Research statement

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1 Introduction

My research is concerned with modeling, design and analysis of interactions between multiple self-interested parties, to achieve computational and economic objectives. While I believe it is important to tackle key theoretical problems in these fields, it is as important to make these findings practical by fielding them in real-world scenarios. In what follows, I will summarize three research themes I have been working on, all at the interface of computer science and economics.

2 Large-scale applied mechanism design

2.1 Theory and practice of water-right market design

[Background: assignment game] The seminal theory of assignment games, developed by Shapley and Shubik [7], is concerned with a centralized market situation where a set of unit-demand sellers trade with a set of unit-demand buyers. Beside the usual computational objective that the designer wants to match the buyers and sellers in a way that maximize social welfare, one also wants to ensure that the resulting matching outcome satisfies the so-called *core* constraint, i.e., no subset of buyers and sellers want to deviate from the centralized matching and trade among themselves. Shapley and Shubik shows that the two objectives can be met at the same time, by solving a single linear program. In other words, the core is non-empty in the assignment games.
[Background: water right market] A water right market, designed for the purpose of redistributing water resource among villages and towns of arid regions, can be regarded as a variant of the two-sided market described in the assignment games, where buyers and sellers have multiple-unit of demand and supply of a homogeneous divisible good. Due to practical reasons, there is a hard constraint that the trading amount between any two agents, can be either zero, meaning that there is no trade taken place between them, or above a certain predefined, minimum amount. The intuition is that, a trade in this market must be significant enough to cover its cost. The problem now, again, is to find a centralized matching that maximize social welfare and satisfy the core property at the same time.
[Our contributions] We first show that, for water right markets, the problem of finding the optimal social welfare is NP-hard and even NP-hard to approximate [5]. We come up with heuristics-based algorithms to solve the problem at practical scales (around 1000 villages) and polynomial-time algorithms when the market graphs have reasonable structures.

However, solving the computation problem alone does not say anything about incentives of the agents. In fact, when we talked to the villages and local government about our optimal matching algorithm, a major concern raised is that the price of trading is undetermined so that they are uncertain about their payoffs if they join the market.

In a follow-up work, we clarify this concern using a Shapley-Shubik style analysis [4]. We first show that the core can be empty for some water right market instances. We then come up with (adapt) the idea of $\alpha - core$ (any coalition can not benefit by α times via deviating.) and show that there always exists a pricing scheme, paired with the maximum matching (computed in the previous AAAI-16 paper), that is in $2 - core$. We also show a lower bound of $\frac{7}{6}$ for α and characterize graph structures where the exact core is nonempty. It is perhaps worth mentioning that this work is among the 3 papers that are nominated for *the best paper of AAMAS-2017*.

We test our theory on the real water market data and find that the marginal incentive to deviate in our proposed mechanism is very low (α is below 10^2). This motivates us to field our mechanism in reality. Collaborating with Hydro-engineering department of Tsinghua and Gansu Province government, we were able to field a version of our design in the ShiYang River Basin region of Gansu Province, China. Up to now, *our market has conducted over 400 hundred major transactions and a total of 25 million cubic meters of water are traded through our market.* It is remarked by the Gansu government that the good design of water right market contribute significantly to the improved efficiency of water resource allocation. Refer to the letter written by Prof. Jianshi Zhao of the Hydro-engineering department of Tsinghua, the PI of this 10-year project (`http://iiis.tsinghua.edu.cn/~kenshin/water_zhao.pdf`), for a detailed introduction of the whole project and my role in it.

2.2 Reinforcement mechanism design [IJCAI-17 early career spotlight]

Over the past decade, China has become one of the leading countries of mobile app usage, generating a huge amount of daily user impressions. To monetize the impressions, major mobile application companies have adopted some sort of economic mechanisms that allocates these impressions to interested parties (advertisers for search engines and retail sellers for e-commerce platforms) who make monetary transfers to these app companies in return. While standard economic theory provide good mechanism frameworks for these companies to begin with, they typically only work under very idealized environments, where the participants are perfectly rational, play only once, and their private information is single-dimensional, statistically known or doesn't change over time, etc. None of these assumptions hold in the practices of these nationwide mobile application settings, where players may have different levels of rationality, come to and leave the app over time, and have private information that may also change over time.

As a result, what the classic theory provides to these company is merely one mechanism in some, usually parameterized, class and all these companies still deploy a team of engineers and scientists to constantly tune and optimize within the class so as to accommodate dynamical information reflected in the huge amount of data generated by daily executions of the mechanisms. Such manual optimizations turn out to be useful in the sense that tiny improvements in a single mechanism can lead to huge revenue gain due to large scale and high execution frequency. On the other hand, they also waste costly human resources and can be erroneous and ad hoc at times. A more sophisticated procedure that can automatically incorporate dynamic information and optimize mechanism parameters should be in place.

