Better Markets via Data and Large-Scale Optimization

Research Statement

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Dynamic systems with strategic agents shape society. One pervasive example is markets: goods are sourced through traditional and combinatorial auctions, organs are allocated through barter exchanges, students are assigned to schools through matching markets, and liquid assets are exchanged in international financial markets. Recent work in *market design* makes strides toward the *principled and practical* organization of markets. I have shown that techniques from computer science and operations research, combined with the recent availability of massive data and cheap computing, can *inform* the design of markets, *augment* these theoretical models when it comes time to field the system, and *enable* the markets by running them in the real world.

I work at the intersection of artificial intelligence, operations research, and economics, with a focus on solving practical societal problems using stochastic optimization, mechanism design, and large-scale computation. ***My long-term research vision is to develop principled, scalable, data-driven optimization techniques to solve problems involving dynamic systems with strategic agents.*** I am particularly interested in healthcare applications, where multiple self-interested parties interact repeatedly in complex ways, both with and without monetary exchange, and with competing incentives. Events in healthcare are recorded in massive data stores from which a market designer can, and should, learn about participants and their interactions, then compute the best adjustments to the fielded system—where deciding on a definition of "best" is itself a complicated problem involving iteration between human experts and the underlying computational system determining low-level market policies. Another research goal of mine is to formalize that iterative discovery of preferences—helping an expert quantify his or her high-level objective for a system even when he or she may not completely know or understand it—in a tractable way with respect to both human effort and computational time.

I field my research in the real world; my code currently allocates kidneys nationwide, prices and schedules TV advertisements, and searches for IED weapons caches. Next, I discuss my current research in designing, building, and fielding a large barter exchange. Following this, I detail ongoing work in developing and fielding a new advertising market for cross-media and linear television, as well as my planned research agenda moving forward as a professor.

1 Thesis Research: Fielded Dynamic Kidney Exchange

The exchange of indivisible goods without money addresses a variety of constrained economic settings where a medium of exchange—such as money—is considered inappropriate. Participants are either matched directly with another participant or, in more complex domains, in barter cycles and chains with many other participants before exchanging their endowed goods. My thesis research addresses the design, analysis, and real-world fielding of dynamic matching markets and barter exchanges.

My thesis presents new mathematical models for general dynamic barter exchange that more accurately reflect reality [2, 5, 10], proves theoretical statements about the characteristics and behavior of these markets [1, 4–9, 13], and develops provably optimal market clearing algorithms for models of these markets that can be deployed in practice [7, 14]. My research shows that taking an *explicit optimization approach* to balancing efficiency and fairness can often practically circumvent negative theoretical results [10, 11].

I support my theoretical and methodological contributions with experimental validation in *kidney exchange*, an organized market where patients with end-stage renal failure swap willing but incompatible donors. With my advisor, Tuomas Sandholm (CMU), I work closely with the United Network for Organ Sharing (UNOS) nationwide kidney exchange, which includes 143 transplant centers—roughly 60% of the centers in the United States. Parts of my thesis have directly set policy at the UNOS exchange [6], while a general matching framework I built—FUTUREMATCH—is used for sensitivity analysis of new high-level matching policies [7, 8, 10]. Furthermore, ***our code is in production as the matching engine at the UNOS exchange***; the first match run was in Oct. 2010, and it currently matches—completely autonomously—twice per week.

My work focuses on three competing dimensions found in both matching markets and barter exchange: uncertainty over the viability of possible trades, balancing efficiency and fairness, and inherent market dynamics.

Uncertainty over the viability of trades

Algorithmic matches in fielded kidney exchanges do not typically result in an actual transplant. Failures occur for a variety of reasons, including failure of the *crossmatch*, a temporally-sensitive medical compatibility test between patient and donor. In work with Ariel Procaccia (CMU) and Tuomas Sandholm [6, 7], and later also with Avrim Blum (CMU), Nika Haghtalab (CMU), and Ankit Sharma (Google) [1], we addressed the problem of cyclic swaps and chains of trades in proposed matches failing *after* the matching algorithm has committed to them.

