Segmenting Two-Sided Markets

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Recent years have witnessed the rise of many successful e-commerce marketplace platforms like the Amazon marketplace, AirBnB, Uber/Lyft, and Upwork, where a central platform mediates economic transactions between buyers and sellers. A common feature of many of these two-sided marketplaces is that the platform has full control over search and discovery, but prices are determined by the buyers and sellers. We summarize our results from [Banerjee et al. 2017] where, motivated by this application domain, we study the algorithmic aspects of market segmentation via directed discovery in two-sided markets with endogenous prices. We consider a model where an online platform knows each buyer/seller's characteristics, and associated demand/supply elasticities. Moreover, the platform can use discovery mechanisms (search, recommendation, etc.) to control which buyers/sellers are visible to each other. We develop efficient algorithms for throughput (i.e. volume of trade) and welfare maximization with provable guarantees under a variety of assumptions on the demand and supply functions.

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1. INTRODUCTION

Though markets are an ancient institution, they have been transformed in recent years by the rise of online marketplaces. Many of today's most important online marketplaces are platforms with both buyers and sellers. These include marketplaces for goods (Amazon, eBay, Etsy), and increasingly, for services: transportation (Lyft, Uber); physical and virtual work (Taskrabbit, Postmates, Upwork); lodging (Airbnb); shipping and delivery (Google Express, Amazon Fresh, Shyp); etc. Unlike traditional markets, these online platforms enable more fine-grained monitoring of participants, and more detailed control via pricing, terms of trade, visibility and directed search, information revelation and recommendation, etc. The

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challenge of harnessing this increase in data and control has led to a growing literature in the design of online marketplaces.

The focus of this work is on *the role of directed discovery mechanisms in matching demand and supply in modern online marketplaces.* In particular, we consider marketplaces exhibiting four characteristics:

i. Buyers/sellers are *horizontally differentiated* – each having heterogenous valuations and preferences for matching with agents on the other side of the market.
ii. Each agent has a *public type*, i.e., a known list of characteristics. Agents' valuations for different matches are independently distributed conditioned on their public type.
iii. The platform has full control over *directed discovery* mechanisms – which sellers (buyers) are visible to a buyer (seller) on the other side of the market.
iv. *Transaction prices are endogenously determined by the agents*, based on who they are shown on the other side of the market.

These features are common in many online marketplaces. For example, in AirBnB, although listing prices are set by the 'hosts' (i.e., *sellers*), the platform can control which listings are visible to a 'guest' (i.e., *buyer*). Similarly in Upwork, the price of a job is determined via negotiation between contractors (buyers) and freelancers (sellers); the platform determines which job-postings are seen by which freelancers. In all these settings, the platform knows the public types of agents, but is unaware of their exact utility except in aggregate.

Techniques to segment buyers via direct control of prices are studied in economics under the heading *price discrimination.* These techniques however do not extend to the settings illustrated above, where direct price control is not allowed. This motivates developing a theory for *search-based market segmentation*, where a platform can segment buyers and sellers in a market based on their types, but prices emerge endogenously (via market clearing) based on which segments have access to each other. We are interested in the algorithmic challenges of optimal segmentation of marketplaces via directed-discovery.

2. MODEL

We now describe our formal model for studying search-based market segmentation.
Agent types and valuations: We consider non-atomic agents, where each arriving buyer/seller belongs to one of a finite number of demand and supply *types.* For any demand-type i, a continuum of agents arrive at the marketplace at a rate d_i; similarly, for any supply-type j, agents arrive at a rate s_j. For any given price p, the platform knows the fraction of arriving buyers/sellers of demand/supply type willing to transact, which are encoded in the form of known supply and demand curves for each type. In more detail: we assume that each buyer of type i has a private reservation value for a transaction, drawn from a *reservation-value distribution* $F_i(\cdot)$, and each seller of supply type $j \in \mathcal{S}$ has a private transaction cost drawn from a *reservation-cost distribution* $F_j(\cdot)$. Consequently, if the transaction price is set to p, then the rate of arrival of type-i buyers is given by the *demand curve* $d_i(1 - F_i(p))$, and similarly, the rate of arrival of type-j sellers is given by

the *supply curve* $s_j F_j(p)$. The supply curves are non-decreasing, while the demand curves are non-increasing.

