Information is incomplete; preferences are at best partially orderable and may not be transitive; rationality isn’t a Boolean function (1 = perfect state of rationality, 0 = anything less than perfect as defined)	Heuristics of action, like those of exploration and exploitation as opposed to simple search	Explanation of biases in terms of heuristical action; computational conservation	Bounded: Simon (1996); Schelling (1978); Horvitz (1987); Russell (1997) Ecological: V. Smith (2003), Gigerenzer (1999), Das (2006); Barkoczi and Galesic (2016)
Agent connectivity encodes informational substructures and directs agent action	Agent connectivity encodes the local nature of agent action, as well as social, political, and trading relationships	Network theory	Asymmetric information; uncertainty; organization; externalities; network goods like money; agent outcome coupling	Potts (2000); Jackson (2008)
Agent action is diachronic; the system of actions and interactions is one of nonequilibrium (and not disequilibrium)	Agents plan and act through time rather than simultaneously. Simultaneous action is not a sufficient idealization or approximation of planning and action.	Agent activation schemes in agent-based models	Institutions like property rights and reputational mechanisms	Shackle (1972), Lachmann (1976), Wagner (2012a,b), Koppl et al (2015)
Agent planning and action is constructive and, at best, computably algorithmic; policy and other mechanisms to alter agent outcomes are constructive and, at best, computably algorithmic	Demonstrating a solution to a fixed-point problem says nothing about how agents and policy-makers can effectively attain that outcome	Agent-based methods; computable algorithms; constructive mathematics	Explains in part why theoretical predictions differ from real actions and outcomes	Velupillai (2007); A. Lewis (1985)

Macro phenomena are generally irreducible to a simple combination of micro behaviors	Parades are not piazzas (and vice versa)	Constructive mathematics; nonlinear analysis	Planned vs. unplanned orders	Kirman (1992); Hayek (1937,1964); Lewis and Wagner (2017)
The economic system of action and interaction is generally coordinated, amidst turbulence	Macroeconomic outcomes are both turbulent and generally coordinated when they are free to be so. Paris gets fed.	Game theory; nonlinear analysis; agent-based methods; network theory	Coordination amidst conflict and competition; the emergence of markets	Smith (1759); Louçã (1997); Wagner (2016); Potts (2000)
Influential agents act inside the model	Big Players influence macroeconomic outcomes from within the system; policies form an ecology	Network information theory	Public choice	Koppl (2002); Wagner (2016); Buchanan and Tullock (1962)
Knowledge is the basis of creative action	Knowledge cannot be flattened to Akerlofian information. Knowledge is distributed, not centralized. Knowledge is multifaceted and evolutionary.	Classifiers and learning theory; agent-based methods	Expert theory; creativity; innovation; the emergence and power of markets; price theory	Hayek (1945); Shackle (1972); Koppl et al (2015)
There is an arrow of time in economics	An arrow of time is a necessary foundation for formal definitions of causal emergence and is essential to life and life's activity. There is a sense in which action is, therefore, irreversible and not subject to any conservation laws.	Agent-based and computational evolutionary methods (like cellular automata)	Creativity and growth; uncertainty and risk; interest rates; speculation; investment	Knight (1921); Shackle (1972)

2.5 Closing Thoughts

Macro theory has been largely conceptualized as an instrument of applied statecraft, with theorists helping political pilots to steer the ship of state. This vision for macro theory seems to follow almost inexorably from the DSGE framework because there is no place within that framework truly to account for variations in the direction of the ship of state. In contrast, OEE recognizes that modern economies are highly complex networks of interaction that defy easy navigation, as contrasted with recognizing that some institutional arrangements might increase variability in economic systems. Even within the simple stag hunt game, the so-called underemployment equilibrium stems from the presumption that all consumption is in common. Within such institutional arrangements, it would be reasonable to expect a good deal of slacking. It would also be reasonable, however, to wonder about the survival of such arrangements.

With respect to institutional arrangements, it is also reasonable to wonder about the coordinative properties of economic systems with large degrees of public ordering in contrast to systems where private ordering predominates. Within the simple ecology of games we advanced, systemic coordination was an emergent feature of private ordering and its associated calculus of profit and loss. Public ordering replaces the calculus of profit and loss with a political and bureaucratic calculus, the properties of which are still relatively underexplored, probably in large measure because macro theorists have given the predominant share of their attention to wrestling with engineering types of questions rather than wrestling with scientific types of questions that require generative rather than stipulative modes of analysis (Mankiw 2006; Epstein 2006). We hope we have illustrated some of the valuable potential an OEE approach to macro theorizing might have for connecting the micro level of human actions, both commercial and political, with the macro or systemic level of the resultants of human interactions.

CHAPTER THREE:
GAME THEORY AS SOCIAL THEORY: FINDING SPONTANEOUS ORDER

Game theory holds out its promise to transform the core of economic theory from a science of rational choice into a science of human interaction. While traditional game theory opens into social interaction, it mostly neglects a central feature of economic intuition: spontaneous ordering of human activity. To provide space for spontaneous ordering, we advance the concept of *synecological game theory*. In this manner, social theory is conveyed not by a single, illustrative game but by interaction among a set of interrelated and evolving games. We thereby replace the presumption of fully coincident perceptions with the recognition that actions operate where perceptions are fundamentally non-coincident. In other words, societal operation entails assembly of more knowledge than can be contained within any player's mind. In this paper, we sketch the central features of importing a synecological orientation into game theory and explore how it expands the analytical agenda of game theory.

3.1 Introduction

John von Neumann and Oskar Morgenstern (1944, pp. 8-12) opened their *Theory of Games and Economic Behavior* by contrasting the concept of rational action within a Robinson Crusoe economy with rational action within a social exchange economy. The point of *Theory of Games* was to take some initial steps in shifting the theoretical focus of economics from a Crusoe economy to a social exchange economy. Neumann and Morgenstern did not intend to banish Robinson Crusoe from the economist's bag of tools, but rather sought to supplement that bag to prepare economists for the numerous instances they thought reduction of a social economy to a Crusoe economy was analytically unsuitable to the challenges economists faced. Morgenstern himself warned theorists that it “is often easier to mathematize a false theory than to confront reality” (Morgenstern 1972: 1169).

While game theory has blossomed over the past generation to include endogenous institutional change (Grief & Laitin 2004; Della Posta et al 2017), evolutionary pressures on strategy selection (Ohyanagi et al 2009), imperfect information, deviations from rational choice theory, preference formation conditional on the preferences of others (Stirling & Felin 2013) and heterogeneous agents playing sequential locally constructive games (Tesfatsion 2017; Kaniovski et al 2000), it still shows its beginnings as an alternative to Crusoe-style economic theory, perhaps a result of its stubborn methodological adherence to the behaviorism of choice theory. In contrast to characterizing individuals as facing problems of selecting an optima or maxima among options, game theorists place people in positions where they must choose among principles of strategic interaction, where one person’s best option depends on what that player anticipates the other player will do.

True to its roots in Neumann and Morgenstern, game theory aspires to become a theory of social interaction, as illustrated luminously by Herbert Gintis’s (2009) wide-ranging compendium of games. While game theory meets that aspiration in the rich array of game situations its proponents have set forth, it falls short as social theory in one significant respect, a respect that hearkens back to the foundations of economic theory in the philosophers of the Scottish Enlightenment. We refer to Adam Fergusons’s recognition that social order is a product of human interaction without being a product of human design, and with Aydinonat (2008) exploring some of the difficulties economists have had in theorizing about invisible hands and spontaneous orders. In this paper, we seek to integrate game theory with the concept of spontaneous orders or invisible hands, at the same time addressing concerns that spontaneous orders may not be representable in a game theoretic framework (Cachanosky 2010). To do this, we borrow the concept of *synecology* from the ecologists, which treats communities as arenas of interaction among species, and note also that ecologists contrast synecology with *autecology*, which treats individual species as if members are duplicates of one another.

With respect to game theory as social theory, we treat human communities not through a universal game given in advance of play but as an ecology of interconnected heterogeneous-player games that are subject to evolutionary selection. This shift in analytical orientation enables us to integrate principles of limited and divided knowledge into the social-theoretic framework of game theory. Central to this effort is recognition that the knowledge that is brought to bear on social processes exceeds the cognitive capacity of any player in the game. Societies work even though no person knows everything necessary for their working. A synecological orientation toward game theory combines social interaction with the generation and assembly of player-useful knowledge through social interaction. Within this synecological framework, societies are evolving ecologies of games that are not reducible to some set of representative games because no player participates in all the games that constitute a society.

As we shall see, our framework conceptually resembles the playing of non-local games between entangled quantum particles. Even if two different games in the societal ecology of games are played by entirely different sets of players, if they are connected to each other via an extended market of other games in the ecology (entangled), players in the two separate games may be better able to coordinate their outcomes with each other, despite the fact that they never directly play with each other and have no direct knowledge of each others' games, strategies, or even their existence. Thus, using game theory in this way, we can model coordination-at-a-distance: spontanteous ordering.

3.2 Traditional Game Theory vs. Game Theory as Social Theory

To date, game theory has been constructed largely along axiomatic lines where some social situation is stipulated in advance of analysis and the properties of that situation are explored. Within this scheme of thought, strategic options, payoffs, and distributions associated with those options are specified in advance of play, and the properties of that game then examined. This is also true of recent work to use game theory to illuminate social behavior, like what Herbert Gintis and Dirk Helbing (2015) call "homo socialis." While axiomatic, solvable game theory is a fine analytical framework for exploring some properties of different sets of rules and payoffs, it does not touch upon principles of spontaneous orders and invisible hands, which are typically glossed for the purposes of analytical tractability as in Gintis's (2009: 223) game theoretic interpretation of Kiyatoki and Wright's (1989) model of the emergence of money. Game theory can't study interaction, and by extension spontaneous ordering, so long as it limits itself to the study of the already-interacted-with. The assumption of order is not something that is deduced from prior action, but rather is a stylized fact theorists use to guide their research into the properties of some postulated order. Social ordering, however, occurs at the level of the *partial and not the universal, complete, or perfect*: partial ordering, partial knowledge, partial foresight. As Cachanosky (2010) notes, a game theory wherein players are necessarily capable of constructivist rationality, using optimization methods to calculate best-responses through dizzingly combinatorially large phase spaces of possibilities may limit agents to strategic action ill-suited to take advantage of ecological rationality (Gigerenzer 2009; Smith 2008).

Within the framework of a social exchange economy as portrayed by traditional game theory, societal outcomes are of human design as well as human action. This property results from an assumption of unidirectional causality from rules to human action, rather than considering how human action may cause rules, which entails bidirectional feedback between human action and rules. Indeed, such bidirectional feedback might require reframing of the social problem in terms of systems theory rather than in terms of representative-agent style equilibrium theory, as Wagner (2010) explores. Social systems are *complex* systems, so the outcomes of social ordering processes will not always be simple steady-states. In addition to steady states (which themselves may be, in reality, quite rare), we should expect to observe simple patterns like cycles between outcomes, complex patterns, and, sometimes, randomness (Bednar & Page 2016). But within a unidirectional rules-to-action scheme of thought, there is no scope for rules or habits to emerge through human actions repeated often enough, nor any scope for a systems-theoretic treatment of social theory that can go very much beyond steady-state outcomes. Traditional game theory is represented by a unidirectional rules-to-action scheme of thought, perhaps due to analytical exigencies and a methodological adherence to equilibrium theory. Game theory as social theory need not, and as we shall show *cannot* be so constrained if it is to be of general use in explicating the emergence of spontaneous orders and their properties.

We start our analysis by exploring interaction among players who face concrete problem situations, and with those interactions subsequently generating social patterns, including game structures and payoffs. This emergent scheme of analysis seeks to explain how a state of social cooperation might, or might not, emerge from interaction among individuals. This emergent line of analysis is exemplified in Bruno Latour's (2005) effort to explain how social arrangements emerge from networked interaction among what were previously non-social entities. It is also exemplified by the papers collected in Joshua Epstein (2006), which examine how social patterns emerge from individual interaction, in contrast to assuming existence of those patterns. To understand the emergence of cooperation, as well as of its possible disintegration, it is necessary that societal cooperation be a possible but not a necessary product of social interaction. Societies clearly exhibit a great deal of cooperation, though they also entail a fair amount of conflict. The analytical challenge for emergence-style theorizing is to enable both cooperation and conflict to emerge through interaction, as against being stipulated in advance of interaction, recurring to James Buchanan's (1964) dictum that markets become competitive through interaction, in contrast to conventional presumptions that markets are either competitive or not.

Within this emergent scheme of analysis, the institutional structure of interaction, including strategic options, emerge through interaction among players, as against being stipulated in advance of play. The standard 2x2 and representative-agent evolutionary presentations necessarily treat societal interactions as simple phenomena because a theorist can apprehend the entirety of the relevant social process and its possible outcomes. In contrast, we explore what analytical offspring might emerge from mating the interactional motif of game theory with the recent interest in social complexity. In this respect we seek to amplify the growing interest in relating game theory and complexity theory, as illustrated by Axelrod (1997) at the beginning of the wave of interest in complexity economics, and more recently in the essays collected in Rosser (2009) and in the context of heterogeneous agent models (Kaniovski et al 2000).

While we support this line of theorizing, we also seek to challenge the stipulative and closed character of traditional game theory. Modern societies, in contrast to small-scale tribal societies, are simply too complex for a theorist to control or engineer societal outcomes, as against exploring some of the general contours and parameters of societal interaction (Schmookler 1995). In this respect, we treat societies as complex ecologies of interacting agents, leading to our construction of synecological game theory as an analytical construction that combines the game-theoretic focus on social interaction with the classical recognition that social exchange economies are deeply polycentric processes of human interaction, as illustrated luminously by Elinor Ostrom's (1990, 2010) many examinations of common property management.

3.2.1 A Theory of Social Cooperation: The Stag Hunt

Our intention is to construct a framework for social interaction that combines strategic interaction with principles of divided and distributed knowledge in conjunction with emergent phenomena and spontaneous ordering. Robert Clower (1994) called upon theorists to analyze the operation of the fingers of the invisible hand, and that is what we are doing with our synecological approach to game theory. We should also note that our analysis of synecological games elevates institutional frameworks over resource allocations as prime variables of analytical interest because institutional relationships among societal participants are prior to the resource allocations that emerge out of those institutional arrangements.

The Stag Hunt game is a particularly apt illustration of how game theory can be used to plumb social cooperation because it has two social equilibria with different material standards of living. Those different standards of living led John Bryant (1994) to describe the Stag Hunt as illustrating the possibility of under-employment equilibrium. The internal operation of the game gives no basis for selecting between the alternative equilibrium outcomes, as Table 3 illustrates.

Table 3 Stag Hunt and Macro Equilibrium

	Low effort	High effort
Low effort	1,1	1,0
High effort	0,1	2,2

The rules require captured game to be eaten in common. Should both hunters exert effort, they will capture a stag. Should they exert low effort, they will each dine on hare. Should one hunter exert high effort while the other sloughs off, the energetic hunter will catch a hare which will be shared with the other hunter while the other hunter will catch nothing. In this case, the lackadaisical hunter receives a net gain of one while the energetic hunter receives a net gain of zero, as the marginal disutility of the intense hunting effort offsets the marginal utility from the hare.

With a one-shot play of this game, which of the two equilibria occurs is accidental. Yet, when faced with a choice between (1,1) and (2,2), each player would prefer the joint supply of high effort. Theorists have sought to escape this accidental feature of the 2x2 representation while working with it all the same by engaging in plausible acts of "interpretation." For instance, Bryan Skyms (2004) introduces the formation of hunting groups, some of which are more successful than others, and with information about relative success diffusing among the tribe as gossip and rumor spread due to some groups returning with stag while others return with only hare. These kinds of activities, while easily understandable, lie outside or beyond the game's framework. While hunters may experiment or learn within some kind of evolving knowledge environment, such contextualization, while reasonable, does not fit within the game's strategy space.

In taking the Stag Hunt or any other construction beyond its 2x2 depiction, a theorist necessarily faces a fork in the theoretical road. One branch of that fork entails engaging in a form of *ex cathedra* speech, where the theorist offers seemingly sensible interpretative remarks outside the model. The benefit of the *ex cathedra* speech is to keep the 2x2 model intact, but in so doing it places the interpretative remarks *outside* the theoretical framework. Inside the model, after all, there is no room for the formation of hunting groups of different size and having different forms of internal organization.

The other theoretical branch entails amending game theory as social theory so that it maps onto synecological schemes of thought. Rather than working with a universal stag hunt, many parties would engage varied hunting games, with those parties differing in both their strategies and their tactics. Note that we do not suggest merely a repeated evolutionary form of the stag hunt, where evolutionary strategies take the form of some ordering of high and low effort so that players maximize their aggregate payoffs over some number of turns, nor merely the traditional evolutionary stag hunt played with heterogeneous agents on a different topology like a grid (as are the games in Axelrod, 1997) or a social network (as are the games in Tesfatsion 2017). Incentives from competition exist for hunters to innovate and change the *nature* of the hunting games they face, the 2x2 structures themselves, or the perhaps some additional game(s) whose outcomes reify the preferred equilibrium in the 2x2 stag hunt (Bednar & Page 2007, 2016). From time to time, new parties would form, possibly deploying new strategy or tactics. Among other things, the synecological orientation would recognize how the latency of experimentation continually threatens to unleash new commercial configurations, transforming options and strategies in the process along the lines that Jason Potts (2019**)** sets forth in *The Innovation Commons*, which pertains to economic activity prior its becoming organized through firms and markets.

Within the traditional stag-hunt framework, the hunters comprise a consumers' cooperative, with all harvest being consumed in common even when effort supplied varies among hunters. Perhaps the hunters will recognize this causal property, but perhaps they won't. Even if they do, there is still a problem of how they might address the situation. No hunter will admit to being a slacker, as all will surely claim they have been working hard; a not-so-classic principal-agent problem, where each hunter is both the principal and the agent of the hunt game. It's imaginable that the consumers' cooperative might be converted into a proprietary firm, with one of the hunters paying wages to the other, transforming a not-so-classic principal agent problem into a classic principal agent problem. Yet the productivity of any hunter's effort depends on the effort supplied by the other hunter. Furthermore, the proprietor in this alternative game framework could not monitor the other player because that would reduce his effort at hunting stag to zero.

Consider the evolutionary stag hunt as another way of conditioning the behavior of hunters to attain a regular (2,2) rather than a (1,1) outcome. The evolutionary Pareto equilibrium requires its own set of preconditions, namely, that of a rather small, unchanging, and tight-knit community. The coordinativeness of such communities is well-known as it reduces monitoring costs, but in the presumption of such a community the problem of how hunters coordinate around better outcomes—social ordering in the verb sense—is assumed away by assuming a set of *N* agents who have all the time in the world to randomly interact and utilize Bayesian updating to form a sense for the distribution of trustworthy hunters. That is, *time* supplements the limited cognitive capacity of hunters enough to solve social ordering problems based on asymmetric information. The vast majority of interesting examples of spontaneous ordering do not benefit from such rarified environments, however, but pertain to environments in which there is constant change and conflict. Defining theoretical social ordering absent change and conflict makes actual ordering appear as if it is especially fragile to change and conflict, but such theoretical exigencies do not plausibly explain observed social patterns.

In short, the use of simple 2x2 games and their evolutionary equivalents to illustrate social cooperation presents inadequate portraits of the problem of finding and maintaining social cooperation. Analytically, traditional game theory is limited by its player-reflexive epistemological presuppositions, formulated to give the analyst-expert the capability to develop prescriptive optimal strategies, updated with probabilistic language during the era of rational expectations. It may be that games with such burdensome epistemological limitations are more suitable for studying military situations, as was their original application (Mankiewicz 2005: 166). The various coordination games that have been used to illustrate potential gains from social cooperation, along with the possibility of such cooperation to fully secure the potential gains from cooperation run afoul of one of the central presuppositions of economic theory, which is an invisible hand style of explanation (Aydinonat 2008).

No single person can apprehend the entirety of any society within an invisible hand explanation. We all reside inside a division of labor and knowledge, the apprehensibility of which is attenuated by a continual temporal movement into the unknown. Both rules and societal coordination in such a system must be an emergent quality of labor- and knowledge-divided action. The typical 2x2 evolutionary models commonly used to illustrate societal coordination or its failure to cohere are not equipped to deal with spontaneous ordering processes without skipping ahead to presumptive equilibrium or loading games with exogenous architecture. We adopt a synecological orientation toward game theory with the end-goal of marrying invisible hand and distributed knowledge types of explanations of social coordination with a game-theoretic framework of societal interaction.

3.3 Introducing Synecological Game Theory, Feet-first

In this section, we build a formulation of synecological game-theory, feet-first. First, we preface with the definition of what we call *extended games*. Extended games are a collection of games on a connected network, such that the nodes of the network represent (not necessarily unique) games, and the edges between game nodes represent that at least one player plays both games. That is, if A ←→ B, where A and B are game nodes and ←→ represents (in this case) an undirected edge between the game nodes, at least one and perhaps all players play both games A and B. If all players play both games, and the edges are directed such that, say, first A is played and then B, we have a traditional sequential game. If a sequence of play is longer than two games, we represent it with directed edges between interior members of the sequence, and an undirected edge between the final and first members of the sequence, like so: A → B → C → D ←→ A. Note especially, however, that synecological games will not represent emergent spontaneous order in a closed-ended evolutionary-in-name-only dynamical system. We will discuss open-ended evolutionary synecological game theory momentarily.

We present an example extended game network in Figure 8. We do not specify the entire game, as we do not know the structure of the games, nor which players play which games. Synecological game theory is dual-layered, where an extended game network as shown in Fig. 2 emerges from repeated gameplay such that players can exert choice over strategies, participation in certain games, and altering the payoffs of existing games. If players who play both games F and E in Fig. 2 decide that playing F then E makes them worse off than starting with E and forgoing F entirely, F will no longer be a part of the extended game. Similarly, preceding games can alter the payoff structure of subsequent games through the shared player. If the outcomes of F are subject to a cost and quality measurement that alters profits in game E, then the shared player who plays both F and E will be in effect altering the possible payoffs to the nonshared players of E.

