Algorithms today are increasingly entrusted with decisions that have tangible impacts on peoples' lives. Take, for example, an online platform whose design impacts which workers can discover which jobs, or an insurance policy that determines where patients can receive treatment and how much doctors will be reimbursed. With real stakes on the line, workers, doctors, and patients will game these systems to improve their outcomes if they can. The field of *algorithmic mechanism design* uses the tools of game theory to design *mechanisms*: algorithms that guarantee that *even when the participants act in their own self-interest*, the algorithm's objectives (e.g. a high number of successful worker-job or patient-treatment matches) are achieved.

My work solves problems at the intersection of theoretical computer science, economics and game theory. My doctoral research has focused on the challenging problem of designing revenue-maximizing auctions. In the future, I will focus my efforts on developing the mathematical foundations of *mechanism design for social good*.

Past Accomplishments

Revenue Maximization. Consider an auctioneer selling m items to n potential buyers, and suppose that the auctioneer has precise knowledge of the distribution from which each buyer's values for items are drawn. What is the optimal auction that the seller can devise to maximize revenue? Unfortunately, despite decades of research on this problem, we are still far from a complete resolution to this question. In fact, a complete characterization of the optimal auction for selling just two items optimally to a single bidder is still not known!

My work addresses problems in revenue maximization by examining models that incorporate the uncertainty and specific constraints that mechanisms face in practice. Studying mechanism design in these settings advances our understanding of real-world scenarios while skirting the intractability of the problem in its full generality.

Interdimensional Mechanism Design: Previous work in revenue maximization depicts a rigid dichotomy between two types of settings. On one hand, we have single-dimensional settings (e.g. single-item auctions), which are completely characterized by a simple closed-form theory [37]. On the other, we have "multi-dimensional" settings (e.g. heterogenous items), where optimal mechanisms are chaotic and often intractable [16]. My work [17, 25] identifies a space that is fundamentally different from both extremes, lying somewhere on the spectrum in between.

In the "FedEx" setting, a customer arrives wanting to ship a package. The customer has a deadline for the package's receipt that is i days from now. If the package arrives on time, it is worth a value of v to the customer, and if it arrives late, it is worth nothing. The customer's private (v, i) pair is drawn from a (correlated) prior distribution F which is known to FedEx. The question is: how should FedEx sell 1-day, 2-day, and up to n-day shipping in order to maximize their revenue? In [25], we characterize the optimal mechanism for the "FedEx" setting, showing formally that it is simpler than optimal mechanisms for even the simplest multi-dimensional setting, yet far more complex than any single-dimensional setting. In subsequent work [17], my co-authors and I generalize the "FedEx" setting to show that this class of problems contains many other natural settings which continue to lie fundamentally in between single- and multi-dimensional settings with respect to menu-complexity, sample-complexity, and other metrics.

The key technical approach is to use a primal-dual method; the main challenge is finding the optimal dual variables. To this end, we first show how to solve the problem when the relevant structures satisfy a certain concavity condition. To handle the general case, we have extended Myerson's "ironing" [37], a randomization technique that enables us to artificially impose concavity.

Behavioral and Informational Assumptions: The standard auction design model is idealized in an unrealistic way, e.g., it assumes that buyers are perfectively rational and risk-neutral. Simplifying assumptions about behavior or information can make it easier to prove a theorem, but in order to have impact, it is important to study settings that are more accurate. My work relaxes these assumptions and overcomes the challenges that arise as a result.

In [12], we study buyers who are "uncertainty averse," i.e. are willing to pay a premium for outcomes that occur with higher certainty. We show that in both one-stage and two-stage settings, with detailed knowledge of a buyer's risk-attitude, we can construct a mechanism that guarantees a constant-fraction of the optimal revenue; however, without precise knowledge, we prove that it is impossible in the two-stage setting to obtain any constant-factor approximation, even if the buyer's risk is bounded. In [23], buyers are "interdependent," i.e. have valuations that depend on the private information of others, a characteristic of any market where an object has resale value. Our goal is to give a single item to the highest-valued bidder; the difficulty here is that one buyer can manipulate the information he reports and thus impact which of the buyers is believed to be highest-valued. We construct a $\sqrt{nc^3}$-approximation to welfare for n buyers whose valuations satisfy a natural relaxed "single-crossing" condition with parameter c. In [9], buyers have "proportional complementarities," i.e. have known correlations for the buyer's boost from getting any bundle of items. We leverage these boosts, showing that the better of (1) selling one bundle of all of the items and (2) randomly giving some items away for free and selling the rest at inflated prices earns a constant-fraction of the optimal revenue. In [28], the designer does not have information about the prior distributions of buyer values, but we use the other buyers in the market to determine a price that is likely to be good, guaranteeing a constant-factor approximation to revenue.