We put forward a modeling and algorithmic framework to design and optimize mechanisms in dynamic industrial environments where a designer can make use of the data generated in the process to automatically improve future design. Our solution, coined *reinforcement mechanism design* [9], is rooted in game theory but incorporates recent AI techniques to relax nonrealistic modeling assumptions and to make automated optimization possible. We instantiate our framework

on the key application scenarios of Taobao and Baidu, two of the largest mobile app companies in China. For the Taobao case, our framework automatically designs mechanisms that allocate buyer impressions for the e-commerce website [1, 2]; for the Baidu case, our framework automatically designs dynamic advertisement auctions for the search engine [8]. Experiments show that our solutions outperform the state-of-the-art alternatives and those currently deployed, under both scenarios.

The two projects described above are acknowledged by Baidu and Taobao respectively. Refer to the letter by Baidu (`http://iiis.tsinghua.edu.cn/~kenshin/Baidu.pdf`) and the Alibaba Innovative research award by Taobao (`http://iiis.tsinghua.edu.cn/~kenshin/Alibaba.pdf`).

2.3 Other work within this category

With respect to the agenda of applied mechanism design, I have worked on several similar domains, such as *lung exchange*, where we propose the first practical mechanism implementation in the lung exchange domain [6] (This work is *among the 4 media press papers of IJCAI-15*) and we design the state-of-the-art near optimal algorithm, which is order-of-magnitude faster than those ILP based exact algorithms (cf [Dickerson et. al. EC-16]), for the kidney exchange domain [3].

3 Pragmatic mechanism design

My work in this category concentrate on studying settings where the optimal mechanisms have simple forms as well as practical solution concepts for single item auctions.

3.1 The first instance where BIC revenue is greater than DIC revenue [11]

In this work [11], we consider the problem of designing revenue-optimal auctions for selling two items and bidders valuations are independent among bidders but negatively correlated among items. Abstractly, this setting can be thought of as an instance with single-dimensional type space but multi-dimensional allocation space. Such setting has been extensively studied in the literature, but all under the assumption that the items are positively correlated. Under the positive correlation assumption, the optimal allocation rules are simple, avoiding difficulties brought by ensuring Bayesian incentive compatibility (BIC) under multi-dimensional feasibility constraints and by ensuring interim individual rationality (IIR) given the possibility that the lowest utility point may no longer be at the boundary of the type domain. However, the nice properties no longer hold when there is negative correlation among items.

In this work, we obtain the closed-form optimal auction for this setting, by directly addressing the two difficulties above. In particular, the first difficulty is that when pointwise maximizing virtual surplus under multi-dimensional feasibility (i.e., the Border feasibility), (1) neither the optimal interim allocation is trivially monotone in the virtual value, (2) nor the virtual value is monotone in the bidders type. As a result, the optimal interim allocations resulting from virtual surplus maximization no longer guarantee BIC. To address (1), we prove a generalization of Borders theorem and show that optimal interim allocation is indeed monotone in the virtual value. To address (2), we adapt Myersons ironing procedure to this setting by redefining the (ironed) virtual value as a function of the lowest utility point. The second difficulty, perhaps a more challenging one, is that the lowest utility type in general is no longer at the endpoints of the type interval. To address this difficulty, we show by construction that there exist an allocation rule and an induced

lowest utility type such that they form a solution of the virtual surplus maximization and in the meanwhile guarantees IIR.

In the single bidder case, the optimal auction consists of a randomized bundle menu and a deterministic bundle menu; while in the multiple bidder case, the optimal auction is a randomization between two extreme mechanisms. The optimal solutions of our setting can be implemented by a Bayesian IC and IR auction, however, perhaps surprisingly, the revenue of this auction cannot be achieved by any (dominant-strategy) DIC and IR auction. In other words, *we discover a setting where a Bayesian IC auction yields strictly more revenue than any IC auction, resolving an important conjecture concerning whether there exists a quasi-linear setting where the optimal revenues differ under the two different solution concepts* (There is a set of Econometrica papers discussing this conjecture. Also see the recent important paper by Yao [15] who independently proves this result for a different setting).

3.2 Optimal mechanisms with simple menus

In this work [10, 12], we consider the seller revenue-optimal mechanism design problem for the case with one buyer and two items. The buyer's valuations towards the two items are independent and additive. In this setting, designing optimal mechanism is notoriously elusive and open for general valuation distributions. We obtain two categories of structural results that partially characterize the optimal mechanisms. These results can be summarized into one conclusion: under certain conditions, the optimal mechanisms have simple menus. To our best knowledge, this is the first work on characterizing simple and *exactly* optimal mechanisms for general distributions. Previous work on the same problem tends to characterize simple and *approximately* optimal mechanisms, or to find optimal mechanisms for *specific* distributions.

The first category of results state that, under a certain condition, the optimal mechanism has a monotone menu. In other words, in the menu that represents the optimal mechanism, as payment increases, the allocation probabilities for both items increase simultaneously. This theorem complements Hart and Reny's recent result regarding the nonmonotonicity of menu and revenue in multi-item settings. Applying this theorem, we derive a version of revenue monotonicity theorem that states stochastically dominated distributions yield less revenue. Moreover, our theorem subsumes a previous result regarding sufficient conditions under which bundling is optimal [Hart and Nisan 2012].