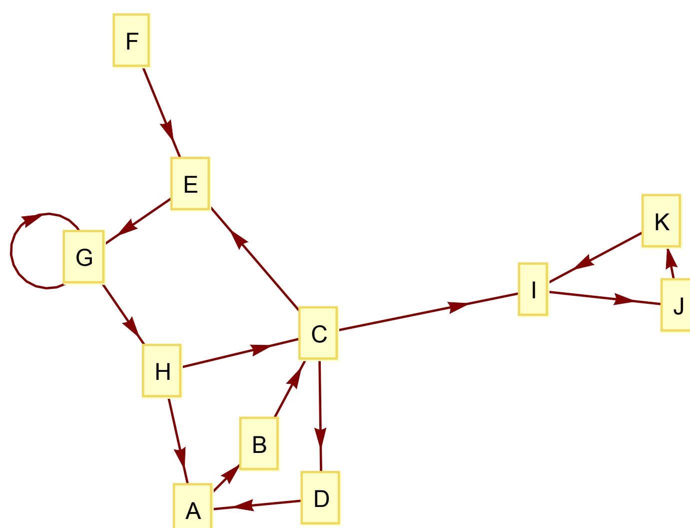


Figure 8 An example extended games network

Figure 8: An example extended game network.

Since action within a social infrastructure is a product of recursive feedback between the individual and the social, we can conceive of extended games both as emerging from individual actions and influencing those actions.

Although sequential games are a subset of extended games, extended games are more general than sequential games, which is why we introduce a new term: a **chain** of games is any connected subnetwork of the larger network of extended games (which is itself connected, by definition). We might visualize a chain of games as in Figure 9.

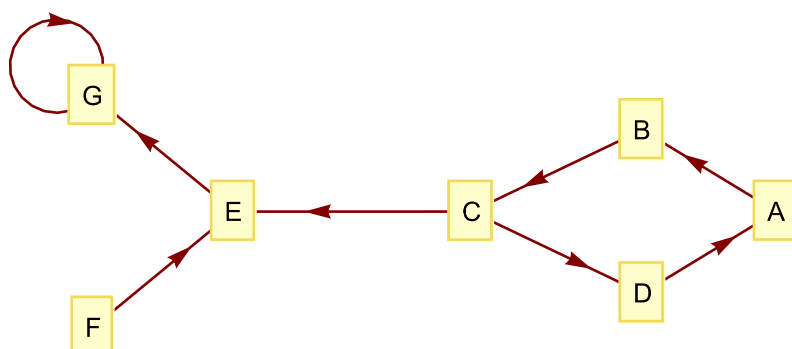


Figure 9 A chain of games

Figure 9: A chain of games, which is a connected subnetwork of the extended game network in Figure 2.

Definition 1: An **extended game** is an *m*-member collection of games with *n* heterogeneous players, where not all players necessarily play every subgame in sequence, such that at least 1 player is shared between sequential subgames in an extended game.

Multistage games are a subset of extended games, where stages are of the same dimensions, share all players in common, and are sequential. An example of a multistage game is the subnetwork in Figure 10, with the edges understood to consist of all the same players.

Figure 10 A multistage game

Figure 10: A multistage game.

Repeated games are a subset of extended games, such that the same game is connected to itself in a self-loop. An example of a repeated game is the self-loop subnetwork shown in Figure 11.

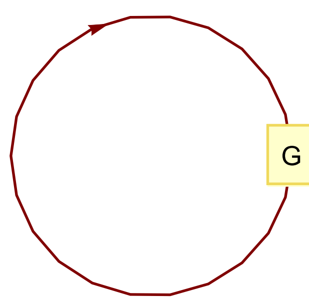


Figure 11 A repeated game

Figure 11: A repeated game, visualized as a self-loop.

A **synecological game** is a chain of an extended game such that: at least one player *but not all* players are shared between sequential games (*weak connectivity*), no single player spans the entire chain (*no-dictator condition*), and outcomes for shared players are coupled between the games they play (*entanglement*). An example of a synecological game is pictured in Figure 12.

Figure 12 A synecological game

Figure 12: The visualization of a synecological game.

Definition 2: A **synecological game** $\Gamma = \{\gamma_1, \ldots, \gamma_m\}$ is an extended game of length *m* where:

i. *Weak Connectivity* - At least one player, but not all players, are shared between sequential games
ii. *No-dictator Condition* - No single player spans the entire extended game
iii. *Entanglement* - Suppose the shared player *i* plays subgame γ_{j-1} first, and subgame γ_j subsequently. Then, the payoffs v_i^j of subgame γ_j are a function of the payoffs of the previous game v_i^{j-1} and the strategic actions of the nonshared players in γ_j.

For example, suppose γ_1 is a principal agent game between employee 1 (player 1) and employer 1 (player 2), and suppose γ_2 is a market competition game between employer 1 (player 2) and employer 2 (player 3). Employee 1 produces product quality through effort, and employer 1 pays employee 1 for their trouble with wages. Suppose the payoffs in γ_1 are in terms of wages minus effort for employee 1, and product quality minus wages for employer 1.

By Def 1 (i & ii), we need a third subgame in the chain γ_3 that employee 1, the shared player between γ_1 and γ_2, does not play. Suppose this is another principal agent game played between employer 2 (player 3) and employee 2 (player 4), with the same general characteristics of γ_1.

By Def 1 (iii), the payoffs employer 1 can expect in γ_2 are a function of product quality and costs of product quality production--that is, a function of the payoffs of γ_1--and the actions taken by employer 2. Similarly, the payoffs employer 2 can expect in γ_3 are a function of the payoffs of γ_3 and the actions taken by employer 1.

The reason why the final condition is called *entanglement* is now apparent to the astute reader. In formulating any best response in this game, employer 1, for instance, would need to take into account not just the payoff structure and strategy space of γ_1 and γ_2, but also of γ_3, even though employer 1 does not participate in γ_3. The outcomes of γ_3 affect the potential outcomes of γ_2. As we shall see below, entanglement allows for other possibilities to arise in the overall synecological game: the emergence of *nonlocal* gameplay between players of the synecological game who never play directly with one another.

Synecological games are specifically defined such that the outcomes of gameplay are subject to fundamentally nonlocal influences. This is the intuition brought forward by the use of the term synecological, which Roger Koppl (2018) has applied to knowledge, in that he defines synecological knowledge as knowledge held outside the individual, in groups or in the social structure of action (including rules and norms).

Note in particular that synecological games are not mathematically equivalent to multistage games. Multistage games are a subset of extended games, as are synecological games, but the two are different from each other. The definition of a multistage game requires that agents are able to observe the history of action after each stage, even if they are technically "doing nothing" during that stage (Fudenberg & Tirole: 70-1). Synecological games hide the history of some stages from other agents. In a minimal synecological game, agents may be able to engage in some kind of pattern classification on historical data they do see in order to determine how it is affected by gameplay outside their direct observation, and may get close enough to inferring the history of relevant gameplay outside their plan to take that behavior into account when they are strategizing in-plan.

Let's write it in the Fudenberg-Tirole terminology. Let the set of all agents be $\mathcal{I}$, the action profile at stage k to be a^k, and the history at the end of stage k to be $h^{k+1} = (a^0, a^1, \dots, a^k)$. The set of actions available to player i at stage k in general depend on what happened before stage k, so then $A_i(h^k)$ denotes the possible k-stage actions available to player i.

Now, synecological games do have histories! Suppose we have a three-member synecological game where games $\gamma_2 \rightarrow \gamma_2 \rightarrow \gamma_3$. Then the history once game 3 is played will be $h^3 = (a^0, a^1, a^2)$. However, player 1 only sees (a^0), player 2 sees (a^0, a^1), player 3 sees (a^1, a^2) and player 4 sees (a^2).

These limited histories do not allow players to solve for optimal solutions *as if* they had the entire history, as they are not aware of all the dependencies, and the system may very well be irreducible to a simpler representation of itself. We see an example of a system irreducible to a more standard characterization proved quite elegantly when games are played on networks, as in Jackson & Zenou (2015: 116-122), where the authors show for a game of positive externalities in effort expended that agents will generally undersupply the effort needed to attain a social welfare optimum if gameplay had not been on a less-than-complete network.

3.4 The Minimal Synecological Game

Suppose we have a minimal synecological game, i.e., $\Gamma = \{\gamma_1, \gamma_2, \gamma_3\}$ with $n = 4$ players, none of whom play all three games by definition. In this game, we have two shared players, one who plays both γ_1 and γ_2, and the other who plays both γ_2 and γ_3. Without loss of generality, let's ignore Nature as a player and allow strategies to be probabilistic or not. We can write out the minimal synecological game in normal form, noting that we specify the graph of the relationship between games in the first entry:

Equation 1 The specification of the incentive synecological game

$$\Gamma = \langle \{\gamma_1 \rightarrow \gamma_2 \leftarrow \gamma_3\}, N = \{\{1,2\}, \{2,3\}, \{3,4\}\}, \mathcal{A} = A^1 \times A^2 \times A^3,$$

$$\{v_1^1(a_1), v_2^1(a_1), v_2^2(v_2^1(a_1), a_2),\ v_3^2(v_3^3(a_4), a_2), v_3^3(a_4), v_4^3(a_4)\}\rangle \quad (1)$$

To best understand how the tensored action space is constructed for the synecological game, and the action spaces accessible to shared players which are strictly *smaller* than the fully synecological action space, and for unshared players, even smaller, we first look at the details of one of the game pairs that make up the three-game synecological chain. Suppose we look at a minimal game pair of 2x2 subgames, namely, $\mathcal{G}_1 = \langle\{\gamma_1, \gamma_2\}, N = \{\{1,2\},\{2,3\}\}, \mathcal{A}_1 = A^1 \times A^2\rangle$ where $\mathcal{A}$ is the overall strategy space.

The strategy space in γ_1 is defined by $A^1 = \{((a_1)_1^1, (a_1)_2^1), ((a_2)_1^1, (a_1)_2^1), ((a_1)_1^1, (a_2)_2^1), (((a_2)_1^1, (a_2)_2^1)\}$. The parenthetical a_i refer to the two actions available to each player (which may be different from one another), the bottom index outside the parentheses indicates which player is acting, and the top index indicates the game being played. Each action pair represents a strategy profile in γ_1.

Define some function *f* that couples the payoffs for the shared player 2, that is, such that that payoffs for player 2 in γ_2 are functions of the payoffs in γ_1. In general, the payoff function for player 2 in game 2 is $v_2^2(f(v_2^1((a_i)_2^1, (a_j)_1^1)), (a_k)_2^2, (a_l)_3^2)$, where v_n^m represents the payoff function for player *n* in game *m*. When the shared player 2 is choosing a strategy in game 2, their choice over the game 2 strategy space $A^2 = \{((a_1)_2^2, (a_1)_3^2), ((a_1)_2^2, (a_2)_3^2), ((a_2)_2^2, (a_1)_3^2), ((a_2)_2^2, (a_2)_3^2)\}$ is a function of *f*. We can understand this better if we conceive of the choice of a strategy as being over both games, or over the 16-member (4^2) direct product of the two strategy spaces:

$$
\begin{aligned}
\mathcal{A}_1 = A^1 \times A^2 = \Big[&\big\{\big((a_1)^1_1, (a_1)^1_2\big), \big((a_1)^2_2, (a_1)^2_3\big)\big\}, \big\{\big((a_1)^1_1, (a_1)^1_2\big), \big((a_1)^2_2, (a_2)^2_3\big)\big\}, \\
&\big\{\big((a_1)^1_1, (a_1)^1_2\big), \big((a_2)^2_2, (a_1)^2_3\big)\big\}, \big\{\big((a_1)^1_1, (a_1)^1_2\big), \big((a_2)^2_2, (a_2)^2_3\big)\big\}, \\
&\big\{\big((a_2)^1_1, (a_1)^1_2\big), \big((a_1)^2_2, (a_1)^2_3\big)\big\}, \big\{\big((a_2)^1_1, (a_1)^1_2\big), \big((a_1)^2_2, (a_2)^2_3\big)\big\}, \\
&\big\{\big((a_2)^1_1, (a_1)^1_2\big), \big((a_2)^2_2, (a_1)^2_3\big)\big\}, \big\{\big((a_2)^1_1, (a_1)^1_2\big), \big((a_2)^2_2, (a_2)^2_3\big)\big\}, \\
&\big\{\big((a_1)^1_1, (a_2)^1_2\big), \big((a_1)^2_2, (a_1)^2_3\big)\big\}, \big\{\big((a_1)^1_1, (a_2)^1_2\big), \big((a_1)^2_2, (a_2)^2_3\big)\big\}, \\
&\big\{\big((a_1)^1_1, (a_2)^1_2\big), \big((a_2)^2_2, (a_1)^2_3\big)\big\}, \big\{\big((a_1)^1_1, (a_2)^1_2\big), \big((a_2)^2_2, (a_2)^2_3\big)\big\}, \\
&\big\{\big((a_2)^1_1, (a_2)^1_2\big), \big((a_1)^2_2, (a_1)^2_3\big)\big\}, \big\{\big((a_2)^1_1, (a_2)^1_2\big), \big((a_1)^2_2, (a_2)^2_3\big)\big\}, \\
&\big\{\big((a_2)^1_1, (a_2)^1_2\big), \big((a_2)^2_2, (a_1)^2_3\big)\big\}, \big\{\big((a_2)^1_1, (a_2)^1_2\big), \big((a_2)^2_2, (a_2)^2_3\big)\big\}\Big]
\end{aligned}
$$

The shared player 2 must select from the above combinatorial strategy space when choosing how to maximize her payoff. But does she have all the requisite information to engage in a maximization procedure? No: because the shared player 3 is choosing over a strategy space that is the Cartesian product of the strategy spaces of games 2 and 3: $\mathcal{A}_2 = A^2 \times A^3$. If player 2 wants to formulate a best response to player 3, player 2 must infer something about the structure of game 3 without knowing anything about game 3 other than how player 3's actions deviate from how she would choose if she wasn't facing a combinatorial strategy space with strategies unknown to player 2.

If we were to take a snapshot of gameplay in the synecological game described by (1), we could define some strategy profile being selected for by the players at each point of time in the 64-member (4^3) list of three-pair lists that describe the state of the synecological game at any given snapshot in time. For example, the state of the synecological game could be: $s = \{((a_2)^1_1, (a_1)^1_2), ((a_1)^2_2, (a_2)^2_3), ((a_1)^3_3, (a_1)^3_4)\}$, which merely indicates which strategies are being used by which players in all the subgames of the synecological game at a given time.

Determining the overall payoffs associated with any given state isn't difficult, as long as we know the coupling functions between payoffs in one game and another for shared players. The difficulty comes in formulating best-response functions without evolution, as we shall discuss later on.

The payoffs in a production-chain game like the synecological Stag Hunt have a certain order to them. Shared players first play a game whereby they obtain inputs, then another game where they sell a finished product, so that the input's nature and quality add to profits, and its costs detract from profits. That is, the topology of the synecological game determines which payoffs are coupled, via the directionality of the edges. Take the synecological game from Figure 6, and make it a minimal synecological game (so that each game is 2x2, and there are four total players). First, games C and F are played, then game D is played with two shared players. If players 1 and 2 play game C, players 3 and 4 play game F, and players 2 and 3 play game D, then the payoff vectors for each game look like:

$$V_C = \{v_1^C((a_2)_1^C, (a_1)_2^C), v_2^C((a_2)_1^C, (a_1)_2^C)\}$$

$$V_F = \{v_3^F((a_2)_3^F, (a_1)_4^2), v_4^F((a_2)_3^F, (a_1)_4^F)\}$$

$$V_D = \{v_3^D(f\ (v_3^F((a_2)_3^F, (a_1)_4^F)), (a_2)_1^D, (a_1)_3^D), v_1^D(g\ (v_1^C((a_2)_1^C, (a_1)_2^C)), (a_2)_1^D, (a_1)_3^D\}$$

A general feature of payoffs of "earlier" games in the synecological game chain is that they do not necessarily map to the reals, as they become inputs in (at least) a two-factor determination of their monetary payoff. So, the first game may be to hunt stag, and the second may be to sell stag on the market. The employer who hires hunters to hunt stag pays the hunters a wage, and then must compete with another employer to sell stag (or hare) on the market.

3.4.1 Incentive Games as Synecological Games

Hunters getting paid a wage may be able to slack off and get away with it; they can claim there were no stags that day, or that their fellow hunter was the one who slacked off. But employers can set wages in a way that entangle hunters in a prisoner's dilemma such that they have no incentive to collude at a (low-effort, low-effort} equilibrium. We call this game an incentive game. Incentive games are principal-agent games where both principal outcomes and agent actions are coupled by market competition, as in Gintis (2009).

Gintis's Allied Widgets game starts with two principal-agent games between owner_1 and manager_1 and owner_2 and manager_2, respectively. Call these games γ_{PA1} and γ_{PA2}. The owners own companies whose products compete with each other. In the principal agent games, managers put in a certain level of effort to discover new, less-costly production methods. Owners attempt to set wage rates that best incentivize this discovery effort, even though they have difficulty monitoring whether or not managers are actually conducting research. The owners compete against each other in a marketplace, where the outcomes of each principal agent game influence the payoffs attainable by the managers, as the outcomes represent higher and lower effort put in by the managers. Call this game Γ_{MKT}. Each Γ_{PA} is connected to Γ_{MKT}: the outcome of the principal agent games influence the outcome of Γ_{MKT}. If one manager puts in high effort and is able to discover a less-costly production method (subject to some play of Nature) and the other manager does not put in this effort, then the first company will attain a higher profit in competition with the second company.

We can represent the incentive game as a synecological game, represented as in Figure 13, where blue edges connect games, and dotted red edges indicate membership of players in games. Directionality indicates which games comes first, from an evolutionary perspective, though as the game is played multiple times we see there is a feedback effect from the outcome of market game back to the incentive structure of the principal agent games.

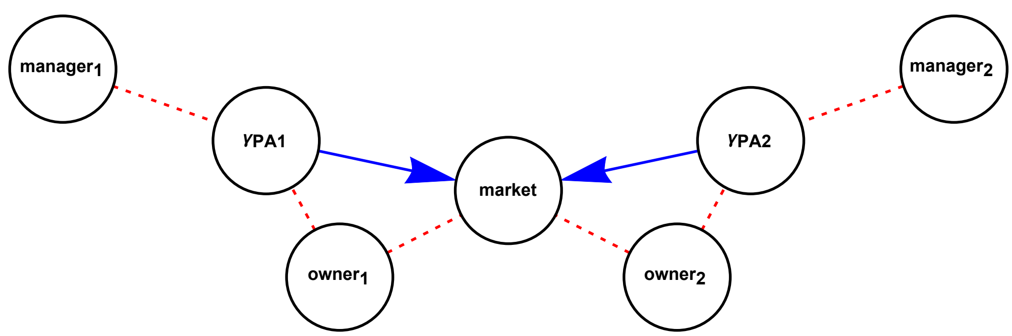


Figure 13 The incentive game as a synecological game

Figure 13: The incentive game as a synecological game

Assume the PA games are identical. The outcomes of the games then determine, via a payoff mapping for each owner *i*, the payoffs available to each owner. Owners use their knowledge of the 1) market game, the 2) symmetry between both PA games, and the 3) marginal costs of producing the outcomes to set wage rates in their respective PA games. These wage rates induce a coupling between managers, which takes the form of a prisoner's dilemma. Call this coupling relationship γ_{PD}. What the owners are doing, in effect, is changing the game managers had been playing with each other, a game in which the managers' fates had been decoupled, into a game where the managers' fates are coupled, i.e., inducing action-at-a-distance.

3.4.2 The Stag Hunt: An Example of a Minimal Synecological Game

To this point, we have amended the standard model of the stag hunt by allowing for different teams of hunters to form and to select different strategies and tactics, possibly but not necessarily leading to a common form of practice. In doing this we have tried to nudge the model toward greater phenomenal complexity, but the extent of such complexity is limited by the environment where only stags and hares can be hunted. This limited phenomenal complexity makes it difficult to step outside the presumption that the theorist has full knowledge of the relevant social options. When a theorist possesses full knowledge, however, the distinction between human action and human design vanishes. Here, we advance a minimal model where there is no person in society who can apprehend the entirety of that society.

Figure 14 depicts an alternative to the stag hunt that entails sufficient phenomenal complexity that no participant can experience the societal entirety. What had been a stag hunt is broken into three overlapping games. The synecological version of the stag hunt could break the stipulated version of the game into three games: two games where stag/hare are hunted by two hunter-pairs employed by two butchers, and a third game where butchers compete with their butchered stags/hares for consumers on the market.

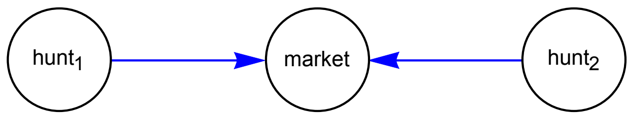


Figure 14 Minimal synecological stag hunt game structure

Figure 14: The minimal synecological stag hunt game: structure of gameplay

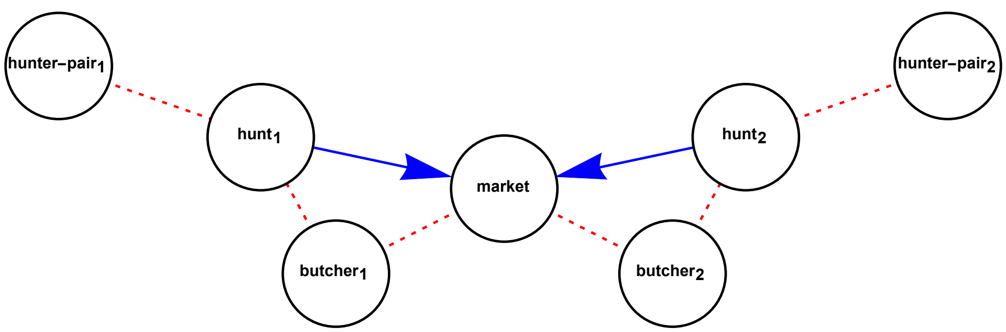


Figure 15 Minimal synecological stag hunt games and players

Figure 15: The minimal synecological stag hunt game: games and players

This four-player, three-game set up is the minimal number of participants for which it can be said that no participant spans the entire set of economic activities. This might be thought to denote the minimal size society where hierarchy must give way to polyarchy, provided that the productive activities of the participants are full-time activities. A synecological approach to game theory as a tool for social theorizing requires recognition that the ecology of transactions that occur within a society cannot be usefully reduced to a representative transaction because reduction assumes away valuable information about how an ecology of transactions acquires coherence. While Figure 15 portrays four as a minimal number for polyarchy to emerge due to limits on knowledge, the actual number could be larger. In any case, pressures for the emergence of polyarchy would surely increase as the division of labor expanded within society.