We began by showing that "failure-aware" kidney exchange can significantly increase the expected number of lives saved (i) in theory, on random graph models with vertices representing agents and edges representing potential transplants; (ii) on data from the UNOS exchange; and (iii) on synthetic data generated via a model of dynamic kidney exchange. We designed a branch-and-price-based optimal clearing algorithm specifically for the probabilistic exchange clearing problem and showed that this new solver scales well on large simulated data, unlike prior clearing algorithms. Perhaps surprisingly, while the model we propose in that work is *more* general than the standard model of kidney exchange, it is empirically easier to clear due to the additional probabilistic information simplifying the pricing problem (although ongoing work [14] with my undergraduate mentee, Benjamin Plaut (CMU), and Tuomas Sandholm may challenge this, due to improvements in the runtime of the deterministic pricing algorithm used).

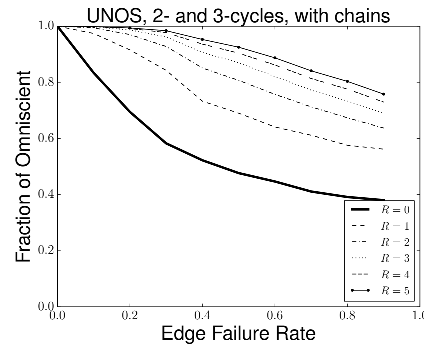

Figure 1: A small number R of edge test rounds yields substantial gains.

Then, we studied the selection of *which edges to test* by recasting the problem as stochastic k-set packing, where the goal is to find a maximum matching (for $k = 2$) or, in general, k-set packing in a graph whose edges are unknown but can be accessed by queries. We provide strong theoretical results relating the number of rounds of querying, where at each round at most one edge incident to each vertex can be tested, to the expected maximum matching or packing, with respect to the omniscient solution. Querying can be done adaptively—with knowledge of the (non)existence of previously queried edges—or non-adaptively.

We applied adaptations of these algorithms to realistic data from the UNOS exchange and found that even a very small number of non-adaptive edge queries per vertex results in large gains in expected successful matches (shown in Figure 1, for $R = 0$ to 5 rounds of testing). This is particularly exciting because the techniques we describe are easy to explain in accessible language—"just do one or two more tests per patient"—and only involve mild changes to the status quo matching policies in fielded kidney exchange. We are currently working to put this into practice. *Appeared at AAMAS-2012, EC-2013 (now under review at a journal) and EC-2015.*

Balancing efficiency and fairness

Fielded kidney exchanges typically match under utilitarian or near-utilitarian rules; this approach marginalizes certain classes of patients. In published and ongoing work with Ariel Procaccia and Tuomas Sandholm [8], we focus on improving access to kidneys for highly-sensitized, or hard-to-match, patients. Toward this end, we formally adapted a recently-introduced measure of the tradeoff between fairness and efficiency—the *price of fairness*—to the standard kidney exchange model. We showed that the price of fairness in the standard theoretical model is small. We then introduced two natural definitions of fairness and empirically explored the tradeoff between matching more hard-to-match patients and the overall utility of a utilitarian matching, on real data and simulated data from each of the standard kidney exchange distributions. While the price of fairness can be high (i.e., bad) in practice, careful automated selection of the matching policy in the right model of kidney exchange can alleviate this efficiency loss (to some extent), which I discuss later in this section. *Appeared at AAMAS-2014, now invited submission at Artificial Intelligence Journal.*

Dynamic arrival and departure

In many dynamic matching applications—especially high-stakes ones like kidney exchange—the competitive ratios of prior-free online algorithms are unacceptably poor. The algorithm should take distributional information about possible futures into account in deciding what action to take now. This is typically done by drawing sample trajectories of possible futures at each time period, but may require a prohibitively large number of trajectories or prohibitive memory and/or computation to decide what action to take. Instead, in work with Ariel Procaccia and Tuomas Sandholm [5], we proposed to learn *potentials* of elements (e.g., vertices or sets of edges) of the current problem. Then, at run time, we simply run an offline matching algorithm at each time period, but subtracting out in the objective the potentials of the elements used up in the matching.