Mechanism Design for Social Good. My inspiration to pursue social good domains originated two years ago from seeing Cynthia Dwork's talk "Theory for Society" [22] which discussed her work founding differential privacy and formalizing algorithmic fairness. In response, I launched a new direction of interdisciplinary research: Mechanism Design for Social Good. I co-founded and co-organized a small reading group [1] where we explored a number of interesting domains: low-income housing, healthcare, education, online labor markets, and more. The group garnered a lot of interest across disciplines, and has grown into a community itself. Today, the community connects researchers, domain experts, and non-profits with problems and facilitates the dissemination of resources to a community of 100+ people. I co-founded and co-chaired the first two iterations of now-annual Mechanism Design for Social Good workshop [2] at the ACM EC conference, which both times featured keynote talks from domain experts and approximately 10 talks and 20 posters of contributed research. In addition, I was invited to speak at WINE 2017, where I delivered a 90 minute tutorial on accessible open directions in Mechanism Design for Social Good [27].

I also have begun my own research in this direction. With Nicole Immorlica and Brendan Lucier, I am designing mechanisms that trade off carbon pollution with economic growth, in the setting where strategic firms emit pollution when producing the goods they sell. In forthcoming work, we have demonstrated the strength of a simple cap-and-price mechanism in the face of uncertainty.

Research Objectives, Methods, and Significance

Healthcare. In 2016, the U.S. spent 3.3 trillion dollars on healthcare, an average of $10,348 per person [26]. Yet in 15 of the largest cities, the wait time for a new patient to see a physician averages 24 days [32]. On top of that, payment structures incentivize doctors to recommend unnecessary medical tests and treatments [8, 40], costing $200 billion annually, and "generating mistakes and injuries believed to cause 30,000 deaths each year" [38]. I propose to address these issues by designing better mechanisms for aligning patient, doctor, insurer, and government incentives. Below are two such examples, but I also plan to opportunistically work on other issues in healthcare that I believe will benefit from mathematical formality and rigorous analysis.

Money Burning. Consider a set of Medicaid patients who each need to receive a medical procedure, the cost of which will be covered by the government. Each patient has some preference over the available hospitals, perhaps based on location or doctor preference. If the patients were allowed to select their favorite hospitals, then certain hospitals would be over-demanded. Clearly, a limited supply of resources means that more urgent needs should be prioritized. However, if a patient's needs are self-reported, he or she might be incentivized to exaggerate in order to receive better or more prompt treatment.

When need is self-reported, Nobel-prize winning work in economics [14, 29, 52] shows that by charging money for services, we can guarantee the most efficient allocation of resources, and prevent patients from manipulating the outcome by misreporting their need. However, in the context of providing healthcare to Medicaid (impoverished) or Medicare (elderly) patients, payments by the patients are either undesirable or infeasible. Instead, Medicaid could charge "payments" in the form of wait times or reduced quality of care. In the economics literature, mechanisms that extract such "payments" are called *money burning mechanisms*, because the payments provide no value to anyone, and thus are essentially "burnt." The goal in money burning mechanism design is to maximize the sum of the true utilities of the agents (i.e., the value they receive from the treatments allocated to them minus the money burnt, e.g., the time spent waiting for service), subject to the constraints that the agents are incentivized to truthfully report their needs, and that the budget constraints of the payer (e.g., the government) are met.

There has been a limited amount of prior work on money burning mechanisms: Hartline and sponsoring scientist Roughgarden [30] studied money burning in the single-dimensional setting, e.g. where there is a single indivisible resource available to be allocated among a set of competing agents. In that setting, they developed a theory of optimal money-burning mechanisms parallel to Myerson's Nobel-prize winning theory [37] for revenue maximization. Other work [7] studies the patient-hospital matching setting exactly when restricted by a budget for total treatment cost, but again in the single-dimensional setting. However, the multi-parameter version (where there are many different kinds of resources to allocate) is very different from the objectives that have been studied so far and is thus still wide open. I am beginning to study it with collaborators Alon Eden, Anna Karlin, and Matt Weinberg.