Coupling outcomes of shared players between the games they play in the synecological game means that there is no simple way to map payoffs to real numbers in every game. Hunters receive a wage in return for hunting where their individual effort levels are concealed from their employers (or really, clients) the butchers. The outcome of the stag hunt—stag or hare—is an input to the market game played between butchers, and analogous to product quality in the Allied Widgets incentive game.

We can extend many games with suboptimal one-off or multistage equilibria into synecological games using this template. Consider the Prisoner's Dilemma, and suppose we extend the game by adding two more players to the original two-player game: the warden and the district attorney. The warden puts the prisoners in solitary confinement (with no communication possible) as a way of manipulating their behavior so that both defect. The warden is incentivized by the district attorney to get *some* kind of confession from the prisoners, perhaps the warden will be promoted if she obtains a number of confessions. The synecological game would have a slightly different structure than the games above, and would require an element of discovery: given the choice between keeping prisoners in the general population and putting them in solitary, the warden would discover that splitting up collaborators generates a higher percentage of confessions than not. But it would not require an assumption that prisoner's cannot communicate, it would generate the conditions by which the prisoners do not communicate through incentives presented to the warden through outside-of-PD gameplay and how the outcomes of PD (confession or silence) are coupled with, in this case, the outcome of the warden's "promotion game" with the district attorney.

In traditional repeated and multistage game theory, games are coupled by virtue of all players being able to influence outcomes, and all players knowing that all players can influence all outcomes implies a particular form to rational action in traditional game theory. And if one player spanned all the subgames of a synecological game, then rational action for nonspanning players would reduce to inferring the joint payoff function of the spanning player over all the games she plays. Powerful enough players in any social context would thereby alter the behavior of other players to be primarily reactive to the power player, described as a Big Player in Koppl (2002).

> **Corollary C3:** Simple profit/utility maximization at each stage of a game decouples games from one another. Therefore, we define what we call a **plan**, wherein agents do not realize payoffs until the plan, which consists of multiples parts (games), has been fully executed. Synecological game theory represents an ecology of plans; plans and plan-contexts are, therefore, basic objects of interest in this methodological framework.

3.4.3 Representing Entanglement and Nonlocality Using Synecological Games

Synecological games exhibit what (Coecke 2017) calls ‘togetherness,’ that is, when the composition of two or more objects—games in our case—produce outcomes that are not accessible through the autonomous operation of the objects individually. A system whose objects exhibit togetherness when composed is irreducible to a sum of its parts. The primary example of togetherness in physics is quantum entanglement (Brandao et al 2013). Note that we do not imply that synecological game theory is a branch of econophysics or representative of Qadir’s (1978) quantum economics, namely, in that an economic agent can always be represented as a point in Hilbert space (ibid: 122). Nor is synecological game theory representative of Meyer’s (1999) quantum games and their subsequent extension into economics (Brandenburger 2010). Rather, quantum entanglement serves as a mathematical and theoretical analogy for the kind of nonlocal outcomes that are natural to a synecological framework.

Consider the entanglement of outcomes in synecological games as an alteration of the state space in which players interact. Consider a synecological game where no upstream forecasting is possible. The fate of players in the system are intertwined but not in a way that can be taken into account until the moment interaction happens. Take the incentive game as an example. We can visualize the states of the system like a particle interaction, where γ_1 and γ_2 change their states to γ_3 and γ_4 respectively after shared players interact via a third game, γ_3, as in Figure 16.

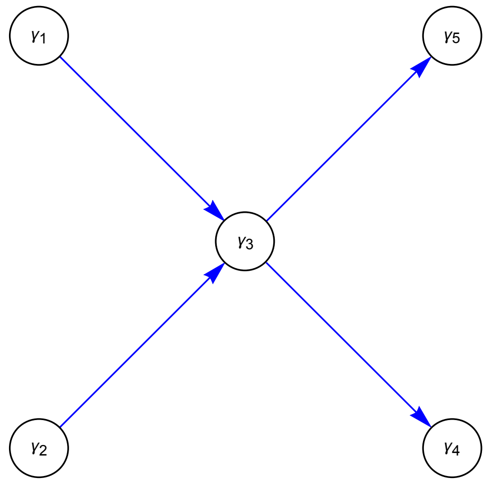


Figure 16 General entanglement of states

Figure 16: General entanglement of states

Games-of-interest (like γ_1 and γ_2) may further change states with other interactions, or serve as catalysts (like γ_3) for other games-of-interest. What's notable in the graph above, given the example of the incentive game, how γ_3 entwines the fates of γ_4 and γ_5 with each other, when before γ_1 and γ_2 operated as if their outcomes were independent of each other. Gintis illustrates this entanglement explicitly, by showing how a prisoner's dilemma (the form of the entanglement) emerges between two principal-agent games (γ_1 and γ_2) after they are entangled via a market game (γ_3). We illustrate this entanglement in time by showing the nature of the interaction that spontaneously emerges between the principal agent games in Figure 17 below:

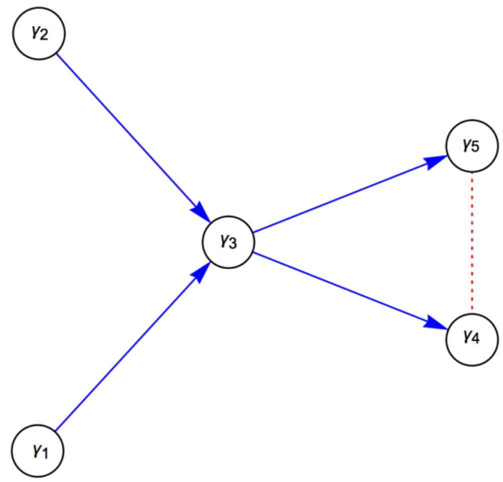


Figure 17 Nonlocality after interaction

Figure 17: Nonlocality after interaction.

In the incentive game, managers never play directly with each other, they are merely incentivized to act as if they do so, given the nature of how the two companies' payoffs are coupled by γ_{MKT}. γ_{DC} and γ_{PD}.

3.4.4 Evolutionary Synecological Game Theory: Moving Beyond the Minimum

Four players with three distinct types of activity is the minimum sized society for which no person can experience the societal entirety. To be sure, this is still a quite small number as it features three monopoly teams and two monopoly middlemen. Modern societies feature both a far greater number of distinct activities than three and more than one team engaged in each of those activities. Our point in raising such a menu of options is to move in the direction of a generative or emergent style of macro analysis where systemic outcomes emerge out of micro-level interactions. By allowing games to compete, and explicitly expressing payoffs as a function of demand and/or expected profits from a producer upstream, we can expose the process of payoff parametrization in such a way that enables us to investigate the ways in which markets operating as usual deal with the kinds of perverse social situations indicated by the stag hunt, principal agent and prisoner's dilemma games.

The standard approach of game theory is to stipulate a set of rules and payoffs the players face, which determines the game's properties. Our synecological framework, however, starts with individuals who interact among other people in a variety of settings, with conventions, practices, and payoffs emerging through those interactions. Where the stag hunt game posits a rule of communal consumption, the synecological formulation is one where rules of consumption and ownership emerge through interactions among the participants. In this respect, we would note the presence of a good deal of anthropological literature that situations of common consumption of game where tribal customs have rules for attributing ownership of game all the same. Whoever receives the attribution of ownership is able to host the meal where the game is served, thus harnessing an interest in status to offset what might otherwise be tendencies toward lassitude.

To put game theory into a synecological framework means that the aggregate or systemic properties of that game cannot be inferred from the solution to a representative game. To the contrary, there must be interaction among games, with the systemic properties stemming from that interaction. At every node in this supply chain, there will be multiple participants connected with one another through webs of expectations and contracts. Performance within the system can't be reduced to performance at one node within the system, nor can a system of independent nodes be reduced to a representative node.

3.5 Using Synecological Game Theory to Explicate Economic Puzzles

A rudimentary society may well be one where people run down deer and hare, then butcher what they catch, after which they eat it. This autarkic image might have fit some societies from long ago (Schmookler 1995), but they do not speak to cooperation within modern societies with extensive divisions of labor which enable pencils to be produced even though no one can truly plan the production of pencils from start to finish (Read 1958). What might appear as the breakdown of social relationships, say in the breakdown of trust in an assurance game, or the breakdown of cooperation in a common-pool resources prisoner's dilemma, may be the emergent result of an extended form of gameplay that illustrates current, though ultimately fungible, institutional contexts (Ostrom 2010).

Game theory offers a framework for understanding this kind of societal coordination, both how it comes about and how it might break down. It is surely desirable to have game theory illustrate rather than conceal the operation of such concepts as emergence, invisible hands, and spontaneous ordering. A synecological orientation offers potential to do this, wherein social cooperation would be explained as emerging within a systemic ecology of games, as against reducing reality to one universal game. Within this ecology of games, individuals participate in multiple interactions or games, with systemic properties of that system of interaction being governed by institutional frameworks that governs interactions within those various games that comprise the ecology of games. In the examples below, we explain how conceptualizing social systems as ecologies of games might shed light on several economic puzzles.

3.5.1 Behavioral Paternalism

Synecological games both shrink and expand the set of improvements to behavior implied as a natural conclusion to experimental findings about human behavior in the context of neoclassical (constructive) rationality, or what the founders of behavioral paternalism call *nudge*. More than a few critiques of behavioral paternalism have rested on how its implications require social and evolutionary decontextualization in order to obtain (see in particular Rizzo & Whitman 2015, 2019). Synecological game theory could be used to investigate how debiasing and economic calculation happen in a social context, where social ordering is both a goal and guidebook to action. In particular, our demonstration about the synecological nature of incentive games could provide a template of how debiasing is incentivized through planning (playing chains of other games), and perhaps more importantly, suggest ways in which people may already be self-debiasing.

Syneocological game theory and its ecology of games framework allow us to properly contextualize choices, in contrast to neoclassical reasoning where the only context is an ideally rational agent choosing in an idealized marketplace. Any deviation from presumed perfect equilibrium in neoclassical reasoning is taken as a fault or bias of the agent or system and not a fault of the model or methodological bias of the modeler.

3.5.2 Public Goods Provision

An obvious analogy exists between the IAD framework of the Ostroms and synecological game theory, especially in that the IAD framework contains an explicit feedback between outcomes of interactions and the community structure, including rules-in-use, that then inform the action situations faced by agents that define some set of interactions that may or may not lead to desired outcomes (refer to the graph in Ostrom, 2010: 415). As noted by Elinor Ostrom herself, the definitive prisoner's dilemma game implicated in many a perverse social outcome requires a greater social infrastructure to operate.

Moving beyond prisoner's dilemmas to public goods with network qualities, like trade unions, climate change amelioration and reputation systems, synecological gameplay gives system participants another avenue of exacting nonlocal influence on each other. Recall that market competition provided the institutional gameplay that allowed the owners of Allied and Axis Widgets to induce a prisoner's dilemma between their respective managers and thereby attain optimal social welfare despite their respective principal agent problems. Using a synecological game theory framework, we can experiment with institutional gameplay that induces emergent prisoners' dilemmas in public goods provision *and* solutions to these dilemmas, and also compare these institutions conditions against each other and to real-world institutional conditions.

3.5.3 Trustworthiness Provision

Trustworthiness is essential to the efficiency of any economic interaction. In China, the lack of trustworthy economic interactions has become such a major issue that the Chinese Communist Party is designing a massive, highly personalized, country-wide reputation system for individuals, businesses, and even regional governments (Devereaux & Peng 2020). But is it necessary for trustworthiness to be publicly provided? Synecological game theory might be able to forge a path out of the Hobbesian jungle, in this respect. Consider the Allied Widgets synecological game explicated above. Designed or *de facto* employer collusion can induce a prisoner's dilemma game between the two managers, effectively erasing their ability to collude in their own interest. But there are two sides to any employment contract.

There are a few ways to ensure contract compliance. Clearly, in an evolutionary game, trigger strategies could provide credible (though costly) threats. But other social technologies exist that can endogenize the costs of trustworthiness. On one side of the labor contract, principals want performance; on the other side, agents want a good job that meets the goals of the plan(s) for which their job was a part (as a source of income, as an outlet of creativity, as a place for socialization, as security).

We showed how a synecological game can induce contract compliance on one side of the contract. It follows that managers are incentivized to develop other social technologies (which can be gamified) like trade unions, professional associations, and standardized signaling mechanisms like certification and licensure that are designed to ensure a certain job quality for the employee. Synecological game theory provides a framework in which we can understand how these social technologies are created and adopted, and what 'mix' of technologies we might find under particular institutional configurations.

3.5.4 Perverse Regulatory Outcomes and Regulatory Capture

Clearly, shared players exert influence on the outcomes afforded to non-shared players in synecological games. Non-shared players are incentivized to alter their actions when other players are executing multi-game plans. Of course, regulation is meant to induce behavioral changes. Analysis of a regulatory system hopes to determine, among other things, what extent are these behavioral changes the result of new incentives, and to what extent are they adaptive to regulatory intervention in a way that encourages more intervention or destroys desirable features of the system (like anti-competitive regulatory capture). Synecological game theory provides an entry point for analysis, in that it is uniquely poised to explore how particular coupling games (like market or public games) entangle the plans of private and public officials for good and for ill.

3.6 Discussion

Institutions are commonly described as rules of the game, as Douglass North (1990) exemplifies. This formulation is not wrong, but it is incomplete, in the same manner as stipulating a game without generating its structure is incomplete. Institutions reflect social structure, but that structure emerges out of prior interactions. Lexicography illustrates this point sharply. Dictionaries both compile how people use language in common practice and serve as references for current language rules. Similarly, common practices can become articulated as institutions which then serve as repositories of rules, illustrating a feedback from instituted rules to practice. Practice is logically prior to formalization of practice into rules.

Rather than starting with rules and payoffs as in traditional game theory, the generative approach of synecological game theory seeks to derive a game structure as emerging from interactions among participants. The structure of the resulting synecological game then encodes a way of doing things that can be used as a reference for new players to solve problems, attain goals, and achieve outcomes without needing to analytically grok the entirety of a social process. Synecological games are therefore both the result of and the rubric for action as time rolls forward; a synecological game in equilibrium is simply an established way of doing things that hasn't yet been disrupted, yet it can and shall be disrupted through both exploration of the adjacent possible and systemic evolution. The game structure emerges through social interaction, rather than existing prior to social interaction. These alternative methodological orientations—emergence of a game structure versus stipulation of a game structure—are surely complementary and not competitive, just as the roles of dictionaries as reflecting usage and as instructing usage are complementary. All the while, however, usage logically must be prior to its codification, as must interaction be prior to the articulation of rules that govern interaction. A synecological orientation toward game theory starts with individuals who interact, and with those interactions is subsequently capable of being codified and thereby employed in the analysis of practice.

In any kind of methodology, we must specify the domain and range of the theory. Strategies are traditionally stipulated in a closed-form fashion, and the domain of game theory becomes all possible combinations of strategies taken among players, or, the space of strategy profiles. For one-off games, the size of the strategy space is relatively small. It is typically much larger for finite and infinite evolutionary games, though always specifiable. When players aren't aware of the extent of strategy space, they can sometimes employ search algorithms or other heuristics to explore the space, but in every case, must explicitly test whether strategies result in solutions that are better in payoffs.

While there is a hypothetical combinatorial strategy space in synecological game theory, players are subject to nonlocal influences that are unidentifiable in the domain of their search. The strategies they sample directly are indirectly influenced by strategies outside the game, from games in which the player doesn't take part. That is, even simple strategy spaces in synecological game theory are not plausibly searchable.

Furthermore, identifying influences and inferring the structure of out-of-play gameplay is generally a hard problem. These demonstrations and realizations require the synecological frame of theorizing to have a concept of *perception*, and in particular, a system of individual perceptions that are fundamentally *non-coincident*. This is a sharp methodological divergence from the idea that plan coordination requires to some extent coincident perceptions, or that coincident perceptions will necessarily improve some measure of systemic welfare.

A theory of entangled governance grants no upper hand to the expert in assisting players in making their perceptions coincident in the subjective interest of every player, a conclusion made in other recent works (Koppl 2018; Wagner 2016) and foreshadowed by Hayek (1937, 1945), whose methodology has been of late rather unfortunately mischaracterized as requiring coincident perceptions (see in particular Bowles et al 2017). Rather, the reality of entangled governance in our model implies that expert intervention projects high-dimensional subjective interests to a lower-dimensional version that promotes some ends at the expense of others, and in the process may destroy synecological substructures that emerge to assist in the perception-coincidence of players whose interests are relatively coordinative. Even when expertise works well, it works along axes of interest and influence, and not for everyone.

The recognition of rationality as a systemic and not individual quality in synecological games changes what we mean by a *solution* of the game. Games within a synecological chain may not have solutions as traditionally conceived, but rather would exist as a part of a larger *ecology* of games. As in biological ecologies, the interests of some players and the games they play may be anathema to the interests of and optimal solutions to the games of others. Systemic rationality consists of a variety of processes serving a variety of coordinative and discoordinative ends, in which the discoordinative elements should not be discounted for ecological roles that go far beyond the mere provision of competitive pressures.

Colloquially, there may be necessary evils to social existence at any cross-section of time. The utopian bias of economic theory in its optimization language is sadly a side effect of an overlysimplistic mathematical foundation that stipulates the coincidence of perception and therefore predicates optimal outcomes on its existence, by assumption. Any aberration is considered a rectifiable flaw. A systems-oriented, process-focused, synecologically-aware theory has no such pretensions to Utopia and is, perhaps by this fact alone, a better foundation for realistic and demonstrative social theorizing.

CHAPTER FOUR:
THE THEORETICAL STRUCTURE OF SYNECOLOGICAL GAME THEORY

> If the whole system of human affairs were subject to systems of polycentric orderings, it would be as though all patterns of order in society were conceptualized as a series of simultaneous and sequential games…
>
> …We might further anticipate that general systems of polycentric orderings applicable to whole systems of affairs would take on the characteristics of competitive games: contestability, innovative search for advantage, and convergence toward successful strategies. If the whole system of human affairs were organized in this way, we would expect to see the emergence of a civilization with greater evolutionary potential than can be achieved by those who call for revolutionary change. (Ostrom 2014: 48)

4.1 Introduction

Can game theory as a social theory embraces the three points of economic modeling sufficiency outlined in Chapters 1-3? Yes, though not perhaps in its current overstrong and analytically-closed form.

In this thesis I refer to *traditional game theory* as the theory of games where all players play the same or same set of one-off or stage games, where there is some kind of common knowledge of strategic choices and payoffs shared by all players in the system even if that knowledge is constrained to some finite window of moves, and where stages of gameplay are structurally independent of each other in that within-game payoffs do not depend on where in the sequence of games a particular game occurs. The central question of game theory is typically whether a game converges to one or some stable set of equilibria.

This chapter sets out a framework and a mode of analysis that can be used to answer these questions while preserving the underlying economic intuition of game theory. More generally, the framework developed in this chapter serves as a basis for the agent-based synecological game theory model presented in Chapter 5. We'll see that basic synecological models *require* categorizing the ways in which agent outcomes can be coupled, leaving open the possibility of emergent synergies in the system dynamics, evidenced by different equilibrium outcomes between the coupled synecological form of the system and its decoupled form. Synergies should never be coded into a model, but should emerge or cast shadows on data outputted from simulations, much like the radio signature of as-yet-unknown phenomena in astronomical data.

In this chapter I outline synecological game theory in a technical fashion. More work needs to be done to deepen the theory in certain areas; I note throughout where the theory needs to be deepened by future work. I begin with the basic definitions that undergird synecological game theory as presented in Chapters 1 and 3, then build the theory from there. Chapter 4 is meant to be a standalone reference for technical structure of synecological game theory, and therefore repeats some of the material in previous chapters.

4.2 Definitions and Theorems

Definition 1: An **extended game** is an m-length chain of games γ_i with N heterogeneous players, where not all players necessarily play every subgame in sequence, and such that at least 1 player is shared between sequential subgames in the extended game. Extended games are a generalized version of multistage and repeated games, where stages 1) can be of different dimensions, and 2) need not have more than 1 player in common.

Definition 2: A **synecological game** $\Gamma = \{\gamma_1, \ldots, \gamma_m\}$ is an extended game of length *M* where the following conditions hold:

(i). *Weak Connectivity* - At least one player, but not all players, are shared between sequential games. That is, the intersection $\gamma_i^{\text{players}} \cap \gamma_{i+1}^{\text{players}} \neq \emptyset$ in the extended game sequence.

(ii) *No-dictator Condition* - No single player spans the entire extended game. That is, $\bigcap_i^M \gamma_i^{\text{players}} = \emptyset$.

(iii). *Entanglement* - Suppose the shared player *i* plays subgame γ_{j-1} first, and subgame γ_j subsequently. Then, the payoffs v_i^j of subgame γ_j are a function of the payoffs v_i^{j-1} of the previous game γ_{j-1} and of the strategic actions of the nonshared players in γ_j.

Definition 3: A synecological game Γ can be specified as a four-tuple in brackets $\Gamma = \langle \mathcal{G}_\Gamma, N_\Gamma, \mathcal{A}_\Gamma, V_\Gamma \rangle$, whose first entry $\mathcal{G}_\Gamma$ is the graph that specifies the topology of Γ, the second entry N_Γ is the ordered membership of each subgame, the third entry $\mathcal{A}_\Gamma$ is the overall strategy space of the synecological game, and the fourth entry V_Γ specifies the payoffs including coupling functions for each game.

I outline some terminological conventions in order to make the following theorems and propositions easier to understand. First, as the graph $\mathcal{G}_\Gamma$ of a synecological game can be written as an adjacency matrix where the vertices are the subgames of Γ, the set $\{\gamma_1, \gamma_2, \dots, \gamma_k\}$, then $|\mathcal{G}_\Gamma| = k$ is a convention that indicates the number of subgames in Γ.

