A Long Way Coming: Designing Centralized Markets with Privately Informed Buyers and Sellers*

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Abstract

We discuss the economics literature relevant to the appropriate design of centralized market mechanisms for environments where both buyers and sellers have private information, as is, for example, the case in the "incentive auction" for radio spectrum license that the FCC has been mandated to run. These two-sided problems are markedly different from their one-sided counterparts where private information pertains to buyers only: a) efficient mechanisms do not generate positive revenue, b) maximal revenue extraction has higher opportunity cost, c) incorporating the sale of assets owned by the mechanism designer may improve outcomes, d) arguments for open designs based on the linkage principle are less compelling, e) the structure of the trading network/matching may be more important than issues of substitutes and complements, and f) the loss of welfare plus revenue from excluding a strong buyer can be greater. Because economists designing two-sided markets will rely in part on intuition gained from one-sided markets, an understanding of these differences can be important. We also consider the practical implications for implementation and avenues for future research.

Keywords: FCC, spectrum license auction, incentive auction, mechanism design
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1 Introduction

Markets have long been recognized as an often astonishingly efficient means of allocating resources. Given that well-functioning markets are so efficient but fail to exist for a variety of valuable goods and services, it seems natural to ask whether government intervention that aims at establishing such "missing" markets would be desirable. This question is fundamental to economics, and over the past half century or so, the economic debates about it have led to a rich body of research. This research has had a substantial impact on public policy and legislation, and, in turn, the changes in public policy seem to have affected the questions on which economists focus. Given that current policy proposals concern the potential value of and appropriate design for centralized markets for the exchange of goods by privately informed buyers and sellers, the academic and political debates have reached a new junction. In this article, we provide the historical background to current debates and review the related literature.

The problem of designing a centralized market where both buyers and sellers have private information, which we refer to as a two-sided market, is fundamentally different from the problem of designing a one-sided market, such as an auction for the sale of goods to privately informed buyers. The most striking difference is perhaps the well-known result that in a two-sided market, efficiency and positive revenue cannot be achieved simultaneously. We review the existing theoretical and experimental literature on two-sided market design and provide a number of new results. We show that maximal revenue extraction has higher opportunity cost in terms of lost efficiency in a two-sided versus one-sided market. We show that combining government and private supply may offer benefits for two-sided market design. We show that arguments for open market designs based on the linkage principle are less clear in the case of two-sided markets.[1] We argue that the structure of the trading network/matching in a two-sided market may be more important than whether agents preferences and costs are characterized by substitutes or complements. We show that the loss from excluding a strong buyer in terms of the reduction in the sum of welfare plus revenue can be greater in the two-sided setup than in the one-sided setup. Because economists designing two-sided markets will rely in part on intuition gained from one-sided markets, it is useful to be aware of these differences. We do not attempt to review every issue of concern in the design of centralized markets with privately informed buyers and sellers, but rather we focus on a set of differences between two-sided

[1] The linkage principle implies that a market designer benefits from promoting information revelation to the bidders. For a more formal statement, see Section 4.1 and Appendix A.

markets and one-sided markets that can be addressed through formal economic analysis.

Economists such as Lerner (1944) have argued that markets offer sufficiently high value to society that governments should actually organize markets where they do not emerge spontaneously. However, Vickrey (1961) argued forcefully against this idea, saying essentially that such counter-speculation would be excessively costly to society. Indirectly, Myerson and Satterthwaite (1983) made a similar point with their well-known impossibility theorem. The reasoning of Vickrey and Myerson and Satterthwaite has had a great impact both on practical design and economic research in focusing economists and policy makers on the importance of efficient primary market allocation mechanisms (see, e.g., Milgrom, 2004, Chapter 1.4.1, and the data summarized in Figure 2 below), where for the purposes of this paper, we define a primary market to mean a situation in which the seller (or possibly the buyer) of the assets also chooses the mechanism, and we define a centralized secondary market to mean a situation in which an entity other than a party to the transaction chooses the trading mechanism and organizes the exchange.

Vickrey (1961) and Myerson and Satterthwaite (1983) show that, under general conditions, any mechanism that efficiently allocates goods between owners or producers of goods and potential buyers of the goods, each with market power and private information, will run a deficit. In order to design a mechanism that produces an efficient allocation, the mechanism designer must be prepared to contribute resources. In the simplest example, consider one buyer and one seller of a good, each with private information about their value for or cost of the good. For efficiency, the buyer and seller must trade whenever the buyer's value exceeds the seller's cost. Thus, an efficient mechanism requires that the buyer and seller truthfully reveal their private information. The mechanism must use the reports from the buyer and seller to determine whether trade should occur, but in order to achieve truthful revelation, the buyer's and seller's payments to and from the mechanism cannot depend upon their own reports. In the simple case where the buyer's value and seller's cost are drawn from distributions with the same support, efficiency and truthful revelation are achieved by having the buyer pay an amount equal to the seller's reported cost, whenever the buyer's reported value exceeds that cost, and by having the seller receive a payment equal to the buyer's reported value, whenever the seller's report is less than that value. But in this simple case, the mechanism designer must contribute the entire value of the gains from trade in order to balance the budget.

Given the pessimistic view for the possibilities for designing centralized markets with privately informed buyers and sellers that flowed from the analysis of Vickrey (1961) and Myerson and Satterthwaite (1983), and given the optimistic view from the analysis of Coase (1960) that decentralized secondary markets might function well in the absence of centralized organization, the focus in market design fell upon the design of primary markets. However, the hands-off approach of the Coase Theorem does not apply to markets in which buyers and sellers have private information, which suggests that government should focus on primary market designs that emphasize efficiency and not rely on decentralized secondary markets to "fix" misallocations.[2]

Government-designed auctions have come to play an important role in the economy. Governments auction offshore drilling leases, timber logging rights, emission permits, and trillions of dollars' worth of securities every year. In 1993, the U.S. Congress directed the Federal Communications Commission (FCC) to design and implement auctions to allocate spectrum licenses, although nothing like that had been done before. The invigorating effect on economic research and practice was dramatic.[3]

There are circumstances that make the satisfactory working, and possibly the design, of centralized secondary markets desirable even if the primary allocation market functions perfectly. In particular, unforeseen and unforeseeable technological change can fundamentally change the nature of the efficient use of assets. For example, the advent of the Internet and mobile telephony has increased the opportunity cost associated with allocating spectrum to uses such as television and radio broadcasting. Furthermore, the conclusion of Myerson and Satterthwaite (1983) may also be viewed in a more optimistic light because, although full efficiency requires a subsidy and may be excessively costly, there exist inefficient but budget balanced mechanisms that do achieve a welfare gain, and these dominate the option of throwing up one's hands and obtaining no welfare gain at all.

Revisiting the debates on designing primary and centralized secondary markets, and re-evaluating the conclusions that have been drawn is also of relevance and interest to economists because, recently, the political/legislative environment has changed. In 2012, the U.S. Congress

[2]This line of reasoning, which can be found, for example, in Milgrom (2004) (see also Maskin (2004)'s review), has emerged as one of the important lessons from the mechanism design literature and is now incorporated in advanced textbooks (see, e.g., Jehle and Reny (2011)).

[3]As stated in Milgrom (2004, p.1), although economic theory had little practical effect on auction design prior to that point, "Since 1994, auction theorists have designed spectrum sales for countries on six continents, electric power auctions in the United States and Europe, CO_2 abatement auctions, timber auctions, and various asset auctions. By 1996, auction theory had become so influential that its founder, William Vickrey, was awarded a Nobel Prize in economics science." The influence of mechanism and market design is also reflected in the 2007 Nobel Prize awarded to Leonid Hurwicz, Eric S. Maskin and Roger B. Myerson "for having laid the foundations of mechanism design theory" and in the 2012 Nobel Prize awarded to Alvin E. Roth and Lloyd S. Shapley "for the theory of stable allocations and the practice of market design." (www.nobelprize.org)

once again directed the FCC to design and implement a new type of mechanism, the "incentive auction," a centralized market for the exchange of spectrum licenses by privately informed sellers and buyers of the licenses, requiring that the FCC design and run a centralized secondary market.[4] Based on the upsurge of academic research relating to auctions that followed the 1993 mandate to the FCC to use auctions to allocate spectrum licences, one may reasonably expect a similar upsurge of interest in designing two-sided markets, and many more applications to flow from this.

The FCC's original spectrum license auctions were a novel design, with design choices that were guided by insights from the economics literature (and economists) of the time. The FCC's incentive auction design will again necessarily be novel; however, some economists have expressed the view that "Auction design and practice is sufficiently advanced that the FCC can successfully implement this type of auction." (Milgrom et al., 2011, p.1) As with the design of the initial one-sided auctions, the design of the FCC's two-sided auctions will rely on intuition gained from the economics literature. This literature highlights the differences between market design with one-sided versus two-sided private information. Some of the tradeoffs and tensions that will have to be balanced differ between the two environments. As was the case with the initial spectrum license auctions, the efforts spurred by the incentive auction in terms of the design of practical centralized markets with privately informed buyers and sellers will spur new economic research that ultimately influences practice around the world. As stated by a number of leading economists in a 2011 letter to President Obama, "Implementing an efficient 'incentive auction' will require substantial thought and care.... The original simultaneous multiple-round auction system implemented in 1994 was novel, but the FCC was able to implement the path-breaking auctions that were the basis for successful auctions around the world. We expect the same will be true of the incentive auction." (Milgrom et al., 2011, p.2)

The design of the initial FCC spectrum license auctions required the resolution of a variety of tradeoffs. Three tradeoffs in particular shaped the debates within the economics literature and among economists. First, auction designs differ in the weight they put on revenue versus efficiency, and this had to be resolved. Second, there were tradeoffs to consider between open versus closed auction formats, with arguments based on the linkage principle favoring an open formats, such as an ascending-bid auction where bidders observe the bids of others as the auction progresses, and concerns regarding collusion favoring a closed format, such as a sealed-

[4]An early proposal that the FCC conduct two-sided auctions of spectrum licenses was put forward by Kwerel and Williams (2002).

bid auction where no information is transmitted between bidders during the course of the auction. Third, there were tradeoffs related to the issue that there were complementarities and substitutabilities among the spectrum licenses for various potential buyers. Concerns about complementarities suggested allowing combinatorial bidding, concerns about substitutability suggested a simultaneous auction format, and both possible solutions raised concerns about the complexity of the auction format. These three tradeoffs continue to be relevant as the FCC embarks on the design of a centralized market for privately informed buyers and sellers; however, the distinctly different nature of this type of mechanism means the nature of the tradeoffs changes. As we describe, the issue of an open versus closed auction format diminishes in importance, and the issue of the role of complementarities and substitutabilities is dominated by new concerns related to the trading network and matching of buyers and sellers (which are trivially absent when the government is the only seller). Thus, two of the tradeoffs for one-sided market design become less important; however, we show that the remaining tradeoff, between revenue and efficiency, is heightened in the two-sided environment because maximal revenue extraction has higher opportunity cost in terms of lost efficiency than in the one-sided environment. Moreover, in developing two-sided markets, designers such as the FCC who own some assets themselves have the additional option of combining elements of primary and centralized secondary markets by adding the assets they own to the supply in the market, thus creating what can be called a "connected" market.[5] We show that carefully designed connected markets soften the trade-off between revenue extraction and social surplus and that such connected markets can lead to efficient allocations without running a deficit.[6]

Throughout the paper, we focus on environments in which utility and profit functions are quasilinear. This means that we do not review the recent matching literature that addresses problems such as matching students to public schools or kidney-patient-donor pairs to each other. This literature remains primarily within the domain of ordinal preferences and, for example for kidney exchanges, does not use monetary transfers.[7] That said, many of the key lessons that follow from the matching literature are relevant in that they suggest that large well-designed centralized secondary markets perform better than smaller ones because size

[5]The FCC's broadcast incentive auction will be a connected market to the extent that unlicensed spectrum ("white spaces") will be included.