Interestingly, this relatively simple idea performs quite well in the dynamic kidney exchange domain, where patients and donors arrive and depart over time, and individual participants' internal states also change. We theoretically compared the power of using potentials on increasingly large elements: vertices (patient-donor pairs), edges

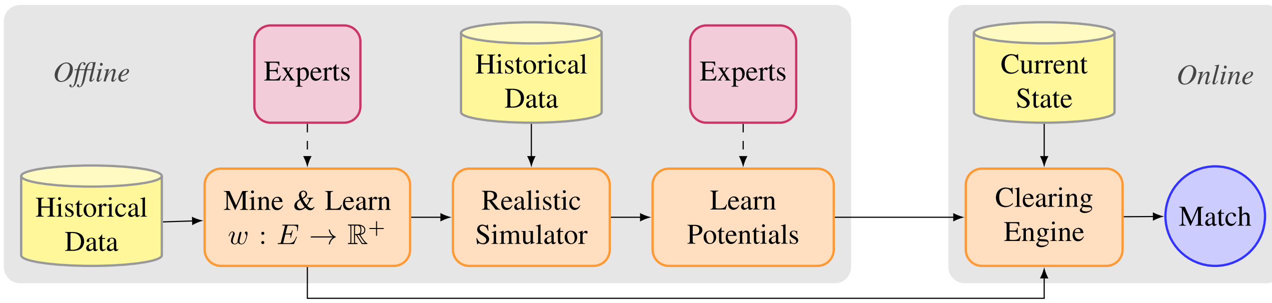

Figure 2: The FUTUREMATCH framework takes human input and prior data to form a concrete quantitative objective, performs heavy but infrequent offline computation to learn an optimal matching policy, then executes quickly online.

(transplants), cycles (complete swaps), and the entire graph (optimum). Then, experiments showed that by learning vertex potentials, our algorithm matches more patients than clearing myopically—and that the algorithm scales to exchanges orders of magnitude beyond those handled by prior dynamic clearing algorithms.

In ongoing work with Sanmay Das (WUSTL), Zhuoshu Li (WUSTL), and Tuomas Sandholm [2], we analyze the social cost of *multiple* exchanges with overlapping pools of agents who arrive and depart over time. Agents can strategically choose an exchange—or multiple exchanges—to join, while exchanges can compete on matching policies. This mimics many real-world market settings (including kidney exchange), where multiple clearinghouses exist and share participants. *Appeared at AAAI-2012 and AMMA-2015.*

Automatically generating a matching policy

My work with Tuomas Sandholm [10] combines all of the dimensions above, along with high-level human-provided guidance, into a unified framework for learning to match in a general dynamic model. This framework, coined FUTUREMATCH and shown in Figure 2, takes as input a high-level objective (e.g., "maximize graft survival of transplants over time" in the case of kidney exchange) decided on by experts, then automatically (i) learns based on data how to make this objective concrete and (ii) learns the "means" to accomplish this goal—a task that humans handle poorly. I validated FUTUREMATCH on UNOS exchange data; critically, on very realistic simulations, dynamic matching in the full complexity of the model used by FUTUREMATCH can increase overall system efficiency and simultaneously increase the expected number of transplants to *highly-sensitized* patients. FUTUREMATCH is now used at UNOS for policy recommendations. *Appeared at AAAI-2015. FUTUREMATCH won the HPCWire "Best Data-Intensive Application" award (presented at Supercomputing-2014, tied with IBM's Watson).*

My thesis also presents models for liver and multi-organ exchange; I show that the latter theoretically and empirically will result in greater social welfare than multiple individual exchanges, even under relatively strict equity assumptions [9]. *Appeared at AAAI-2014, now R&R at J. Artificial Intelligence Research.*

