Studies on the Computational Modeling and Design of Financial Markets

Doctoral Consortium

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ABSTRACT

Electronic marketplaces and the automation of trading have transformed the financial market from a human-decision ecosystem to an algorithmic one. Questions and challenges that arise from this new algorithmic ecosystem naturally lend themselves to computational approaches. My research builds computational models to understand trading behaviors, designs market mechanisms robust to manipulation, and proposes algorithms to facilitate order matchings.

KEYWORDS

Market manipulation; agent-based simulation; trading agents; mechanism design.

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1 INTRODUCTION

Electronic trading platforms have transformed the financial market landscape, by supporting the automation of trading, removing graphical constraints, and consequentially increasing trading volume and speed. Automated traders have unprecedented ability to exploit and react to market information from a broad variety of sources, including transactions and order books exposed by many market mechanisms. Novel financial instruments have been created and become actively traded to help investors conveniently control risk and diversify investment portfolio. All these innovations and developments in market operation, trading technology, and financial instruments undeniably offer new opportunities for economic and social development, but at the same time brings new challenges and threats. Employing techniques from game theory, agent-based modeling, machine learning, and optimization, my research builds computational models to understand strategic trading behaviors, designs robust markets to prevent potential risks, and proposes computationally efficient algorithms to facilitate order matchings.

2 MANIPULATION IN FINANCIAL MARKETS

Market manipulation is of increasing concerns with the unprecedented interconnectedness of trading venues and the prevalence of autonomous trading. Manipulators tend to use automated programs to spread deceitful information, while other investors exploit market information (including the misleading ones) to make trading decisions. Manipulators, in turn, profit from investors' misled beliefs about supply and demand. The US Securities and Exchange Commission formally defines manipulation as "intentional conduct designed to deceive investors by artificially affecting the market". One recent lawsuit claimed evidence of thousands of such manipulation episodes in US Treasury futures market during 2013 and 2014 [3], and new allegations have been emerging on a regular basis.

My studies focus on order-based manipulation, where the manipulators submit spurious orders to mislead other traders. I aim to (1) understand manipulation (its practice, intent, and impact), (2) design mechanisms and trading strategies that are robust to manipulation, and (3) develop detection algorithms to identify any manipulation activity. I employ agent-based simulation and empirical game-theoretic analysis to evaluate the efficacy and impact of manipulation, answering questions about the first two aims. For the last aim, I propose to use a machine learning approach to combine simulated data and unlabeled real market order streams to construct a large-scale and realistic dataset. This synthetic dataset can further help to develop a high-fidelity manipulation detector.

2.1 An Agent-based Model of Manipulation.

To understand manipulation in financial markets, most previous efforts characterize its practice through analyzing historical trading data [4, 10]. They provide limited understanding of its impact, which can only be inferred from counterfactual information – what would have happened under a different circumstance. In [9], I built the first agent-based model of manipulating prices in financial markets through *spoofing* – a common order-based manipulation practice. Built around the standard limit-order mechanism, the model captures a complex market environment with combined private and common values, the latter represented by noisy observations upon a dynamic fundamental time series. Besides a manipulator, I consider two types of trading agents: zero-intelligence traders who ignore market information to trade and learning traders who learn from the order book to predict price outcomes. The model provides a basis to perform agent-based simulations and conduct game-theoretic analysis upon simulated data to study traders' rational choices of strategies in equilibrium under different conditions. Thus, one can acquire counterfactual information and evaluate the impact of manipulation by comparing markets with and without manipulation.

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I demonstrated the designed spoofing strategy is profitable and can effectively mislead other rational traders. A comparison of equilibrium outcomes shows that manipulation hurts market welfare and decreases the number of learning traders. Perhaps surprisingly, I found a consistently "spoofable" market: the presence of a manipulator fails to eliminate all learning traders, and their persistence may, in turn, incentivize a manipulator to continue successfully spoofing the market. This indicates that the deterrence of manipulation requires active measures.