Theorem 0: $\mathcal{G}_\Gamma$ is a connected graph.

Proof of (Thm 0): Suppose $\mathcal{G}_\Gamma$ is a disconnected graph. But that violates the definition of synecological games as extended games, where at least 1 player is shared between subsequent games.

Next, I introduce minimal synecological games, which are the basic unit of analysis in synecological game theory.

Theorem 1: A *minimal* synecological game Γ_{MIN} has $N = 4$, of which 2 are shared players. Then the number of subgames in the minimal synecological game is $|\mathcal{G}_{MIN}| = 3$.

Proof of (Thm 1): Suppose $|\mathcal{G}_{MIN}| < 3$. If $|\mathcal{G}_{MIN}| = 2$, there are only two games in the system. Consider Definition 2, which defines synecological games. By Def 2.(i) (weak connectivity), at least one player *i* must play both games in Γ_{MIN}. But that contradicts Def 2.(ii) (the no-dictator condition), as *i* would then span all the games in the system. The argument is identical for $|\mathcal{G}_{MIN}| = 1$. Suppose now that $|\mathcal{G}_{MIN}| = 3$ and $N = 4$ where there are two shared players and two players who only play one game. The system is weakly connected by construction, satisfying Def 2.(i). No single player spans the system by construction, satisfying Def 2.(ii). And one can define coupling functions along the lines of the incentive synecological game, defined in detail in Chapter 3, giving us an example of coupling functions satisying Def 2.(iii) for this system. Therefore, we have discovered a minimal synecological game (there are many more) which necessarily has $N = 4$ and is $|\mathcal{G}_{MIN}| = 3$.

Generally, I refer to payoffs that players experience whose best replies can be derived directly from the strategy spaces of the games of which they are direct members as **decoupled payoffs**. That is, $v_i^{\text{decoupled}}$ is the decoupled payoff for player *i*, where the strategy space in which represents the games in which *i* directly plays is $\mathcal{A}_i = \{\times A_{\gamma_i}\}_{\gamma_i \in \mathcal{G}_i}$. It follows then that the **coupled payoff** v_i^{coupled} depends not just on the direct strategy space but on the entire strategy space of the synecological game $\Gamma = \langle \mathcal{G}_\Gamma, N_\Gamma, \mathcal{A}_\Gamma, V_\Gamma \rangle$, such that $\mathcal{A}_\Gamma = \{\times A_k\}_k$, and $|\mathcal{G}_\Gamma| = k$.

Proposition 2: The strategy space experienced, but never seen in its entirety, by any player *i* is a Cartesian product of the strategy spaces A_k of each subgame γ_k in the synecological game, or $\mathcal{A}_\Gamma = \{\times A_k\}_k$.

Proposition 3: A minimal strategy space $\mathcal{A}_{\Gamma MIN}$ of the minimal synecological game Γ_{MIN} is the 64-member Cartesian product $A^1 \times A^2 \times A^3$ of the strategy spaces of each game, respectively.

To see the validity of Proposition 3, one need only to consider the combinations of the strategy profiles of 3 sets of 2 by 2 games: $2^2 * 2^2 * 2^2 = 64$.

Lemma 1: Suppose player *i* is a member of the synecological game $\Gamma = \langle \mathcal{G}_\Gamma, N_\Gamma, \mathcal{A}_\Gamma, V_\Gamma \rangle$, and directly participates in the subgraph $\mathcal{G}_i$, where $|\mathcal{G}_i| = l < k = |\mathcal{G}_\Gamma|$. Then *i*'s direct-play strategy space $\mathcal{A}_i = \{\times A_{\gamma_i}\}_{\gamma_i \in \mathcal{G}_i}$ does not generally provide *i* access to all the potential best-replies in the system. That is, there may exist a pure or evolutionary strategy $a_i \in \mathcal{A}_i$ such that $v_i^{\text{decoupled}}: \mathcal{A}_i \to \mathbb{R}$ where $v_i^{\text{coupled}}: \mathcal{A}_i \to \mathbb{R}$ is a different mapping on the same members $a_i \in \mathcal{A}_i$. In general, $v_i^{\text{decoupled}}(a_i) \neq v_i^{\text{coupled}}(a_i)$.

<u>Proof of (Lm 1):</u> It is enough to note a single exception. Consider a synecological game $\Gamma = \langle \mathcal{G}_\Gamma, N_\Gamma, \mathcal{A}_\Gamma, V_\Gamma \rangle$ such that $|N_\Gamma| = N$ players, and $|\mathcal{G}_\Gamma| = k$ games. Suppose there exists a synecological strategy profile $\boldsymbol{a} \in \mathcal{A}_\Gamma$ such that $\boldsymbol{a} = \{\boldsymbol{a}_1, \dots, \boldsymbol{a}_i, \dots, \boldsymbol{a}_N\}$ and a synecological strategy profile $\boldsymbol{a}^* = \{\boldsymbol{a}_1^*, \dots, \boldsymbol{a}_i, \dots, \boldsymbol{a}_N^*\}$ such that $v_i^{\text{coupled}}(a) = r_1 \in \mathbb{R}$ and $v_i^{\text{coupled}}(\boldsymbol{a}^*) = r_2 \in \mathbb{R}$ such that $r_2 \neq r_1$. That is, we suppose a non-trivial coupling of the sort defined in Def 2.(iii). Suppose $v_i^{\text{coupled}}(a_i) = v_i^{\text{decoupled}}(a_i) = r_1$. Since the value of $v_i^{\text{decoupled}}(a_i)$ is only dependent on the direct strategy space $\mathcal{A}_i$ where $|\mathcal{A}_i| <$

$|\mathcal{A}_\Gamma|$ by Def 2.(ii), then $v_i^{\text{decoupled}}(a_i) \neq r_2$ under any circumstances. But we showed that $v_i^{\text{coupled}}(a_i) = r_2$ for the synecological strategy profile $\boldsymbol{a}^*$. So $v_i^{\text{coupled}}(a_i) \neq v_i^{\text{decoupled}}(a_i)$ in this circumstance. **QED**

It follows, then, that in general a subgame-perfect behavior-strategy profile $\sigma_i^{\text{decoupled}}$ does not hold for the larger synecological strategy space. We see this very same phemonenon in the difference between finite stage games and infinite stage games, or one-shot games and repeated games. That is, in general, $\sigma_i^{\text{decoupled}} \neq \sigma_i^{\text{coupled}}$. In order to discover $\sigma_i^{\text{coupled}}$, the player *i* cannot simply associate strategy profiles from the games in which they directly participate to real payoffs as the strategy profiles of the games in which they participate are a lossy projection of the full strategy space on which their payoffs depend.

To understand payoff coupling, it helps to present a small example. Take the synecological game $\Gamma = \langle \mathcal{G}_\Gamma, N_\Gamma, \mathcal{A}_\Gamma, V_\Gamma \rangle$, where $\mathcal{G}_\Gamma = \{\gamma_1 \rightarrow \gamma_2 \leftarrow \gamma_3\}, N_\Gamma = \big\{\{1,2\}, \{2,3\}, \{3,4\}\big\}, \mathcal{A}_\Gamma = A^1 \times A^2 \times A^3$, such that each $|A^j| = 2$ and therefore $|\mathcal{A}_\Gamma| = 64$. Even without yet specifying V_Γ, we visualize Γ's synecological game graph in Figure 18.

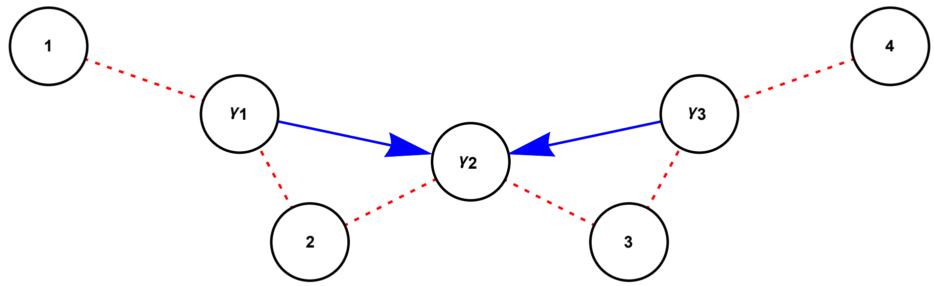


Figure 18 Graph representation of a synecological game

Figure 18: The graph representation the synecological game $\Gamma = \langle \mathcal{G}_\Gamma, N_\Gamma, \mathcal{A}_\Gamma, V_\Gamma \rangle$, where $\mathcal{G}_\Gamma = \{\gamma_1 \to \gamma_2 \leftarrow \gamma_3\}, N_\Gamma = \big\{\{1,2\},\{2,3\},\{3,4\}\big\}, \mathcal{A}_\Gamma = A^1 \times A^2 \times A^3$, such that each $|A^j| = 4$.

We can represent V_Γ as a matrix $V_\Gamma = \{V_1, V_2, V_3\}$, where $|V_j| = 2$. The coupled payoff functions for an example synecological strategy profile $\boldsymbol{a} = \{((a_2)_1^1, (a_1)_2^1), ((a_2)_3^2, (a_1)_4^2), ((a_2)_1^3, (a_1)_3^3)\}$ of the 64-member strategy space look like:

$$V_1 = \{v_1^1((a_2)_1^1, (a_1)_2^1), v_2^1((a_2)_1^1, (a_1)_2^1)\}$$

$$V_2 = \{v_3^3(v_3^2((a_2)_3^2, (a_1)_4^2), (a_2)_1^3, (a_1)_3^3), v_1^3(v_1^1((a_2)_1^1, (a_1)_2^1), (a_2)_1^3, (a_1)_3^3\}$$

$$V_3 = \{v_3^2((a_2)_3^2, (a_1)_4^2), v_4^2((a_2)_3^2, (a_1)_4^2)\}$$

where the parenthetical a_i refer to the two actions available to each player, the bottom index outside the parentheses indicates which player is acting, and the top index indicates the game being played. Each action pair represents a strategy profile in their respective subgame. The functions *f*, *g* couple the payoffs of subgames for the shared players 2, 3 respectively, and where v_n^m represents the payoff function for player *n* in game *m*.

The structure of the coupling can be inferred from the direction of the arrows in Figure 18, which tell us which games are coupled with which other games. We define functions like v_3^3, v_1^3 in V_2 that explicate and resolve the structure of the coupling between the games as a mapping from $A^1 \times A^2 \times A^3 \to \mathbb{R}$ as **resolution functions**. We will take a closer look at the importance of the concept of resolution functions below, and how they differ from traditional stage payoffs.

Corollary 1 to Lemma 1 (Coupling): In evolutionary play, non-shared players in γ_k can act in ways that influence the outcomes of a subsequent subgame in the synecological game γ_{k+1}. We can see this by simply noting that players in γ_k can condition their play on the long-term payoff of a player *j* who plays both γ_k and γ_{k+1}. This is because *j*'s play includes (compressed) information about how *j*'s payoffs in γ_k are coupled with *j*'s payoffs in γ_{k+1}.

Corollary 2 to Lemma 1 (Entanglement): We know from Corollary 1 that non-shared players in γ_k can act in ways that influence the outcomes of γ_{k+1}. The outcomes of another subgame γ_{k+2} in the synecological game are coupled with the outcomes of γ_{k+1} by virtue of shared player *l* who plays both γ_{k+1} and γ_{k+2}. Therefore, non-shared players in γ_k can act in ways that influence the outcomes of γ_{k+2}. Furthermore, this couples payoffs between players in γ_k and γ_{k+2}, who never directly interact with each other.

Let's consider an example of a minimal synecological game, to condition thought for subsequent analysis. The game we cover illustrates how the solution space of a principal agent problem expands when coupling two "production plans" together by means of simple competition, thereby incentivizing agents to exert higher levels of effort even in the absence of perfectly enforceable employment contracts. In short: principal agent problems, when embedded in a market context, cease to become problems. This "incentive" synecological game will then be agentized in Chapter 5.

4.3 Example: The "Incentive" Synecological Game (a one-shot analysis)

In his 2009 book *Game Theory Evolving,* Herbert Gintis introduces an extended game he calls "The Allied Widgets problem" with two arenas of action, two principal agent (PA) games between a rival company owners (Allied and Axis Widgets, respectively) and their managers who are tasked with discovering the lowest-cost method of producing their final product, and a Cournot competition game between the two owners. Nature is also a player. The PA games happen first, between each respective owner and manager. No information flows between the two PA games at this stage.

The internal structure of the principal agent problem faced by each manager is (Gintis: 83):

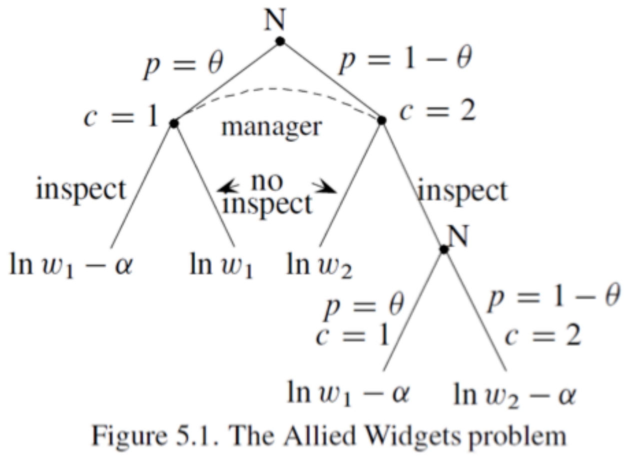


Figure 19 The Allied Widgets problem

Figure 19: The Allied Widgets problem, managerial decision tree

Nature (N) 'sets' the marginal cost (c) of using one production technique, e.g., fusion vs. fission. The manager employs costly search to inspect the state of Nature ($p = \theta$ is the probability of the current/inspected state to have marginal cost $c = 1$). Inspection cost is represented as α. The owner observes c, but cannot observe whether the manager inspected or not. If $c = 1$, then the manager pays a higher wage w_1, and if $c = 2$ the manager pays the lower wage w_2. The reservation wage is w_0, and, generally, $w_2 > w_1 > w_0$.

Can the owner *choose* values of w_1, w_2 that somehow incentivizes the manager to always inspect? In the isolated principal agent game, there doesn't seem to be a way to do this. But suppose we explicitly model market competition between the two owners—who both sell widgets—as another game in the system. Let demand be some exogenous function of the total market quantity of widgets, $P(Q) = a - b\,Q = a - b(q_1 + q_2)$, where q_1 is the quantity of widgets produced by the owner of Allied Widgets, and q_2 is the quantity of widgets produced by the owner of Axis Widgets. Each owner i then faces a profit maximization problem: $profit_i = revenue_i - costs_i = (a - b(q_1 + q_2))q_i - (c_i + w_i)$, where q_i is the variable of choice in the short run, but where w_i is an evolutionary variable of choice.

The solution space is technically infinite-valued, as w_1, w_2 in each game are effectively real-valued. However, we can determine the solution space by making assumptions about the game. We assume that managers have some kind of reservation wage w_0 under which they will not work, thus creating a wage-incentive floor. We assume both games are symmetric, $(w_0, w_1, w_2)_1 = (w_0, w_1, w_2)_2 = (w^*, w^-, w^+)$. We assume that Nature provides the same environment of marginal cost realities $p = \theta$ for each owner/manager pair, that managers cannot collude, and that managers have identical utility functions and effort α. Given this rarified setup, we can deduce an incentive compatibility constraint that allows owners to choose (w^*, w^-, w^+) in a way that effectively changes the game from one where the managers' fates had been decoupled, into a game where the managers' fates are coupled in a prisoner's dilemma, inducing interaction-at-a-distance (Gintis 2009: 86):

Table 4 An induced prisoner's dilemma that incentivizes players to defect ("inspect")

	Inspect	Shirk
Inspect	$\ln w^* - \alpha$ $\ln w^* - \alpha$	$\phi \ln w^* + (1-\phi) \ln w^+ - \alpha$ $\phi \ln w^* + (1-\phi) \ln w^-$
Shirk	$\phi \ln w^* + (1-\phi) \ln w^-$ $\phi \ln w^* + (1-\phi) \ln w^+ - \alpha$	$\ln w^*$ $\ln w^*$

where $\phi = 1 - \theta - \theta^2$ is the probability that both managers choose equal-cost technologies when one manager chooses *inspect* and the other chooses *no inspect*. Weakening any of these assumptions destroys Pareto optimality.

We can write the Allied and Axis Widgets game as a synecological game, which we shall call the incentive synecological game. The graph is below (Figure 20). Solid blue lines indicate directional relationships between games, and dotted red lines indicate agent membership in gameplay.

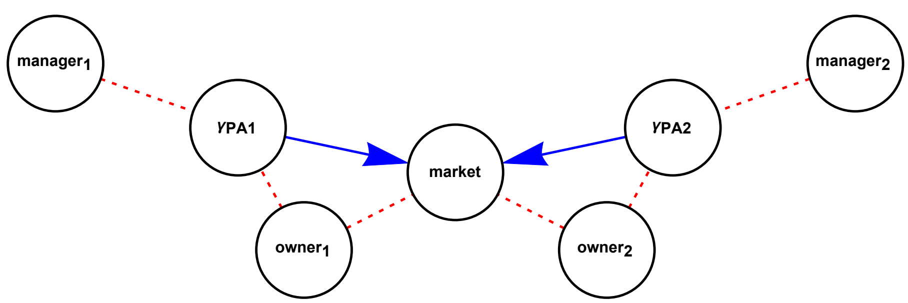


Figure 20 The incentive game as a synecological game

Figure 20: The incentive game as a synecological game

We notice that the abstract structure of the incentive synecological game is basically identical to Equation 1:

$$\Gamma = \langle \{\gamma_1 \rightarrow \gamma_3 \leftarrow \gamma_2\}, N = \{\{1,2\},\{2,3\},\{3,4\}\}, \mathcal{A} = A^1 \otimes A^2 \otimes A^3,$$
$$\{v_1^1(a_1), v_2^1(a_1), v_2^2(v_2^1(a_1), a_2),\ v_3^2(v_3^3(a_4), a_2), v_3^3(a_4), v_4^3(a_4)\}\rangle$$

where $\gamma_1 = \gamma_{\text{PA1}}, \gamma_2 = \gamma_{\text{PA2}}, \gamma_3 = \text{market}$. 1 = manager_1, 2 = owner_1, 3 = owner_2, 4 = manager_2, $(a_1)_2^1 = (a_1)_4^2 = no\_inspect$, and $(a_2)_2^1 = (a_2)_4^2 = inspect$. Recall that $(w_0, w_1, w_2)_1 = (w_0, w_1, w_2)_2 = (w^*, w^-, w^+)$. Then, the expected payoffs to each manager if they don't search versus if they do are:

$$v_{2,4}^1\big((w^-, w^+), \text{no\_inspect}\big) = \theta \ln w^- + (1-\theta)\ln w^+$$
$$v_{2,4}^1((w^-, w^+), \text{inspect}) = [1-(1-\theta)^2]\ln w^- + (1-\theta)^2 \ln w^+ - \alpha$$

The payoff to each owner in each principal agent game is more of an outcome: the cost of the production process used, C. That cost relates to the payoffs in the final game by its inclusion in the profit function $v_i^3 = \pi$. Recall that the cost of production is the marginal cost of production plus the wage paid to the employee.

$$\mathrm{g}\left(v_{1,3}^1\big((w^-, w^+), \text{no\_inspect}\big)\right) = \mathrm{C}\left((w^-, w^+), \text{no}_{\text{inspect}}\right) = \theta(w^- + 1) + (1-\theta)(w^+ + 2)$$
$$\mathrm{g}\left(v_{1,3}^1\big((w^-, w^+), \text{inspect}\big)\right) = C\ ((w^-, w^+), \text{inspect})$$
$$= [1-(1-\theta)^2](w^- + 1) + (1-\theta)^2(w^+ + 2)$$

The final payoffs to each owner are revenue minus costs, which are functions of wages, marginal cost, and the quantities sold by each owner. So, for owner *i* playing with owner *j*:

$$v_i^3\big(\mathrm{C}\big((w^-, w^+), \text{no\_inspect}\big), q_i, q_j\big)$$

$$= \pi_i\left(\mathrm{C}\left((w^-, w^+), \text{no}_{\text{inspect}}\right), q_i, q_j\right)$$

$$= \big(a - b(q_1 + q_2)\big)q_i - [\theta(w^- + 1) + (1 - \theta)(w^+ + 2)]$$

$$v_i^3\big(\mathrm{C}\big((w^-, w^+), \text{inspect}\big), q_i, q_j\big) = \pi\big(C\big((w^-, w^+), \text{inspect}\big), q_i, q_j\big)$$

$$= \big(a - b(q_1 + q_2)\big)q_i - ([1 - (1 - \theta)^2](w^- + 1) + (1 - \theta)^2(w^+ + 2))$$

In an evolutionary synecological game, agents progress through many rounds of play and use heuristic ranges to test how profits and utilities respond to different values of the variables over which they have influence. In the incentive synecological game, owners choose the wage differentials. So even if it is rather unlikely for owners to solve for wages that induce a prisoner's dilemma given the abstract expected payoffs above—particularly as in even a somewhat realistic system owners cannot expect the system to be idealized and symmetric—owners will have many rounds to discover the wages that induce a prisoner's dilemma between their respective managers. As we shall see in Chapter 5, this doesn't imply that new "better" solutions made available through synecological gameplay are easy to find.

4.4 Synecological Game Theory: Further Abstractions

4.4.1 Endogenous inputs and outputs, and coupling functions

Synecological game theory is characterized by functions that couple outcomes of two games. In order to couple the outcomes of two games, variable(s) are passed from a previous game to be used in the coupling function of the subsequent game. For the incentive synecological game, wages (w) and marginal cost (c), both determined in the first two principal agent games, are passed along to be used in the determination of profits in the subsequent market competition game. Call these kinds of endogenous variables *inputs* when they are imported from a previous game to be used in the determination of the payoffs of the current game, and *outputs* when they are exported from the current game to be used in the coupling function of a subsequent game.