Agent compatibility and directed discovery mechanisms: A buyer/seller's type also determines the set of compatible types on the other side of the market (i.e., types of agents with whom she can transact). For instance, on Upwork, the requirements of a job should be reasonably close to the skills of the freelancer; on AirBnB, the desired location of a guest should be close to the location of the host's listing; and so on. We assume this information is given to the platform designer in the form of an *interaction graph*, a bipartite graph between demand and supply types with edges connecting compatible types.

The platform only controls which buyer/seller types have access to each other in the marketplace; subsequently, transactions take place at endogenously defined *market-clearing prices*. The algorithmic challenge faced by the platform designer is to choose a *bipartite visibility graph*, i.e., any subgraph of the interaction graph, in order to maximize a given objective. The platform can then be designed to ensure that agents of a given buyer/seller types can only view compatible types which are included in the visibility graph. The objectives we consider are *throughput* (i.e., rate of successful matches), and *welfare* (i.e., social surplus generated by the matches); the former is a proxy for revenue in settings where the platform receives a fixed commission per match.

3. SUMMARY OF OUR RESULTS

In the above setting, we want efficient algorithms to choose visibility graphs that (approximately) optimize throughput and welfare. Both objectives can be viewed as set functions of the supply and demand types that are pooled together, and we prove that even in very simple settings (in particular, for a complete bipartite visibility graph), these functions are (approximately) super-additive. This presents a significant technical hurdle, as, for such functions, obtaining even a coarse approximation of the maximum objective is NP-Hard. In fact, we prove that both throughput and welfare are NP-Hard to approximate beyond a constant multiplicative factor.

In view of the above, our aim is to find properties of the supply and demand curves that are plausible in practice, but moreover, admit polynomial-time approximation algorithms. To this end, we show the following:

- For general supply and demand curves, we provide algorithms that obtain a 4 approximation to the optimal segmentation for throughput, and a 3.164 approximation for welfare.
- For concave supply and demand curves, we provide a simpler algorithm that gets a 4 approximation for throughput and 8 approximation for welfare, and moreover, is oblivious to the exact curves, only needing to know the maximum supply or demand for each type.
- For identical and log-concave supply/demand curves, we provide a simple greedy algorithm which improves the approximation ratio for throughput to 3.164.
- Finally, we show via simulations the efficacy of search-based segmentation in markets, as compared to a natural full-access baseline, wherein supply is matched to demand under the endogenously-determined uniform pricing.

A key technique underlying all our results is a common structural characterization: we show that for *any interaction graphs and arbitrary demand and supply curves*, there exists a 2-approximate solution where each segment either contains only one demand type or only one supply type. Using this result, we show that the throughput (resp. welfare) functions become sub-additive (resp. submodular) instead of being super-additive! This makes the problem tractable and amenable to existing algorithms for sub-additive (resp. submodular) welfare maximization.

4. RELATED WORK AND CONCLUSION

Two-sided markets have a rich literature in Economics. There is a large body of work on two-sided *matching markets* [Shapley and Shubik 1971; Azevedo and Leshno 2014] where one/both sides of the market are assumed to be atomic, and prices can be set per agent. In contrast, marketplace platforms typically deal with a large mass of agents on both sides of the market, with market-clearing determining the equilibrium prices. Algorithmically, this makes the segmentation problem NP-Hard in our setting, while it is poly time if the price can depend on the match.

Our work is closer in spirit to price-theoretic models of two-sided markets with non-atomic agents. Much of this work assumes however that prices can be set for different sides of the market with the goal of getting agents to report their types truthfully [Gomes and Pavan 2011], maximizing social surplus or revenue of the platform [Weyl 2010], or modeling competing platforms [Armstrong 2006; Rochet and Tirole 2003]. In contrast, we focus on *search-based segmentation* with endogenous prices, where the platform only controls which type of users on either side are visible to each other. This model is new to the best of our knowledge and is a relevant model for two-sided platforms in diverse contexts.

On the other hand, search frictions in two-sided markets have also been widely studied, in particular, in the context of labor markets [Diamond 1982; Rogerson et al. 2005] and dating platforms [Halaburda et al. 2015]. In contrast to our work, these models do not have prices, and instead, focus on how market segmentation determines probability of discovery, which in turn can lead to larger welfare.

