My research spans multiple areas in theoretical computer science including algorithmic game theory, approximation algorithms, optimization, and online algorithms. I apply and extend techniques from these areas to address theoretical problems that capture real-world applications. For example, my work in algorithmic game theory explores formal connections between theoretical models and empirical data. Another example is my dissertation research in which I designed approximation algorithms for a number of graph-theoretic problems that apply to data networks and interconnected systems. This document presents an overview of the work I have done and highlights my future research plans.

Approximation and Optimization in Game-Theoretic Settings

My current research interests lie in algorithmic game theory. Results in this field use theoretical models and solution concepts, like equilibria, to understand and predict the behavior of self-interested entities such as human players and organizations run by human agents. These solution concepts are central game-theoretic constructs, and questions related to their complexity have been a driving force behind research in algorithmic game theory. Over the last decade, significant progress has been made on these topics, and the basic message that has emerged is negative: determining solution concepts in economic models is, in general, computationally hard. Still, the design and analysis of game-theoretic models require algorithmic tools to determine the underlying solution concepts. Specifically, since equilibria model likely or stable outcomes, in many strategic settings we need to algorithmically determine equilibria in order to understand/predict the outcome of design decisions and economic policies. My research in this area is motivated by these considerations, and aims to develop positive results that address complexity barriers in game-theoretic settings. This research program entails two complementary directions and, in particular, focuses on Nash equilibria, which are one of the most well-studied solution concepts in game theory.

(i) Approximating Equilibria: To address the hardness results for Nash equilibria, a natural approach is to consider computation of approximate Nash equilibrium. In fact, determining whether approximate Nash equilibria can be efficiently computed in two-player games is a central open question in algorithmic game theory. My recent work [1] addresses this question and, specifically, it identifies a relevant class of two-player games that admits efficient computation of approximate Nash equilibria. This work [1] entails the development of an approximate version of Carathéodory’s theorem; given the fundamental importance of Carathéodory’s theorem, this approximate version is interesting in its own right. Also, I developed the best known algorithm for computing approximate Nash equilibria in multi-player games, in joint work with Yakov Babichenko and Ron Peretz [2].

(ii) Rationalizing Equilibria: My other results in this field complement the approximation approach and are based on a perspective that is prevalent in game theory and economics, but is somewhat unconventional in computer science. The idea is that players’ payoffs, which are used in economic models to quantify the incentives of the players, are typically unobserved theoretical constructs. Even though most work in algorithmic game theory implicitly assumes that these payoffs are given as explicit input, in most strategic settings the input is, in fact, the observed behavior of players. In such contexts, economists use payoffs as tools to rationalize—i.e., explain—observed behavior, in the sense that the equilibria predicted by the payoffs should match the observed behavior. Since specific observed behavior can be potentially rationalized by different payoffs, we have some flexibility in which payoffs to use. My work in this field leverages this flexibility to obtain positive results in the context of bimatrix games. I showed that, in a number of relevant cases, observed behavior can be rationalized via payoff matrices of low rank, in joint work with Umang Bhaskar, Federico Echenique, and Adam Wierman [3]. Computing a Nash equilibrium under general payoff matrices is a computationally hard task, but the problem becomes tractable

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1Intuitively, an equilibrium denotes a distribution over the strategies of the players at which no player can benefit, in expectation, by unilateral deviation.

2A Nash equilibrium is an equilibrium that is defined to be a product of independent distributions, one of every player.

3An $\varepsilon$-approximate equilibrium, where $\varepsilon > 0$, is a distribution over the strategies of the players at which no player has more than an $\varepsilon$ incentive to deviate.

4Such games represent strategic settings in which two self-interested players select actions to maximize their own payoffs. The payoffs of the two players is specified by two matrices.
when the payoff matrices have low rank. Therefore, these results show that, in many relevant cases, observed behavior can be rationalized by tractable model instances that admit efficient computation of equilibria. I have established similar results for the case in which players use deterministic strategies, i.e., the pure Nash equilibria case [4].

Future work: My research on approximating and rationalizing equilibria initiates a number of interesting avenues for future work. Below I present specific examples of such problems that I plan to explore in depth.

Along the lines of my work on Nash equilibria, I plan on addressing hardness results for other solution concepts, which appear in settings like markets and auctions. Since computation of equilibria (and other solution concepts) can be formulated as a mathematical program, my overarching goal is to study algorithms for mathematical programs with equilibrium constraints. Specifically, it is appealing to understand if particular properties of such programs can be leveraged to efficiently approximate the underlying solution concepts.

In the context of bimatrix games, my work shows that we can efficiently determine payoffs that rationalize the observed behavior, or assert that the behavior cannot be rationalized. Determining the unobserved parameters of the model from empirical data is an important task in many settings. I plan to address these settings and approach this inference task by considering cases in which it can be formulated as a tractable optimization problem. More broadly, I will consider if tools from computational and statistical learning theory can be used to infer the unobserved parameters of the model. Another question that I intend to explore is whether we can design experiments or induce settings so that the obtained empirical data admits efficient inference of the unobserved parameters. This question is especially relevant in situations where data collection is costly.

