Research Statement

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I use mathematical models to study how communities work, in both ecological and social settings. **Transitions between competitive and cooperative dynamics across multiple scales** are a recurrent theme, as well as **long-term changes in structure and process** in these **complex communities**. The thread that connects my research is my underlying interest in **distributed governance**: how to coexist to mutual benefit when control is not centralized but immanent throughout the community. All of these are critical questions not only in understanding how ecological communities work and how to protect them, but also in striving for collective survival and peaceful coexistence as times grow increasingly uncertain.

In my work on **biological models**, I have focused primarily on how adaptation due to natural selection drives structural changes in ecological communities. In two separate projects, I have uncovered new and original results involving the emergence of cooperation (see below for more detail about these two projects). First, I have shown mathematically that **ecological mutualism** is in a meaningful sense the **default tendency of coevolution**, and demonstrated that under very simple, unbiased model assumptions **antagonistic interactions spontaneously convert to mutualistic ones**. The conclusion is not that mutualism is the outcome of every coevolutionary system, of course, but that when it is not, causes can be identified that interfere with selection for mutualism. In an analogous evolutionary game theory model, both mutual defection and costly cooperation (the two horns of the prisoner's dilemma) give way to a different game structure in which mutualistic **byproduct cooperation** is the unique stable strategy, and the analogous conclusion applies. Second, in models of closed, coevolving ecosystems, I have demonstrated the existence of **a process that can reliably produce self-regulating ecological community structures**, where that had been thought impossible because natural selection does not act on whole ecosystems.

In my biological research I have also connected **frequency-domain analysis and calculation of exit times in nonlinear maps**, in the context of extinction risk in Pacific salmon populations [1]; proved **a new theorem** refining the known conditions for **coexistence in three-species generalized Lotka-Volterra equations** [2]; and demonstrated **emergent regulation of nutrient concentrations in the ocean environment** by coexisting populations (i.e. the Redfield ratio) [2]. As a student I made the key discovery that led to a joint paper [3] explaining how to reduce a complex model of hierarchically competing populations to a nested collection of scaled copies of the one-species model.

More recently, I have begun to work with **socially motivated models**. In a schematic model for consensus formation, I have shown that while **centralization improves a network's accuracy** when individuals are reliable, it simultaneously **concentrates power**, making the network vulnerable to an abusive or unreliable individual (see below). I hope to move toward more literal models of consensus seeking and other collective deliberation processes.

As a separate project, I am writing an ambitious custom software package that makes the MediaWiki software system into a wiki environment customized for collaborative online creation, publication, and archival of $\LaTeX$ journal articles, simulation software, and datasets and the software to analyze them [4, 5].

1. Evolution of interactions selects for mutual benefit

One of my ongoing projects centers on the mutation process illustrated in figure 1a, in which independent mutations apply directly to the terms of the Lotka-Volterra interaction matrix. Conventionally, model organisms' traits are mutated and interactions are derived from the traits. When mutations are applied to interactions rather than to traits, with selection induced by the dynamics of Lotka-Volterra equations, the result is consistently like the one shown in figure 1c. A negative diagonal term (competition) gives way to a pair of positive off-diagonal terms (mutualism). When a given species mutates, increase in the terms of that species's row confers a selective advantage, while changes in other rows are selectively neutral, so each row follows a random walk with a bias toward increase.

After discovering and analyzing this result as a graduate student, I developed a more general mathematical demonstration that selection in Lotka-Volterra systems favors reducing antagonistic interactions and increasing mutualistic ones, and that when mutual harm does not give way to cooperation, specific causes can be identified that thwart that tendency (figure 2). This is the reverse of the accepted accounts of cooperation, in which temptation not to cooperate is the norm, and it suggests a framework for further study of the causes that interfere with mutually beneficial coexistence [2, 6].

I have translated this simulation result in the Lotka-Volterra system to a corresponding one in game theory, showing that temptation to defect can be removed from the famous prisoner's dilemma by a simple process of mutation and selection among behavioral patterns [7] (figure 1b,d).

