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Research Statement

Vision

I am broadly interested in algorithmic game theory, mechanism design, and how strategic behavior impacts computer systems' security and fairness. While algorithmic game theory studies algorithmic design under incentive constraints, information security explores the protection of a computer system against adversaries. In one direction, game theory provides new perspectives in designing secure systems because in many real-world settings, adversaries are not intentionally malicious but rather rational and economically driven. By considering a rational adversarial model, we can solve problems that otherwise would be impossible. For example, Bitcoin [Nak19] solves the permissionless Byzantine agreement by monetarily rewarding honest behavior.

In the other direction, the Internet and the World Wide Web brought the need to rethink the traditional adversarial model in algorithmic game theory. Since its inception, mechanism design has focused on designing algorithms to allocate scarce resources where a trusted center is responsible for collecting data and implementing the allocation algorithm to rational agents. Information democratization and system decentralized brought by the Internet started to challenge the concept of a central trusted authority. Questions such as "Who should be accountable when things do not go as expected?" have no clear answer on Internet systems. For that reason, Internet mechanisms often lack transparency and unclear responsibilities with online misinformation, and lack of transparency in online auctions being a few examples.

Towards the goal of designing secure, fair, and accountable computer systems, my research focuses on:

- Rethinking the traditional mechanism design framework for an age where Internet systems are increasingly less transparent and decentralized. For that, we must design accountable mechanisms – that is, even when the mechanism designer is an adversary, users must have confidence that the system is fair.
- Designing decentralized mechanisms that scale, are energy efficient, and are secure against rational adversaries. Blockchains are a powerful tool in this direction, but existing solutions like Bitcoin are not energy efficient and do not scale. For large-scale adoption, we must develop blockchains that are energy-efficient and provides a good user experience.
- When system design alone cannot provide sufficient guarantees for fairness and security, we must understand how policy and regulation can help achieve the goal of having secure and fair systems.

Dissertation Research

Credible Auctions. Second-price auctions (where the highest bidder wins the item and pays the second-highest bid) inspired many online auctions. Compared with first-price auctions, this simple pricing scheme removes any incentive for strategic bidding, providing a better user experience. However, for many settings, second-price auctions introduce a strong assumption that the auctioneer will honestly implement the promised auction.

In online auctions such as eBay, it is impossible to guarantee that the platform would not collude with sellers and impersonate fake bidders. As an example, consider an eBay second-price auction where two bidders Alice and Bob bid $\$10$ and $\$5$, respectively. If the auction is honest, Alice wins the item and pays only $\$5$. Still, a malicious auctioneer can easily announce a third bid of $\$9.99$ after observing Alice's bid to obtain an additional revenue of $\$4.99$.

My research addresses the question of designing credible and strategyproof auctions. That is, auctions that neither bidders nor the auctioneer have any incentive to be strategic. By introducing mild assumptions, I showed that a simple modification of the second-price auction removes any incentive for the auctioneer to manipulate the auction.

Theorem 1 ([FW20a]) *Assume there exists a cryptographically secure commitment scheme. Then, there is a two-round optimal auction that is both strategyproof and credible.*

By introducing the assumption that the auctioneer is computationally bounded, I overcome an impossibility result due to Akbarpour and Li [AL20] that states that the only strategyproof, credible auction requires unbounded rounds of communication with the auctioneer. Moreover, my auction is relatively simple. In the first round, bidders cryptographically commit to their bids. In the second round, bidders reveal their bids, and the auctioneer implements the second-price auction. The auctioneer ignores any unrevealed bids, but any bidder who refuses to participate in the second round pays some penalty to the winner. I characterize necessary and sufficient conditions for that a small penalty exists so that the auctioneer prefers to be honest.

Over the years, the trusted center assumption has been a decisive factor for the slow adoption of second-price auctions [Kle02, Slu19] and my research shows that we can implement efficient strategyproof optimal auctions without requiring any trust from the auctioneer.

Incentives in Energy-Efficient Blockchains. Blockchains and smart contracts are useful tools to construct transparent mechanisms without a trusted center. As a result, there are many use cases in application domains where market barriers outweigh technical limitations. As an example, Ripple's decentralized ledger allows cross-border payments that circumvent market barriers in international banking.

Unfortunately, to this date, there are no fully decentralized and scalable blockchains. Bitcoin's solution is fully decentralized; however, its Proof-of-Work (PoW) consensus is wasteful and can only process seven transactions per second. In the hope of scaling blockchains, significant effort is invested in developing novel energy-efficient consensus algorithms with Proof-of-Stake (PoS) receiving the most attention.

A blockchain is fair if there is no strategy for a miner that owns x fraction of a scarce resource (e.g., computation in PoW and currency in PoS) that allows that miner to own more than x fraction of the blocks in the blockchain. Eyal and Sirer [ES14] showed that when $x > 1/3$, a miner can own more than x fraction of the blocks in the longest-chain by executing withholding attacks. Since miners obtain revenue only from blocks that end up in the longest chain, this strategy creates incentives for miners to form collusion. Moreover, many blockchains allow blocks to vote on system parameters – i.e., Ethereum allows each block to vote on future block sizes. Thus withholding attacks allow miners to increase their voting power in relevant operational decisions unfairly.

For PoW blockchains, as long as $x < 0.329$, honest mining is a Nash Equilibrium [SSZ16, KKKT16] – i.e., no strategy allows a miner to own more than his fair share of the blocks in the blockchain. Unfortunately, previous results do not apply to PoS blockchains. Without a proof-of-work, there is no cost for PoS miners to mine at multiple forks, making the strategy space exponentially larger. I develop new techniques to study strategic mining in PoS blockchains [FW20b], and give necessary and sufficient conditions for which honest mining is a Nash Equilibrium in PoS blockchains.

