ICMMA 2025

International Conference on
Cooperative Strategies and Dynamics in Social Systems:
from Human to Insect Societies

Abstracts

Room 603, 6th floor, Nakano Campus, Meiji University

January, 2026

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Fumiko Ogushi (Meiji Gakuin University, Japan)
"Characteristics of the Ecology of the Digital World of Wikipedia: Analysis and Modelling Using Self-consistent Metrics"

Yusuke Notomi (The University of Tokyo, Japan)
"Species specificity and state-dependent flexibility of visually guided behavior in ants"

James Wolfe (University of Pennsylvania, USA)
"Multi-Agent Learning in the Iterated Prisoner's Dilemma"

Joshua Plotkin (University of Pennsylvania, USA)
"The role of uncertainty and risk in behavioral evolution"

Thursday 15th

Yohsuke Murase (RIKEN, Japan)
"Social norms, correlated opinions, and group structures: key ingredients in indirect reciprocity"

Kenji Itao (RIKEN, Japan)
"Self-organized institutions in evolutionary dynamical-systems games"

Hirotaka Goto (Meiji University, Japan)
"When does it pay to teach?: Population thresholds and the evolution of teaching"

Hye Jin Park (Inha University, Republic of Korea)
"The role of vacancies for the evolution of cooperation"

Joe Yuichiro Wakano (Meiji University, Japan)
"Eco-cultural range expansion model of modern humans and the effect of spatial bottleneck"

Friday 16h

Alex McAvoy (University of North Carolina, USA)
"Expectation-enforcing strategies for repeated games"

Hisashi Ohtsuki (The Graduate University for Advanced Studies, SOKENDAI, Japan)
"Conditions for the establishment of creole languages from an evolutionary game perspective"

Evolving evolutionary graph theory: multilayer networks, temporal networks, and eco-evolutionary consideration

Naoki Masuda
University of Michigan

Population structure is a major determinant of the evolution of cooperation. A large body of work suggests that network reciprocity often promotes cooperation in prisoner's dilemma-type interactions. However, it remains unclear how robust these conclusions are as network models become more realistic. In this presentation, I will discuss three projects on network reciprocity. First, recent analytical results show that multilayer networks can increase the fixation probability of cooperation relative to single-layer networks when players participate in different donation games across layers. We extend this framework to a setting in which one layer need not be a prisoner's dilemma game layer, reflecting the fact that not all everyday interactions are social dilemmas. Second, we consider network models of eco-evolutionary dynamical games. A key modeling choice is where the environmental state variable, which degrades and recovers in response to players' behavior, should be placed (e.g., on nodes, edges, or communities). We assign an environmental variable to each edge with reason and present a mean-field analysis of the evolutionary dynamics on a network with two equal-sized communities. Third, we revisit cooperation on time-varying networks. We argue that seemingly conflicting claims about whether scale-free networks enhance cooperation depend on what is being measured and under which selection regime—e.g., equilibrium cooperation levels under strong selection versus fixation probabilities under weak selection. We provide a theoretical framework based on temporal networks that helps reconcile these different perspectives.

Characteristics of the Ecology of the Digital World of Wikipedia: Analysis and Modelling Using Self-consistent Metrics

Fumiko Ogushi
Meiji Gakuin University

Wikipedia is a paradigmatic example of a digital knowledge space organized in a collaborative, bottom-up way with voluntary contributions. To investigate the fundamental mechanisms of Wikipedia, we introduce a self-consistent metric that measures editors' scatteredness and articles' complexity based on Wikipedia edit relationships. This metric is based on the assumption that editors have two intrinsic editing tendencies: content edits that increase article complexity and maintenance-like edits with relatively low costs. Applying our metric to English Wikipedia allows us to characterize diverse types of articles and editors. Motivated by these empirical results, we construct a minimal model of editing dynamics and successfully reproduces the fundamental characteristics of collaborative edits on Wikipedia. In this talk, we present the proposed self-consistent metrics, and discuss the results from empirical data analysis and the minimal model of Wikipedia.