2.2 A Mechanism to Deter Manipulation

In a follow-up study, I investigate market designs to systematically mitigate manipulation [8]. To design low-risk but effective strategies, manipulators often rely on the instant order book information disclosed by standard continuous double auctions (CDA) [2, 6]. For instance, spurious buy orders are typically placed at prices just lower than the highest buy price to mislead other investors, and withdrawn with high probability before any market movement could trigger a trade. In [8], I extend the traditional CDA mechanism with a *cloaking* parameter, which specifies the number of price levels to hide symmetrically from inside of the order book. The goal is to introduce risks and degrade the influence of malicious orders through partially cloaking market information. Designing such a market faces a natural tradeoff: insufficient cloaking may not be effective to deter manipulation, whereas too much cloaking may degrade the usefulness of market information. To balance this tradeoff, I extended the agent-based model of manipulation [9] to support order book hiding, and employed empirical mechanism design [7] to analyze investors' trading behavior under different degrees of cloaking. Results demonstrate in markets with moderate cloaking (e.g., hiding one or two price levels from the order book), the benefit of information hiding to mitigate manipulation outweighs its efficiency cost.

2.3 A Dataset for Manipulation Detection

Instead of disincentivizing manipulation through mechanism designs, a more direct approach is to detect any manipulation activity. However, this is not easy. Catching certain trading actions (e.g., order cancellations and modifications that are known as manipulation signatures) in isolation is not enough, as they can also be legitimate actions of many non-manipulative participants [1]. Thus, reliably detecting manipulation requires learning the malicious intent behind the order stream associated with an individual trader, which records trading activities interacting with different market states and subsequent outcomes over time.

However, modern learning-based approaches require large labeled datasets to train and test, and real market order streams identifying manipulation simply does not exist. This makes developing a high-fidelity manipulation detector a challenging task. A promising approach is to train a learning model on simulated order streams. Our established simulator is an agent-based one, and agents are developed and classified into trader classes (e.g., fundamental traders, arbitrageurs, and manipulators) according to their trading behaviors and intents. It can generate order streams of individual agents indefinitely up to computational limits, and directly label simulated data with corresponding trader classes. However, synthetic data may not be realistic enough, causing learning models to overfit to simulated artifacts and fail to generalize on real data.

To overcome limitations in both data sources, I propose to combine our simulator with unlabeled real market data to construct an order-stream dataset that is both realistic and labeled with trader class. The idea is to learn an adversarial neural network to refine simulated order streams in a way that the refined outputs satisfy two things: (1) indistinguishable from real data, and (2) preserving the labeled trader class associated with the original simulated inputs. In a preliminary work [5], we demonstrated the effectiveness of employing GANs on financial data to generate realistic trading activities of an aggregated market. In effect, our market simulator can work together with this trained adversarial network to produce realistic order streams with labeled trader class. This improved realism can further help to train learning models to detect manipulation without any data annotation effort.

3 COMBINATORIAL FINANCIAL OPTIONS

To adapt to this new fast-paced trading landscape, novel financial instruments are designed to help investors conveniently control risk and diversify investment portfolio. Efficiently matching the supply and demand of complex financial contracts is an important but challenging problem. I study market designs to support trading a novel type of financial instruments, *combinatorial financial options*[1].

Traditional financial options specify agreements upon future trades of a single security. Market treats options of different securities with disparate specifications separately, having each publicly traded in a distinct and independent CDA. Over the past decades, the suite of option offerings has been expanded to contracts of specified portfolio of securities. Chicago Board Options Exchange has been actively facilitating the trade of options on S&P 500 Index and Dow Jones Industrial Average, and plans to further launch options on ten S&P Select Sector Indices. These newly emerged options can all be considered as special forms of combinatorial options, with their contracts written on certain popular combinations.

We propose a more general and flexible combinatorial options market, where investors can bid or offer any linear combination of securities specified at their will. This provides investors the opportunities to bet on future correlation between stocks, conveniently hedge risks, and express interests in any investment portfolio. However, designing a market to match combinatorial option orders is difficult. Different option contracts can no longer be traded in independent markets, as matching contracts of the same portfolio becomes very unlikely and investments will get dispersed in extremely sparse markets.

I took a first step to design a computationally efficient mechanism to facilitate trading combinatorial options in a single market. I showed that the combination of arbitrage theory in financial economics and optimization can efficiently derive a *matching* solution. The technique can match options of different combinations of securities in polynomial time, while guarantee no future loss for the exchange. However, whether there exists any polynomial-time algorithm to *clear* a market – ensuring that no match exists among the remaining orders – remains an open problem, which I plan to further investigate.

[1] Part of this work was done during Xintong Wang's internship at Microsoft Research.

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