Algorithmic Collusion at Test Time: A Meta-game Design and Evaluation

Yuhong Luo
Rutgers University

Daniel Schoepflin
DIMACS, Rutgers University

Xintong Wang
Rutgers University

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Algorithmic Collusion

- Firms are increasingly adopting algorithms to make economic decisions.
- Algorithms can interact in ways that lead to anti-competitive or collusive outcomes.

Real-world examples include

- German gasoline dynamic pricing (Assad et al., 2020)
- E-commerce e.g., Amazon Marketplace (Musolff, 2022)

Research Question

Can algorithmic collusion emerge at *test time* among *rational* algorithmic choices?

Test time:

- Limited *time horizon.*
- *Costs* of exploration and learning.
- *Asymmetric* economic settings.
- *Asymmetric* algorithmic choices.

Rational:

- Algorithm adopters are *strategic and rational*.

Previous Work

Collusion can occur among *symmetric* players using each algorithm below at *convergence*.

- Q-learning
  - Pricing (Calvano et al. 2020)
  - Auction (Banchio and Skrzypacz 2022)
- UCB (Hansen et al. 2020)
- LLMs (Fish et al. 2024)

A Meta-game Framework

Initial policy: Defines actions conditional on states. Typically generated by pretraining with symmetric algorithms.

Initial policy category: Categorization along two dimensions: (1) propensity to collude with the train-time partner, and (2) robustness against the best response.

Strategy: The combination of an initial policy sampled from one category, and an adaptation rule drawn from a feasible set.

Meta-strategy: The algorithm adopter's choice of initial policy category and the adaptation rules.

Meta-game: interactions simulated among players using different meta-strategies.

Empirical Evaluation

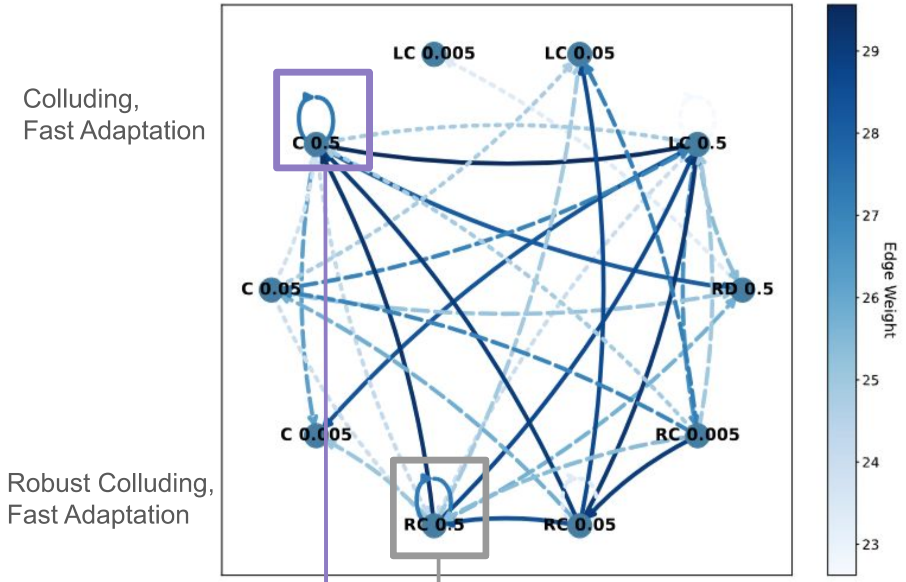
Conduct meta-game analysis on

- Q-learning, UCB, LLMs
- Asymmetric cost players
- Optimistic v.s. pessimistic initialization

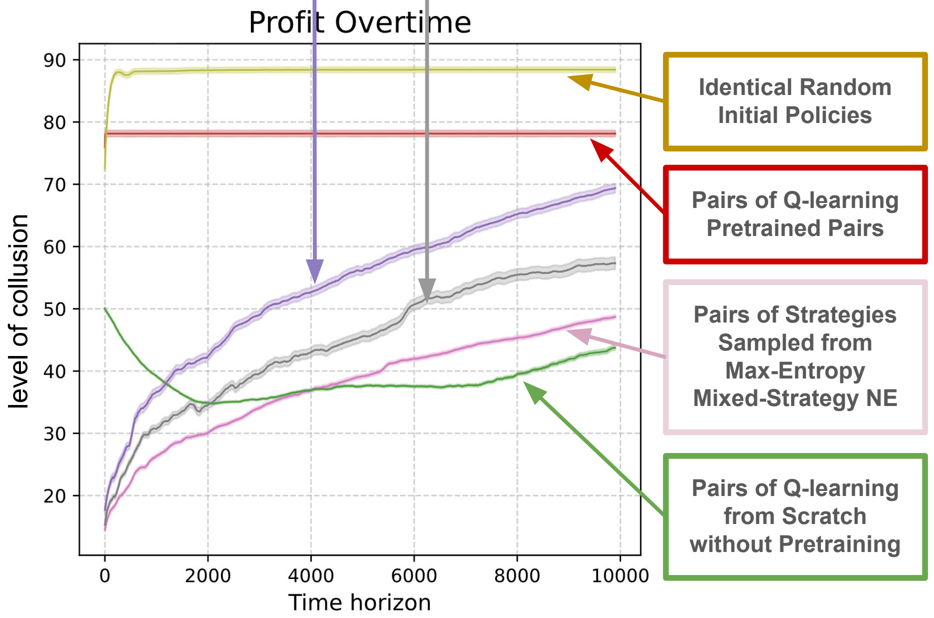
Insights: Collusion can be an *equilibrium outcome* at test-time, but diminishes under

- **shorter interaction horizons,**
- **asymmetric costs,**
- **pessimistic initialization.**

Meta-game with Q-learning



Best Response Graph of Q-learning-Based Meta-strategies



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