Coupling functions, therefore, have domains that are at least as large as the dimension of the set of inputs into the current game. In the market competition Cournot game of the incentive synecological game, the domain of the coupling function—the payoff function that was symmetric between both owners—had four-dimensional domain $R_4 = Q \times Q \times \mathrm{MC} \times W$, where Q is the set of all feasible quantities that each widget company can produce, MC = {1, 2}, and W is the set of all feasible wage values. The range of the coupling function in the Cournot game was the real numbers.

We begin to see, then, that coupling functions represent real technologies, synergies, and other kinds of relationships between variables whose values are determined during the process of plan-realization. Suppose we add a new intermediate stage to the production process exemplified in the incentive synecological game, say, an interaction with a public official to place constraints on competitors or acquire subsidies that then alter how the production process is transformed into profits. The domain of the coupling function that determines profits in the final stage of the game may then expand to include the subsidies, and the Cournot game might then *output* a variable that is then inputted into a new, political game, perhaps a percentage of profits or some other kickback. Thus we see how what seems like a market competition game can transform into a hub whose wheel-spokes lead to a variety of opportunists, who exist by virtue of the institutional environment.

4.4.2 Coupling functions and traditional game theory's "identity" coupling function

Consider a synecological game $\Gamma = \langle \mathcal{G}_\Gamma, N_\Gamma, \mathcal{A}_\Gamma, V_\Gamma \rangle$ such that $|N_\Gamma| = N$ players, and $|\mathcal{G}_\Gamma| = k$ games. Suppose there exists a synecological strategy profile $\boldsymbol{a} \in \mathcal{A}_\Gamma$ such that $\boldsymbol{a} = \{\boldsymbol{a}_1, \dots, \boldsymbol{a}_i, \dots, \boldsymbol{a}_N\}$. Label γ_k the game whose payoff vector $\boldsymbol{V}_k$ is the *resolution vector* of the synecological game, as described in Section 5.2. For the incentive synecological game described in Section 5.3, the resolution vector was symmetric in both components (same resolution functions for each principal), and for a particular principal and a particular strategy profile $\boldsymbol{a} = \left\{(w^-, w^+), \text{no\_inspect}, q_i, q_j\right\}$ the resolution function was:

$$
\begin{aligned}
&v_i^3\left(\mathrm{C}\left((w^-, w^+), \text{no}_{\text{inspect}}\right), q_i, q_j\right) \\
&\qquad\qquad = \pi_i\left(\mathrm{C}\left((w^-, w^+), \text{no}_{\text{inspect}}\right), q_i, q_j\right) \\
&\qquad\qquad = \left(a - b(q_i + q_{-i})\right)q_i - \left[\theta\left(w^- + (MC = 1)\right) + (1-\theta)\left(w^+ + (MC = 2)\right)\right]
\end{aligned}
$$

which can be written more abstractly as

$$v_i^3(C\ ((w_i^-, w_i^+), \text{no\_inspect}), q_i, q_j) = v_i^3(f_i^1(a^1), a^3) = f_i^3(f_i^1(a^1), a^3)$$

More generally, for subsequent games $\{\gamma_1, \gamma_2, \ldots, \gamma_k\}$ of the synecological game for any given player *i*, that is, where the player's direct playspace is $A_1 \times A_2 \times \ldots \times A_k = \mathcal{A}_i \subset \mathcal{A}_\Gamma = A_1 \times A_2 \times \ldots \times A_k \times \ldots \times A_M$ for *M* subgames in the synecological game, the resolution function representing the overall coupling function faced by player *i* is the recursive nested function

$$f_i^k(f_i^{k-1}(\cdots(f_i^2(f_i^1(a^1), a^2)\cdots), a^{k-1}), a^k)$$

where the dots · represent subsequent recursive nestings of f_i^3 to f_i^{k-2}.

Note particularly that $f_i^k: \mathcal{A}_i \to \mathbb{R}$. $f_i^3 = \pi_i$ in the incentive synecological game example above, a complicated function that combines the outcome of the first game with actions from the third game (and implicitly the second) to calculate a value that is revenue minus cost. But much simpler coupling functions can be considered (we'll come back to the "profit" coupling function later).

The simplest coupling function for a given player *i* is $f_{IC}^k(\cdots(f_{IC}^2(f_{IC}^1(a^1), a^2)\cdots), a^k) = \boldsymbol{v}(\boldsymbol{a})$ where *k* is the number of games played by *i*, and $f_{IC}^j(a^j) = a^j$ for all $j \neq k$. Call this coupling function the **identity coupling function** (IC).

Theorem 2: The identity coupling function resolves into the standard game theoretical linearly additive payoff function for a stage game of length *k*: $f_{IC}^{k}(\cdots(f_{IC}^{2}(f_{IC}^{1}(a^1),a^2)\cdots),a^k) = v_1(a_1) + \cdots + v_k(a_k)$

Proof: Since $f_{IC}^{j}(a^j) = a^j$, then $f_{IC}^{k}(\cdots(f_{IC}^{2}(f_{IC}^{1}(a^1),a^2)\cdots),a^k) = f_{IC}^{k}(\cdots f_{IC}^{3}(f_{IC}^{2}(a^1,a^2),a^3)\cdots),a^k) = f_{IC}^{k}(a^1,a^2,a^3,\dots,a^k) = \boldsymbol{v}(\boldsymbol{a}) = v_1(a_1) + \cdots + v_k(a_k)$.

The overall payoff in a multistage game is the sum of the payoffs at each individual stage. We see this is also true for the identity coupling function where $f_{IC}^{j}(a^j) = a^j$ for all $j \neq k$ for all intermediate game stages. This is *not* the case in general for synecological game theory. Synecological game theory is interested primarily in cases where the intermediate couplling functions are not the identity.

Consider the incentive synecological game. The coupling function in this case is a function of how the input variables affect revenue minus a function of how the input variables affect costs. That is, $f_{\mathrm{PC}}(f_1^i(\boldsymbol{a}^1),\boldsymbol{a}^2) = Revenue(\boldsymbol{a}) - Cost(\boldsymbol{a})$, where "PC" means "profit coupling." For the incentive synecological game, $\boldsymbol{a} = \{v_{1,employee}(w^-,w^+) = w, v_{1,principal}(\,effort_1) = \mathrm{MC}, q_1, q_2\}$, where the values of *w*, MC are determined in γ_1, and the values of q_1, q_2 are determined in γ_3. Then, in our example,

$$f_{\mathrm{PC}}(f_1^i(\boldsymbol{a}^1),\boldsymbol{a}^2) = R_i(w,\mathrm{MC},q_1,q_2) - C_i(w,\mathrm{MC},q_1,q_2)$$

$$= q_i(a - b\,(q_i + q_j)) - (q_i * \mathrm{MC} + w)$$

There are many other conceivable coupling functions. Consider a matching game that couples the ‘production processes’ of the plans of *N* people. Examples could be marriage/dating markets, or academic job markets. The coupling function in this case utilizes a variety of variables outputted during the plan realization process, as well as direct strategies employed during the matching game itself.

We can also consider coupling functions that represent measurable but non-monetized goals, like in Schelling segregation, where people act to eventually realize a situation whereby the fraction of people like them is greater than or equal to some $l \in [0,1]$. For instance, we could consider a coupling function that demonstrates a kind of Schelling-esque discrimination in employment. A synecological segregation game might, for instance, look at segregation within and between fields. In the first game, students act in departmental clusters to form hierarchies within the clusters. In the second game, students play with departments who are hiring, and who rate along two metrics: merit, and similarity (intellectually and demographically) to the median characteristics of the department. The coupling functions in this case draw on some characteristics determined during the first stage of play to form the Schelling similarity metric. An evolutionary agent-based synecological model might allow for students to form expectations of discrimination depending on the field or department, and we could model intellectual and demographic sorting within and between fields.

Defining more coupling functions and considering the dynamics of their resultant synecological games will be a large part of future work in developing synecological game theory, and hopefully will be fruitful in opening more questions in economics and social science to ready analysis.

4.4.3 Topological considerations: the compatibility of games, social networks, and influence

In order to evaluate the success or failure of plans at any step, plans need to resolve. Topologically, this means we can have no cycles in our game relationship graphs. Note in particular that the shared players in the minimal synecological game are particularly influential players, the bridges between pairs of games. Shared players have the opportunity to leverage gameplay in other action arenas to channel the synergistic gains from coupled games to themselves. Therefore, a systems-level model of multiple games, like an agent-based evolutionary synecological game, should include ways of talking about the network macrostructures (like clusters), microstructures (like in-stars and transitive triads), and include measures of node-level influence both when looking at the social network and the game-level network.

As Bednar (2018: 3) notes, multiple games analyses require the modeler to specify how the different games are related in the agent's mind, or in reality. In Bednar (2018) and Bednar and Page (2016, 2007), games are related by way of conditioning behavior. Games occupy unrelated arenas of action, linked only in that the same agents play them and condition their play in subsequent games depending on how they played in previous games. In synecological game theory, games are explicitly related, with the outputs of some games being inputs to other games. Certain games are compatible with other games. Define a compatibility set $\mathcal{C}_{\gamma}^{f}$ in the space of all games relative to any particular game γ and coupling function *f* in the system. These are games $c \in \mathcal{C}_{\gamma}^{f}$ who output the right number and type of variables needed to satisfying the necessary input variables of γ given some coupling function *f*, or vice-versa.

We see immediately that the coupling of plans must happen in a way that respects the compatibility between the coupled games given some coupling function. Synecological systems theory thereby resembles the theory of generalized autocatalytic sets (GACS) in biochemistry. The modeling of production processes as autocatalytic sets is a current research area of complexity economics (Padgett 1996; Steel 2000; Padgett et al 2003; Padgett et al 2012; Zia et al 2014). Future work in this area will be to explore the structural similarities between GACS and a system of synecological games, and using these similarites to inform an evolutionary synecological systems theory.

4.4.4 Are synecological games reducible to multistage games?

The definition of a multistage game requires that agents are able to observe the history of action after each stage, even if they are technically doing nothing during that stage (Fudenberg & Tirole 1991: 70-1). In contrast, synecological games *hide* the history of some stages from other agents. In a minimal synecological game, agents may be able to engage in some kind of pattern classification on observed data to determine how their experienced outcomes are affected by gameplay outside their direct observation, and may get close enough to infer some aspects of relevant gameplay outside their plan when they are strategizing in-plan.

Let's write it in the Fudenberg-Tirole terminology. Let the set of all agents be $\mathcal{I}$, the action profile at stage k to be a^k, and the history at the end of stage k to be $h^{k+1} = (a^0, a^1, \dots, a^k)$. The set of actions available to player *i* at stage *k* generally depends on what happened before stage *k*, so then $A_i(h^k)$ denotes the possible *k*-stage actions available to player *i*. Now, synecological games *do* have histories. Suppose we have a three-member synecological game where $\gamma_2 \rightarrow \gamma_2 \rightarrow \gamma_3$. Then the history once game 3 is played will be $h^3 = (a^0, a^1, a^2)$. However, player 1 only sees (a^0), player 2 sees (a^0, a^1), player 3 sees (a^1, a^2) and player 4 sees (a^2).

These limited histories do not allow players to solve for optimal solutions as if they had the entire history, as they are not aware of all the dependencies, and the system may very well be irreducible to a simpler representation of itself. We see an example of a system irreducible to a more standard characterization proved quite elegantly when games are played on networks, as in Jackson & Zenou (2015:116-122), where the authors show for a game of positive externalities in effort expended that agents will generally undersupply the effort needed to attain a social welfare optimum if gameplay had not been on a less-than-complete network.

4.4.5 A folk theorem of synecological game theory?

When discussing evolutionary game theory it’s natural to consider whether or not a particular theory has a folk theorem like the folk theorem associated with evolutionary repeated and multistage gameplay. The folk theorem basically says that, given enough repetitions and the right conditions, players can obtain any equilibrium of the game. Players can, for instance, develop evolutionary strategies that incentivize their opponents to effectively co-realize any of the available equilibria in the evolutionary game. All it takes is knowledge of all possible strategy combinations, perfect recall, and a little integral calculus.

I contend that, precisely due to its 1) modest knowledge and computational assumptions and 2) the open-ended nature of truly evolutionary synecological game theory, that synecological game theory cannot effectively reproduce the folk theorem of traditional evolutionary game theory except as an artifact of the closed-ended nature of any deterministic model.

I sketch a proposed proof of the effective lack of a folk theorem in synecological game theory, which, despite needing to be deepened and made more precise in future work, is fairly intuitive.

The **folk theorem** as stated by Fudenberg and Tirole (1991: 152) for repeated, complete-information games is: "For every feasible payoff vector $\boldsymbol{v}$ with $v_i > \underline{v}_i$ for all players i, there exists a $\delta < 1$ such that for all $\delta \in (\underline{\delta}, 1)$ there is a Nash equilibrium of $G(\delta)$ with payoffs $\boldsymbol{v}$." (bold mine)

First, recall the definition of a minmax value to be:

$$\underline{v}_i = \min_{\alpha_I}[\max_{\alpha_I} g_i(\alpha_i, \alpha_{-i})]$$

where the payoffs to the stage game are g_i, the pure strategies a_i, and the mixed strategies α_i in the Fudenberg-Tirole terminology. $\underline{v}_i$ is the lowest payoff player i's opponents can hold them to by any choice of α_i provided that player i correctly foresees α_{-i} and plays a best response to it.

The proof provided by Fudenberg & Tirole presumes first of all the existence of a minmax value $\underline{v}_i$ for each player *i*, which requires complete information. Let $H^k = (A)^k$ be the space of all possible k-stage histories. In multistage and repeated games, all players observe h^k. So a pure strategy a_i for player i is a sequence of maps $a_i^k: H^k \rightarrow A_i$, one for each stage *k*. A mixed strategy σ_i in a multistage or repeated game is a sequence of maps $\sigma_i^k: H^k \rightarrow \mathcal{A}_i$. I first note that, in the absence of a computationally costly search over a huge combinatorial search space or assumptions to make the system simpler (like closed-endedness), synecological games are defined so that players inherently have incomplete knowledge; player *i* does not have access to all the histories h^k required to formulate a best response $\sigma_i^k(h^k)$.

Implicitly, the existence of a minmax value allows one to infer minmax strategies, which players then use as "relentless punishment" mechanisms if other players deviate from an action vector ***a*** such that $g\ (\boldsymbol{a}) = \boldsymbol{v}$, where as defined in the folk theorem, $\boldsymbol{v}$ is some feasible payoff vector with $v_i > \underline{v}_i$ for all players *i*. But the kind of knowledge that is inherently incomplete in synecological gameplay—whereby players do not have access to all histories of play, not even a complete vision of the "last turn" of play—denies players a plausible way of deriving minmax strategies. Therefore, it is unlikely that synecological game theory has a folk theorem, though, clearly, a deeper and more precise proof of whether or not synecological game theory has a folk theorem is in order, and will be the subject of future work.

4.4.6 "Crosstalk" vs. Synecological Coupling

In 2018, a paper by Reiter et al. argued that "crosstalk in concurrent repeated games" impedes the ability for players to access cooperative solutions in repeated games like the tit-for-tat reciprocity equilibrium. In their model, a shared player plays two games whose outcomes are structurally independent, with two different players. This game looks like (Figure 21):

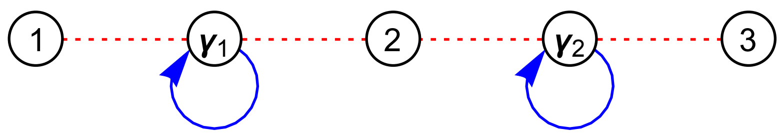


Figure 21 Graph of crosstalk between two independent repeated games

Figure 21: A graph of crosstalk between two independent repeated games. Like in the other graphs in this chapter, a dotted red line indicates membership of player *i* in a game, blue solid arrows indicate direct relationships between games—a self-reflexive relation in the case of repeated games.

Note in particular that there is no structural relationship between the two games γ_1 and γ_2, unlike in our example of a minimal synecological game (where the graph directionality is chosen arbitrarily in this case) (Figure 22):

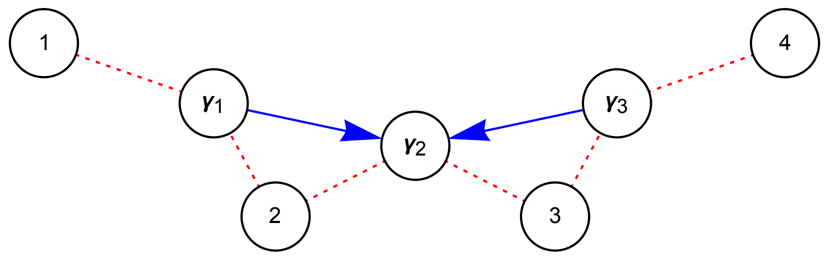


Figure 22 A minimal synecological game

Figure 22: A minimal synecological game. A dotted red line indicates membership of player *i* in a game, and blue solid arrows indicate direct relationships between games: an outcome-coupling relationship in the case of synecological games.

Reiter et al (2018) define crosstalk as when a shared player (player 2, in the case of Figure 21) conditions their strategy in one independent game γ_2 on the outcome of another independent game γ_1, even though the games are not *structurally* related as they are in synecological games. So even though there is no blue arrows between the games in Figure 21, that is, their outcomes aren't some function of the outcome of the game to which they are coupled, the shared player 2 in the crosstalk game shown in Figure 21 treats the independent games γ_1 and γ_2 *as if* they were somehow structurally related.

It isn't difficult to intuit that if players treat two independent games like they are not independent, the player's strategic choices may fall short of perfect rationality and result in a system that can't coordinate as well as a system in which shared players do not make that mistake. Reiter et al (2018) find exactly that. In short, synecological game theory is fundamentally different in its inherent structure than crosstalk models, and therefore the result that crosstalk impedes the discovery of Pareto optima can't be applied to synecological models.

CHAPTER FIVE:
AN AGENT-BASED MODEL OF SYNECOLOGICAL GAME THEORY

5.1 Introduction

Synecological game theory bakes in epistemological limitations at the agent-level. Agents learn from patterns in the real-valued metrics of the success or failure of their plans over many iterations to choose the values for control variables that make them best off. Furthermore, in synecological game theory, games themselves can be objects of choice and discovery. Agents endeavor to realize plan-ends; synecological games represent a means to realize plan-ends.

Synecological systems theory is, in the terminology of Dopfer & Potts (2004), a description of the *meso-level* of structured interactions. Agent-based computational economics provides a sufficient framework to describe the complexity of synecological games, in heterogeneous agent characteristics, relationships, game memberships, and how learning and play might evolve over time, particularly as it is unlikely (barring the kind of symmetry assumptions made by Gintis (2009)) that synecological games admit analytical solutions in general (though this hypothesis is yet to be proved).

In this Chapter, I present an agentized version of the incentive synecological game discussed in Chapters 3 and 4. I keep the model as simple as possible, with only two employees, two principals, a market for goods, and no labor market as such (meaning employees must accept whatever wages principals choose to pay them). However, principals choose wage ranges based on their desire for more profit, not to simply minimize costs, as there is a more complex relationship between wages and profits than mere cost minimization.

I consider three cases of the model: where the two principal agent games that constitute the incentive synecological game are either implicitly or explicitly coupled by means of information principals utilize to make decisions about how to strategically set high and low wages, and where there is no coupling. My primary question is whether or not coupled synecological games provide a richer solution space than uncoupled games, and my secondary question is whether my very simple couple model can attain a solution greater in overall utility than the uncoupled case, as derived analytically by Gintis (2009) and discussed at length in Chapters 3 and 4.

5.2 Model

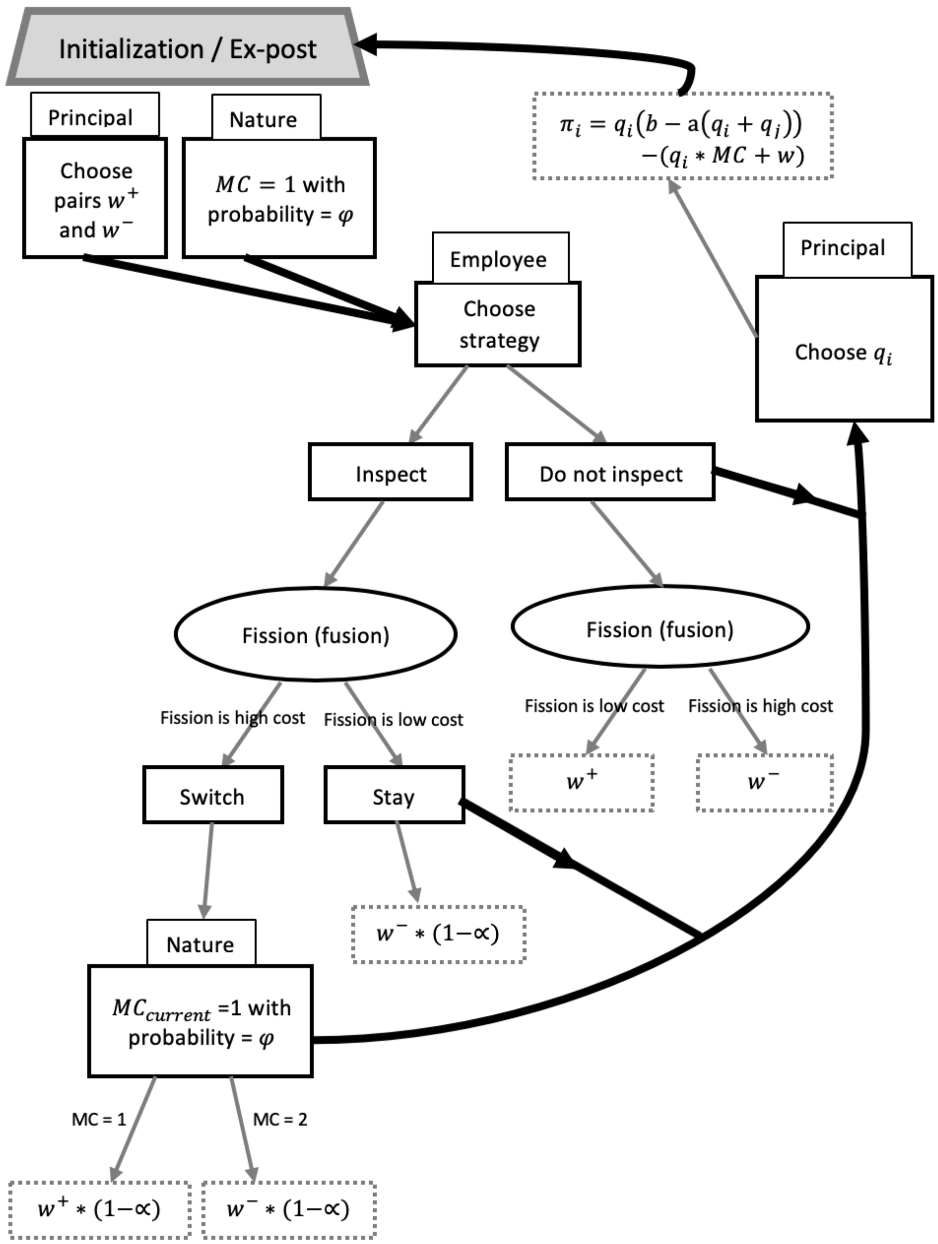


Figure 23 Pseudocode for an agent-based model of the Incentive Synecological Game

Figure 23: Detailed graphical pseudocode for an agent-based model of the Incentive Synecological Game. Bold arrows show transitions between games and stages. Dotted

gray boxes are payoffs. Bold square boxes are actions. Action boxes are labeled when actors change.