2. Emergence of biospherical self-regulation

A separate project originates in an investigation of the Gaia hypothesis of Lovelock and Margulis. Critics of the hypothesis pose the question of why a planetary community of "cooperating" creatures would not be betrayed by defector creatures that enjoy the well-regulated climate while undermining it [8, 9]. This is an ecological variant of Hardin's "**tragedy of the commons**" scenario [10], resulting from **niche construction** [*cf.* 11]. Using simulation models of idealized planetary ecological communities, I have demonstrated a process by which community structures that are vulnerable to subversion from within are short-lived and structures that successfully "cooperate" over the long term are long-lived, so that stable Gaian self-regulation is the norm. This "sequential selection" process [12] performs many of the functions that processes like kin selection or group selection do in other settings, defeating "temptation to defect" on the individual scale by weeding out variants that are not well adapted. Sequential selection is new and different from the known mechanisms that can foster cooperation among coexisting actors, and is generally unexplored to date. I believe my models are the first to demonstrate sequential selection in action. This result gives new plausibility to the Gaia scenario [13, 14].

3. Recent and Proposed Research

Over the past two years I have been exploring with a group of collaborators the "evolutionary graph theory" introduced by Nowak's group at Harvard [15]. In a social interpretation of these models (which also have a biological interpretation) the probability of a network-structured population's unanimously adopting the "better" of two propositions depends on how the network is structured. Whether centralization is good for the collective outcome depends on details of the pairwise interaction dynamics. I have done work that generalizes to directed graphs existing results [16] relating this consensus probability to degree distribution on undirected graphs, and also original results identifying which positions in the graph have more and less influence over the outcome (figure 3). Nowak's team argues that centralization "will enhance the spread of favorable ideas" [15] because it increases the probability of network-wide adoption of the fitter variant. My result suggests a complementary advantage to distributed structure: **central individuals**

have disproportionate power over the outcome of the collective deliberation, and the whole network is vulnerable if those individuals are corruptible or otherwise unreliable [17].

I have a lasting interest in coordination and collective action, and I hope to develop more faithful models of **collective deliberation processes**. I am interested in studying collective organization and decision making using ideas of protocols [18], swarm dynamics [19] or consensual coordination [20] as alternatives to the network metaphor. I intend to explore these questions in a context including decision theory and social psychology, with an eye to developing well-defined, productive, and parsimonious modeling questions. One way may be to look at group decision making as collective motion in "opinion space," which makes it in a sense an extension of existing research on dynamics of animal swarms [*e.g.* 19]. This may be modeled as a process of collective search in a system of linked (and possibly changing) Boolean fitness landscapes, or a similar space of acceptable and unacceptable alternatives. This project may extend known results regarding network structures, opinion cascades and political contagion. It can build on Scott Page's exciting work on collective problem solving [21], **extending the investigation from problem solving to deliberation**, by looking into situations in which participants do not agree on a common task or on what outcomes are desirable, and must negotiate and potentially transform their own preferences and solution spaces in order to construct a mutually acceptable outcome.

A related set of questions is about the arts of coordination and transformation in social collectivities. I am interested in tensions between deliberation and autonomous action, and relationships between gradual and abrupt processes of change. More concretely, I am fascinated by emerging forms of horizontal organizing in social change projects, both **fully distributed projects** like Food Not Bombs [22] and Critical Mass [23], which are not organizations, but ways of acting that are adopted by anyone who chooses to, and the "**open spaces**" of, for instance, the World Social Forum, which explicitly aims not to direct the multitude of the world's social movements but rather to connect them together and allow coordination, cross-pollination and innovative collaborations to emerge [*e.g.* 24].

