Learning dynamics and decision paradigms in social-ecological dilemmas

Abstract

Collective action is required to enter sustainable development pathways in coupled social-ecological systems, safely away from dangerous tipping elements. Yet, in order to investigate the preconditions for cooperation, there is the challenge how to formally understand such social-ecological systems from a conceptual, mathematical modelers perspective.

Without denying the usefulness of other model design principles, this thesis proposes the agent-environment interface as the mathematical foundation for the design of social-ecological system models. From this perspective, it extends the concept of a social dilemma to a social-ecological dilemma. Social dilemmas have often been studied by evolutionary dynamics in repeated games with only one environmental state. Instead, this thesis uses stochastic games with multiple environmental states to investigate social-ecological dilemmas. Thereby, it extends the domain of social physics to social-ecological physics.

Yet, the majority of previously used evolutionary dynamics are not able to deal with multi-state environments. Therefore, this thesis focuses on the related concept of learning dynamics. It refines techniques from the statistical physics literature on learning dynamics to derive a deterministic limit of established reinforcement learning algorithms from artificial intelligence research. This enables a dynamical systems perspective on reinforcement learning in multi-state environments. Illustrations of the resulting learning dynamics of different learning algorithms across multiple example environments reveal a wide range of different dynamical regimes, such as fixed points, periodic orbits and deterministic chaos.

Eventually, this thesis applies the derived multi-state learning equations to a particular newly introduced environment, referred to as the Ecological Public Good. It models a coupled social-ecological dilemma, extending established repeated social dilemma games, such as the Prisoner's dilemma, by an ecological tipping element. The preconditions for both the emergence and stability of cooperation are investigated using a combination of numerical and analytical methods. This model is able to explain empirical observations as well as to reproduce known theoretical results. Novel qualitatively different parameter regimes are discovered, including one in which agents prefer to collectively suffer in environmental collapse rather than cooperating in a prosperous environment. Further, it can be shown that cooperation can remain stable despite considerable shortsightedness of the agents. However, this is only the case if the expected damage in the case of collapse is large. Conversely, this means that such reward-optimizing learners will break off the cooperation agreement, if they do not believe in likely and severe consequences of a tipping catastrophe.

Since optimization approaches have also been criticized in other contexts of environmental governance, this thesis challenges the reward optimizing paradigm of the learning equations. Prominent alternatives to the decision paradigm of economic optimization are sustainability and the safe operating space. This thesis presents a novel formal comparison of these three decision paradigms for the governance of an environmental tipping element. There, it can be shown that optimization alone can lead to safe and sustainable behavior and policies, but is by no means guaranteed to do so. In fact, no paradigm guarantees fulfilling requirements imposed by another paradigm. Further, the absence of a master paradigm is shown to be of special relevance for governing the climate system, since the latter may reside at the edge between parameter regimes where economic welfare optimization becomes neither sustainable nor safe.

In summary, this thesis demonstrates the usefulness of the agent-environment interface for the design of social-ecological system models, leading to a deeper theoretical understanding of such systems and in particular of the preconditions for successful collective action towards ecologically safe and socially just sustainability.

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