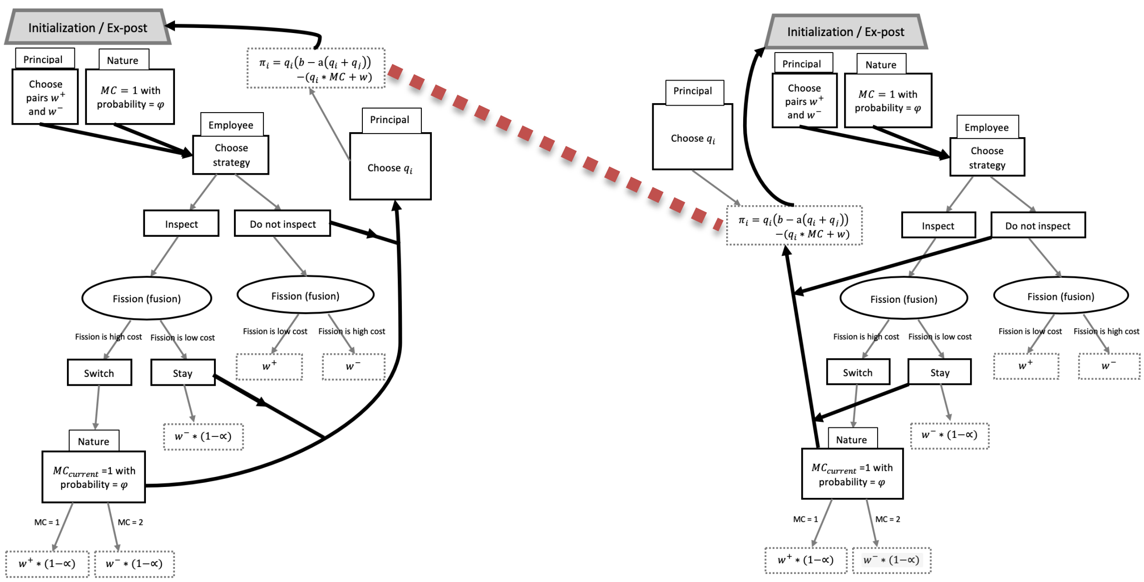


Figure 24 Coupled representation of the pseudocode

Figure 24: Coupled representation of the pseudocode. The left graph is simply a reflection of the right graph. The dotted orange line represents where the coupling between the two games takes place, namely, that principals use the information they get—about the marginal cost (MC) faced by their competitor in the *implicit* coupling mode, and wages set by their competitor in the *explicit* coupling mode—to guide their choices of $\{w^-, w^+\}$.

I construct a specific instance of a synecological game by agentizing the Incentive Synecological game described above. Each round of the game starts with an initialization/ex-post stage, where the principals choose a $\{w^-, w^+\}$ wage pair based on a low-intelligence best-reply function with basic agent learning, and Nature chooses the marginal costs of production via fusion and fission. See Figures 23 and 24 for a graphical representation of the pseudocode. The minimal game requires at least two principals and two employees in the system. As in the principal agent (PA) game between managers and owners described above, there are two kinds of production technologies (fusion and fission), such that θ is the probability that fission (fusion) has marginal cost (MC) = 1. After the very first randomized initialization, managers are initialized with whatever tech they used during the last step.

Employees select either to inspect the state of Nature to see whether or not their current tech has MC = 1 or 2 (*inspect*) or not to inspect (*no_inspect*). If they choose *inspect* and MC = 2, they switch to the other technology, which has probability = θ of having its MC = 1. Managers decide whether to inspect based on a simple algorithm that is described in Section 5.2.4 (Learning) below.

After employees make their choices between *inspect* and *no_inspect* they receive their payoffs, and the wage cost is set to the high (low) wage if the marginal cost of the resulting production process equals 1 (2). At this stage, the owner plays a Cournot quantity-setting game with the other principals in the system given an exogenous demand $P(Q) = b - a\,Q = b - a\sum_{i=1}^{N} q_i$, where there are *N* agents in the system. Each principal i must choose a quantity q_i based on a low-intelligence best-reply function that attempts to infer how q_i correlates with profits $\pi_i = q_i(b - \mathrm{a}(q_i + \sum q_{-i})) - (q_i * MC + w)$, where I use q_{-i} as a shorthand for "the quantities of all other agents." The specific learning algorithm is described in Section 5.2.4 (Learning) below.

5.2.1 Setup

This is a simple model with only *N* = 4 agents. Two agent-employees, and two principal-employers.

Employees have the following attributes: [$counter$, $strategy_t$, $noregret_t$, $commitmentleft_t$, $fusion_t$, $wage_t$, $utility_t$]. The *counter* tracks what step of the evolution it is, $strategy_t$ builds a list of strategy choices through time so that the last member of the list is the current strategy being employed by the employee, $noregret_t$ keeps a list of whether or not employees regretted their previous strategic choice, determined by an algorithm on a sampling window of income described in the Section 5.2.4 (Learning) below, $commitmentleft_t$ tracks whether the employee is still in the strategy sampling window, $fusion_t$ is a list that tracks the production technology employed by the employee at every step, with the last member of the list being the current production technology, and $utility_t$ tracks the utility of the employee at each step, which is calculated as wages minus a percentage of wages if the employee exerted effort (inspected the state of Nature).

Principals have the following attributes: [$counter$, $noregret_t$, $commitmentleft_t$, q_t, $profit_t$, $utility_t$, $wageplus_t$, $wageminus_t$, $wagechosen_t$, mc_t]. The *counter* tracks what step of the evolution it is, $noregret_t$ keeps a list of whether or not employers regretted their previous choices of $wageplus_{t-1}$ and $wageminus_{t-1}$ determined by an algorithm on a sampling window of income described in the Section 2.4 (Learning) below, $commitmentleft_t$ tracks whether the employee is still in the income sampling window, q_t tracks the quantity the principal produced at each step, $profit_t$ tracks the profit made at each step, $utility_t$ tracks the utility of each step (which is the same as the profit in the current version of the model), $wageplus_t$ tracks the high incentive wage w^+ chosen at each step, $wageminus_t$ the low incentive wage w^-, $wagechosen_t$ the actual wage paid to the employee at each step, and mc_t the actual marginal cost of production at each step.

I initialize agents with random values that allow them to play the first round of their individual games. In particular, I randomize first round employee strategies ($s_i = \{inspect, no\_inspect\}$), as well as the first round production technologies ($k_i = \{fission, fusion\}$).

For each principal *i*, I initialize the pairs $\{w_i^+(0), w_i^-(0)\}$ randomly within a range whose boundaries are the parameters w_{min}, w_{max}. Note that $q_i(0)$ is not randomized at first, but set to 1. This is because the algorithm that helps principals determine production levels $q_i(t)$ is fairly sensitive to initial conditions. These algorithms are described in Section 5.2.3 (Learning).

5.2.2 Games

Agents play two kinds of games in this system: principal agent games between each employee and their principal, and a Cournot quantity-setting "market" game between principals. Figure 3 is a stylized extensive form of the principal agent game. Employee *i* responds to incentive wages $\{w_i^+, w_i^-\}$ and the cost of effort α (a fraction of the wage lost to effort, set as a parameter) to decide whether or not to inspect the state of Nature, i.e., the marginal cost of the current technology being employed to produce widgets. If the employee decides to inspect Nature and discovers that their current production technology is expensive, they then switch to the other production technology, which is inexpensive with probability = φ (this probability is a parameter, and in our current model is fixed to 0.3).

The Cournot quantity-setting game is a gamified version of Cournot competition, where principals face an exogenous market demand $P(Q) = b - a\,Q = b - a(q_1 + q_2)$, as there are two principal-producers in this system. The principal *i* strategizes to choose a q_i and a high-low wage pair $\{w_i^+, w_i^-\}$ that maximizes $\pi_i = q_i\big(b - \mathrm{a}(q_i + q_j)\big) - (q_i * MC + w)$ –or really, expected profits in the next testing window of the game, as we'll describe in Section 5.2.3 (Learning).

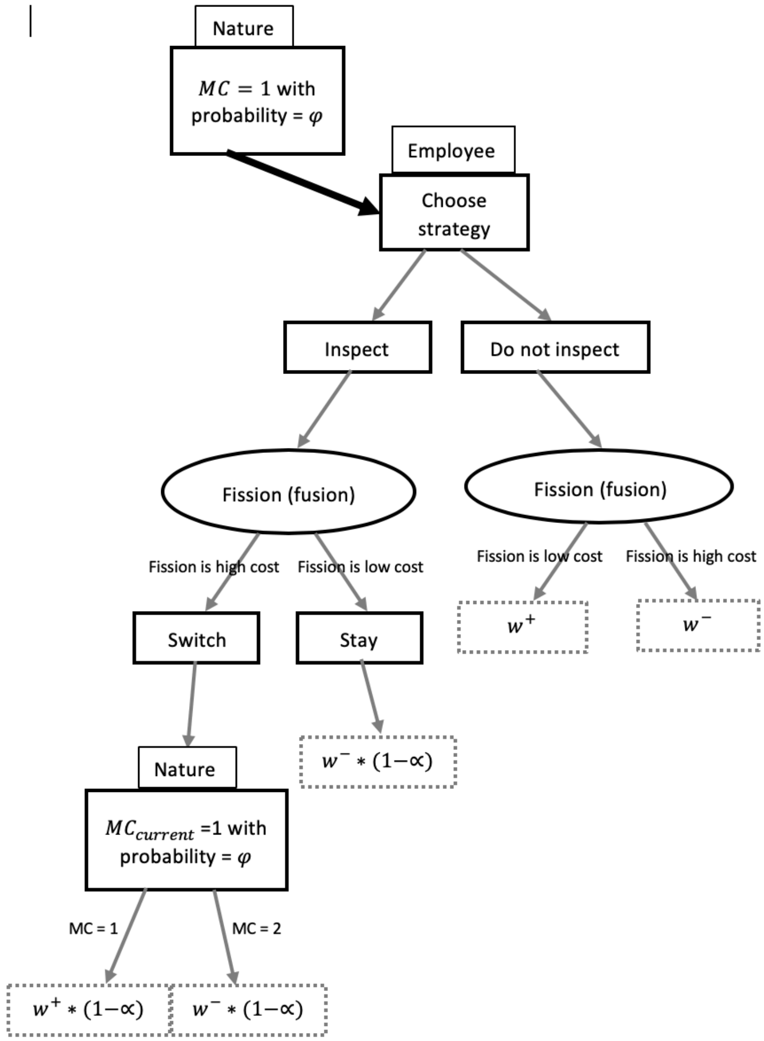


Figure 25 Extensive form principal agent game

Figure 25: A stylized representation of the extensive form principal agent game played between each principal and their employee. The one-shot version of this game leads to a Pareto suboptimal welfare result (when combining the utilities of both principal and employee).

5.2.3 Learning

Agent learning in this model is simple reinforcement learning over "windows" of results and basic reasoning over that window of results. I keep employee and principal learning as similar as possible. I also discovered that having large windows, or differently sized windows between employees and principals, resulted in slower learning. As I'll describe below, the learning of principals drives wage changes, which then drives the changes employees make to their strategies; no changes, no dissatisfaction, no desire to change strategies.

I start with employee learning, as employees "move" first. Employee learning has only a single mode. During gameplay, employees calculate their income depending on their strategy (inspect, not inspect) and the states of Nature. $\delta_i^{tech}(t) = 1$ when the employee *i*'s tech = fusion, and 0 when tech = fission. $\delta_{fusion}(t) = 1$ when Nature has determined fusion is expensive (for the entire system), and 0 when Nature has determined fusion is cheap, and $\delta_{fission}(t) = 1$ when Nature has determined fission is expensive, and 0 when fission is cheap. $\delta_i^{strategy}(t) = 1$ if the strategy is to inspect and effort is exerted, and 0 if the strategy is no_inspect and no effort is exerted. Remember that $\{w^+(t)\,, w^-(t)\}$ are set before employees choose their strategies at each step *t*. Then the wage an employee *i* gets at time *t* given their strategy choices and the states of Nature is:

$$w_i(t) = \delta_i^{tech}(t) * (w_i^+(t) * \left(1 - \delta_{fusion}(t)\right) + w_i^-(t) * \delta_{fusion}(t)) + (1 - \delta_i^{tech}(t)) * (\delta_{fission}(t) * w_i^-(t) + (1 - \delta_{fission}(t)) * w_i^+(t))$$

Their income *I* at time *t* is:

$$I_i(t) = w_i(t)(1 - \delta_i^{strategy}(t) * \alpha)$$

Employees then make a simple comparison: if $I_i(t) \geq I_i(t-1)$, then they have "no regrets" about how they chose their strategy on that round. That is, $noregrets_i(t) = 1$. $I_i(t) < I_i(t-1)$, then $noregrets_i(t) = 0$, that is, they have regrets about how they chose their strategy on that round, as their income ended up going down compared to the last round.

But how do employees choose their strategies in the first place? So far, I haven't described the origin of $\delta_i^{strategy}(t)$. For this part, I use the same general learning algorithm for both the principal and employee. The parameter $m_{employee}$ denotes the length of an employee's "testing window," or how many steps they test the consequences of changing $\delta_i^{strategy}$. If $m_{employee} = 10$, for instance, then $\delta_i^{strategy}$ can only change when *t* is a multiple of 10 (of course, an employee may end up choosing the same strategy after the testing period is over). Because employees play with principals who cannot observe directly an employee's strategy, I build in a "cooldown period" at the beginning of each testing window that allows principals to adjust to strategic changes that employees make. $c_{employee}$ is the length of the cooldown period, which is another parameter of the model. At the end of the testing period, employees take the mode of the last $m_{employee} - c_{employee}$ steps of $noregrets_i(t)$. If the mode = 0, then employees regret the strategy they employed this testing window, and change it for the next testing window. If the mode = 1, they have no regrets, and keep their strategy the same for the next testing window.

There is, of course, no guarantee that employing even the same strategy the next testing window will yield the same results, as principals continue to search for the incentive wages that will entangle the employees in the system in a prisoner's dilemma (or whatever new solutions might exist in the coupled synecological game).

The parameter $m_{principal}$ denotes a principal's "testing window," or how many steps they test the consequences of changing w^+ or w^- before they determine whether or not to change w^+ or w^- again. $c_{principal}$ denotes the "cooldown period," a number of results after changing w^+ or w^- that are disregarded when deciding whether or not to change w^+ or w^- again, as the principal's employee needs some steps to adjust a change of w^+ or w^- . Similarly, employees have an $m_{employee}$ and a $c_{employee}$, testing the consequences of changing their strategy (or keeping it the same) for $m_{employee}$ steps while disregarding the first $c_{employee}$ steps.

To test the hypotheses, I define three regimes in which a random walk takes place: 1) **implicit coupling**, where principals use information about their competitor's marginal cost to inform their decisions about wage changes, 2) **explicit coupling**, where principals use information about both their competitor's marginal cost and their wages to condition how to change wages, and 3) **no coupling**, where principals do not condition their decision to change wages based on information gleaned from their competitor.

The random walk for each form of coupling is the same. The kind of coupling determines the direction the wage is to be changed at the next step. The magnitude of the wage change, w_Δ, is a random number normally distributed on $N(w_\mu + \omega, w_\sigma)$, where w_μ, w_σ are parameters, and ω depends on the coupling type.

Equation 2 Magnitude of the wage change

$w_\Delta \sim N(w_\mu + \omega, w_\sigma)$ (Eq 2)

<u>1. Implicit Coupling:</u> When coupling is implicit, principals use information about the marginal cost of their competitor to determine the value of ω. Suppose we have principal *i* and competitor *j*. Then, if $MC_i > MC_j$, principal *i* 'punishes' an employee choosing either a new w_i^+ or w_i^- from a normal distribution whose mean had been reduced by ω_i. Otherwise, if $MC_i \leq MC_j$, the principal *i* chooses either a new w_i^+ or w_i^- from a normal distribution whose mean hasn't been reduced. We can write the implicit coupling case as:

$$\omega_i^{+,-} = \begin{cases} -\Delta, & MC_i > MC_j \\ 0, & MC_i \leq MC_j \end{cases}$$

<u>2. Explicit Coupling</u>: When coupling is explicit, principals use information about both the marginal cost of their competitor and their competitor's current incentive wages to determine the value of ω. Suppose we have principal *i* and competitor *j*. Then for ω_i^+,

$$\omega_i^+ = \begin{cases} -\Delta, & \{MC_i > MC_j, w_i^+ > w_j^+\} \\ +\Delta, & \{MC_i > MC_j, w_i^+ < w_j^+\} \\ 0, & otherwise \end{cases}$$

and for ω_i^-,

$$\omega_i^- = \begin{cases} -\Delta, & \{MC_i > MC_j, w_i^- > w_j^-\} \\ +\Delta, & \{MC_i > MC_j, w_i^- < w_j^-\} \\ 0, & otherwise \end{cases}$$

3. No Coupling: When coupling is disabled between principals, principals do not condition their decision to change $\{w_i^+, w_i^-\}$ based on their competitor's characteristics or behavior. Instead, they randomly choose the sign on Δ, randomly choose whether w_i^+ or w_i^- will be updated, then update that wage based on the formula in Equation 2 above.

5.2.4 Solution Space

Principal *i* optimizes profits over a strategy space, $\{w_i^+, w_i^-, q_i\}$ where the optimal triplet *varies* depending *i*'s direct relationships ($principal_j, employee_i$) *and* indirect relationship with $employee_j$ through $principal_i$. The principals search for incentive wages that make the principals themselves better off by increasing their profits, presumably by decreasing their marginal costs on average (and not entirely offsetting that improvement with a bigger wage bill). As I will discuss in Section 4 (Results), it takes some time for principals to become sensitive to the way wages and marginal costs effect their profits.

Gintis (2009) proposed that explicitly coupling two principal agent games expands the solution space of the system relative to a pair of decoupled principal agent games such that principals have access to a specific set of incentive wages that entangle them in a prisoner's dilemma. However, that specific additional solution may not be the only additional solution with a different utility profile in the coupled game solution space. I programmed implicit and explicit coupling such that information flows between the two principals whose interaction couples the two principal agent games.

I conduct a randomized search whose constraints and degrees of freedom are discussed in Section 5.2.5 (Parameterization). The heart of the search are the random walks on wages defined in Section 5.2.3 (Learning) above.

5.2.5 Parameterization

I conducted sensitivity tests to narrow down the ranges of the parameters in order to reduce the vast search space. The current parameterization for the data collected in the randomized search is in Table 1. The parameters that are allowed to vary randomly in the multiple runs are assigned a range, and the hard-coded parameters are assigned a value. I also conduct a few special runs focusing on a particular set of parameters, which are specified explicitly in the results below.

Table 5 Parameter table for the synecological incentive game model

Parameter	Value or Range	Comment
$w_{\text{min}}, w_{\text{max}}$	[10, 200000]	min wage, max wage
a, b	a = 0.25, b = 1000	slope and intercept of exogenous demand curve
α	%of wage	utility cost of employee effort
$q_{\text{min}}, q_{\text{max}}$	[1, 3000]	min q and max q
ϕ	[0,1], 0.3	probability that fusion is expensive
m_{nature}	[10, 500]	Nature's memory window
$m_{\text{principal}}$	[4, 20]	principal's memory window
m_{employee}	[4, 20]	employee's memory window
$c_{\text{principal}}$	[2, 10], $c_{\text{principal}} < m_{\text{principal}}$	principal's 'cooldown' period
c_{employee}	[2, 10], $c_{\text{employee}} < m_{\text{employee}}$	employee's 'cooldown' period
$MC_{\text{fusion}+}, MC_{\text{fusion}*}$	[0.1, 1], [1, 300]	MC = (binary variable + $MC_{\text{fusion}+}$) $*$ $MC_{\text{fusion}+}$
s	{0, 1}	toggles whether coupling is strong=1 or weak=0
Δ	[1, 50000]	magnitude of random walk on wages
w_{μ}	0	mean of wage random walk
w_{σ}	[2, 5000]	standard deviation of wage random walk

5.3 Hypotheses

As mentioned in the introduction, I carry into this model questions rather than hypotheses as such. However, if I were to word my primary and secondary questions as hypotheses, then they would be:

Hypothesis 1: A Richer Solution Space: Synecological (coupled) systems are more likely to exhibit multiple equilibria than uncoupled systems.

Hypothesis 2: Finding Solutions with Higher Average Utility: Synecological (coupled) systems can produce outcomes with greater overall utility that aggregate sums of uncoupled outcomes without the heroic knowledge assumptions of evolutionary gameplay.

5.4 Results

5.4.1 Contours of Exploration and Sensitivity Tests

It is unclear how sensitive agents are to initial conditions in the long run, but in the short and medium runs, they are quite sensitive to initial conditions, particularly in the case of low means and standard deviations of the wage random walks (w_{μ} and w_{σ}, respectively). In Figures 26 I demonstrate that it takes often at least 10^6 runs or more for one of the multiple equilibria in the solution space to be discovered.

