# Research Statement

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## Research Interests

I am particularly interested in emergent patterns in complex multi-agent systems. I study both how to design effective autonomous decision-making systems as well as the rationale behind decisions of living agents in natural systems. Consequently, my transdisciplinary work connects engineering [1, 5, 10, 11, 15], computer science [12–14], and behavioral ecology [7, 9]. Recent projects have included decentralized algorithms for intelligent lighting in the built environment, formal safety verification for autonomous urban vehicles, ecological rationality in solitary foragers, and resource allocation in natural and artificial swarms. Presently, I work in a social-insect laboratory where I do both empirical and theoretical studies to infer how group-level rationality emerges from the aggregated actions of individuals. This work is equally focused on bioinspired design as it is on fundamental biology. In general, I use theories from optimization, parallel computing, networks, dynamical systems, stochasticity, and formal logic to explain or design emergent system-level phenomena. Here, I describe some of my prior research successes and pending work.

### Control of Groups: Cooperation, Optimal Resource Allocation, Safety, and Swarms

Whereas my past work focused on the interactions of individuals with complex environments, my more recent work considers systems of many interacting individuals. In the engineering design cases, I am interested in decentralized implementations of collective group behavior that rely on little communication or coordination between individuals. In the behavioral analysis cases, I am interested in the individual proximate mechanisms that, when combined with the environment, lead to synergistic group behaviors.

**Cooperative task-processing networks:** When a number of agents with similar capabilities are connected on a network, each agent may share its own task-processing resources with its neighbors. Rather than depending on a centralized computational strategy to determine the best cooperation policy, I implemented a fictitious trading economy that induces individual agents to dynamically adjust cooperation frequency based entirely on locally received incentives [3, 11]. Rather than reducing communication ability of each agent and studying the "price of anarchy," I use a novel individual-level utility function that couples the actions of neighboring individuals so that good performance is possible without explicit communication. As shown by formal theoretical analysis, certain motifs present in the network help to guarantee the stability of the decentralized algorithm to solutions that are qualitatively similar to those of a centralized load balancer. As this system exhibits non-trivial coupling between individual utility and network structure, I have presented these results in complex adaptive systems venues [6]. Moreover, although this approach is focused on flexible manufacturing systems and autonomous-air-vehicle surveillance systems, it is inspired by animal examples of cooperative breeding among unrelated individuals, and I have presented it at sociobiomimicry venues as well [8]. Several extensions of this work are possible.

**Distributed resource allocation under non-separable constraints:** Depending on the optimization criterion, it is often possible for a team of distributed agents to find optimal solutions in a decentralized fashion so long as solution-space constraints are separable. However, realistic constraints are non-separable and induce tradeoffs between agents; the actions of one agent have to be mirrored in another in order to maintain the constraint. In these latter cases, distributed solution methods are effectively centralized due to necessary communication and coordination. With this problem in mind, I study how to replace explicit communication between agents with anonymous modifications of the shared environment. I have presented results [3, 4] that show how a decentralized bank of lights in a building can achieve multiple illumination constraints using minimum power without any explicit communication between the lights. A similar method could be used for other systems that share access to a physical resource, like distributed power generation systems. I am currently doing empirical work with *Temnothorax rugatulus* ants to determine the decentralized rules that individuals use to simultaneously regulate the intake of several colony-level macronutrients to set points. These rules can be used for bio-inspired design of non-separable distributed resource allocation algorithms. Additionally, this work may provide insight into behavioral factors of colony collapse disorder in honeybees.

**Safety verification in mixed-traffic urban environments:** In the far future, autonomous vehicles may chauffeur human occupants within a highway system with a complicated communication infrastructure that guarantees coordinated motion between the vehicles. During the transition to that future, vehicles on highways will have varying levels of autonomy, and there may be little-to-no direct communication between them. Whereas my other work focuses on collective optimization with little coordination, here I study collective safety constraints in cases of little coordination. For this task, I have combined physical specifications of the environment with software verification methods that are normally accustomed to guaranteeing safety constraints in discrete-time and discrete-space systems [12, 13]. Prior work that uses similar methods focuses on vehicles that can be specified with homogeneous parameter sets. Instead, I allow for heterogeneity, and the resulting software solutions are less conservative and thus provide more comfortable performance while still ensuring safety.