I am investigating the idea of working directly with some of these projects, as a system dynamics consultant or action researcher. Ideally I can help them (as an equal partner in conversation, with access to an applied mathematician's tools and perspectives) to investigate the theoretical challenges they are facing in self-organizing, leaderless collectivities seeking to organize around generally compatible but non-identical goals, while they simultaneously help me to develop the discipline of complex system modeling, potentially in unexpected and fertile new directions. I am currently in contact with several scholars of social movements and organizational theory, investigating potential collaborations or consultations.

The Gaia project I described above can be seen as a part of the project of understanding how change is possible, particularly in its planned second phase. In this phase I will look in detail at the specific dynamics of how global dynamics bring about "cooperative" structures, to expose the specific ways that "cooperation" fails and **how communities transform from failed to successful alignments of evolutionary interest**. As I currently understand it, these results go beyond contradicting the prediction that communities will succumb to the tragedy of the commons, by challenging the question: the tragedy of the commons is a overly simple model that can't encompass the rich variety of scenarios in which players have radically different interests and impacts on the shared evironment. Instead there is a complex spectrum of harmonious and discordant possibilities, including ecological murder and suicide (with Hardin's scenario as a simple case). In this way, this modeling project may enrich our palette of narratives about how diverse actors may or may not coexist, and how their arrangements change, both gradually and abruptly. It may offer specific insights into non-tragedy-of-commons scenarios that are of use in economics, international relations or other fields.

Closing

Currently I am actively working on the evolutionary graph theory project and the second phase of the Gaia project, described above. I have a number of projects going at once, including publishing existing results and developing the projects outlined here.

There are a variety of opportunities for collaboration or consultation with SFI researchers whose projects connect to mine, including Bowles and Gintis's work on transformation of patterns of governance [*e.g.* 25], Krakauer's work on niche construction and ecological coexistence [11], and Scott Page's work as mentioned, and I have common interests with many others concerned with ecology, coevolutionary dynamics, collective intelligence, or random dynamics on graphs. Beyond those proposals, I am ready for new ideas and opportunities for collaboration. I am always interested to learn new mathematical and computational techniques, and I am actively curious about others' work — whether faculty, students, or neighbors — and eager to share my resources and ideas.

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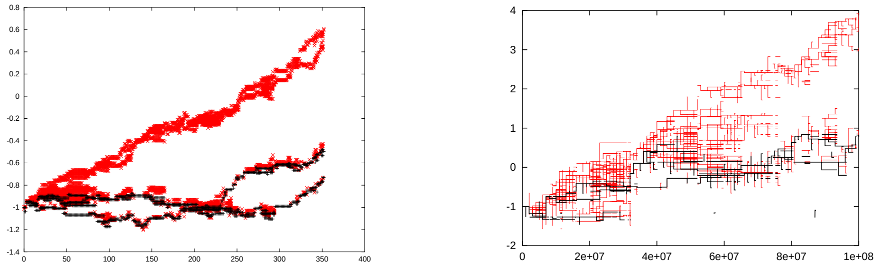
$$\begin{pmatrix} -1 & -1+\Delta a_{12} \\ -1+\Delta a_{21} & -1+\Delta a_{22} \end{pmatrix}$$

(a) Mutation on a Lotka-Volterra matrix, from a 1×1 matrix for a single type with competitive self-interaction term to a 2×2 matrix for the former type and a new variant type.

$$\begin{pmatrix} 3 & -2 & -2+\Delta p_{13} \\ 4 & -1 & -1+\Delta p_{23} \\ 4+\Delta p_{31} & -1+\Delta p_{32} & -1+\Delta p_{33} \end{pmatrix}$$

(b) Mutation on a prisoner's dilemma payoff matrix, from the 2×2 matrix for the standard C and D behaviors to a 3×3 matrix for C and D plus a new variant behavior.



(c) Evolution of Lotka-Volterra matrix entries, from competition to mutualism.

(d) Evolution of payoff matrix entries, from mutual defection to byproduct cooperation.