It takes some time in models with active random walks—30,000 steps for some parameterizations—to become sensitive enough to wage and marginal cost considerations to start activating the "regret" logic in the employees. For early parts of the model, employees appear to have no regrets and in general stick with the same strategy. As the model passes a certain point, where most of the gains to changes in q_{i} have been made, then principals begin to have more regrets themselves—the state of wages and marginal costs impact the profit changes more—and they are thus more likely to change wages, which trickles down to employees and causes them to have regrets and attempt to change their strategies to compensate for them.

5.4.2 Convergence to Solutions, or, Exploring the Solution Space

I found some interesting parameterizations in the course of exploring the space, which seem to indicate the existence of multiple equilibria in the solution space. Even at 2×10^6 steps, I was still finding system transitions. The equilibria are also not necessarily stable.

In Figures 26-28, I show two runs of the same parameters.

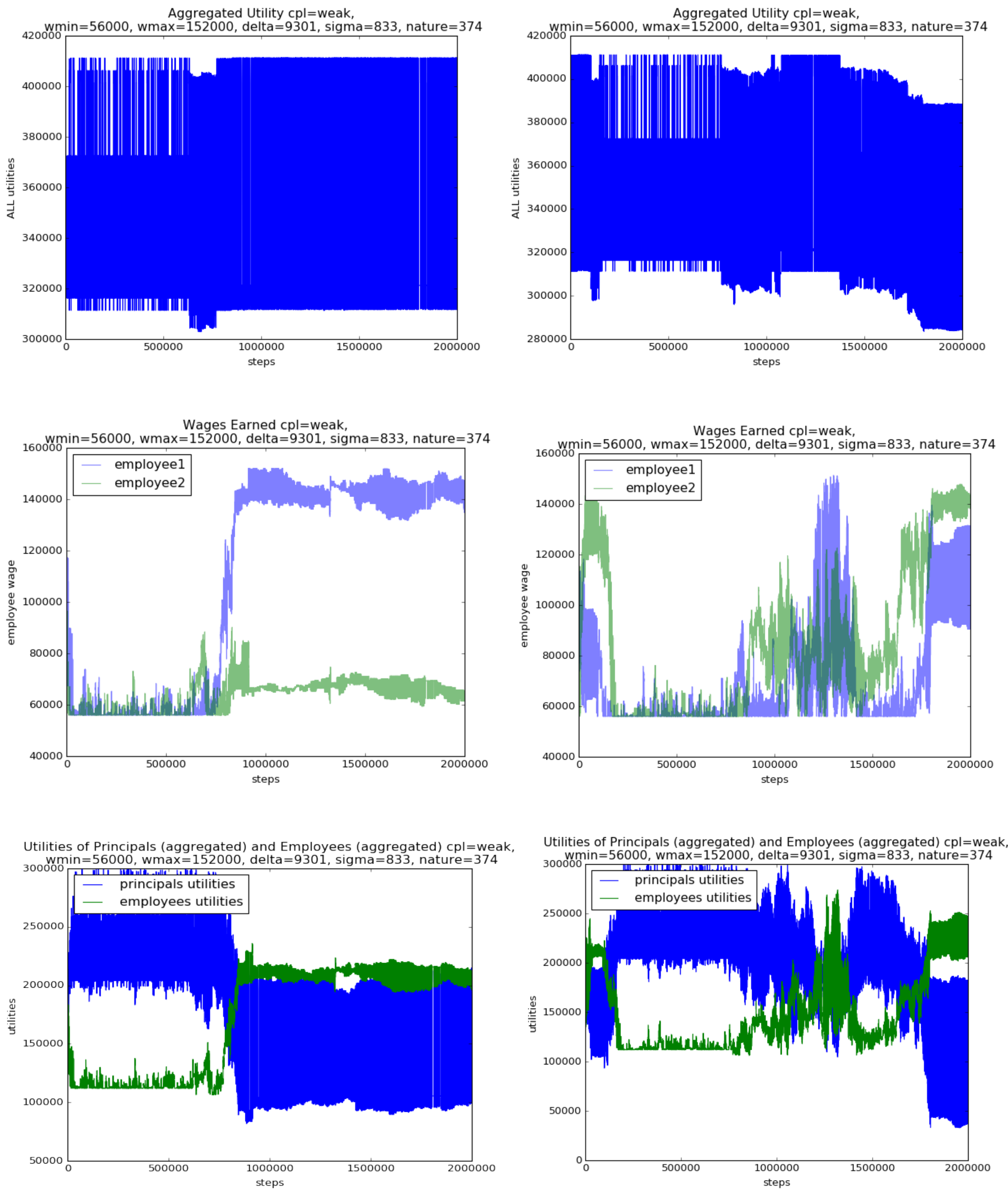
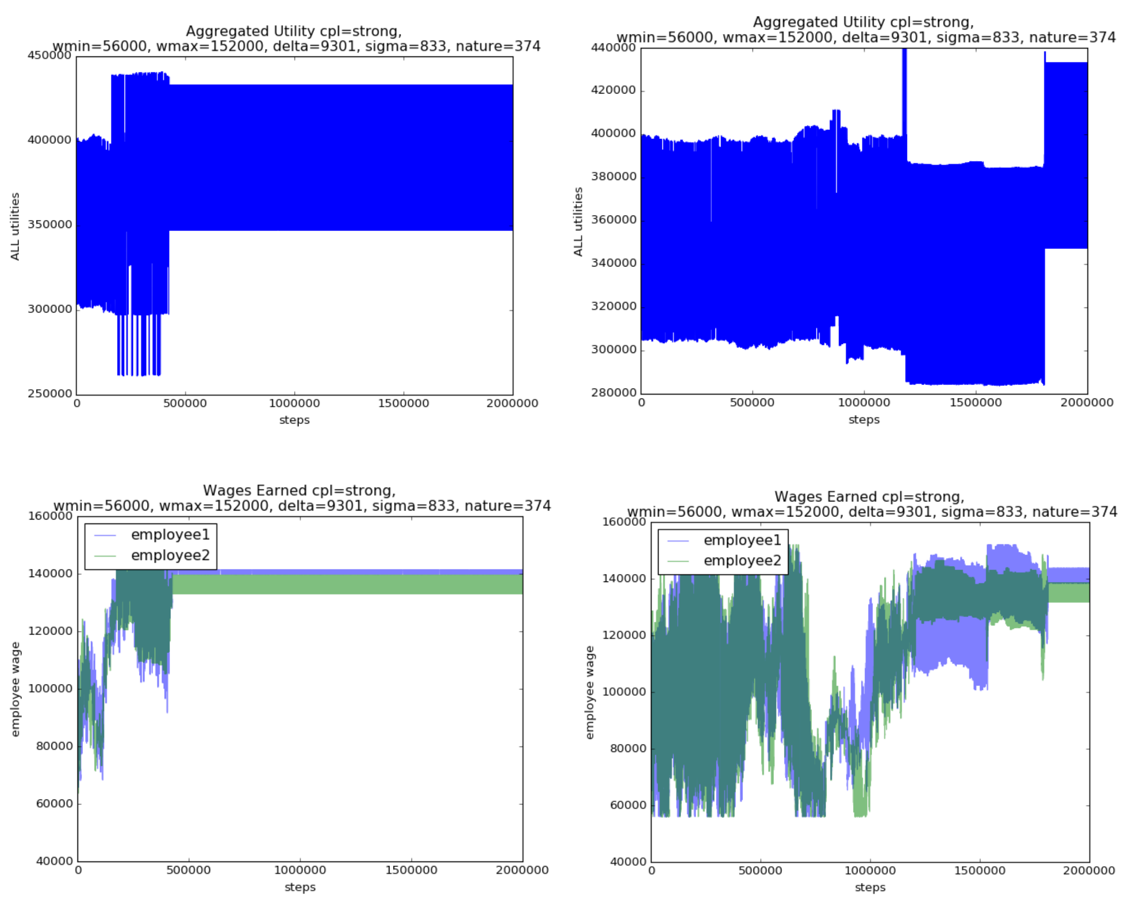


Figure 26 Different runs with the same parameters

Figure 26: The average utility, wages earned of each employee, and the profits of principals for two implicitly coupled runs of the same length and parameterization $\{w_{\min} = 56000, w_{\max} = 152000, \Delta = 9301, w_{\sigma} = 833, m_{\text{nature}} = 374\}$, with different dynamics.

At first blush, implicit coupling produces sharp phase transitions and allows agents in the space to explore multiple equilibria. As on the left side of Figure 4a above, it can take almost 10^6 steps for the first phase transition to occur.



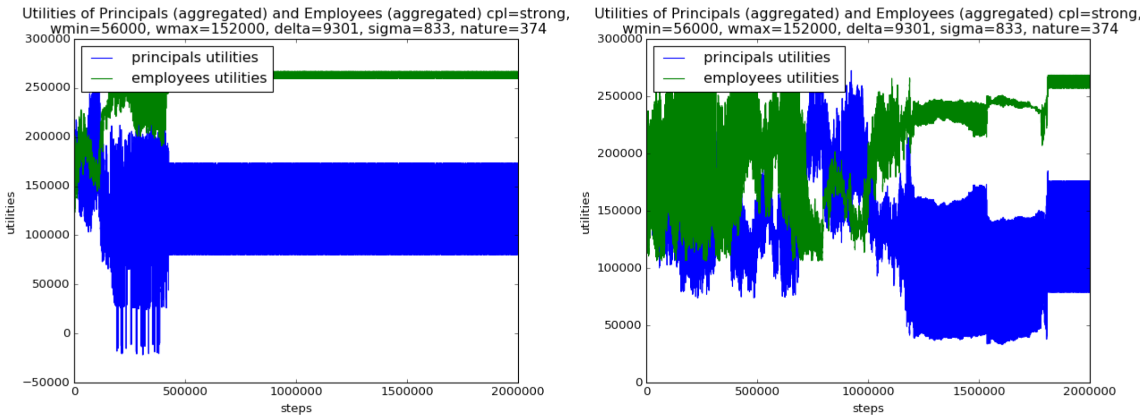
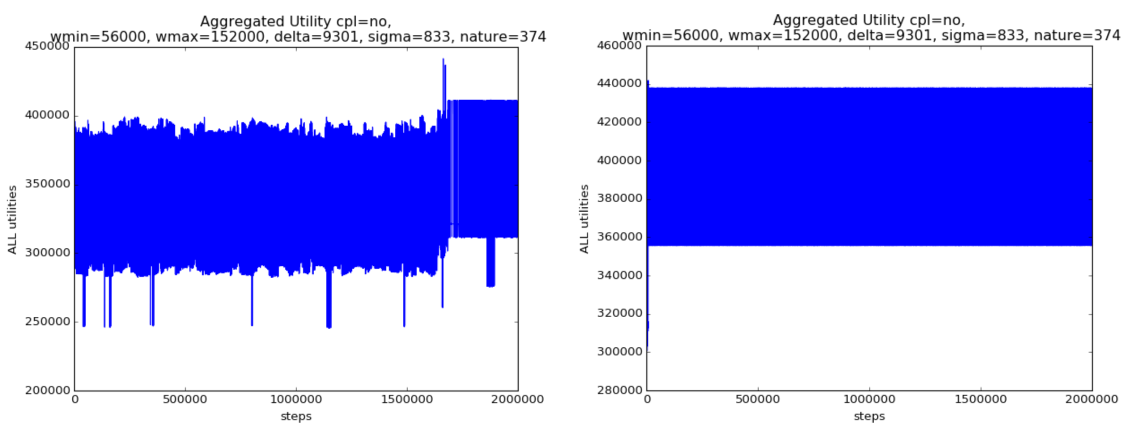


Figure 27 Different runs with the same parameters

Figure 27: The average utility, wages earned of each employee, and the profits of principals for two explicitly coupled runs of the same length and same parameterization $\{w_{\min} = 56000, w_{\max} = 152000, \Delta = 9301, w_{\sigma} = 833, m_{\text{nature}} = 374\}$, with different dynamics.



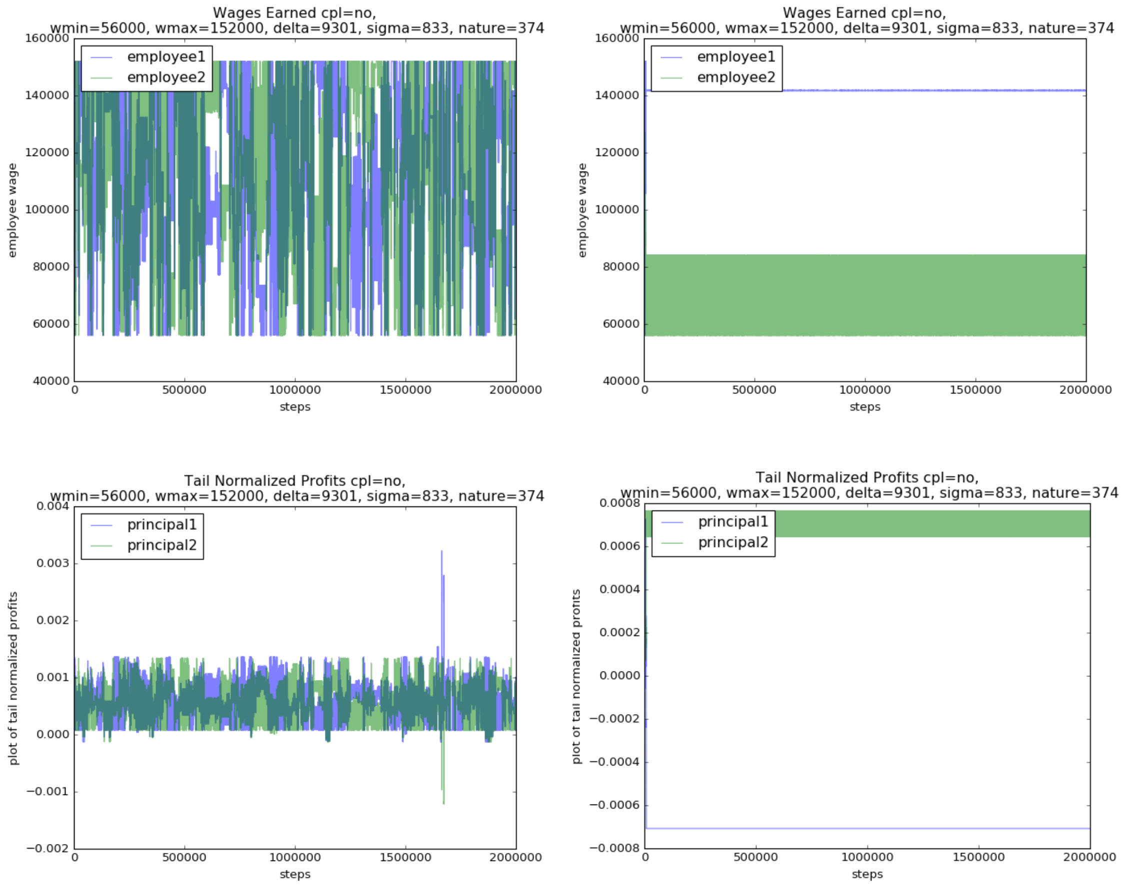
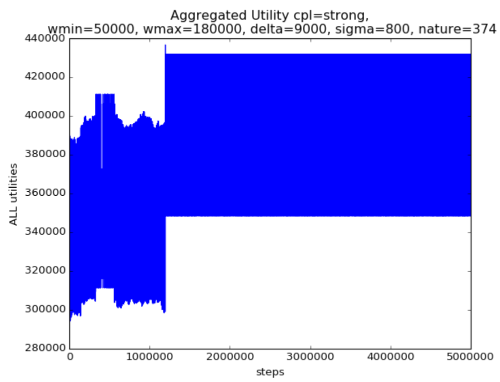


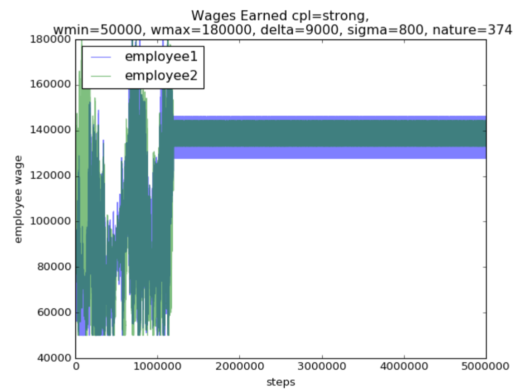
Figure 28 Different runs with the same parameters

Figure 28: The average utility, wages earned of each employee, and the normalized profits of principals for two runs whose wage-setting walks are decoupled from one another for the same parameterization $\{w_{\min} = 56000, w_{\max} = 152000, \Delta = 9301, w_{\sigma} = 833, m_{\text{nature}} = 374\}$.

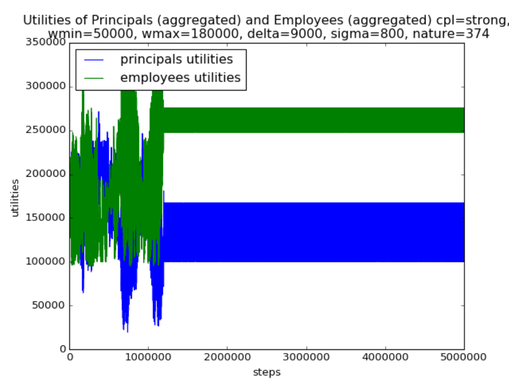
Furthermore, I found solutions other than what Gintis (2009) predicted, solutions that may depend on asymmetry; i.e., the large class of possible solutions that focusing on mathematically tractable solutions ignores (so, again, ceteris is not paribus). Consider in particular the following solution whereby, under explicit coupling, *employees* are able to coordinate around wage pairs that shift most of the improved utility of their decision to them:



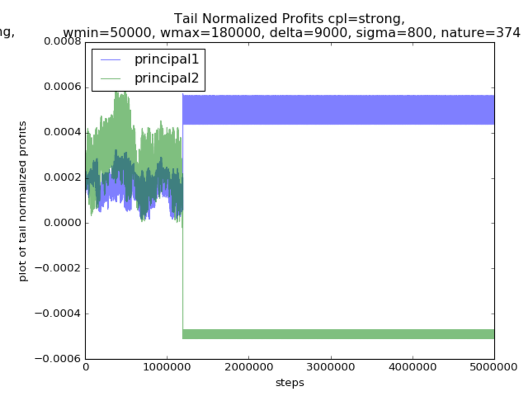
(a)



(b)



(c)



(d)

Figure 29 Employees shifting utility gains to themselves

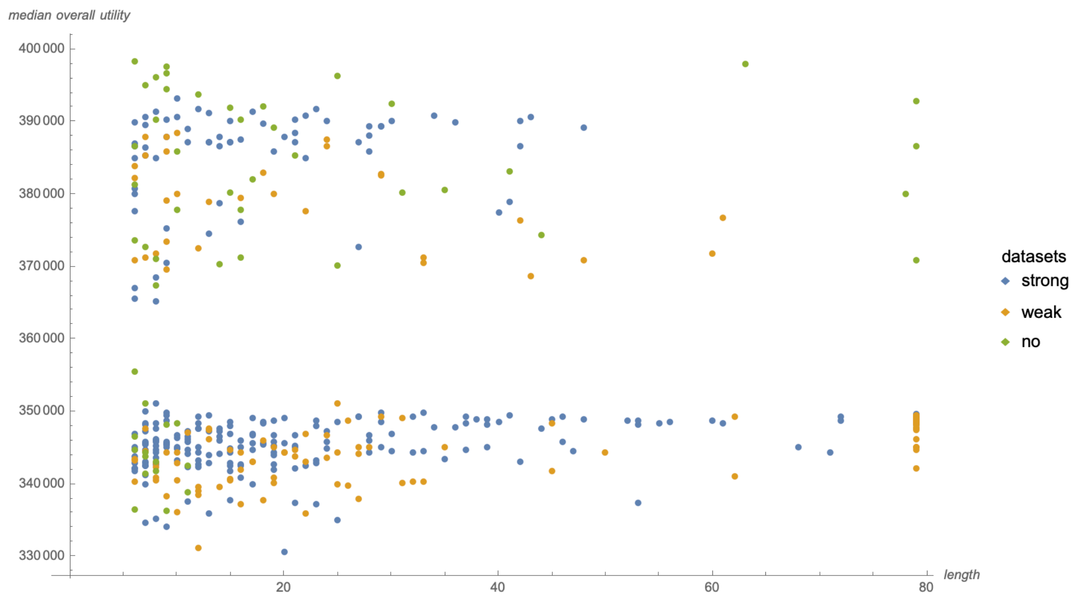
Figure 29: Employees i coordinating around a similar set of $\{w_i^+, w_i^-\}$ pairs in (b) realizes a higher overall utility for the system in (a), while capturing most of the gains for themselves (c). This solution is apparently sustained asymmetrically, with only 3 out of 4

players of the synecological game realizing gains from the sustained state and principal 2 being the apparent odd man out (d).

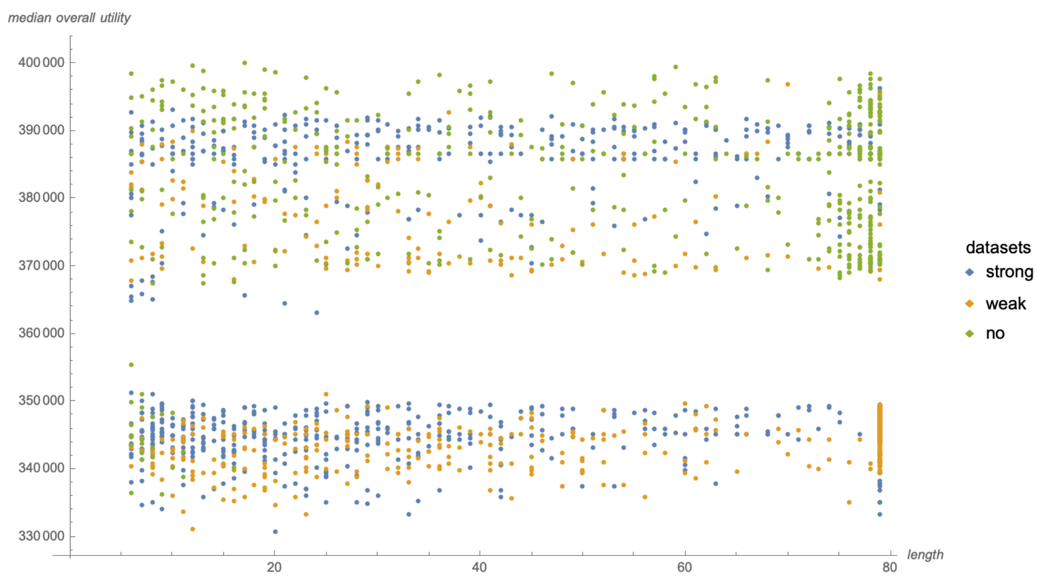
5.4.3 Statistics on Many Runs: Trends and Evolutions

I conduct two experiments over a data set whose characteristics are: $\{N = 1016, steps = 3 \times 10^6,\ w_{\min} = 50000, w_{\max} = 180000, \Delta = 9000, w_\sigma = 800, m_{\text{nature}} = 375,\ m_{\text{employee}} = m_{\text{principal}} = 7, c_{\text{employee}} = c_{\text{employee}} = 3\ \}$. For this data set I record averages and standard deviations in both the entire 3×10^6-long series and in chunks of 37,500 steps each (80 total chunks).