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Species specificity and state-dependent flexibility of visually guided behavior in ants

Yusuke Notomi[1,2], Stephan Shuichi Haupt[2], Shigeto Dobata[1]

1. Department of General Systems Studies, Graduate School of Arts and Sciences, The University of Tokyo

2. Research Center for Advanced Science and Technology, The University of Tokyo

notomiant@gmail.com

Behavioral rules and their modulation show substantial diversity across species. Research focused on a single model species is therefore insufficient, underscoring the need to compare behavior across multiple species and contexts.

In this study, we investigate the condition-dependency of an innate visually guided behavior in individual ants. We focused on a spontaneous approach toward a conspicuous landmark, typically a dark vertical stripe, which we refer to as ***beacon-aiming***. This behavior is often categorized as "scototaxis" in ethological contexts and is known to be conserved across insect orders. When we examined responses to a dark landmark in six ant species with varying degrees of visual system development, we found that five species—like many other insects—approached the landmark. In contrast, the Japanese carpenter ant, *Camponotus japonicus*, did not show beacon-aiming [1].

We found that *C. japonicus* workers exhibited beacon-aiming when they fell onto a water surface; they approached the landmark as they swam or waded [2]. They also showed beacon-aiming when swimming in non-aqueous liquids (a mixture of glycerol and 2-propanol). Moreover, even on a dry substrate, the ants showed beacon-aiming when walking upside down on a ceiling. These experimental settings present adverse conditions to the ants. An additional experiment using water revealed that the beacon-aiming persisted for at least several seconds after direct experience of the adverse condition. These results suggest that *C. japonicus* workers possess an internal mechanism that integrates diverse adverse conditions and outputs the beacon-aiming. Our findings reveal an aspect of the flexibility of an insect behavior, which has traditionally been regarded as rather fixed.

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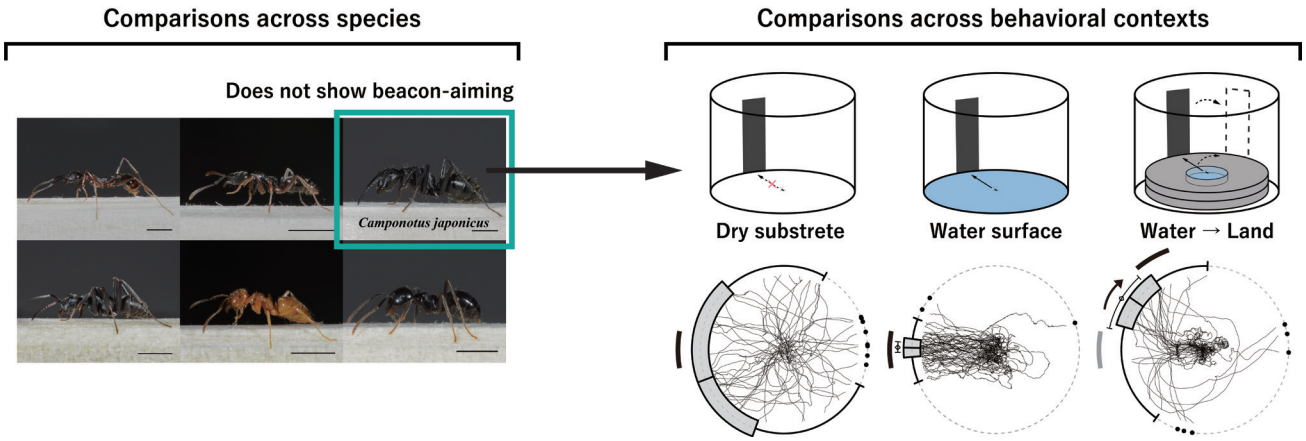

Multi-Agent Learning in the Iterated Prisoner's Dilemma

James Wolfe
University of Pennsylvania

The iterated prisoner's dilemma (IPD) is the classic game-theoretical framework for studying the evolution of cooperation through reciprocity. Often, evolutionary models involving payoff-biased birth/death or imitation are used to explain the proliferation of strategies in the IPD. Here, instead, we allow agents using reactive memory-one strategies to update their strategies simultaneously via gradient ascent, moving locally in the direction which most rapidly improves their respective payoffs. We find that heterogeneity in learning rates, which modulate how far the agents move along their gradients, can qualitatively change the outcome of the population. A randomly initialized population with uniform learning rates will go to the socially non-optimal always-defect strategy (ALLD); while that same population with variable learning rates will move towards a socially optimal generous-tit-for-tat strategy (GTFT). The results suggest that in large populations that are strategically flexible, without any genetic predisposition to altruism, purely selfish and myopic learning can lead to stable cooperation provided the population harbors intrinsic variability in learning rates.