Theorem 2 ([FW20b]) *A honest mining is a Nash Equilibrium for PoS blockchains only if it has access to an unbiased*[1] *and unpredictable*[2] *randomness source. If a PoS blockchain has access to an unbiased and unpredictable randomness source, honest mining is a Nash Equilibrium if no miner owns more than 30.8% of the currency. Moreover, honest mining is* not *a Nash Equilibrium if a miner owns more than 32.7% of the currency.*

This result shows that even an ideal PoS blockchain (with access to unbiased and unpredictable randomness) is fundamentally different from PoW blockchains because the threshold where honest mining is a Nash Equilibrium for PoW is 32.9%. My work overcomes the complex strategic landscape in PoS blockchains by using reductions to characterizing the strategy space. My characterization allows us to go beyond current theoretical work on PoW and form the foundations of PoS blockchains. Theorem 2 is the first step towards that goal by showing that economic incentives for honest behavior in PoS blockchains can be close to economic incentives in PoW blockchains.

Information security and tech policy. Recent years have seen the proliferation of large profile attacks in Internet-of-Things (IoT) devices [Jer17]. Manufacturers and users could improve their security, but there are few incentives to do so. Implementing better security features such as regular updates increases engineering costs. Adopting better security practices such as strong, unique passwords and two-factor authentication is costly for users.

External regulation can be an alternative to introduce incentives for improving security. In [CFF$^+$19], we consider two classes of regulations:

- Regulating manufacturers: requiring manufactures to implement minimum security standards.
- Regulating buyers: encourage users to adopt better security practices via rewards or penalties in the event of their IoT device participate in an attack.

A regulator wishes to minimize the externalities caused by security vulnerabilities (i.e., the probability of DDoS attacks from vulnerable devices), subject to a minimum impact on the seller's revenue. It is not surprising optimal regulations must regulate both sellers and buyers. If users make poor security choices, no investment in security standards will completely mitigate an attack's risks. Similarly, if devices are vulnerable, then risks are independent of the user's behavior.

The challenge of optimizing and adopting complex regulations motivates the search for simple regulations that regulate only manufacturers or only buyers. In [CFF$^+$19], we show that there is always simple regulations that are approximately optimal.

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[1] A randomness source is unbiased if a miner that owns x fraction of currency has probability x of winning the block at time t.

[2] A randomness source is unpredictable if the winner of the block at time T is unknown until time $t \geq T$. Many PoS blockchains scale by using predictable randomness [KRDO17].

Theorem 3 ([CFF$^+$19]) *There is a regulation that regulates* only *buyers or regulates* only *manufacturers that is approximately optimal (where the optimal regulation potentially regulates both buyers and manufacturers).*

Ongoing and Future Directions

Understanding the Design Space of Credible Auctions. My previous research has shown that it is possible to construct communication efficient single-item credible auctions by introducing cryptographic assumptions and assumptions in bidders' distributions. To construct credible auctions in more general settings, we need to understand how our assumptions expand the design space of credible auctions: are there other single-item auctions that are credible, strategyproof, and optimal under weaker assumptions?

Another research direction is to expand the theory of credible mechanisms beyond single-item auctions. In recent years, multi-round combinatorial auctions (such as the FCC spectrum auctions [Mil04]) are becoming increasingly popular.

Auctions with multiple items with arbitrary combinatorial constraints bring unique challenges because the auctioneer can use previously disclosed information regarding one item to form beliefs about other items. Thus, it is unknown if there is a credible general implementation of combinatorial auctions. It would be interesting to characterize the class of combinatorial auctions that have credible implementation without cryptographic assumptions. Then investigate how the techniques developed for single-item auctions can expand the design space of multi-item credible auctions.

Blockchain Transaction Fee Mechanisms.

Designing robust applications on the blockchain is challenging because block space is limited. Whenever there is a high demand for blockchain access, we must allocate block space to a subset of users. We cannot hope that all users have access to the blockchain, but we can maximize social welfare by awarding blockchain access to those willing to pay the highest transaction fees. Guarantees that transaction fee mechanisms are easy to participate in, are robust to manipulation, and have predictable outcomes are the first steps towards having robust systems in the blockchain.

Traditionally, blockchains have credibility as a first-order constraint when designing their transaction fee mechanism. For that reason, all blockchains use first-price auctions instead of second-price auctions since miners cannot be trusted to implement the auction honestly. That is, miners can easily extract higher revenue from second-price auctions by submitting fake transactions. However, user experience is also becoming a first-order concern in the blockchain community. The complexity of optimizing bids and clearing price volatility in first-price auctions have pushed the agenda of redesigning the transaction fee market [Rou20, Yao].

Blockchain mechanisms can only access and process data included in blocks. Since block space is scarce, any practical blockchain mechanism must be communication efficient. Transaction fee auctions are not different and have the first-order constraint of requiring minimum communication between users and the blockchain. *My previous research on credible, strategyproof auctions [FW20a] is a first step towards addressing this question*. Still, my solution would require all bidders to communicate twice with the blockchain, which is prohibitively expensive.

As future research directions, we can leverage blockchain decentralization. Traditionally, the main challenge of designing credible auctions comes from the fact the auctioneer can mischaracterize all interactions with bidders. But in blockchains, the consensus algorithm selects a random miner to be the auctioneer in each round. Thus, we can exploit decentralization to construct dynamic mechanisms that are robust to manipulation.

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