Question 1. *What mechanisms are optimal or simple-but-approximately-optimal for the money-burning objective in multi-parameter settings?*

I plan to leverage my expertise in multi-parameter revenue maximization, in addition to some of the great technical successes in the field in the last ten years [3, 10, 11, 13, 24, 25] (e.g., Lagrangian duality, ex-ante relaxation, and prophet inequalities), to build a theory of approximately-optimal multi-parameter money burning mechanisms, ideally simple enough to be used in practice.

Payment Contracts for Medical Care. One current topic of debate is how doctors should be paid for the medical care they give. Currently, most contracts are "fee-for-service," which pays doctors according to each service they administer. This causes frequent *upcoding*—exaggerated diagnoses, excessive testing, and over-treatment—with the goal of increasing payments. To compensate, there has been a recent push for "pay-for-performance" contracts, which would pay doctors for the health outcomes of their patient instead of each treatment. However, this method may not adequately cover costs when more extensive treatments are needed to obtain the same outcome, or may incentivize doctors to avoid treating sicker patients. Surprisingly, little formal analysis has been done from a game-theoretic or computational perspective on this question (exceptions include [4, 5]). One approach would be to design simple contracts with near-optimal guarantees. Recent work by sponsoring scientist Roughgarden and others initiates the study of simple vs. optimal contracts [20], and similar tools seem promising for this more specific domain.

Question 2. *To maximize patient health minus cost of treatment, what are optimal and approximately optimal contracts for medical care? How do fee-for-service and pay-for-performance compare? How do we mitigate upcoding?*

Online Labor Markets. Online matching platforms that match users on one side to opportunities or users on the other side are ubiquitous today, and are thus a natural candidate for mechanism design with a social good objective. One interesting example is online labor markets, such as Upwork or Task Rabbit, where workers form one side of the platform, and employers or jobs form the other side. In these platforms, there are several key questions to address. What does it mean to make good matches? How should a platform go about eliciting, aggregating, and displaying information? How can the platform's choices improve societal welfare, or unintentionally cause social harm? And, how can we build on the rich literature in mechanism design and algorithmic game theory to effect real change? I plan to investigate several of these and other questions. Below are just two examples of the many related projects that I will pursue.

Discrimination. In online labor markets, one of the trickiest platform design questions is how to facilitate search so as to ensure high quality employer-worker matches. The problem is that the set of potential matches (e.g., employees to hire) is so large that it is infeasible for an employer to explore all of the possibilities and then pick the best one—it is simply too costly. To remedy this, platforms make design decisions that affect the order in which options are considered and the information available about each option. One of the most consequential aspects of these decisions is the extent to which they mitigate or exacerbate various types of discrimination, or increase opportunities for members of historically disadvantaged populations.

For instance, in any platform that uses employer reviews to determine whether workers may continue to participate in the market, discriminatory reviews could effectively prevent a worker from being allowed to work. As another example, the platform could choose to hide information, such as ethnicity, in order to prevent employers from using this attribute to discriminate. However, this may have unintended consequences, e.g., a different form of discrimination by proxy [19].

This issue raises a variety of interesting and important questions: What attributes of potential employees should be exposed and when? What sorts of interactions between employers and job applicants should be encouraged or disallowed, and how should these evolve over time? What incentives can be provided to employers to broaden their search, or to consider applicants with less experience? Can the platform regulate hiring policies by making sure that applicants are presented in a group-aware or group-blind way? Should the platform exclude employers that don't offer a certain minimum wage?

Question 3. *What unifying theoretical model captures a multitude of online labor markets? Under what settings do various platform decisions, such as those listed above, perpetuate or mitigate discrimination? How can presentation design increase opportunity for all?*

This may not appear on first glance to be a mathematical problem, but my goal is to translate these social concepts into mathematical notions that we can attack formally. In recent years, this has been done in computer science and machine learning for privacy [21] and fairness [34], now foundational concepts. I hope to do for discrimination what these communities have been able to do for privacy and fairness.