The role of uncertainty and risk in behavioral evolution

Joshua Plotkin
University of Pennsylvania

Humans update their social behavior in response to past experiences and changing environments. Behavioral decisions are further complicated by uncertainty in the outcome of social interactions. Faced with uncertainty, some individuals exhibit risk-aversion while others seek risk. Attitudes towards risk may depend on socio-economic status; and individuals may update their risk preferences over time, which will feedback on their social behavior. Here we study how uncertainty and risk preferences shape the evolution of social behaviors. We extend a game-theoretic framework for behavioral evolution to incorporate uncertainty about payoffs and variation in how individuals respond to this uncertainty. We find that different attitudes towards risk can substantially alter behavior and long-term outcomes, as individuals seek to optimize their rewards from social interactions. In a standard setting without risk, for example, defection always overtakes a population engaged in the classic Prisoner's Dilemma, whereas risk-aversion can reverse the direction of evolution, promoting cooperation over defection. When individuals update their risk preferences along with their strategic behaviors, a population can oscillate between periods dominated by risk-averse cooperators and periods of risk-seeing defectors. Our analysis provides a systematic account of how risk preferences modulate, and even co-evolve, with behaviors in an uncertain social world.

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Social norms, correlated opinions, and group structures: key ingredients in indirect reciprocity

Yohsuke Murase[1,2,3]

[1]RIKEN Center for Interdisciplinary Theoretical and Mathematical Science (iTHEMS), Wako, Japan
[2]RIKEN Center for Computational Science, Kobe, Japan
[3]Graduate School of Science and Engineering, Saitama University, Saitama, Japan
yohsuke.murase@riken.jp

Indirect reciprocity offers a powerful explanation for large-scale cooperation: people help others to build a good reputation and, in turn, receive help in the future. Yet the key factors that allow indirect reciprocity to evolve and be sustained are still not fully understood. In this talk I synthesize three complementary pieces of this puzzle from our recent works: social norms, opinion synchronization, and group structure.

The first piece concerns social norms and their evolutionary stability [1]. Norms determine how individuals assess others based on actions and reputations. While classical work identified successful norms such as the leading eight, a complete characterization of evolutionarily stable norms has been lacking, especially under errors and costly punishment. We develop a general framework to analyze the stability of third-order norms in the public assessment model.

I will then discuss the second piece, opinion synchronization [2]. While the above analysis assumes a shared view of reputations, in reality, opinions differ due to private assessment or incomplete information. We model correlated opinions across the population and show how this correlation shapes the stability of cooperation.

Lastly, we discuss how norms evolve in the first place [3]. We perform a large-scale analysis over the full space of third-order norms and their transitions. Once this full norm space is allowed, cooperation in well-mixed populations is surprisingly fragile: evolutionary trajectories cycle among norms and spend most of the time near ALLD. By contrast, introducing group structure changes the outcome. Cooperation can evolve reliably, and the most successful norm is particularly simple: it treats cooperation as universally good and defection as negative except when it constitutes justified punishment.

Taken together, these studies show that indirect reciprocity depends on three key ingredients: appropriate social norms, a high level of opinion synchronization that aligns reputations, and an appropriate group structure that channels evolutionary dynamics toward cooperative outcomes.

References

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Self-organized institutions in evolutionary dynamical-systems games