[6]It also provides another marked contrast to one-sided environments, for which skeptical views have emerged about the usefulness of combining primary and centralized secondary markets.

[7]For recent reviews, see for example Sönmez and Ünver (forthcoming) and Abdulkadiroglu and Sönmez (forthcoming).

allows for more matches and that, whenever possible, efficiency should be achieved through primary markets because centralized secondary markets endow agents with market power.[8] And, of course, allocating goods efficiently in a primary market is not always possible. This is obviously true for, say, kidneys.

In this paper, we survey the literature that will play a role in guiding and informing the "substantial thought and care" that will be required for successful incentive auctions and provide a context for understanding the political and economic debates surrounding the design of these mechanisms. We begin in Section 2 by offering insights into the economic rationale for market making by governments and by providing historical context for the case at hand. In Section 3, we analyze the main differences between market design with one-sided versus two-sided private information. Section 4 discusses complications and open issues. Section 5 concludes. Topics for future research arise throughout.

2 Background

In this section, we first provide a discussion of the economic arguments in favor of government intervention for setting up and organizing centralized secondary markets. Second, we review the historical background for the development of primary market allocation mechanisms and the role of the FCC and the debates within the FCC that led to these developments.

2.1 A Case for Intervention in Designing Two-Sided Markets

Clearly, whether there is a case for government intervention in designing and organizing centralized markets in setups with privately informed buyers and sellers critically depends (i) on the welfare properties of the market microstructure that would emerge absent government intervention and (ii) on the welfare properties of the centralized secondary market induced by government action. To address (i), we first discuss a simple model in which the market microstructure is determined endogenously, and we show that it is possible that the socially desirable market microstructure fails to emerge in equilibrium. Interestingly, such "market failures of market making" are not monotone in the parameter that captures the efficiency of the market structure that emerges absent a centralized trading platform.

[8] Indeed, there is a close analogy between the matching literature and the mechanism design literature reviewed here, where under fairly general conditions efficient, incentive compatible mechanisms that do not run a deficit exist for primary markets but not for centralized secondary markets: For one-to-one matching problems, it is possible to match agents efficiently via a strategy proof mechanism (the celebrated deferred acceptance algorithm of Gale and Shapley (1962)) if only agents on one side of the market have to be incentivized to reveal their preferences but not if agents on both sides have to be incentivized.

With regard to (ii), we propose to view the results from the literature on mechanism design with two-sided private information from a different angle. Besides the well-known result that ex post efficient trade without running a deficit is not possible, this literature has also delivered positive results concerning constrained efficient trading mechanisms that do not run a deficit. Though running public deficits to finance efficient trade in a particular market is probably unviable politically and probably a bad idea economically (because of distortions in raising the tax revenue and because it gives rise to rent seeking), we illustrate in a simple example that the welfare gains that can be achieved through constrained efficient mechanisms may be substantial.

2.1.1 Market Failure in Market Making?

We consider a simple model in which the market microstructure is determined endogenously as a function of a fixed cost of operating a centralized market and the frictions associated with trading in a decentralized, random matching market. In particular, we show that whether the equilibrium market exchange involves a substantive volume of (constrained efficient) centralized trade or consists only of trade in a random matching market depends on the frictions in the random matching market and the fixed costs of market making in a non-trivial manner. A private, profit-seeking market maker does not internalize the full social surplus he creates, which, under certain conditions, results in what could be called a *market failure in market making.*

Largely following Gehrig (1993), we consider a model with a continuum of buyers with unit demand and a continuum of sellers with unit supply, where each side of the market has mass one.[9] Buyers and sellers independently draw their valuations and costs from the uniform distribution on the unit interval.[10] In the equilibrium of a centralized Walrasian market, this results in linear demand and supply functions that intersect at the price $p^W = 1/2$, with the equilibrium quantity traded also being $1/2$. Consequently, the resulting Walrasian equilibrium welfare is $W^W = 1/4$. However, so as to analyze to equilibrium incentives for a centralized

[9]Models along these and similar veins have been studied by, among others, Gehrig (1993), Spulber (1996, 2002), Wooders (1997), Rust and Hall (2003), and Loertscher (2007). Our treatment here focuses on Gehrig's model with minor adjustments as this model seems the most parsimonious one for our purposes. Our treatment differs from Gehrig's by assuming that there is a fixed cost of entry for the market maker, and like Spulber (2002) we assume Nash bargaining in the bilateral matching market. The Nash bargaining assumption could be replaced with the assumption of a double auction à la Chatterjee and Samuelson (1983) without affecting any of the qualitative results.

[10]The assumption that there of a continuum of agents does not only simplify the exposition but also helps us separate conceptually the equilibrium incentives for a market maker to enter from the mechanism design the market maker faces once he has entered.

market maker to enter and to understand the welfare properties of the emerging equilibrium market microstructure, we need to spell out what happens outside the Walrasian equilibrium.

For that purpose, assume that buyers and sellers always have the option of trading in a bilateral matching market, where upon a match a buyer with valuation v and a seller with cost c trade at the price $(v + c)/2$ provided $v \geq c$. Otherwise they do not trade. Letting $\lambda \in [0, 1]$ be the probability that a buyer and a seller are matched (in a bilateral trade market with equal masses of buyers and sellers), expected welfare absent any centralized trade is $W^{BT} = \lambda \int_0^1 \int_0^v (v - c) dc dv = \lambda/6$. Given a match, efficient trading occurs in a Coasian fashion. The probability λ that such a match occurs is, thus, a measure the efficiency of a decentralized secondary market. Full efficiency is not achieved even for $\lambda = 1$ because of excessive entry by low valuation buyers and high cost sellers.[11]

Consider next a market maker who, upon bearing a fixed cost K, enters and posts a publicly observable buyer's price p_B at which he stands ready to sell and a publicly observable seller's prices p_S at which he stands ready to buy, with $p_B \geq p_S$ being necessary to avoid running a deficit. Buyers and sellers observe (p_B, p_S) and then simultaneously decide whether they want to go to the market maker, join the bilateral matching market, or remain inactive. In equilibrium, the market maker sets prices p_B and p_S that are symmetric around 1/2 and trades with all the buyers with $v \geq 3/4$ and all sellers with $c \leq 1/4$; buyers and sellers with valuations and costs between 1/4 and 3/4 participate in the bilateral matching market, and all other agents remain inactive.[12] Let $V_B(v)$ and $V_S(c)$ be the expected payoff of the buyer of type v and sellers of type c of participating in the bilateral trade market. All else equal, $V_B(v)$ and $V_S(c)$ will be increasing in λ.[13] The equilibrium prices p_B^* and p_S^* must then be such that the marginal buyer, whose valuation is 3/4, and the marginal seller, whose cost is

[11] Assuming Nash bargaining and $\lambda = 1$, the efficient outcome is obtained if all buyers with $v \geq 1/2$ and all sellers with $c \leq 1/2$ entered the matching market and no one else. However, all buyers and sellers can benefit from participating in the matching market, and so will enter, resulting in an inefficient outcome.

[12] Multiple equilibria always exist in this model because an individual is indifferent between staying home and going to the market if everyone else stays home. However, given a positive spread $p_B - p_S > 0$, there are gains from participating in the bilateral matching market for all sellers and buyers with types between p_S and p_B. Thus, the equilibrium with an inactive matching market and positive spread requires large scale coordination failure and is not robust with respect to small trembles. In the simple setup, other equilibria exist where the buyers with valuations below 1/4 and sellers with costs above 3/4 enter the market instead of staying inactive. These can be eliminated by assuming that there is a positive fixed cost of market participation and then letting this cost go to 0 (see e.g. Gehrig, 1993). Lastly, for given prices by the market maker there could be different quantities traded through the market maker because agents on the long side would be rationed. However, if the market maker is committed to buying any quantity he is offered at price p_S and if rationing is efficient, then iterated elimination of dominated strategies yields a unique equilibrium outcome.

[13] For $v, c \in [1/4, 3/4]$, $V_B(v) = \lambda E[\max\{(v - c)/2, 0\} \mid 1/4 \leq c \leq 3/4] = \lambda \int_{1/4}^{v} (v - c) dc = \lambda (v - 1/4)^2/2$ and similarly $V_S(c) = \lambda \int_c^{3/4} (v - c) dv = \lambda (3/4 - c)^2/2$. Thus, $V_B(3/4) = V_S(1/4) = \lambda/8$.