Gains From Trade. Of course, a matching platform's job is to form matches, so the most fundamental question is: how should the platform best form matches? One common notion of "good matches" is the *gains from trade* objective: the value gained by an employer minus the working cost incurred by the worker.

A natural approach is to try to apply techniques from the revenue setting. However, in the revenue setting, the auction designer owns all of the items, whereas in the platform setting, the items (labor) are owned by strategic individuals. Extending mechanisms from the revenue setting so that they additionally align incentives for strategic workers would enable a reduction from (approximate) gains from trade to (approximate) revenue and let us build on 10+ years of brilliant results. In ongoing work with Yang Cai, Anna Karlin, and Mingfei Zhao, we study this question.

Question 4. *How can we reduce the problem of maximizing gains from trade in a two-sided matching market to that of maximizing revenue in a one-sided market?*

Justification of Sponsoring Scientist, Institution, Career Impact

Sponsoring Scientist Tim Roughgarden won the 2012 Gödel-prize for laying the foundations of the field of algorithmic game theory. He has written two of the popular textbooks on algorithmic game theory and mechanism design [39, 45], and his lectures are a go-to resource for new researchers interested in the area. Roughgarden has pioneered numerous research areas: selfish routing [41], price of anarchy of simple mechanisms [48], and smoothness in games [44]. He also initiated the directions of simple mechanisms [31, 43], prior-independence and prior-free [6, 18, 49, 50], and learning from samples [15, 33, 35, 36, 47, 51]. Much of his work focuses on computability and formulating more realistic guarantees than the absolute worst-case [42, 46], all of which are important to bring theory into practice. He would be the best possible mentor to guide me as I embark on a new direction within my research community.

Columbia University is also home to several other researchers whose interests intersect with mine. This includes Christos Papadimitriou, co-Gödel-prize winner for algorithmic game theory with Roughgarden, as well as Yash Kanoria and Nick Arnosti, experts in matching markets from the Operations Research department. Also nearby is: Microsoft Research New York, with numerous experts—Nicole Immorlica, Jenn Wortman-Vaughan, Solon Barocas, and more—in the intersection of algorithms and discrimination; New York University, with online labor market expert John Horton; and Princeton University, where collaborators Matt Weinberg and Mark Braverman are working on problems in healthcare. I already have relationships with all of these researchers, and most are also engaged in the Mechanism Design for Social Good group or workshop.

My career goal is to take my expertise in and passion for mechanism design and to transfer it to have real impact. This is an ambitious agenda, but I have already begun the process. Being in such a supportive environment with a mentor who has successfully pioneered new areas, as well as having domain experts to collaborate with, will enable this to happen. This will allow me to become the impactful theoretical researcher that I am aiming to be.

Broader Impacts

The proposed research is motivated by and focused on broader societal impact in the realm of healthcare and online labor markets. My research goals include collaboration with practitioners to ensure that the theory is useful to those who might implement it.

Like all researchers in my area, I publish articles, disseminate work through talks at conferences and seminars, and make my work available through arXiv and my website. Beyond this, I organized the Mechanism Design for Social Good (MD4SG) group, two MD4SG workshops, delivered two different 90-minute tutorials at EC and WINE, and have written articles for academic special interest group newsletters *Sigecom Exchanges* and *AI Matters*. I plan to continue engaging in these and similar activities. For example, I am beginning to prepare a survey on the topic of Menu Complexity for *Sigecom Exchanges*. During my postdoctoral work, I aim to write a survey on Mechanism Design for Social Good, and to lay the foundations for a future course on the topic.

Further, I am committed to increasing the participation of underrepresented groups in computer science and mathematical fields. Throughout undergraduate and graduate study, I have been very involved in women in computing and math organizations, frequently serving as founder and co-chair of initiatives, including programs to mentor junior women. For these efforts and others, I was awarded the 2016 Google Anita Borg Memorial Scholarship. I also secured grants for the MD4SG workshops to bring researchers who otherwise would not be able to attend the workshop; the group was 41% women, 47% people of color, and included three students from African nations. During my postdoctoral fellowship, I will continue to work toward equal encouragement and access to STEM fields for all. I plan to participate in women-in-computing activities at Columbia, to mentor junior students, and to use my position and energy to advocate for members of underrepresented groups.