Overall, my goal is to develop a structural understanding of algorithmic game theory. The objective is to identify classes of games that are both tractable, i.e., admit efficient computation of exact or approximate equilibria, and expressive, i.e., are able to rationalize large classes of empirical data.

**Discrete Optimization in Computational Systems**

Beyond algorithmic game theory, I am interested in approximation algorithms, optimization, and online algorithms. The ideas and techniques that I have acquired in these fields significantly influence my approach to research. A common thread tying my work in these areas is an algorithmic study of optimization problems that arise in computational systems such as data networks. My current research results and future plans are described below.

**Approximation Algorithms for Data Networks:** Data networks are fundamentally different from networks that carry physical flow—data, unlike physical objects, can be easily replicated, compressed, and combined. Hence, classical network optimization models (which were initially formulated to represent flow of physical objects) have considerable limitations when it comes to representing flow of data. In order to address optimization in data networks, my research in this area focusses on extending classical network optimization models and developing approximation algorithms for such generalizations.

I have considered a framework in which the links of the network can remove duplicate data packets, in joint work with Shuchi Chawla and Seeun Umboh, see [5] and [6]. In comparison to classical flow models, our framework is more representative of data flow, especially in systems like content-aware networks. Within this new framework, we develop a constant factor approximations for instances where the packet sets of the routing terminals form a laminar set family. In addition, we obtain a logarithmic approximation for particular hierarchical set families in uniform networks. Within this framework we also studied a facility location problem with laminar packet sets. For this problem, we developed a multi-phase algorithm that rounds a linear program and achieves a constant approximation ratio. Overall, our framework presents an expressive and algorithmically interesting class of problems, since it models data flow and still maintains the tractable nature of commodity (physical-flow carrying) network design.

A fundamental question in combinatorial optimization is to find a low-cost cut which disconnects a weighted graph. A natural generalization of finding small cuts is to determine a low-cost set of edges/nodes whose removal reduces the connectivity of the graph to below a certain threshold (not necessarily zero). This generalization is called the multi-route cut problem and it arises in the context of networks reliability. I proposed a new linear programming formulation for this problem, in collaboration with Shuchi Chawla [7]. Using this, we generalized a cut-finding technique (region growing) that led to approximation algorithms for several variants. This work also presents the first non-trivial bi-criteria, with respect to cost and connectivity, approximation for this problem.
Approximation Algorithms for Classification: Problems involving classification and labeling of interconnected objects arise in many contexts such as machine learning and computational biology. A common instance is one where we are given a partial labeling of a set of items along with a neighborhood structure over them and the objective is to complete the labeling in the most consistent way possible. These problems naturally translate into a graph-theoretic setting. Specifically, we can formulate labeling problems in terms of packing cuts in a graph. I considered the multiway cut packing problem in joint work with Shuchi Chawla [8]. The problem is NP-hard and we developed a constant-factor approximation algorithm for it. Our work shows that every instance of the problem admits a near-optimal fractional solution in which no pair of cuts cross and uses this insight to develop a rounding algorithm. When all of the multiway instances consist of exactly two terminals and they share a common sink, we obtained an approximate solution with cost at most one more than the optimal. Since this special case is also NP-hard we achieve the best possible approximation for it unless \( P = NP \).

Convex Optimization: Scalable and efficient algorithms for error correction are necessary in many communication systems. In certain signal to noise ratio environments, linear programming based decoding algorithms are able to correct more errors than conventional belief-propagation methods, but with standard LP solvers these algorithms do not scale up. Instead of relying on standard solvers, I employed distributed optimization techniques to develop a scalable algorithm that solves the decoding linear program for a family of codes (LDPC), in joint work with Stark Draper, Xishuo Liu, and Ben Recht [9]. Our key technical contribution is a quasilinear-time Euclidean-projection algorithm which serves as a subroutine in the decoding method and is of independent interest. We also show that the algorithm is empirically successful and can lead to real-world decoding systems.

Online Algorithms: Numerous real-world systems, like data centers and electricity grids, require online resource allocations and real time decisions. Typically the algorithmic issues faced by such systems are studied using online algorithms. Since efficiency in such online systems is a relevant concern, my work in this area has focused on developing online algorithms that obtain tight approximate solutions and exploring the performance limits inherent to online settings.

I studied the relationship between two central performance metrics that are used to evaluate online algorithms: regret and competitive ratio; in joint work with Katrina Ligett, Minghong Lin, Adam Wierman, and others [10]. For a general class of online optimization problems we show that these metrics are incompatible. That is, even though there exist algorithms which independently achieve low regret or constant competitive ratios, no algorithm (deterministic or randomized) can simultaneously achieve low regret and a constant competitive ratio.