2 Industrial Application: Optimized Markets, Inc.

Concurrently with my Ph.D., with Tuomas Sandholm I am working extensively on Optimized Markets, Inc., a CMU spin-off company that is launching a new expressive marketplace for buying and selling television and cross-media advertising campaigns, deciding which campaigns to accept or reject, and mapping those campaigns to the underlying inventory of the seller. We use a variety of search, mathematical programming, and machine learning techniques to, among others: price campaigns based on thousands of underlying attributes of expected viewership and competing demand, optimize "makegood" management (payments or discounts returned to a buyer due to a partial or complete campaign failure), accept or reject campaigns dynamically, and pack campaigns into inventory in a way that honors business constraints and maximizes seller revenue.

Optimized Markets is currently in a late-stage pilot with one of the largest multi-system operators (aka "cable companies") in the US, and works with a variety of other smaller firms in the space.

3 Ongoing & Future Research

My long-term goal is to combine principled market design with new scalable, data-driven optimization techniques to create accurate—and deployable—models of dynamic systems with strategic agents. I am motivated by applications that benefit society, specifically those in healthcare. Some high-level research directions follow.

Quantifying the tradeoffs between fairness and efficiency

In many systems, especially those in healthcare and education, the tradeoffs between utilitarian and egalitarian objectives are stark. For example, in organ allocation, certain classes of patient are very difficult to match and would be underserved by efficient matching algorithms, yet prioritization could impose an untenable global cost. There is no clear "correct" balance of efficiency and fairness in most applications, but—as FUTUREMATCH shows—a mixture of (i) fundamental theory, (ii) data-driven sensitivity analysis performed in an automated and optimal planning framework, and (iii) interaction with policymakers can be used to strike a balance that is acceptable to all parties *and still benefits from optimization*. I plan to continue advancing each of the three points above through increased formalization, experimentation, and multidisciplinary interaction with policymakers.

Optimization, expressiveness, and data

With Optimized Markets, we are introducing new expressiveness constructs that are not present—or are, but honored in ad-hoc ways through handshake agreements—on both the buy- and sell-sides of an advertising market. By moving toward *principled quantitative elicitation* of participants' wants, and by explicitly representing these complexities in models, we reduce inefficiencies by better satisfying both sides of the market. Increased expressiveness begets more complex market clearing problems, which must be handled via new scalable optimization techniques. As we design new types of markets, or improve existing ones, I anticipate a similar arms race between model realism and tractability—and I will continue to create new optimization methods to handle that complexity, both through theoretical advances and adaptations to problems encountered in practice.

Fielding new markets and other systems

I am driven by taking research from idea to practice, and by using practice to inform new research ideas. I am actively involved in the creation, development, and deployment of various barter exchanges and advertising markets. Previously, my work in counterterrorism—also based on strategic analysis of multi-party systems, and decision-making by way of mathematical programming and machine learning—resulted in field tests and policy recommendations [12, 15, 16]. Moving forward, I will continue to translate my ideas into fielded systems through collaborations with government, industry, and academic groups (e.g., in medicine and public policy).

Funding. My research is and will continue to be attractive to both government and industry funding sources. Improvements in healthcare process benefit the US government; funding availability for data-driven approaches to making healthcare more efficient are likely only to increase as data availability continues to explode. My kidney exchange research is funded primarily by the government, specifically NSF grants and a three-year NDSEG graduate fellowship through the Army Research Office—as well as a Siebel Scholarship and a two-year Facebook Fellowship. My work in large-scale optimization of advertising markets is funded by the NSF through a $150,000 Small Business Innovation Research (SBIR) grant [3], a Facebook Fellowship, and the clients of Optimized Markets. Innovation in commercial markets benefits the US by increasing the competitiveness of its constituent firms; as such, my research will likely continue to garner privately- and publicly-sourced funding.

For more information and copies of published and working papers, please visit http://jpdickerson.com.

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