In Figure 30(a), I define equilibria to be sequential chunks of average overall utility within 10,000 of the median utility for that sequence of chunks, and where the sequence of chunks is at least 5 chunks long. In Figure 30(b), I define equilibria to be sequential chunks of average overall utility within 7,500 of the median utility for that sequence of chunks, and where the sequence of chunks is at least 5 chunks long.



(a)



(b)

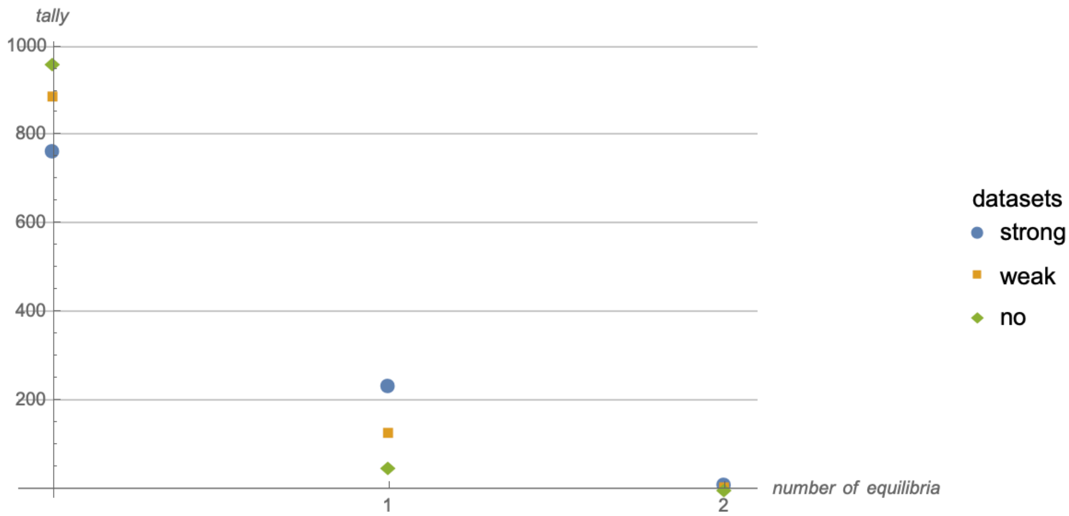
Figure 30 Median overall utility grouped by coupling method

Figure 30: The average utility of equilibria for each observation (where $N = 1016$) of implicit, explicit, and no coupling is plotted versus the length of time the equilibrium is

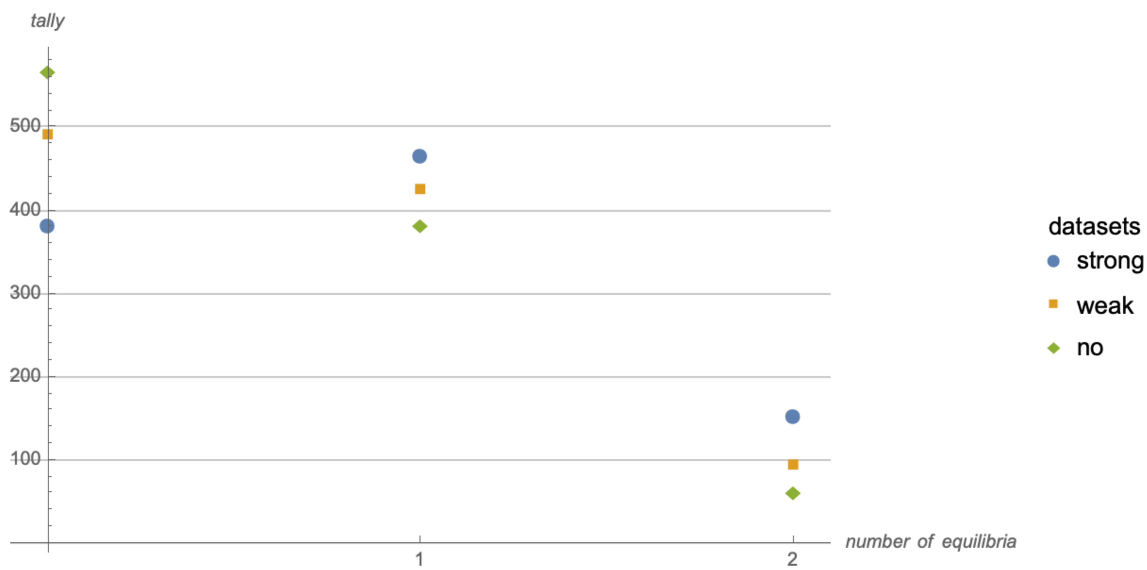
sustained. In (a) the average utility window is 7,500 steps, and in (b) the average utility window is 10,000 steps.

In analyzing Figures 30 we notice that, in general, no coupling attains higher average utility earlier in the evolution than implicit and explicit coupling, particularly when the equilibrium average utility is allowed to vary more. This seems to go against my secondary hypothesis, that coupled gameplay can discover greater-average-utility-solutions than simply aggregating outcomes of the uncoupled system. However, a range of equilibria are shown to exist in this system, and we note that while equilibria for implicit and explicit coupling a few different levels of average utility, no coupling tends to cluster around just one. We can see two distinct average utility clusters in Figure 30(a), and at least three in Figure 30(b).

Which coupling regimes are more likely to exhibit 1) single equilibria 2) multiple equilibria 3), or chaos (defined by no equilibria)? In what proportion generally do we find 1-3 in each of the coupling regimes?



(a)



(b)

Figure 31 A tally of multiple equilibria in average utility

Figure 31: A tally of multiple equilibria in average utility over all observations (where N = 1016) of implicit, explicit, and no coupling plotted versus the number of equilibria

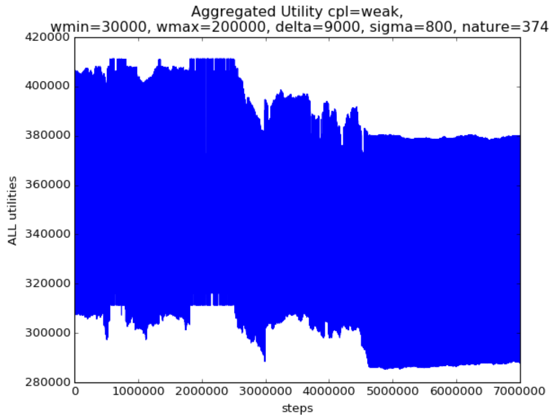
present in each observation. In (a) the average utility window is 7,500, and in (b) the average utility window is 10,000.

We see in Figure 31 that no coupling generally has fewer equilibria than weak coupling, which generally has fewer equilibria than strong coupling. As noted previously, I'm not certain these results are artifacts of the length of the experiment. However, a question left to prove, one that I'll hypothesize for future longer evolutions of the system, is that coupled behavior does indeed unlock a richer solution space, which is what both Figures 30 and 31 seem to indicate.

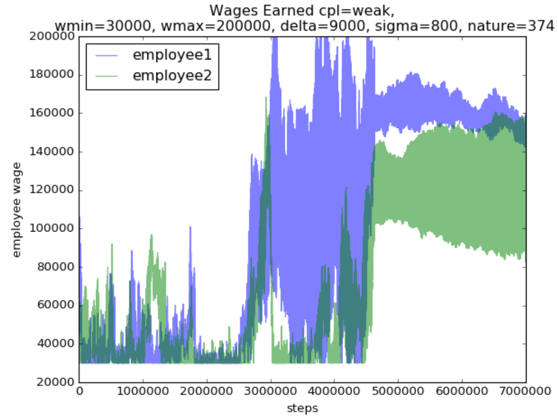
5.5 Known Problems, and Future Directions

5.5.1 Is the number of steps sufficient to allow for slow-moving discovery processes to find solutions?

To partially answer this question, I present evidence that implicit coupling meanders quite slowly over the search space. In Figure 32 below, we see that the implicit evolution meanders slowly and doesn't seem to come to a sharp coordinative equilibrium even by 7×10^6 steps.



(a)

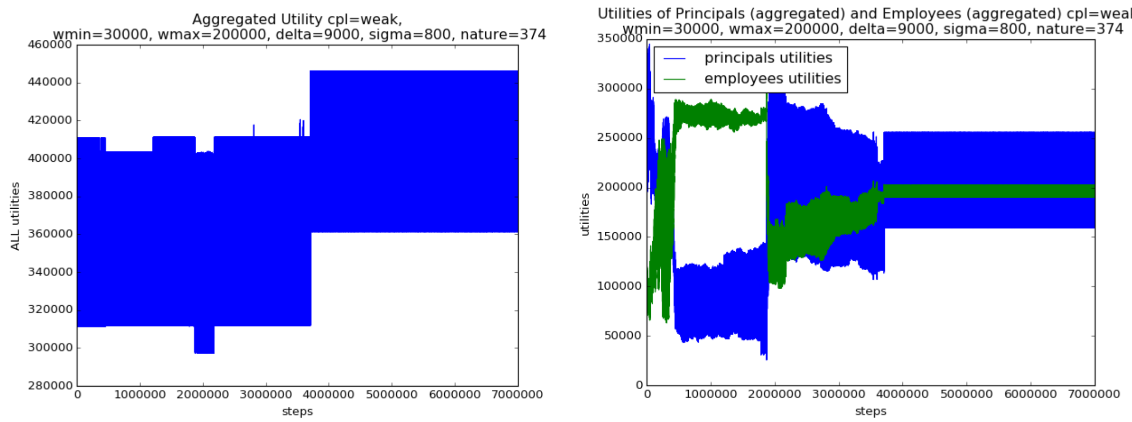


(b)

Figure 32 The synecological game with implicit coupling

Figure 32: A single run of the synecological game with implicit coupling with $\{steps = 7 \times 10^6,\ w_{\min} = 30000, w_{\max} = 200000, \Delta = 9000, w_{\sigma} = 800, m_{\text{nature}} = 375, m_{\text{employee}} = m_{\text{principal}} = 7, c_{\text{employee}} = c_{\text{employee}} = 3\ \}$ The graph on the left (a) is overall utility versus steps, and the graph on the right (b) is wages earned by each employee versus steps.

If we went on the $steps = 3 \times 10^6$ statistics, we might mischaracterize the best-performing coupling as no coupling (which does best in our experiment). But when we run for over twice the length of our experiment, implicit coupling is still finding solutions. We see in Figure 33 below that implicit coupling attains a somewhat higher average utility (403,700) than no coupling in our experiment (400,216) at nearly 4×10^6 steps.



(a) (b)

Figure 33 The synecological game with implicit coupling

Figure 33: A single run of the synecological game with implicit coupling with $\{steps = 7 \times 10^6,\ w_{\min} = 30000, w_{\max} = 200000, \Delta = 9000, w_\sigma = 800, m_{\text{nature}} = 375, m_{\text{employee}} = m_{\text{principal}} = 7, c_{\text{employee}} = c_{\text{employee}} = 3\ \}$. The graph on the left (a) is overall utility versus steps, and the graph on the right (b) shows the aggregated utilities of employees and principals versus steps.

The next experiment, therefore, should focus on a smaller number of runs that go for far more steps. 7×10^6 might not be enough for implicit coupling to search the entire space. It is unclear how many steps are needed; clearly the great improvement over no coupling derived in Gintis (2009) isn't easy to discover.

5.5.2 Is the system getting "stuck" in suboptimal solutions?

Once a cycling equilibrium is reached (where the average utilities for all and each of the agents cycles between two distinct and unchanging values) I have no examples of systems able to escape it. But clearly not all cycling equilibria are equal. The aggregated utility graph in Figure 34 below might look like it switches between two cycling equilibria, but the first equilibrium has an unchanging upper edge but a very very slightly changing lower edge, with just enough variation to apparently make the switch between two equilibria possible.

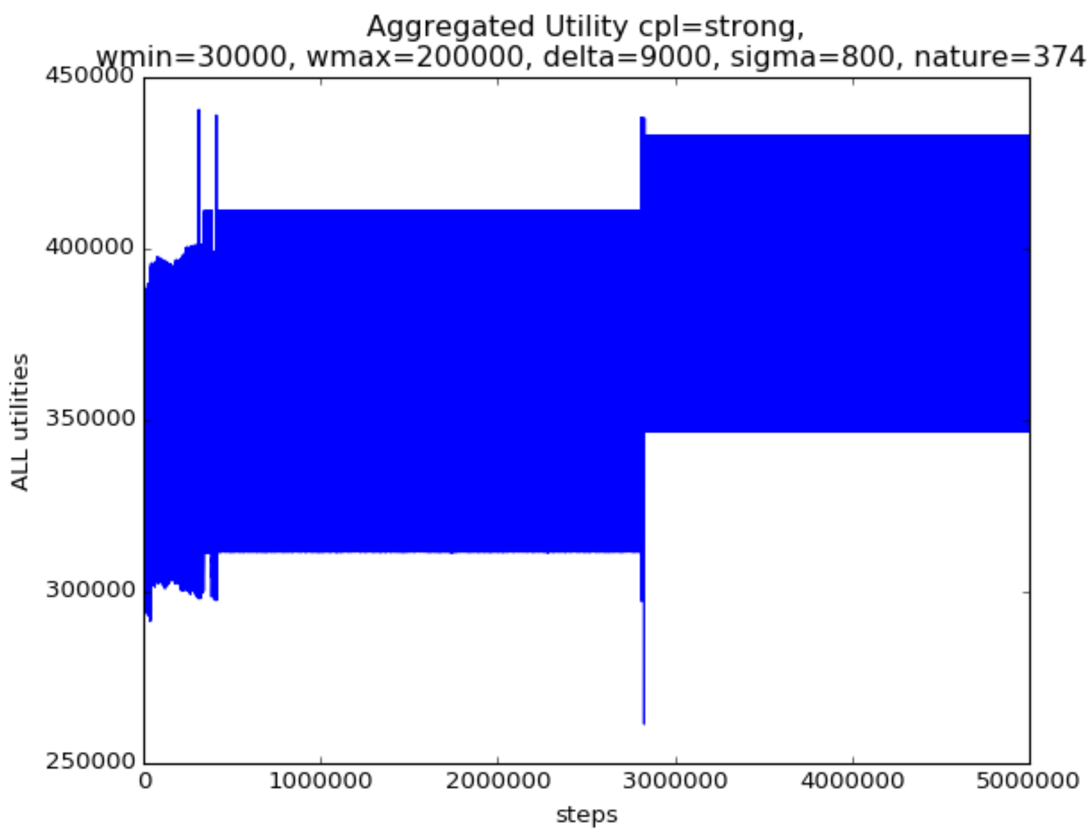


Figure 34 Aggregation utility graph with slight variation before equilibrium

Figure 34: If one squints, one can see the very slight variation in the bottom edge of the first equilibrium in this aggregation utility graph.

These suboptimal equilibria, however, may merely be artifacts of the small size of the model (only four total players) and the lack of interdependencies between other games of interest to the players of the incentive synecological game. A question moving forward with generalizing the incentive synecological game to M players and embedding it in a larger ecology of gameplay would be whether expansion or entanglement with other games provides enough variance to drive the discovery of new solutions.

CHAPTER SIX: CONCLUDING REMARKS

> Every aristocracy that sets itself entirely apart from the people becomes powerless. That is true in letters as well as in politics. (Tocqueville, Democracy in America Vol. 3: 807).

In his *Wealth of Nations*, Adam Smith famously explicates the combinatorial beauty of the decentralized production of both needles and wool coats (Smith 1776). By the mid-20th century, economic theory had settled around the concept of *technology* being that from which the “extra stuff” of the decentralized combinatorial production process derives: a more efficient machine providing a better ether of production than the same process with a less efficient machine. Empirical macroeconomic modeling exposed the significance of technology to the production process without sufficiently explaining it (Barro 1991).

But by explicitly taking into account the “extra stuff” generated by interaction in an ecology of games framework, we can see the insufficiency of traditional modes of valuing inputs as weighted sums of the value of the final product. In the Chapters above, I illuminated how some of the unexplained value of “technology” in the decentralized combinatorial process of production derives from decentralization and combination—that it, the decentralized combinatorial process itself.

Built upon the framework I lay down in this and the other Chapters of this thesis, as well as the future work required to deepen, strengthen, and generalize the theory and its applications, I envision a synecological systems model that does a few things no standard-use economic model has done before:

1. **Analytical Polycentricity** - Incorporate the public and political arenas of action in a way that exposes how plans react with and reroute through the public and political arenas both in an exploitative (taking advantage of opportunities as they are created) and an explorative (creating new opportunities for exploitation) fashion.
2. **Endogenous Complexity** - Graduate macroeconomics from studying simple behavior perturbed by random noise to studying complex behavior.
3. **Open-ended Evolution** – Utilize (1) and (2) to model semi-endogenous movement into the adjacent possible economic phase space.

Synecological systems theory intends to answer questions like: why do some policies fail unexpectedly, or take many more resources than expected, or generate the opposite behavior than was intended? Or: how can systems evolve to be robust against predatory behavior, like the collection and use of surveillance capital to alter the choices of individuals to be in line with the interests of system designers? Or: how can it become effectively impossible over time to build affordable housing in growing cities which not only need more affordable housing, but subsidize it? Or: how do robust financial systems become fragile and subject to behavioral cascades when certain channels of synergy are blocked and others enabled to emerge in their absence?

The advantages of synecological systems theory over current ways to microfound macro theory are: (1) it is capable of describing emergent, spontaneous and polycentric orders; (2) it allows for the endogenization of contextual choice without the need for the theorist to analytically derive a solution space, meaning that contextualizing a prisoner's dilemma is as simple as adding new games and players and relationships in, say, an agent-based simulation where such additions are simple; (3) it blurs the line between "public" and "private" activities and interactions, encouraging theorists to include all relevant interactions in a model of a particular sphere of interest instead of leaving out how public intervention in particular effect private behavior; (4) its knowledge assumptions are weak; (5) it is designed to be mathematically constructive at the system level and to require the use of computational simulations to study system-level characteristics for any reasonably sized system, thus avoiding the computability problems that increasingly plague traditionally microfounded macro theory (Lewis 1985; Velupillai 2007).

As to point (5) in particular, Chapter 5 presents a very simple agent-based model of synecological game theory's potential to enrich the solution space of gameplay, thereby proving advantage (1) (ability to describe spontaneous order) and (2) (endogenizing contextual choice) despite (4) (inherent knowledge limitations). Clearly, it would take a different or larger model to address (3) (including public and private interactions in the same modelspace). To that end, I claim that the agent-based model in Chapter 5 can be extended and standardized, to be used as-is with new, different, or larger synecological games. The primary difficulty in synecological game theory is a familiar one to most economists: how to describe the key interactions that people have, and how the outcomes of the various stages of our various plans are entangled with the outcomes of the various stages of others' various plans. In order to use the agent-based modeling framework laid out in Chapter 5 it is crucial to have modeled these entanglements ahead of time. In the incentive synecological game, we know just how the exertion of effort by employees is entangled with a principal's profit, and just how each principal's profit is entangled with their competitor's profit.

In order to exploit the full promise of synecological game theory as something that provides the infrastructure of McGinnis's (2011) networks of adjacent action situations, or of Long's (1958) ecology of games, or perhaps even a generalized autocatalytic system (as in Zia et al 2014) representative of open-ended economic evolution, economists must have models of ordinary social, interpersonal and commercial behaviors. The promise of synecological game theory is a call to study these behaviors more deeply, something to which the Ostroms in particular devoted their research. A synecological game theorist can use resources like the Ostromian heuristics for self-organizing common pool resource provision to encode relations into a synecological game theory model.

As Elinor Ostrom (2010) noted, the true prisoner's dilemma requires more players than just the prisoners. One needs a warden to order the solitary isolation of the prisoners; one needs a district attorney to incentivize a warden to obtain confessions in the first place and, arguably, one needs the trappings of social system with the political and financial means to imprison rulebreakers. With each new player comes new interactions, not between all players in the system, but in local clusters, with payoffs reflective of the concerns of the players at that juncture and likely divergent from the concerns of players at distant junctures of gameplay. The synecological game theorist categorizes and understands these interactions and how the warden's desire to maximizer her salary is entangled with the district attorney's desire to win the election is entangled with the pocketbooks of the special interests the DA vows to serve if she wins, and so on. Adam Smith's example of the wool coat illustrates how the division of labor makes more possible than if one person had managed production all on her own. I'm interested in how *combinations themselves* can have a synergy to them, a way of creating new paths of action, planning, and solving problems that don't exist when people try to solve their problems on their own; when theorists theorize people act *as if* they are solving problems independently of other problem solvers.

Rather than from the division of labor, the synergy I study arises from a combination of sympathetic interests, sympathies interacting parties need never reveal to gain access to synergistic solutions to their problems. Synecological systems theory is, at bottom, the study of combinatorial synergies between the people and institutions that make up our societies: an alternative foundation for economic analysis. Amidst theoretical traditions that do their damnest to reduce individual interactions to teleological action and reaction to reach an inevitable and predicted equilibrium, synecological systems theory seeks the many and complex ways our sympathies align to make individuals and their societies more than simply the sum of their parts.

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