Kenji Itao
RIKEN, Center for Brain Sciences
kenji.itao@riken.jp

How do communities self-organize social institutions to manage a changing environment? Institutions are systems of shared norms and rules that regulate people's behaviors, often emerging without external enforcement [1]. They provide criteria to distinguish cooperation from defection and establish rules to sustain cooperation. To address the mechanisms of their emergence, we introduce the evolutionary dynamical-systems game theory that couples game actions with environmental dynamics and explores the evolution of cognitive frameworks for decision-making (Fig. 1). We analyze a minimal model of common-pool resource management, where resources grow naturally and are harvested. Players use decision-making functions to determine whether to harvest at each step, based on environmental and peer monitoring. After evolution, decision-making functions enable players to detect selfish harvesting and punish it by degrading the environment. This process leads to the self-organization of norms that classify harvesting actions as cooperative, defective, or punitive. The emergent norms for "cooperativeness" and rules of punishment serve as institutions. The environmental and players' states converge to distinct modes characterized by limit-cycle attractors, representing temporal regularities in socio-ecological systems. These modes remain stable despite slight variations in individual decision-making, illustrating the stability of institutions. We measure evolutionary robustness of decision-making functions, defined as the capacity to keep dominance against invasion. It is revealed that plasticity, the ability to adjust actions to cope with diverse opponents, allows for such robustness. This work introduces foundational concepts in evolutionary dynamical-systems games and elucidates the mechanisms underlying the self-organization of social institutions [2].

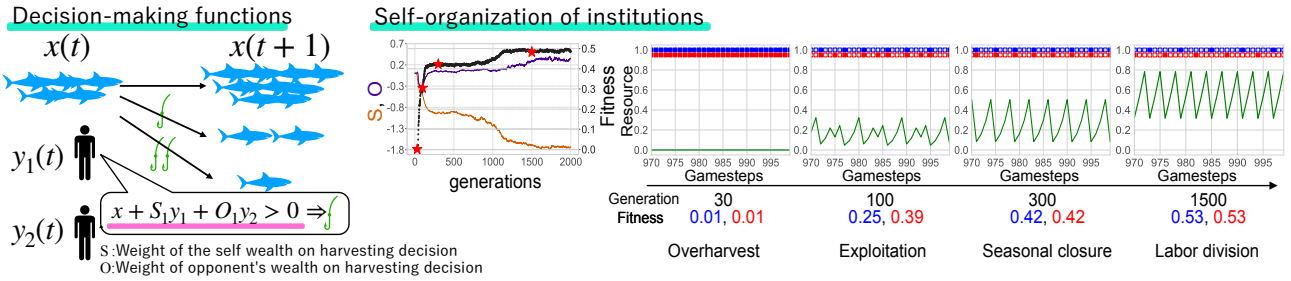

Figure 1: Players' strategies are represented as "decision-making functions." Each function takes as inputs the current resource level, the player's own wealth, and the opponent's wealth, and returns a harvesting decision as output. The weights placed on own and opponent wealth evolve across generations. Through this evolutionary process, temporally periodic harvesting patterns emerge, supported by self-organized institutions that specify acceptable and unacceptable behaviors and impose punishments on norm violators.

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When does it pay to teach?: Population thresholds and the evolution of teaching

Hirotaka Goto
Meiji University, Japan

Teaching is a defining feature of human societies, yet it remains unclear why some individuals are allocated to teach full-time rather than directly contribute to productive work. Using a simple mathematical model, we identify the tradeoff between the size of a population and its collective level of expertise, and we analyze the optimal proportion of a population that should serve exclusively as teachers across diverse scenarios. We show that teaching becomes advantageous only after a population exceeds a critical size, and even in large societies only a limited fraction of individuals should be dedicated to teaching. Subsequently, the peak demand for education is achieved at an intermediate population size, and it never surpasses one half of the population. For more complicated tasks, the optimal allocation of teachers develops a layered structure that depends on population size. These findings offer insight into the conditions that favor the evolution of teaching and help explain its prevalence in both human and some non-human species. Finally, we will discuss how teaching can emerge in an evolutionary model.

The role of vacancies for the evolution of cooperation

Hye Jin Park
Inha University

Assortment—the tendency for cooperators to preferentially interact with and benefit other cooperators—is a cornerstone mechanism for the evolution of cooperation. One of the most common ways to achieve this is through spatial structure, where individuals only interact within a close spatial proximity. Traditionally, studies of spatial reciprocity focus on populations with fixed structures or constant sizes. Here, we introduce a simple model of spatial games that incorporates both strategy evolution and variable population size. Crucially, as the environmental harshness increases, the system undergoes an absorbing phase transition from a growing population to extinction. We find that the transition point is dependent on the strategies present. In particular, we discover a 'cooperative window' in the parameter space where only cooperators can persist. A mutant defector can briefly proliferate, but over time, naturally occurring vacancies physically separate cooperators from defectors, effectively purging the defectors and driving them to extinction. Our model reveals that naturally arising vacancies can dramatically enhance the positive effects of spatial structure. We are currently investigating active rules for generating vacancies to further explore this mechanism's potential in promoting cooperation.