1/4, are indifferent between centralized and decentralized trade. That is, p_B^* and p_S^* satisfy $3/4 - p_B^* = V_B(3/4)$ and $p_S^* - 1/4 = V_S(1/4)$. Inserting $V_B(3/4)$ and $V_S(1/4)$ from the previous footnote reveals that the equilibrium prices are $p_B^* = 3/4 - \lambda/8$ and $p_S^* = 1/4 + \lambda/8$. Observe that p_B decreases and p_S increases in λ. That is, the more efficient is the bilateral matching market, the smaller will be the market maker's profit. This adverse effect on the market maker's profit is due to the outside options of traders to join the bilateral matching market, which becomes more attractive as the matching frictions become smaller. Because the quantity the profit maximizing market maker trades is 1/4 and the spread he earns per unit traded is $p_B^* - p_S^* = (2-\lambda)/4$, the market maker's equilibrium profit, gross of the fixed cost of entry K, is $(2-\lambda)/16$. (The line $K = (3-2\lambda)/12$ is the dashed line in Figures 1(a) and 1(b).) Keeping the fixed cost K constant, the equilibrium incentives for the market maker to enter thus decrease in λ. However, this does not generally imply that, keeping K fixed, the equilibrium outcome becomes unambiguously worse as λ increases because, as we show below, the welfare gains from having a centralized exchange also decrease in λ.

If the planner can affect both the market maker's entry decision and regulate his pricing rule, it is optimal, conditional on entry, to induce the Walrasian pricing rule $p_B = p_S = 1/2$, which results in zero variable profits and a welfare gain of $W^W = 1/4$, gross of the fixed cost K. Alternatively, one can interpret the first-best scenario as being applicable for design problems that admit an efficient practical solution (for example, a generalized second-price auction when buyers have unit demand and sellers unit supply), so that if this mechanism is run, all gains from trade are exhausted, and there is no scope for a decentralized market. It follows that, under a first-best scenario, it is socially optimal to have a centralized exchange if and only if $W^W - W^{BT} = (3-2\lambda)/12 > K$. The line $K = (3-2\lambda)/12$ is the solid line in Figure 1(a). Therefore, for $(2-\lambda)/16 < K < (3-2\lambda)/12$, which is the shaded but unlined region in Figure 1(a), there is *market failure in market making* relative to the first-best regulatory scenario.

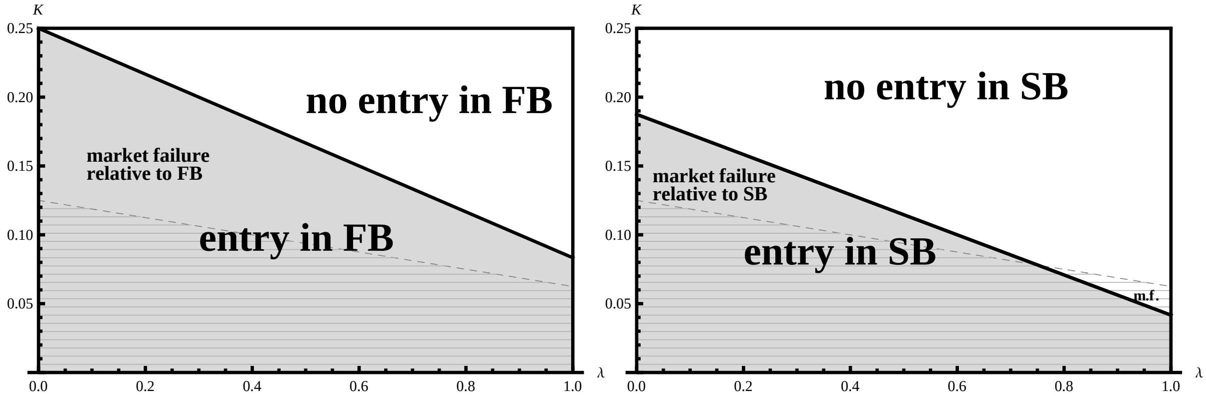
Consider next the second-best scenario in the spirit of, say, Mankiw and Whinston (1986), in which the social planner is assumed to be able to affect the market maker's entry decision, for example by subsidizing the business, but cannot influence the pricing decision. Given that the market maker enters, equilibrium welfare is thus $W^{M*} = 3/16 + \lambda/48$, where 3/16 is the welfare created by the agents who trade in the central exchange run by the market maker and $\lambda/48 = \lambda \int_{1/4}^{3/4} \int_{1/4}^{v} (v-c)dcdv$ is the welfare created in the simultaneously open bilateral trade market. From society's perspective, a profit maximizing market maker should therefore enter if and only if $W^{M*} - W^{BT} > K$, which is equivalent to $K < (9-7\lambda)/48$. The line $K = (9-7\lambda)/48$ is the solid line in Figure 1(b). However, the market maker only enters if $K < (2-\lambda)/16$, which is the lined region in Figure 1(b). Consequently, for $(2-\lambda)/16 < K < (9-7\lambda)/48$, which corresponds to the shaded but unlined region in Figure 1(b), there is *market failure in market making* because a market maker fails to enter in equilibrium when it would be socially desirable that he enters. Therefore, in this region government intervention in market making could, potentially, increase social welfare.

Conversely, for $(9-7\lambda)/48 < K < (2-\lambda)/16$, there is a market failure in market making with excessive entry because a market maker enters in equilibrium when, from society's perspective, there should be no entry. This region corresponds to the small lined but unshaded area to the right of $\lambda = 3/4$ in Figure 1(b).[14]

An alternative interpretation of the second-best scenario is that it is relevant whenever the design problem the market maker faces is too complex to admit an efficient solution (for example, because of complicated package problems; see Section 4 for details), so that even a market maker who is exclusively focused on welfare will not exhaust all gains from trade, thereby inevitably opening the scope for a decentralized matching market.

Within a simple model of market making we have thus provided conditions under which there is insufficient centralized market making in equilibrium and so there is scope for government intervention in market making. As the model shows, the value added from a centralized exchange is largest when the efficiency of the decentralized market is smallest (as the decentralized market becomes more efficient, i.e. λ increases, setting up the exchange becomes less urgent, all else equal, i.e. holding K fixed). One might therefore think that market failures occur when the decentralized market is relatively inefficient but become less of a problem as this efficiency increases. However, the model shows that one must also consider the incentives for the profit seeking market maker to enter, which, for a given K, decrease in the efficiency of the decentralized market. As a result, market failure may occur only for intermediate efficiency of the decentralized market (for a given K market failure may occur only for intermediate val-

[14] This region of excessive entry appears to be an artefact of the Nash bargaining assumption, which makes the random matching market appear more efficient than it would be under the assumption that information is privately preserved. For example, under Nash bargaining, the welfare created in a random matching market without a centralized exchange is $\lambda/6$, while under a double auction á la Chatterjee and Samuelson (1983) or with take-it-or-leave-it offers, it is only $9\lambda/64$ and $\lambda/8$, respectively. All else equal, market making less desirable from a social perspective under Nash bargaining than it would be with private information. At the same time, and for somewhat subtle reasons, Nash bargaining induces a larger profit for the market maker than would be the case with a double auction and private information, thereby inducing more entry in equilibrium. Consequently, there is no such region under either double auctions or take-it-or-leave-it offers.



(a) first-best scenario (b) second-best scenario

Figure 1: In both panels, the area of equilibrium entry is denoted by the lined area below the dashed line. In panel (a), equilibrium entry is contrasted with entry in the first-best (denoted by the shaded area) in which the market maker sets socially optimal prices. In the shaded but unlined region, there is market failure in the sense that there is insufficient entry into market making relative to the first-best. In panel (b), equilibrium entry is contrasted with entry in the second-best (denoted by the shaded area) in which the market maker sets prices to maximize his own profits. In the shaded but unlined region, there is again market failure in the sense that there is insufficient entry into market making relative to the second-best. In the small lined but unshaded region (labeled m.f.), there is market failure in the sense that there is excessive entry into market making relative to the second-best.

ues of λ).[15] Thus, a reduction in frictions associated with trading in the decentralized market may either result in market failure or resolve it, and the case for government intervention does not necessarily require that the decentralized market be highly inefficient but may only require that it be moderately efficient.[16]

Even though the above model provides a possible (and arguably plausible) rationale for government intervention in market making, it does not by itself imply that government, or governmental institutions, should be organizing the centralized secondary markets even if there is a case for government's supporting such an exchange. After all, the role of market making could be outsourced or delegated to private entities (perhaps using an auction mechanism). It is well-known that setting up a platform, such as centralized exchange, is a non-trivial

[15]For example, considering Figures 1(a) and 1(b), when K fixed at, say, 1/10, the market failure occurs for intermediate values of λ only for both the first-best and second-best scenarios.

[16]Notice also that under the first-best scenario the possibility of market failure does not vanish at λ close to or equal to 1. Even at $\lambda = 1$ the matching frictions do not disappear because there is only one round of random matching. Consequently, there is excessive entry by buyers and sellers into the matching market which promises positive gains from trade to every agent no matter what type, except for the buyers with valuation 0 and sellers with costs equal to 1. In contrast, under second-best there is no possibility for market failure when λ is large because the added value of having a market maker with unregulated monopoly prices is limited.

challenge that requires bringing both sides, that is buyers and sellers, on board. Therefore, if an institution, like the FCC, has played an important role as the trustworthy organizer of a primary market, it seems a priori in a good starting position to set up such a platform and to bring both sides on board.[17] Moreover, in the context of spectrum licenses, the FCC would be involved in allocating and fine-tuning spectrum allocations even if it were not in charge of running the centralized secondary market. Therefore, it seems plausible to assign the role of market maker for the centralized secondary market to an institution like the FCC whenever such an institution already exists.[18]

2.1.2 Is the Glass Half Full or Half Empty?

As mentioned in the Introduction, a well-known and influential result is the impossibility result of Myerson and Satterthwaite (1983), which states that under fairly general conditions it is impossible to have ex post efficient trade without running a deficit while respecting the buyer's and seller's incentive compatibility and individual rationality constraints. In order for the auctioneer to discover whether it is efficient for trade to occur, the bidding parties must be induced to reveal the values at which they are willing to trade. Analogously to a one-sided auction, they will be willing to reveal these values only if the prices they pay or receive are better than and do not depend on these reported values. But if each side is to see a better price than that corresponding to the efficiently traded quantity, the auctioneer must be willing to make up the difference between the price the buyer pays and that which the seller receives.

[17] In some loose sense, this can be interpreted in the context of the model above as a situation in which the existing government agency has a smaller fixed cost for operating the centralized exchange than a private operator.