In terms of algorithmic techniques, partitioning items into sets in order to maximize welfare is a well-studied problem, with constant factor approximation algorithms for subadditive [Feige 2009] and submodular [Nemhauser et al. 1978; Vondrak 2008] welfare functions. Our functions are approximately super-additive, and in general, partitioning is a computationally hard problem. There has been work on developing good approximation algorithms for restricted classes of super-additive functions [Feige et al. 2015; Abraham et al. 2012]; however, our functions do not fall into these classes.

While our work is a first step in the algorithmic study of two-sided platforms with non-atomic users, we list some open questions below:

- *Complex constraints on pools*: e.g., flow constraints in an electricity market with generators and consumers [Bose et al. 2014].
- *Incorporating heterogenous service-costs*: Our work extends to handle certain models for service costs; however handling general models of cost depending on supply and demand types is an open problem.
- *Posted prices with endogenous customer choice*: An alternate setting is to set a

price for each pool, and allow agents to selfishly choose their optimal pool. This has applications in settings where each pool corresponds to a time interval, and the platform matches riders and rides with the goal of minimizing congestion (cf [Gomes and Pavan 2011; Besbes and Lobel 2015] for related models). Do such settings admit to efficiently computable Walrasian equilibria?

REFERENCES

Abraham, I., Babaioff, M., Dughmi, S., and Roughgarden, T. 2012. Combinatorial auctions with restricted complements. In *Proceedings of the 13th ACM Conference on Electronic Commerce*. EC '12. 3–16.

Armstrong, M. 2006. Competition in two-sided markets. *RAND Journal of Economics 37,* 3, 668–691.

Azevedo, E. M. and Leshno, J. D. 2014. A supply and demand framework for two-sided matching markets. *Available at SSRN 2260567*.

Banerjee, S., Gollapudi, S., Kollias, K., and Munagala, K. 2017. Segmenting two-sided markets. In *Proceedings of the 26th International Conference on World Wide Web*. ACM, 63–72.

Besbes, O. and Lobel, I. 2015. Intertemporal price discrimination: Structure and computation of optimal policies. *Management Science 61,* 1, 92–110.

Bose, S., Cai, D. W. H., Low, S. H., and Wierman, A. 2014. The role of a market maker in networked cournot competition. *CoRR abs/1403.7286*.

Diamond, P. A. 1982. Aggregate Demand Management in Search Equilibrium. *Journal of Political Economy 90,* 5, 881–94.

Feige, U. 2009. On maximizing welfare when utility functions are subadditive. *SIAM Journal on Computing 39,* 1, 122–142.

Feige, U., Feldman, M., Immorlica, N., Izsak, R., Lucier, B., and Syrgkanis, V. 2015. A unifying hierarchy of valuations with complements and substitutes. In *Proceedings of the Twenty-Ninth AAAI Conference on Artificial Intelligence*. AAAI'15. 872–878.

Gomes, R. and Pavan, A. 2011. Price discrimination in many-to-many matching markets. Tech. rep., Northwestern University, Center for Mathematical Studies in Economics and Management Science.

Halaburda, H., Piskorski, M. J., and Yildirim, P. 2015. Competing by restricting choice: the case of search platforms. *Harvard Business School Strategy Unit Working Paper 10-098*.

Nemhauser, G. L., Wolsey, L. A., and Fisher, M. L. 1978. An analysis of approximations for maximizing submodular set functions. *Mathematical Programming 14,* 1, 265–294.

Rochet, J.-C. and Tirole, J. 2003. Platform Competition in Two-Sided Markets. *Journal of the European Economic Association 1,* 4, 990–1029.

Rogerson, R., Shimer, R., and Wright, R. 2005. Search-theoretic models of the labor market: A survey. *Journal of Economic Literature 43,* 4, 959–988.

Shapley, L. S. and Shubik, M. 1971. The assignment game I: The core. *International Journal of Game Theory 1,* 1, 111–130.

Vondrak, J. 2008. Optimal approximation for the submodular welfare problem in the value oracle model. In *Proceedings of the Fortieth Annual ACM Symposium on Theory of Computing*. STOC '08. 67–74.

Weyl, E. G. 2010. A price theory of multi-sided platforms. *The American Economic Review*, 1642–1672.