The second category of results state that, under certain conditions, the optimal mechanisms have few menu items. Our first result in this category says that, for certain distributions, the optimal menu contains at most 4 items. The condition admits power (including uniform) density functions. Our second result in this category works for a weaker (hence more general) condition, under which the optimal menu contains at most 6 items. This condition is general enough to include a wide variety of density functions, such as exponential functions and any function whose Taylor series coefficients are nonnegative. Our last result in this category works for unit-demand setting. It states that, for uniform distributions, the optimal menu contains at most 5 items. All these results are in sharp contrast to Hart and Nisan's recent result that finite-sized menu cannot guarantee any positive fraction of optimal revenue for correlated valuation distributions.

3.3 Non-Clairvoyant Mechanisms [Working paper, R&R at Econometrica]

Despite better revenue and welfare guarantees for repeated auctions, dynamic mechanisms have not been widely adopted in practice. This is partly due to the complexity of their implementation as well as their unrealistic use of forecasting for future periods. We address these shortcomings and present a new family of dynamic mechanisms that are simple to compute and require no distribution knowledge of future periods.

This work introduces the concept of non-clairvoyance in dynamic mechanism design, which is a measure-theoretic restriction on the information that the seller is allowed to use. A dynamic mechanism is non-clairvoyant if the allocation and pricing rule at each period does not depend on the type distributions in future periods.

We develop a framework, called *bank account mechanism* for characterizing, designing, and proving lower bounds for dynamic mechanisms (clairvoyant or non-clairvoyant). This framework is used to characterize the revenue extraction power of non-clairvoyant mechanisms with respect to mechanisms that are allowed unrestricted use of distributional knowledge.

3.4 Pragmatic solution concept for first price auction [13]

Ever since Vickrey's seminal work on the closed form solution of Bayes Nash equilibrium for first price auction on two symmetric uniform distributions, researchers have been interested in solving closed-form solutions for more general distributions. Unfortunately, until today, the solution has only been extended to the case of asymmetric uniform distributions.

The idea here is to consider an alternative solution concept, solve for its closed-form in the general case and show that it nicely interprets of the reality. The solution concept we consider is the so-called Stackelberg equilibrium (aka. commitment): a leader optimizes his committed strategy, given the fact that a following player will best response to every commitment made by the leader. In the case of Bayesian game, the leader will announce a Bayes strategy (a function that maps type to bid), without revealing his actual type.

Our main contribution in this work [13] is the *closed-form solution of Bayes Stackelberg equilibrium in first price auction*. The interpretation of this solution is striking: the leader bids very passively in that he commits to bidding 0 when his type is below a certain threshold. This is against the doctrine in first price auction that bidding 0 has no chance of winning at all! However, a close consideration tells us otherwise: by committing to a passive bid strategy, the leader (credibly) ensures the follower that he has no intention to compete with a lower type, thus effectively brings down the follower's bid (since the follower does not know the leader's actual type) and eventually can win the auction with a low payment when he has a high type. The solution is largely consistent with the collusive behaviors widely observed in first-price auction, where set of players jointly bring down the bidding prices. Our solution suggests a collusive behavior that does not require communication: the trust between the players is built by the rationality of the follower, as well as the leader's credibility to commit.

Of technical interest, we put forward a routine for solving general Bayes Stackelberg equilibrium with quasi-linear utility. The techniques include a clean use of equal-utility curve as well as a new representation technique that reduces a functional optimization to derivative.

3.4.1 Price of prior dependence in auctions

We recently propose to study *the price of prior dependence* in auction design [14], where we consider the possibility that the buyers may commit to a fake bid distribution in a prior-dependent truthful auctions, in order to let the design form a wrong belief about their type distributions which benefit themselves in the future. We show that, under this model, perhaps surprisingly, the Myerson auction is revenue equivalent to first price auction in this model and reserve-based (prior dependent) second price auctions are inferior to the standard second price auction.

4 Computer-aided theorem discovery [AIJ-09, AIJ-10, GEB-11]

My PhD dissertation work is a methodology to automatically prove and discover theorems in economics. The main idea is to use AI tools (first order logic, constraint satisfaction problem) to represent the target theory and then search through the language for valid sentences (theorems). One interesting observation is the so-called finitely verifiable property, where sentences of certain forms can be verified using finitely many semantic models, thus can be exhaustively checked by computer programs. We initiate this theory and methodology and test it on the domain of game theory, where we find theorems related to the uniqueness of pure nash equilibrium. We also test it on the domain of social-choice theory and come up with a unified, computer-aided proofs for nearly all famous impossibility theorems in social choice theory (Arrow, Gibbard-Satterthwaite, etc). The methodology is now recognized as a standard way to prove impossibility theorems and introduced as an independent chapter in a social choice theory handbook[1].

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