[18] First, the FCC's experience and reputation as a primary market maker for spectrum licenses puts it in a better position as far as implementation and also in terms of winning the trust of participants. Second, FCC approval is required for spectrum license transfers, so FCC involvement would be required at some level. Third, specific to the proposed incentive auction, which will reassign spectrum from broadcasters to mobile wireless service providers, the FCC uniquely has the ability to "repack" broadcasters not offering their spectrum to the mechanism and thereby optimize the spectrum that is offered into appropriately redefined blocks for mobile wireless services. For more detail, see Kwerel, LaFontaine, and Schwartz (2012), who state: "[M]ore than one broadcast station would need to sell their spectrum to create paired channels that would be suitable for wireless systems. Moreover, since wireless systems rely on uniform channel separation nationwide, there would also need to be coordination of broadcasters across the country to create a uniform nationwide bandplan that determines the frequencies that are allocated to wireless use and how channels are defined in those frequencies. Coordination would also be needed to aggregate freed-up broadcast spectrum into broader geographic areas that would be suitable for wireless systems. ... Most importantly, efficient spectrum use generally requires spectrum users with similar architectures to be grouped together. Wireless systems can operate on frequencies that are adjacent to one another but not on frequencies that are adjacent to high-power broadcasters without guard bands between them. To create large contiguous blocks of spectrum in which multiple wireless providers can be grouped together requires the consolidation of the remaining broadcasters on the minimum number of channels nationwide while meeting all of the interference constraints. Only an auction that operates in conjunction with the FCC's centralized reassignment of broadcasting channels is likely to be able to do this." (Kwerel, LaFontaine, and Schwartz, 2012, Section 1.1.2)

As an illustration, consider the bilateral trade problem of a buyer and a seller whose types v and c are independently drawn from the continuous distributions $F(v)$ and $G(c)$ with positive densities $f(v)$ and $g(c)$, respectively, on the identical support, which we take to be $[0, 1]$. Under ex post efficiency, the good changes hands if and only if $v \geq c$. Therefore, expected welfare W^* is

$$W^* = \int_0^1 \int_0^v (v - c)g(c)f(v)dcdv. \tag{1}$$

By the well-known revenue equivalence theorem (see e.g. Krishna (2002)), the expected revenue any mechanism that induces ex post efficient trade in equilibrium and respects individual rationality is no more than the expected revenue under a second-price double auction (or Vickrey or Vickrey-Clarke-Groves (VCG) mechanism), in which the buyer pays c and the seller receives v whenever there is trade and no payments are made otherwise.[19] Expected revenue under this mechanism, denoted R^{VCG}, is

$$R^{VCG} = \int_0^1 \int_0^v (c - v)g(c)f(v)dcdv = -W^*. \tag{2}$$

Thus, a subsidy of the size of the expected welfare gains is necessary to induce ex post efficient trade. In the words of Vickrey (1961, p.8), the demands this would impose on the fiscal resources of the state would indeed seem inordinately expensive. Broadly based on such impossibility results, the economics literature, and the practice of market design, have focused on the design of primary markets (see, for example, Milgrom (2004, Chapter 1)). The reasoning is simple and compelling: whenever one has the option to get the allocation right in the first place one should certainly do so.

However, getting the allocation right in the first place may not always be an option. For example, unforeseen and unforeseeable technological change such as the advent of mobile telephony and the internet may render an initially efficient allocation of resources socially undesirable. If the original property rights are permanent, then without depriving some owners of their rights, it is impossible to allocate these assets more efficiently without relying on some kind of secondary market. The question thus arises what guidance the literature can provide for the design of such markets. As we argue now, though they are obviously important, the impossibility results may have been overemphasized in the literature insofar as there are also more moderate but not less important possibility results.

[19] The VCG-mechanism is named after Vickrey (1961), Clarke (1971), and Groves (1973) and introduced formally in Section 3.2.

To fix ideas, assume that F and G are both uniform on $[0, 1]$ and consider the linear equilibrium of the double auction of Chatterjee and Samuelson (1983). In this auction, the good changes hands if and only if the buyer's bid exceeds the seller's. As the payment is simply a transfer from the buyer to the seller, the mechanism is budget-balanced ex post and individually rational because of every agent has the option of not trading. In the linear equilibrium of this auction, the good changes hands if and only if $v \geq c + 1/4$, which results in a welfare of $W^{SB} = 9/64$.[20] Observe that for F and G uniform, $W^* = 1/6$. Though it is true that under ex post efficiency welfare would be larger by 5/192, or roughly 16% (as percentage of maximum welfare), the welfare gain of going from no exchange at all to W^{SB} is 27/192 or approximately 84% of maximum welfare. If it is possible to induce constrained efficient trade through an appropriately chosen mechanism at costs that are not exuberant to society, then this may well be a worthwhile endeavour. It is in this sense that the question for designing secondary markets is whether the glass is 84% full or 16% empty.

2.2 Tradeoffs in Spectrum License Auction Design

An example of the evolution of market design approaches and key tradeoffs that have influenced market design decisions can be found in the development by the FCC of mechanisms to allocate spectrum licenses. That history shows that research initially focused on developing primary market allocation mechanisms with improved efficiency and revenue generation and more recently towards facilitating secondary market transactions.

In the 1940s, Lerner (1944) advocated for a role for government involvement in markets or "counterspeculation," arguing that the optimal resource allocation could only be achieved through intervention (Lerner, 1944, p.199). In the 1950s, Herzel (1951) specifically addressed the question of spectrum licenses, arguing for government auctions for spectrum licenses. According to Coase, "While [Herzel] was an undergraduate, Herzel had become very interested in the debate over whether a rational, efficient system for allocating resources would be possible under socialism. As a result, he read Abba Lerner's *The Economics of Control* soon after it was published in 1944. This debate, particularly Lerner's detailed proposal for market socialism in *The Economics of Control*, was the inspiration behind his views." (Coase (1993)) Joining the debate, Coase (1959) also argued for auctioning spectrum licenses.

[20] As shown by Myerson and Satterthwaite (1983), for the uniform-uniform case the double auction is a second-best mechanism in the sense of maximizing expected welfare subject to budget balance and incentive and individual rationality constraints.

The arguments of Herzel and Coase turned out to be ahead of their time, and their proposals faced opposition. Coase (1998) describes a number of examples of the widespread opposition to his proposal at the time it was made, including one opposition argument that "the spectrum was a public good and consequently a market solution was not appropriate." (Coase, 1998, p.580)

As described by Hazlett (1998), the idea of auctions for spectrum licenses remained shelved throughout the 1960s and 1970s; however, in the 1980s, as the demand for mobile wireless services and the number of licenses to be allocated increased, there was a growing need to move beyond the comparative hearings being used at the time. In addition, the new mobile wireless services differed from broadcasting, which had been the dominant concern, in that public interest commitments on the part of broadcasters were not an issue, reducing the desire by key policy makers for comparative hearings. Congress declined to grant the FCC the right to auction spectrum but did allow for lotteries for non-broadcast licenses, which were authorized in 1981 and came into use in 1984.[21]

While the decision to oppose auctions in the 1950s appears to have been philosophically motivated, the decision not to authorize auctions in the 1980s appears to have been based primarily on concerns over downstream market organization.[22] A window into these concerns is provided by the questions posed to the FCC by Congress at the time.[23] The questions reveal that the greatest concerns centered on the impact of the auction on the telecommunications industry, including the effects of auctions on incentives for innovation, warehousing,[24] and the efficient use of spectrum; effects of auctions on small and rural businesses; and the concern that auctions might lead to higher prices for consumers.[25]

Moving into the 1990s, the inefficiencies associated with lotteries became apparent,[26] the

[21]See Hazlett (1998) for a detailed discussion of the evolution of spectrum assignment procedures. For a summary of spectrum license assignment methods used in the United States, see Hazlett (1998, Table 1), and for a timeline of unsuccessful proposals to price spectrum access from 1927 to 1992, see Hazlett (1998, Table 2).

[22]The decision not to authorize auctions for broadcast licenses may relate to concerns that if broadcasters had to pay for licenses, they might not be subject to the same public service obligations (Hazlett, 1998).

[23]"Spectrum Auctions: FCC Proposals for the Airwaves," Hearing before the Subcommittee on Telecommunications, Consumer Protection, and Finance of the Committee on Energy and Commerce, House of Representatives, Ninety-Ninth Congress, Second Session, October 1, 1986, Serial No. 99–170, U.S. Government Printing Office, 1987, letter from Representative Timothy E. Wirth, Chairman of the Subcommittee on Telecommunications, Consumer Protection, and Finance of the Committee on Energy and Commerce, to the Chairman of the FCC.

[24]Warehousing refers to holding a spectrum license without using it to provide service to customers, perhaps to keep the license out of the hands of rivals.

[25]Other questions related to auction details and an estimate of bid preparation costs, the effect of the auction on public safety, and the interaction of the auction with spectrum already designated for allocation or in the process of being allocated.

[26]As stated by Milgrom (2004, p.3): "The lotteries of small licenses contributed to the geographic fragmen-

high willingness to pay of service providers for licenses was revealed by decentralized secondary market transactions,[27] heightened attention to the state of the national budget made the prospect of auction revenues particularly attractive, and an economics literature on auctions was developing, along with expertise in the design of auctions among economists. With this backdrop, in 1993 Congress granted the FCC authority to auction licenses with multiple objectives,[28] including "efficient and intensive use of the electromagnetic spectrum" and recovering "a portion" of the value of the licenses for the public (47 U.S.C. 309(j)(3)). The FCC first began holding auctions for spectrum licenses in 1994.[29]

The auction design was influenced by economics and economists. Economic theory and experimental work informed various design choices. Theory identified efficient mechanisms and optimal mechanisms for various theoretical environments.[30] However, theory did not identify a single optimal design for the complex real-world environment of spectrum licenses, particularly given the goals of both efficiency and recovering a portion of the value of the licenses.[31] The number of potential design variables made an exhaustive experimental study of all dimensions intractable. Instead, the general role of laboratory experiments was to test the operational rules of the auction in simple cases and to identify both unforeseen design problems and departures of strategies from those predicted by theory.[32]

tation of the cellular industry, delaying the introduction of nationwide mobile telephone services in the United States."

[27] See Hazlett (1998, Table 5).

[28] For a summary of the reasons that made FCC spectrum license auctions palatable to Congress in 1993, see Hazlett (1998, Table 6)

[29] The Omnibus Budget Reconciliation Act of 1993 gave the FCC authority to use auctions (Kwerel and Strack (2001)). On the performance of FCC auctions, see e.g., McMillan (1994), McAfee and McMillan (1996a), Cramton (1997), Kwerel and Rosston (2000), Marx (2006), and Brusco, Lopomo, and Marx (2009).

