An Entropy-Driven Framework for Early Prediction of Phase Transitions in Strategic and Combinatorial Systems

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Strategic system stability depends on sustained cooperation, yet these frameworks frequently undergo phase transitions into competitive or destructive states. This research utilizes an entropy-driven framework to evaluate classical versus quantum-inspired game-theoretic models in predicting these shifts within an iterated Prisoner's Dilemma. By monitoring Shannon entropy and the entropy rate of change (ROC) as primary indicators, the study identifies the specific lead times required to signal a transition from non-zero-sum to zero-sum or negative-sum outcomes. The experimental findings demonstrate that quantum-inspired models, which represent strategies as fluid potential states rather than fixed choices, detect statistically significant entropy spikes well in advance of classical benchmarks. These shifts function as reliable early warning signals, flagging a loss of coordination before any measurable collapse in payoff occurs. Notably, the quantum-inspired dynamics achieved superior detection accuracy ($p < 0.0001$) across broad parameter ranges, providing larger actionable warning windows. While this detection remained robust across varying agent counts and noise levels, the quantum advantage proved fragile under conditions of extreme uncertainty. The significance of this work lies in providing measurable lead times before systemic collapse in noisy multi-agent systems, such as financial markets, biological protein folding, and social cooperation networks. Because predictability precedes collapse even when outcomes appear chaotic, this framework offers a mechanical basis for intervention, mitigation, or controlled shutdowns in critical real-world environments.

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