Classically, online decision rules have been studied in the framework of secretary problems. Here candidates arrive in a random order and the goal is to select the best candidate for a secretary position. The challenge lies in the fact that irrevocable select or reject decisions must be made once the candidate arrives. I considered a generalization of the secretary problem where more than one candidate can be selected and the objective is to maximize profit, the value of the selected set minus its cost. This is joint work with Shuchi Chawla, David Malec, and Seeun Umboh [11], and we considered the problem under various feasibility constraints. Our work presents online algorithms with expected approximation factors within a constant times the factors known in the absence of costs. The generalization models complex tradeoffs faced by real-world resource allocation environments like cloud computing and wireless spectrum allocation, where the server incurs a cost based on the total size of the allocated requests.

In joint work with Yeye He and Jeffrey Naughton [12], I considered online algorithms in the context of complex event processing (CEP) systems. CEP systems are deployed to monitor and report specified patterns in continuous event streams. While the CEP model has gained popularity in research communities and commercial technologies, the problem of gracefully degrading performance under heavy load in the presence of resource constraints, or load shedding, has been largely overlooked. In this work we construct shedding algorithms with performance guarantees and supplement them with inapproximability results. I have also worked on approximation techniques for preserving privacy in CEP systems, in joint work with Yeye He, Jeffrey Naughton, and Di Wang [13]. An application addressed by this work is an RFID based monitoring system in a hospital which tracks and reminds health-care workers of hygiene compliances. There are direct privacy implications of such a reporting system, for instance, an eavesdropper might be able to infer private information from reported patterns. To enforce privacy we can suppress some events at the cost of some utility. We showed that in general it is hard to approximate, within a non-trivial factor, a privacy-preserving suppression method that achieves optimum utility. Complementing this result, we proved that under some natural
assumptions we can obtain much better approximations. The work initiates a formal study of privacy in CEP systems and sheds light on the practical issues which CEP systems must tackle to enforce privacy.

**Other Results:** Among other research projects, I have studied privacy implications of dynamic data-publishing schemes in joint work with Yeye He and Jeffrey Naughton [14]. Our work presents sufficient conditions that ensure updates of census data, or statistical databases, preserve privacy. I have also developed approximation algorithms for membership testing of strings in a large corpus of text data, in joint work with Chong Sun and Jeffrey Naughton [15].

Another example of my work in approximation algorithms is the result I have on the reordering buffer problem, in joint work with Shuchi Chawla and Seeun Umboh [16]. This problem provides a unified model for studying scheduling with limited buffer capacity and, hence, arise in applications like storage systems and job shops. We develop a bi-criteria approximation for this problem that achieves a logarithmic approximation in cost while using no more than a constant times the specified buffer capacity.

My work in algorithmic game theory also includes lower bounds for determining equilibria. In joint work with Yakov Babichenko [17], I consider a framework in which an underlying game is specified via a black box that returns players’ payoffs at action profiles. For such a querying model, we establish that the number of queries required by any deterministic algorithm in order to compute a correlated equilibrium is exponential in the number of players. This result address an open question posed by Sergiu Hart.

**Future work:** I continue to work on relevant optimization problems raised by my prior work on approximation algorithms. Below I present specific examples of such problems along with promising solution strategies and my long-term goals.

I am excited to continue my research on redundancy-aware network design. An immediate goal is to generalize the result to address inputs in which the packets sets have arbitrary intersections. My experience tells me that near optimal solutions of such a generalization may have structural properties that can potentially lead to stronger linear-programming formulation. Often, a stronger formulation is amenable to rounding and leads to better approximation guarantees. Furthermore, I intend to extend this framework to allow the edges of the network to not just remove duplicates but also combine similar data packets. This can be formally modeled, say, by considering the load on an edge to be a submodular function of the packets that use it.

In the long run, I would like to continue on this path and build upon my current work to develop algorithms for multi-instance optimization problems. In computational systems, we often need a solution which is robust to change in inputs. One way to model this is by considering multiple input instances and determining a low-cost solution that is feasible for each input individually. My work on redundancy-aware network design and cut packing are examples of this multi-instance framework. I plan to explore general algorithmic techniques for multi-instance optimization problems. A concrete target, in this direction, is the virtual private network design problem with multiple demand matrices: Given a set of traffic matrices we are required to install capacity on edges such that the constructed subgraph has a low cost and can support any one of the demand matrices. Previous work solves this for a highly structured set of traffic matrices, but I wish to consider this for general input instances. Furthermore, I would like to understand specific conditions under which we can transform an algorithm for a single-instance problem into an algorithm, with comparable performance, for the multi-instance version.

Through the years I have realized that research is a highly creative activity and requires effective collaboration not only among researchers in an area but also with members of other fields. I look forward to expanding my group of collaborators and applying my research in other areas. Research is a continual and meaningful endeavor, and in this pursuit I anticipate an exciting journey ahead of me.
References