[30] "One plan for the auction of licenses called for a sequence of English auctions (Weber, 1993a, 1993b), a second called for a sequence of Japanese auctions (Nalebuff and Bulow, 1993a, 1993b), and a third called for simultaneous sales of licenses (McAfee, 1993a, 1993b; Milgrom and Wilson, 1993a, 1993b). Some proposals insisted on admitting bids for bundles of geographically linked licenses, whereas others favored restricting bids to individual licenses only." (Nik-Khah, 2008, p.78)

[31] "The spectrum sale is more complicated than anything in auction theory. No theorem exists—or can be expected to develop—that specifies the optimal auction form. The auction designers based their thinking on a range of models, each of which captures a part of the issue. The basic ideas used in designing the auction and in advising the firms on bidding strategy include the way the different bidders' valuations are related—they are partly idiosyncratic and partly common, or affiliated—and the effects of this on bidder behavior (Milgrom and Weber, 1982); how auctions reveal and aggregate dispersed information (Wilson, 1977); and the logic of bidding in the face of the winner's curse (Wilson, 1969; Milgrom and Weber, 1982). Other ideas used include the revenue increasing effect of bid discounts (Myerson, 1981; McAfee and McMillan, 1988, 1989) and reserve prices as substitutes for bidding competition (Myerson, 1981; Riley and Samuelson, 1981)." (McAfee and McMillan, 1996b, p.171)

[32] Experimental evidence was highly influential in the question of sequential versus simultaneous bids, information revelation in the auction, concerns over cognitive limits of bidders, decisions between the simultaneous auction and sequential Japanese auctions with package bidding, withdrawal procedures, and implementation. See Plott (1997), Porter (1999), McCabe, Rassenti, and Smith (1989), and Banks, Ledyard, and Porter (1989) for a discussion of experimental economics and its influence on early auction designs.

The debate surrounding the initial design of spectrum license auctions returned frequently to the following three key tradeoffs.

1. *Revenue versus efficiency*: As we describe more formally in Section 3.3, the theory of Bayesian mechanism design with independent private values identifies not only efficient mechanisms and revenue-maximizing mechanisms, but also mechanisms maximizing any weighting between efficiency and revenue. When there are k units for sale (assume production cost of zero for the seller) and there are N buyers each with single unit demand and private values $v_1, ..., v_N$, efficiency can be achieved while generating positive expected revenue using a Vickrey-Clark-Groves (VCG) mechanism. In this mechanism, the buyers submit reports of their values to the mechanism. The units are allocated to the k buyers with the highest reports and each of those k buyers pays an amount equal to the $k + 1^{\text{st}}$ highest report. By the usual second-price auction logic, it is a dominant strategy for each bidder to truthfully report its value, so the mechanism is efficient. The revenue maximizing auction would be different and would involve allocating units to the k buyers with the highest nonnegative virtual values,[33] possibly not selling all of the units.

   Results in the economics literature on the impossibility of efficient bilateral trade in environments with two-sided private information (e.g., Myerson and Satterthwaite (1983)) provide arguments for an emphasis on efficiency in the FCC auctions since decentralized secondary market transactions cannot be relied upon to quickly correct any inefficiencies in the initial allocation. The reality of frictions in the decentralized secondary market was evident during the period of time in which lotteries were used to allocate spectrum licenses. As argued by Milgrom (2004, p.4), "With so many parties and interests involved, the market took many years to recover from the initial fragmentation of spectrum ownership. During those years, investments were delayed and consumer services degraded. Getting the allocation right the first time does matter." However, the possibility of substituting revenue from a spectrum license auction for revenue obtained through distortionary taxes provides an argument for at least some emphasis on revenue.[34]

[33] A buyer's virtual value is an adjusted version of the buyer's value, taking into account the distribution from which the value is drawn. As shown by Bulow and Roberts (1989), the virtual valuation can be interpreted as marginal revenue.

[34] As described by Milgrom (2004, pp.19–20), critics of an auction approach to allocating spectrum licenses have argued based on the Coase Theorem, saying: "[O]nce the licenses are issued, parties will naturally buy, sell, and swap them to correct any inefficiencies in the initial allocation. Regardless of how license rights are distributed initially, the final allocation of rights will take care of itself. Some critics have gone even farther, arguing on this basis that the only proper object of the government is to raise as much money as possible in the

In resolving this tradeoff, the FCC was attentive to the authorizing legislation for auctions (the Communications Act of 1934 as amended by the Telecom Act of 1996), which suggests that efficiency concerns should dominate revenue concerns. Section 309(j) of the Act states that one objective of the auctions is "recovery for the public of a portion of the value of the public spectrum," but it also states that "the Commission may not base a finding of public interest, convenience, and necessity solely or predominantly on the expectation of Federal revenues." The FCC chose an ascending-bid auction format that, in the absence of reserve prices, is efficient at least in certain settings, such as when buyers have single-unit demand. With recoveries of value for the public in mind, the FCC established minimum opening bids, but minimum opening bids and reserve prices at FCC auctions have not been aggressive.[35]

We examine the revenue versus efficiency tradeoff in the context of centralized markets with privately informed buyers and sellers in Section 3.

2. *Open versus closed auctions*: We use the term "open" to describe auctions that allow information to be transmitted between bidders during the course of the auction and "closed" to refer to auctions that do not. Within each category, there can be differences in information revelation. For example, closed auctions may differ in what information is revealed to the public ex post, which may be important if bidders have a preference for privacy. Open auctions may differ in the type and amount of information bidders are given at each point in time, which may be important for preventing some collusive strategies.

The literature related to the "linkage principle," first identified by Milgrom and Weber (1982) and also referred to as the "publicity effect" in Milgrom (2004), argues for open

sale, because it should not and cannot control the final allocation."

[35]In the FCC's first auction, the minimum opening bids for the largest licenses were set at $500,000, but winning bids were $80 million. (FCC Auction 1 procedures are available at http://wireless.fcc.gov/auctions/01/releases/bip1.pdf and results are available at http://wireless.fcc.gov/auctions/01/charts/1_sum.gif.) In the FCC's 700 MHz Auction, reserve prices were based on auction results for AWS-1 spectrum licenses, which was believed to provide a conservative estimate of the market value of the licenses because the characteristics of the 700 MHz band were viewed as superior to those of the AWS-1 band. As stated in the procedures public notice for the 700 MHz Auction, "For the A, B, C, and E Blocks, we base the reserve prices on the respective market value estimates using AWS-1 bids, adding one percent, and rounding to the nearest thousand dollars. Because of the value-enhancing propagation characteristics and relatively unencumbered nature of the 700 MHz Band spectrum, we believe these are conservative estimates." (FCC Public Notice (DA 07-3415), paras. 53–54) With revenue in mind, the 700 MHz auction procedures specified that if the reserve price for the C block licenses was not met, then those licenses would be immediately reauctioned without the open access restrictions imposed on them. (See Brusco, Lopomo, and Marx (2011) for discussion of the contingent reauction format.)

auctions. The linkage principle states that, on average, auction revenues are enhanced by providing the bidders with as much information as possible about the value of the good. (For a formal statement of the linkage principle, see Appendix A.) When bidders' values have common value components, equilibrium bids must account for the information about other bidders' values that is revealed upon learning that you are the high bidder. This generates the so-called "winner's curse"—the information that you are the winner is negative in the sense that it indicates that other bidders' value estimates were lower than yours. In an ascending-bid environment with common values, a bidder will only remain active if the expected value of the object, conditional on all remaining bidders exiting at the next bid increment, remains greater than the price to be paid at the next bid increment. In such environments, theory predicts that ascending auctions have superior efficiency and revenue properties relative to sealed-bid auctions.[36] Intuitively, the information revealed at an ascending-bid auction as the auction progresses is that the remaining bidders' values remain above an increasing threshold, increasing the remaining bidders' conditional expected values. This effect is not present at a first-price sealed-bid auction. In addition, the linkage principle suggests that the seller should make available to bidders all information it has about the objects being sold. McAfee and McMillan (1987, p.730 and p.734) state, "More accurate information about the item's true value mitigates the effects of the winner's curse in causing the bidders to be cautious ..." and "You can encourage the bidders to raise their bids by having a policy of publicizing any information you yourself have about the item's true value."[37]

The experimental literature also supports the use of open formats as it facilitates learning and price discovery. Experimental evidence suggests that open formats are easier to understand for bidders than closed formats and strategies employed in open formats tend to be more consistent with those predicted by theory.[38] As suggested by Banks, Ledyard, and Porter (1989) and summarized concisely in Kwasnica and Sherstyuk (2013), the

[36] More formally, if bidders' expected values are increasing in their types and their types are affiliated (see, e.g., Milgrom, 2004, Section 5.4.1), then for each type of bidder, the conditional expected price in the ascending-bid auction, given that the type wins, is higher than the corresponding bid at the first-price auction (see, e.g., Milgrom, 2004, Theorems 5.4.14 and 5.4.17). Furthermore, under additional conditions, the equilibrium of the ascending-bid auction is efficient (see, e.g., Milgrom, 2004, Theorem 5.4.12 for the definition of the relevant equilibrium bidding strategies and Theorem 5.4.13 on efficiency).

[37] For a formalization, see Milgrom (2004, Theorems 5.4.15 and 5.4.18).

[38] See Kwasnica and Sherstyuk (2013) for a review of this literature in relation to multi-unit auctions. See the reviews of Kagel and Roth (1995) and Kagel and Levin (2013) for a survey of this literature as it relates to English auctions and second-price sealed bid auctions.

decision to allow for ascending bids was motivated in part by "... the feeling, based on experimental evidence, that in an environment in which the basis for common knowledge are little understood and controlled, iterations with commitment allow subjects to 'feel their way'...." Experimental researchers also note that combinatorial clock designs, in which the auctioneer incrementally increases the price while bidders submit bids for the packages they would like to purchase at each price, perform best when not all information is given to bidders.[39] For instance, Smith writes, "strategic behavior is controlled by feeding back only the information bidders need to know (item prices) in order to avoid bidding more than their maximum willingness to pay. For this purpose bidders do not need to know who is bidding, how many are bidding, and on which items or packages." (Smith, 2006, p.xiv)

In contrast, the literature on collusion at auctions argues for closed auctions. Sealed-bid auctions minimize the possibility that bidders might support collusive equilibria by retaliating against one another for deviations.[40] Sealed-bid auctions also minimize opportunities for strategic bidding such as retaliatory bidding, attempts by bidders to establish reputations for retaliatory bidding to deter others from bidding against them, attempts to signal divisions of the market or trades of licenses in different geographic areas, gaming of the auction's activity rule,[41] and other attempts to deter or foreclose entry into markets.