**Stochastic strategies for the maintenance of teams within swarms:** My most recent work focuses on swarms of independent agents where each agent must allocate itself to one of a number of tasks. For example, a swarm of robots on Mars may be tasked with collecting rocks of different sizes and carrying them back to a central station for sophisticated analysis. Some rock loads will require more team members to carry than others. So to maximize the chances of finding many interesting specimens, it is desirable to allocate only as many agents to carrying as is necessary. Rather than relying on communication between the agents, each agent may be viewed as an entity of a gas which attaches and detaches from the object according to certain probabilities that are designed *a priori*. Just as chemical reaction networks tend to concentrations that are well-described by kinetic theory, agents will tend to teams with sizes that are determined by "programming" the "reaction" probabilities. By comparing to empirical data, my colleagues and I have shown that such stochastic-hybrid-system models are good fits to the phenomenon of collective food transport observed in ants, which can form appropriately sized teams around food items and carry those items back to their home nest [1]. The allocation of agents around loads is not unlike classical adsorption processes on surfaces in chemistry that have equilibrium surface allocations that depend on the pressure of the gas. For robotic applications, we have introduced enzyme-inspired robot-to-robot interaction rules that ensure equilibrium surface allocations are independent of such environmental parameters. The result is a decentralized stochastic algorithm for formation of teams with stable and predictable sizes that do not vary with total number of robots or geometry of the space [15]. Ongoing work involves the use of such methods for nano-scale medical applications.

### Solitary Agents and their Environments: Optimization and Irrationality

I summarize some key results from my past work, which focused less on the complex systems comprised of groups of individuals and more on the systems formed by a single individual and its complex environment. Most of these results are connected to foraging theory that describes how solitary animals make choices in an uncertain environment. There is a convenient homomorphism between autonomous task-processing agents (e.g., military patrol vehicles) and solitary foraging animals. In both cases, the agent (forager) faces an incoming queue of tasks (prey) according to a merged Poisson process with a specified rate. Processing tasks (feeding) and searching are both costly activities, but the agent must process tasks in order to accumulate value (calories) necessary for proliferation by the designer (natural selection). Good designs choose which encountered tasks to process and how long to process each task until returning to search so as to maximize the value the agent will accumulate over its runtime (lifetime).

**Modular objectives:** Stochastic dynamic programming (SDP) is the natural solution to the solitary agent problem. However, realistic static optimization objectives can be used to increase analytical tractability or reduce real-time computational complexity. Models from behavioral ecology are too specific to be directly applied to engineering problems, and these engineering problems often use different optimization criteria than those used in ecological modeling of natural selection. So I generalized the intuitive analysis methods used in behavioral ecology to apply to a broad class of objective functions more amenable to the engineered ecology of mobile robotics [2, 10]. Moreover, I simplified models of speed-dependent sensor accuracy so that traditional models of speed–accuracy tradeoffs in predation could be used to design optimal speed–task combinations for mobile autonomous agents [5].

**Ostensibly irrational decision making:** Behavioral ecologists and human psychologists have often shown that human and non-human animals make irrational choices in some laboratory environments. Rather than assuming that natural selection has failed to adapt these animals to their environment, I have shown that impulsiveness in the laboratory can be the effect of simple behavioral heuristics that induce optimal behaviors only when simultaneous encounters with mutually exclusive options are rare [7]. So animals may simply be maladapted for the operant laboratory. Similarly, by using more realistic modeling approaches, I have shown that sunk-cost effects (i.e., where past costs of a task lead to increased persistence in continuing that task) can also be optimal in some harsh environments [9].

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