Eco-cultural range expansion model of modern humans and the effect of spatial bottleneck

Joe Yuichiro Wakano
Meiji University

Eco-cultural range expansion model assumes a positive feedback loop between skilled human density and carrying capacity, based on the theory of cultural evolution. The model is formulated by a reaction diffusion system, and there exist several kinds of traveling wave solutions. When applied to the modern human dispersal in Paleolithic, the model predicts the first wave (ecological spread), in which modern humans invade and coexist with archaic humans, and the second wave (cultural spread), in which modern humans establish high density supported by advanced culture and archaic humans go extinct [1,2].

Yet, the effect of the geographical boundaries on this process remains poorly understood. Here, we extend the model to a two dimensional space where two large habitats are connected by a narrow corridor (spatial bottleneck) with reflecting boundaries [3]. We find that a wave of ecological invasion is unaffected by the bottleneck, whereas a cultural wave can be blocked by sufficiently narrow corridors. The maximum bottleneck width that prevents propagation depends on the domain shape, and it converges to the threshold value when the habitat to be invaded gets larger. Our results align with mathematical results on a bistable reaction diffusion equation, particularly mean curvature flow, based on which we provide an approximate formula of the threshold bottleneck width. Applied to the Middle—Upper Paleolithic transition, the findings suggest that while the spread of modern humans was robust to spatial bottlenecks, the expansion of advanced Upper Paleolithic culture could be delayed or halted by narrow corridors. Archaeological records point to potential cases where such geographic bottlenecks constrained cultural dispersal.

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Expectation-enforcing strategies for repeated games

Alex McAvoy
University of North Carolina

The theory of repeated games describes interactions that unfold over time. Strategies for repeated games can condition on the past in complex ways, and it is known that this behavioral complexity yields rich spaces of equilibria. However, it often results in an equilibrium selection problem, and in many interesting games there isn't a reliable way to get to "good" outcomes. In this talk, I will describe a class of "autocratic" strategies that allow a player to unilaterally control the space of possible outcomes. Examples include fairness (e.g., my payoff equals yours, on average) and extortion (e.g., my payoff equals twice yours, on average). These strategies have nice adaptive properties in the sense that they incentivize a self-interested opponent to also act in the interests of the group. Within this class of strategies, I will describe how an agent can always find an autocratic strategy with short memory, which takes into account information from only one round into the past. In particular, we can characterize precisely which payoff relationships are enforceable using strategies of arbitrary complexity. This memory reduction indicates that certain kinds of reciprocal payoff control might be feasible for humans (who are notoriously bad at synthesizing information over long time horizons). It also demonstrates the sufficiency of a short-memory search space for autocratic strategies in reinforcement learning. This talk is based on joint work with Nikos Dimou.

Eco-cultural range expansion model of modern humans and the effect of spatial bottleneck.

Conditions for the establishment of creole languages from an evolutionary game perspective

Hisashi Ohtsuki

The Graduate University for Advanced Studies, SOKENDAI

Creole language is a mixed language that emerges upon the contact of multiple ancestral languages and become fixed and spoken in a population. There are about a hundred of creole languages on the globe, but the process of how these languages have been established after language contact is not known well. Some linguists believe that at an initial phase of plantations, called homestead phase, which is characterized by a small population size and by nearly equal proportions of Europeans and native colonial workers, a creole language has already been established. To elucidate the conditions under which a creole language becomes established in the population, we construct an evolutionary game model. We assume that there is positive frequency-dependence in the "language game", where a language with more speakers is more advantageous because its speakers can communicate with more others. Our analyses of both replicator equations for an infinitely large population and a Moran model for a finite population reveal three factors that can favor the establishment of a creole language; that (1) two ancestral languages are linguistically distant, that (2) population sizes are small, and that (3) the initial fractions of speakers of two ancestral languages are nearly balanced. Our results confirm that the homestead phase provided a favorable condition for the establishment of creole languages.