The resolution of this tradeoff was that, based on the guidance of the linkage principle, the FCC chose an open auction format. "Although the experts agreed that collusion among the bidders (which ultimately did occur; The Economist, May 17, 1997, p. 86) is more easily sustained within an open auction, in the end the faith placed in the linkage principle outweighed this concern and an open auction format was employed. Indeed, according to McMillan (1994), the experts 'judged [the negative collusion effect] to be outweighed by the bidders' ability to learn from others' bids in the open auction.'" (Perry and Reny, 1999, p.895) In the words of Evan Kwerel, "In the end, the FCC chose an ascending bid mechanism, largely because we believed that providing bidders with more information

[39] Evidence is mixed on how much information should be omitted. Adomavicius, Curley, Gupta, and Sanyal (2012), for instance, finds improvement in efficiency when bidders are informed about winning allocations in addition to simply observing bids placed.

[40] In an open auction setting, opportunities for collusion can be reduced by using an auction format that limits information on bidder identities. The FCC took steps in this direction starting with its proposal for an "anonymous" auction format for Auction 66 (AWS-1) in 2006, and has since moved to an ascending-bid auction format that does not reveal the identities of bidders during the course of the auction (Marx (2006)).

[41] See Marx, 2006, n.6.

would likely increase efficiency and, as shown by Milgrom and Weber (1982), mitigate the winner's curse." (Introduction by Kwerel in Milgrom, 2004, p.xvii)

We take up the issues of common values and collusion in the context of centralized secondary markets in Section 4.

3. *Complexity of multi-object auctions with complements and substitutes*: When initially developing its auction design, the FCC had to address the issue that it needed to auction a large number of heterogeneous licenses where there were potentially strong complementarity as well as substitutability among various licenses. When the objects being sold at a multi-object auction are potentially complements with one another, then bidders can face an "exposure problem"—when bidding on a set of complementary licenses, bidders risk winning only a subset of those licenses, in which case the value of the subset may be less than the amount paid if the bids on the licenses were based on the value of the entire set.[42] The presence of complementarities among spectrum licenses and the exposure problem favor the use of combinatorial or package bidding; however, the associated complexity can be daunting. When objects being sold are substitutes, bidders value the ability to switch among objects as information is revealed about the relative prices of the objects.[43] Thus, the substitutability of spectrum licenses favors the simultaneous auction of licenses, with a simultaneous closing rule that continues to allow bidding on any license until there are no longer bids on any license (otherwise, a bidder that is outbid on one license might not have an opportunity to place a bid on a substitute).

   In resolving this tradeoff, the FCC adopted an auction format that simultaneously auctioned the licenses and that included a simultaneous closing rule, addressing the issue of substitutes. There were concerns regarding the complexity of allowing combinatorial bids.[44] Combinatorial auctions can quickly become complicated as the number of objects grows, and with many overlapping packages, just determining the identity of the winner is a computationally hard problem (Milgrom, 2004, p.298). Instead, in order to address the exposure problem, the FCC allowed bidders the option to withdraw bids subject to a

[42]For example, licenses to operate in the north and south may not be of great value without a license to operate in the central area in between.

[43]For example, suppose a bidder is interested in purchasing the pair of licenses A and B or the pair of licenses C and D, depending on the prices, but not both pairs. After initially bidding on A and B, the bidder might learn that the pair C and D offers better value, and so prefer to focus instead on those licenses.

[44]The combinatorial auction design proposed by the National Telecommunications and Information Administration "seemed far too complex for the FCC to implement in the time available." (Introduction by Kwerel in Milgrom, 2004, p.xxii)

penalty.[45] With this option, a bidder could avoid the situation where it wins only a subset of its desired licenses. It was argued based on the theory and experimental evidence that the FCC could achieve most of the benefits of a combinatorial auction with the simpler simultaneous design (Introduction by Kwerel in Milgrom, 2004, p.xxii).[46]

We discuss in Section 3 the issue that in the design of centralized secondary markets, concerns related to complementarities and substitutabilities may be dominated by concerns regarding the trading network.

Ultimately, based on substantial input from FCC and academic economists, the FCC developed a simultaneous multiple round (SMR) auction. This basic auction format, with various modifications and extensions,[47] continues to be used today.[48] The overwhelming conclusion has been that auctions have offered a superior market design relative to prior options used by the FCC: "Our experience has been that auctions are superior to the alternatives because they are more likely to award licenses fairly and efficiently." (Kwerel and Strack, 2001, p.1)

Economic theory and experimental work provided a valuable foundation for the development of these auctions, and, along with empirical work, has continued to inform modifications to the design in the years since 1994.[49] The FCC has allowed limited combinatorial bidding at certain auctions. The FCC recognizes the benefits of what it refers to as package bidding,[50] but the

[45] In recent FCC auctions, bidders have been allowed one round in which they may withdraw any of their standing high bids, subject to a withdrawal payment that is equal to the difference between the amount of the withdrawn bid and the amount of the winning bid for the license in that auction or a subsequent auction in which the license sells (47 C.F.R. 1.2104(g)).

[46] The alternative design was an auction in which bidders could submit a value for packages of licenses and then single licenses would be auctioned sequentially one at a time using a Japanese auction in which bidders dropped out as prices rose. At the end of the auction, if a package had a higher value than the individual licenses, the objects were allocated to the package bidder at the sum of the component prices. This auction was shown experimentally to be less efficient and more complicated than the format eventually adopted (Plott (1997)).

[47] A number of relatively minor modifications to the original design have been made to address susceptibility to collusion by bidders. See, e.g., Brusco and Lopomo (2002), Cramton and Schwartz (2000, 2002), Kwasnica and Sherstyuk (2001), McAfee and McMillan (1996a), and Marx (2006). Regarding the use of a contingent re-auction format, see Brusco, Lopomo, and Marx (2011).

[48] "In a simultaneous multiple-round (SMR) auction, all licenses are available for bidding throughout the entire auction, thus the term 'simultaneous.' Unlike most auctions in which bidding is continuous, SMR auctions have discrete, successive rounds, with the length of each round announced in advance by the Commission. After each round closes, round results are processed and made public. Only then do bidders learn about the bids placed by other bidders. This provides information about the value of the licenses to all bidders and increases the likelihood that the licenses will be assigned to the bidders who value them the most. The period between auction rounds also allows bidders to take stock of, and perhaps adjust, their bidding strategies. In an SMR auction, there is no preset number of rounds. Bidding continues, round after round, until a round occurs in which all bidder activity ceases. That round becomes the closing round of the auction." (FCC website, http://wireless.fcc.gov/auctions/default.htm?job=about_auctions&page=2, accessed June 28, 2012)

[49] For a less generous view of the role of economics in FCC auction design, see Nik-Khah (2008).

[50] "This approach allows bidders to better express the value of any synergies (benefits from combining complementary items) that may exist among licenses and to avoid the risk of winning only part of a desired set." (FCC website, http://wireless.fcc.gov/auctions/default.htm?job=about_auctions&page=2, accessed June 28, 2012)

FCC has balanced these benefits with the potential costs of complexity by limiting the set of packages on which bidders may submit bids, generally to a set of packages with a hierarchical structure ("hierarchical package bidding" or HPB).[51] Under some reasonable restrictions on preferences, it may be possible to maintain efficiency with only restricted package bidding, such as hierarchical package bidding. Experiments to test various package bidding formats have led, at least in part, to further work on the ability of bidders to deal with complex choices.[52] The FCC has also used an auction design in which the auction mechanism itself selects among multiple competing band plans, which differs from the FCC's standard approach of predetermining the single band plan under which licenses will be offered at auction.[53]

Since 1994, the FCC has held more than 80 auctions, has issued more than 36,000 licenses, and has raised more than $50 billion for the United States Treasury.[54] The program has been viewed as a great success and has been emulated around the world.[55] As indicated by Figure 2, the FCC's use of auctions starting in 1994 seems to stimulated research in the economics discipline, which saw an upsurge of interest in auctions in the 1990s and 2000s.[56]

Until now, FCC auctions have focused only on getting licenses designated by the FCC into

[51]When packages have a hierarchical structure, they are nested so that whenever two packages overlap, one is completely contained within the other. The hierarchical structure of HPB was suggested by Rothkopf, Pekec, and Harstad (1998). The pricing mechanism for HPB was proposed by Goeree and Holt (2010). In the decision to use the SMR-HPB design, a number of other formats were studied experimentally. See Kwasnica, Ledyard, Porter, and DeMartini (2005), Brunner, Goeree, Holt, and Ledyard (2010), Goeree, Holt, and Ledyard (2007), Banks, Olson, Porter, Rassenti, and Smith (2003), and Porter, Rassenti, Roopnarine, and Smith (2003). The FCC used the SMR-HPB format in Auction 73 for C-block licenses, allowing bidding on three packages that provided a partition of the C-block licenses as well as the individual licenses. (FCC website, Auction 73 Procedures Public Notice, available at http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-07-4171A1.pdf, accessed June 28, 2012)

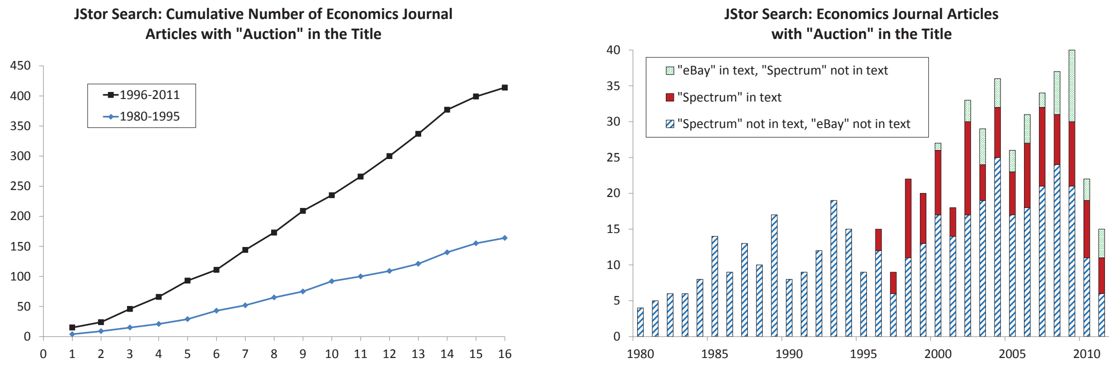
[52]See, e.g., Scheffel, Ziegler, and Bichler (2012) and Kagel, Lien, and Milgrom (2010).