Figure 1: Mutation and selection on matrix entries. An existing row and column of the matrix are duplicated, and independent, small random perturbations are added to every entry in the new row and column. Rows and columns are removed as the system's dynamics removes some variants from the population. Diagonal matrix entries are plotted in black, all others in red. [2, 7, 6]

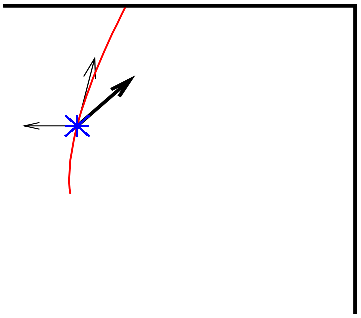
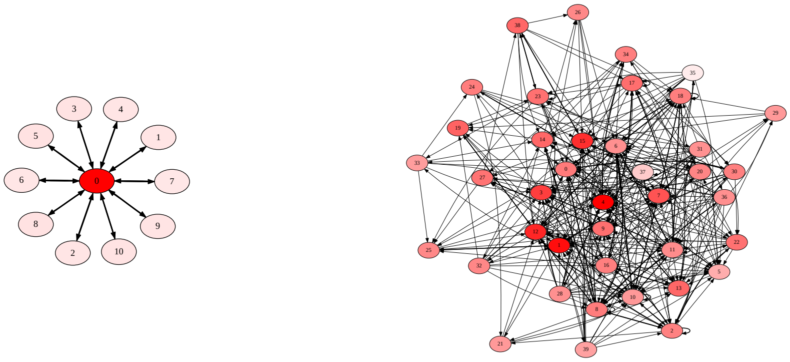
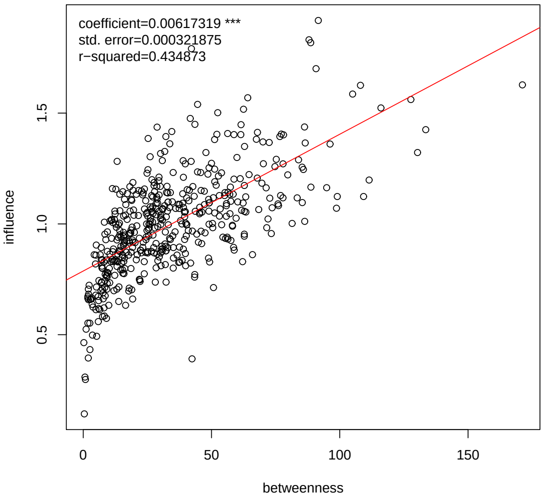


Figure 2: In Lotka-Volterra dynamics, the gradient of selection on phenotypic traits is the projection of the selection gradient on interaction terms $a_{ij} = a(p_i, p_j)$ onto the space of available variation parametrized by the phenotypes p. The selection gradient on the terms a_{ij} for a given i (bold arrow) is the vector of partial derivatives $\frac{\partial}{\partial a_{ij}} \left(r_i + \sum_j a_{ij} \hat{X}_j \right)$, which are the average population values $\hat{X}_j$, all positive. This implicit positive direction of selection is mediated by two factors: (1) the projection of that vector onto the space of available variation of the phenotype p_i (upward-pointing arrow), and (2) the effect of selection on p_j for each a_{ij} (left-pointing arrow), which may tend to decrease or increase a_{ij} [2, 6].



(a) Influence (red) coincides with centrality in star graph.

(b) Influence correlates visually with centrality in power-law graph.



(c) Influence *vs.* betweenness centrality in 12 power-law graphs of 40 nodes each.

Figure 3: Define **influence** of a node i as normalized marginal change in probability of network-wide adoption of the 'fitter' option (P) as node i's preference for the 'fitter' option (r_i) varies ($\partial P/\partial r_i$). In the star graph, strong influence can be shown analytically to coincide with graph centrality (a). In randomly assembled graphs (b), influence and betweenness centrality are strongly correlated (c). Similar correlations are found for a number of other centrality measures [17].