[53]In this type of mechanism, bidders submit bids on licenses defined under multiple band plans and the band plan implemented is the one with the greatest total bids. See the FCC website, Auction 65 Procedures Public Notice, available at http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-06-299A1.pdf, accessed June 28, 2012.

[54]Congressional Hearing on "Keeping the New Broadband Spectrum Law on Track" (U.S. House Energy and Commerce Committee, 12 Dec. 2012), statement of FCC Commissioner Jessica Rosenworcel.

[55]Most countries initially adopted the SMR design. Some countries have since switched to combinatorial clock or clock-proxy designs. See Porter, Rassenti, Roopnarine, and Smith (2003), Banks, Olson, Porter, Rassenti, and Smith (2003), Ausubel, Cramton, and Milgrom (2006), and Charles River and Associates Inc. and Market Design Inc. (1998).

[56]A search of JStor for articles in economics journals in English that have "auction" in the title (searching on auction* to allow for variations) reveals a significant uptick in the average number of papers per year between the years 1980–1995, when the average number of papers with "auction" in the title was 10.25/year, and 1996-2011, when the average was 25.875/year. Based on JStor searches, 1996 is the first year in which there is a paper with "auction" in the title and "spectrum" in the text. In 1998, 50% of the papers with "auction" in the title mention "spectrum" in the text. In 13 of the 16 years 1996–2011, "spectrum" paper are 20% or more of the papers with "auction" in the title. The increase in auction research is also motivated by internet auctions. A search for "auction" papers that mention eBay in the text shows papers starting in 2000, with a peak in 2009. Still, it appears that the spectrum license auctions played a role in boosting auction-related research.



(a) Cumulative auction papers starting in 1980 versus starting in 1996

(b) Auction papers referencing spectrum versus not referencing spectrum

Figure 2: Growth in the economics literature on auctions

the hands of buyers. Users of spectrum have relied on these auctions as well as privately negotiated secondary market transactions to adjust their holdings as demand, technology, and the set of market participants evolve over time.[57] However, things are about to change. In February 2012, Congress authorized the FCC to conduct an "incentive auction," which will transfer a set of licenses to be determined by the incentive auction itself from television broadcasters to providers of mobile wireless services.[58] The FCC is charged with designing a two-sided market that will facilitate the transfer of broadcast licenses from the current holders of those licenses to providers of mobile wireless services. The authorizing legislation for the incentive auction states that, in order for any transactions to occur, the sale of licenses to providers of wireless services must raise funds sufficient to cover: (i) the accepted bids of the television broadcasters, (ii) the FCC's out-of-pocket costs of conducting the auction, and (iii) the expected reimbursement costs of broadcasters and certain other parties associated with the license reassignments occurring as part of the auction.[59] Although the legislation authorizing incentive auctions does not require that the FCC raise a minimum amount of revenue or that it maximize proceeds from

[57]FCC approval is required for all license transfers. Historically, the FCC has handled repurposing administratively (for examples see Kwerel, LaFontaine, and Schwartz, 2012, Section 1.1.1).

[58]The reassigned licenses will be for flexible use (Kwerel, LaFontaine, and Schwartz (2012)). Beyond just authorizing the use of auctions, the Spectrum Act orders that the FCC may only accept a bid if at least two competing licensees have participated in a reverse auction to determine the amount of compensation for voluntarily relinquishing spectrum usage rights (47 U.S.C. 309(j)(8)(G)(ii) and FCC NPRM "Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions," p.12, n.52).

[59]Public Law 112-96, Section 6403(c)(2)(B), http://www.gpo.gov/fdsys/pkg/PLAW-112publ96/pdf/PLAW-112publ96.pdf.

the auction, statements made by both members of Congress and FCC Commissioners reveal that substantial revenue is expected from the auction.[60] This leaves the FCC in the position of needing to develop a centralized market that provides incentives for broadcasters to relinquish spectrum rights, "repacking" those who do not (reassigning them to different channels), and allocating the reformulated licenses to wireless service providers, all while generating revenue for the public.

Just as the call to design primary markets for spectrum licenses mobilized economists and spurred thinking, research, and debate on auctions, there is the potential for a similar effect in the wake of the call for the design of an incentive auction.[61] The literature explicitly addressing incentive auctions of the type envisioned by the FCC is thin at the moment,[62] and many of the foundational results required to advance this literature still need to be developed.

3 Market Design with Two-Sided Private Information

In this section, we lay out the underpinnings of market design with privately informed buyers and sellers. We introduce in Section 3.1 the general setup. In Section 3.2, we show that with

[60]In a Congressional Hearing on "Keeping the New Broadband Spectrum Law on Track" (U.S. House Energy and Commerce Committee, 12 Dec. 2012), FCC Commissioner Robert McDowell stated, "The overarching goals of the law are to auction all reclaimed spectrum to offer consumers more opportunities to harness wireless broadband, while raising badly needed funds for the U.S. Treasury and attempt to fund a nationwide, interoperable, mobile broadband public safety network." In the same hearing, FCC Commissioner Ajit Pai argued that if the incentive auction did not yield any net revenues, "That would mean no money for the First Responder Network Authority (FirstNet) to build out a nationwide, interoperable public safety broadband network; no money for state and local first responders; no money for public safety research; no money for deficit reduction; and no money for next-generation 911 implementation. Most of the problem stems from the structure of the proposed auction. The only closing condition set forth in the NPRM is that the revenues from the forward auction must cover the costs of the reverse auction." In the question-and-answer portion of the hearing, the FCC Commissioners were asked, "Should the commission ensure that the auction raises $7b [for a nationwide interoperable public safety network]?" The responses were: "Pai: Yes, we should focus on maximizing revenue. Rosenworcel: Yes, absolutely. Clyburn: Absolutely. McDowell: Yes. Genachowski: Yes." According to the *New York Times* ("Republicans Tell F.C.C. Not to Give Away Airwaves," Edward Wyatt, 12 Dec. 2012), "Representative Greg Walden, an Oregon Republican who is chairman of the subcommittee on communications and technology, said that the law that gave the F.C.C. the ability to conduct 'incentive auctions' of newly available spectrum required 'maximizing the proceeds from the auction."' According to *Politico Pro* ("Terry: FCC's spectrum auction all about raising $24 billion," Tony Romm, 9 Jan. 2013), "Rep. Lee Terry emphasized the agency is under a strict mandate to raise some big bucks. 'Let's not fool ourselves, the major underlying maybe unstated reason for this auction is the money,' said the Nebraska Republican, speaking at the 2013 International CES. 'It was estimated we could raise $24 billion. That's not specifically laid out, but I can guarantee you that was part of the discussion. So we want the FCC to design the rules to get us at least $24 billion."'

[61]The FCC has hired teams of economists to advise the process: "To help design and implement incentive auctions the FCC retained leading experts in auction theory and implementation from Auctionomics and Power Auctions. The auction design team is composed of Professors Paul Milgrom, Jonathan Levin, and Ilya Segal of Stanford University, and Professor Lawrence Ausubel of the University of Maryland." (Kwerel, LaFontaine, and Schwartz, 2012, n.1)

[62]Existing papers include Bazelon, Jackson, and McHenry (2011), Mayo and Wallsten (2011), and Yun, Sarkani, and Mazzuchi (2012).

two-sided private information it is often impossible to allocate goods efficiently in an incentive compatible, individually rational manner without running a deficit. Thus, the tradeoff between revenue and efficiency appears to be more salient in environments with two-sided private information than in environments where only agents on one side are privately informed. We discuss this tradeoff from a Bayesian mechanism design perspective in Section 3.3 for the homogenous goods model in which buyers have unit demand and sellers have unit capacities. In Section 3.4, we discuss a number of mechanisms that are deficit free and thus likely to be practical in various circumstances. These include McAfee's (1992) dominant strategy mechanism for buyers and sellers with unit demands and unit capacities and a modification of this design that connects primary and centralized secondary markets in order to improve efficiency.

3.1 Setup

We consider a setup with B buyers $b \in \mathbb{B}$ and S sellers $s \in \mathbb{S}$, where $\mathbb{B}$ and $\mathbb{S}$ denote, respectively, the sets of buyers and sellers. Let $\mathbb{O}$ be the exogenously given set of indivisible objects or goods, whose cardinality is denoted K. These K goods can be combined into $P = 2^K - 1$ distinct (that is, mutually exclusive) and nonempty packages. Let $\mathbb{P} = 2^{\mathbb{O}}$ be the set of all possible packages, including the null package $\emptyset$, where a package is just a feasible set of objects x. An allocation specifies which seller produces which sets of goods, or packages, and which buyer receives which sets of goods. An allocation is feasible if the set of goods buyers receive is a (weak) subset of the goods that the sellers produce. In what follows, attention will be implicitly confined to feasible allocations. Implicit in this definition is the assumption that the packages that the sellers produce can be split up arbitrarily and recombined without any costs into alternative packages that the buyers receive. While this condition will naturally be met in many applications that come to mind, such as markets for spectrum licenses, it will not be satisfied universally. For example, if the objects are services that sellers provide to the buyers, such repackaging may entail costs.

We confine attention to quasilinear payoff functions. That is, if buyer b receives package x and makes the transfer payment t, her payoff is $v_b(x) - t$, where $v_b(.)$ is her valuation function. Similarly, if seller s produces package x and receives the transfer t his payoff is $t - c_s(x)$ with $c_s(.)$ denoting his cost function. We assume that $v_b(.)$ and $c_s(.)$ are private information of b and s for all $b \in \mathbb{B}$ and for all $s \in \mathbb{S}$. Let $\underline{v}$ and $\overline{v}$ be, respectively, the lowest and highest possible valuation of every buyer for any package and let $\underline{c}$ and $\overline{c}$ be, respectively, the lowest and highest possible cost of every seller for producing any package. We shall assume that

$$\underline{v} \le \underline{c} \quad \text{and} \quad \overline{v} \le \overline{c} \tag{3}$$

and that these bounds are common knowledge; in particular, they are known to the mechanism designer. Condition (3) implies that, depending on the buyers' and the sellers' types, no trade at all can be optimal. This condition guarantees that the least efficient buyer and seller types are well-defined and never trade under an efficient allocation rule. Absent this condition, it is well known from the setup with single-unit demand and supply that ex post efficient trade without a deficit may be possible. Makowski and Mezzetti (1993) observe the possibility of ex post efficiency without a deficit in a model with multiple buyers and one seller; see also Makowski and Mezzetti (1994) for a general characterization of Bayesian first-best mechanisms. Williams (1999) provides conditions for possibility of ex post efficiency without a deficit for the general model with multiple buyers and sellers in relation to the ordering of the bounds of the supports and the numbers of buyers and sellers.[63]

To make the problem interesting, we will also assume

$$\underline{c} < \overline{v}, \tag{4}$$

which implies that for some types of the buyers and sellers, some trade is efficient. We will also often assume that buyers' types and sellers' types are drawn independently from continuous distributions whose densities are positive everywhere on their respective supports $[\underline{v}, \overline{v}]^P$ and $[\underline{c}, \overline{c}]^P$.

The valuation of receiving and the cost of producing no package is normalized to 0. That is, $v_b(\emptyset) = 0 = c_s(\emptyset)$ for all b and s. It is sometimes convenient to denote by $\mathbf{v}_b = (v_b^1, .., v_b^P)$ buyer b's valuations for the P packages and by $\mathbf{c}_b = (c_s^1, .., c_s^P)$ seller s's costs of producing any of the P packages, and to let $\mathbf{v} = (\mathbf{v}_b)_{b \in \mathbb{B}}$ and $\mathbf{c} = (\mathbf{c}_s)_{s \in \mathbb{S}}$. Sometimes we will refer to $\mathbf{v}_b$ (and $\mathbf{c}_s$) as buyer b's (seller s's) type.

Observe that this setup encompasses a variety of models as special cases. **Homogenous goods** with decreasing marginal utility and increasing marginal costs correspond to the case in which for all $b \in \mathbb{B}$ and $s \in \mathbb{S}$, $v_b(Y)$ and $c_s(Y)$ depend only on the cardinality of Y

[63] Another possibility result has been obtained by Cramton, Gibbons, and Klemperer (1987) when initial ownership shares are interior. They show that the joint ownership of an indivisible good can be resolved efficiently with an incentive compatible, interim individually rational mechanism if the initial ownership shares are sufficiently close to equal. Intuitively, fractional initial ownership shares reduce the incentives for misrepresentation because agents may end up as either buyers or sellers.

and for all sets Y and $x, y \notin Y$, $v_b(Y \cup \{x\}) - v_b(Y) > v_b(Y \cup \{x, y\}) - v_b(Y \cup \{x\})$ and $c_s(Y \cup \{x\}) - c_s(Y) < c_s(Y \cup \{x, y\}) - c_s(Y \cup \{x\})$.[64] A special case of the homogenous goods model is the **unitary framework**, in which for any x and y, $v_b(\{x\}) = v_b$ and $c_s(\{x\}) = c_s$ and $v_b(\{x, y\}) - v_b(\{x\}) = \underline{v}$ and $c_s(\{x, y\}) - c_s(\{x\}) = \overline{c}$.[65] The **assignment model** of Shapley and Shubik (1972), in which each seller s has the capacity to produce one unit of a (possibly idiosyncratic) good s at some cost c_s, while every buyer has unit demand but possibly heterogenous valuations for the goods produced by different sellers, can be incorporated by first identifying good or object o_s with seller s for all $s \in \mathbb{S}$ and second by assuming $c_s(o_s) = c_s$ and $c_s(p) = \overline{c}$ for any $p \neq \{o_s\}$ and $v_b(o_s) = v_b^s$ and $v_b(p) = \underline{v}$ for any $p \notin \mathbb{O}$. **Heterogenous objects with substitute preferences and costs** (or with substitutes, for short) corresponds to the case where for any disjoint and nonempty sets Y and Z it is true that $v_b(Y \cup Z) \leq v_b(Y) + v_b(Z)$ and $c_s(Y \cup Z) \geq c_s(Y) + c_s(Z)$ for all b and s. The **one-to-one matching model**, introduced by Shapley (1962), encompasses the assignment model and the unitary framework as special cases. However, it is strictly more general than these because it imposes no specific restrictions on the sets of goods traded by a buyer and a seller who are matched or on their valuation and cost functions. It only assumes that all matches are pairwise.[66]

Let $X = ((x_b)_{b \in \mathbb{B}}, (x_s)_{s \in \mathbb{S}})$ be a feasible allocation that gives buyer b the package consisting of the set of objects x_b and induces seller s to produce the goods x_s. Social welfare $W(\mathbf{v}, \mathbf{c}; X)$ given valuations and costs $(\mathbf{v}, \mathbf{c})$ and allocation X is given as

$$W(\mathbf{v}, \mathbf{c}; X) = \sum_{b \in \mathbb{B}} v_b(x_b) - \sum_{s \in \mathbb{S}} c_s(x_s). \tag{5}$$

Let X^* be a maximizer of $W(\mathbf{v}, \mathbf{c}; X)$. When there is no risk of confusion, we drop the dependence on $(\mathbf{v}, \mathbf{c})$ and simply denote maximum welfare by W, that is $W := W(\mathbf{v}, \mathbf{c}; X^*)$. Notice also that X^* will vary with $(\mathbf{v}, \mathbf{c})$. It is also useful to denote $W_{-i,-j} = \max_X \sum_{b \in \mathbb{B} \setminus i} v_b(x_b) - \sum_{s \in \mathbb{S} \setminus j} c_s(x_s)$. When only buyers i or sellers j is excluded, we write $W_{-i,\cdot}$ or $W_{\cdot,-j}$, respectively.

[64]This was the setup studied by Vickrey (1961).

[65]The assumption of homogenous good with unit demands and supplies is a standard assumption in the literature on Bayesian mechanism design.

[66]Shapley (1962) framed the problem as that of pairwise matching workers and machines, where every pair $i - j$ produces some surplus α_{ij}. Setting $\alpha_{ij} = \max_p v_i(p) - c_j(p)$ this is isomorphic to the problem of interest here.

3.2 Impossibility of Ex Post Efficient Trade without Running a Deficit

We derive a well-established result that pertains to market making in environments with private information on both sides of the market: Under fairly general conditions, it is impossible to allocate objects efficiently while respecting agents' individual rationality and incentive compatibility constraints without running a deficit.

The well-known revelation principle (Myerson (1981)) implies that without loss of generality we can restrict our attention to direct mechanisms, that is, mechanisms according to which every agent is simply asked to report his type. A similarly well-known result, often called the revenue equivalence theorem, states that under general conditions, which will be satisfied here, the expected payoff of any agent of any type will differ across two mechanisms with the same allocation rule $X(\mathbf{v}, \mathbf{c})$ by at most a constant.[67] Consider the VCG mechanism, so named after the independent contributions by Vickrey (1961), Clarke (1971), and Groves (1973). The VCG mechanism is a direct mechanism that uses an efficient allocation rule $X^*(\mathbf{v}, \mathbf{c})$. The transfer payment t_b from buyer b to the mechanism when the types are $(\mathbf{v}, \mathbf{c})$ is

$$t_b(\mathbf{v}, \mathbf{c}) = W_{-b,\cdot} - (W - v_b(x_b^*)) \tag{6}$$

while the transfer payment t_s to seller s is

$$t_s(\mathbf{v}, \mathbf{c}) = W + c_s(x_s^*) - W_{\cdot,-s}, \tag{7}$$

where x_b^* is the package b receives and x_s^* is the package s produces under $X^*(\mathbf{v}, \mathbf{c})$. Notice that under the VCG mechanism, revenue when the types are $(\mathbf{v}, \mathbf{c})$, denoted $R(\mathbf{v}, \mathbf{c})$, is

$$R(\mathbf{v}, \mathbf{c}) = \sum_{b \in \mathbb{B}} t_b(\mathbf{v}, \mathbf{c}) - \sum_{s \in \mathbb{S}} t_s(\mathbf{v}, \mathbf{c}) = W + \sum_{b \in \mathbb{B}} (W_{-b,\cdot} - W) + \sum_{s \in \mathbb{S}} (W_{\cdot,-s} - W).$$

The VCG mechanism is incentive compatible because every agent has a dominant strategy to report his type truthfully. It is also individually rational because $v_b(x_b^*) - t_b(\mathbf{v}, \mathbf{c}) \geq 0$ and $t_s(\mathbf{v}, \mathbf{c}) - c_s(x_s^*) \geq 0$ for any $b \in \mathbb{B}$ and any $s \in \mathbb{S}$ and any $(\mathbf{v}, \mathbf{c})$.

The revenue equivalence theorem implies that all mechanisms with the same allocation rule have the same payment rule up to a constant. This constant corresponds to the payment given to buyers and sellers who do not trade in equilibrium. Condition (3) implies that the least efficient type of a seller (that is a seller whose cost of production is $\overline{c}$ for every package) and

[67] A first instance of revenue equivalence was noticed by Vickrey (1961, 1962). Myerson (1981) and Riley and Samuelson (1981) provide general formulations and formalization. The revenue equivalence theorem we are invoking here is due to Krishna and Maenner (2001); see also Krishna (2002).

the least efficient type of a buyer (that is, a buyer who values every package at $\underline{v}$) never trade under an efficient allocation rule. Given that the VCG mechanism is based on such an allocation rule, and $W_{-b,.} = W$ and $W_{.,-s} = W$ for any b and s that do not trade, it follows that the payments to and from such agents are 0, and so are their payoffs. A consequence of the revenue equivalence theorem is, therefore, that any other incentive compatible, individually rational and efficient mechanism generates weakly less revenue than $R(\mathbf{v}, \mathbf{c})$ when the types are $(\mathbf{v}, \mathbf{c})$. Consequently, to prove that, under conditions that are to be specified, it is impossible to allocate objects efficiently while respecting agents' individual rationality and incentive compatibility constraints without running a deficit, it is sufficient to show that the VCG mechanism runs a deficit.[68] This is what we do now.

As additional notation, let L^* denote the network of trading links in the bipartite graph that is induced by the efficient allocation X^* whose typical element is $l^*_{bs} \in \{0, 1\}$ with $l^*_{bs} = 1$ meaning seller s produces a non-empty set of goods for buyer b and $l^*_{bs} = 0$ meaning that seller s produces nothing for buyer b.[69] Accordingly, the set of goods s produces for b under X^* is denoted x^*_{bs}. An allocation rule $X(\mathbf{v}, \mathbf{c})$ specifies for every possible $(\mathbf{v}, \mathbf{c})$ a feasible X that will be implemented. An allocation rule is ex post efficient if it specifies an efficient allocation for every $(\mathbf{v}, \mathbf{c})$.

We make the following two assumptions: For any $(\mathbf{v}, \mathbf{c})$, we assume that

$$W_{.,-s} - W_{-b,-s} + W_{-b,.} - W_{-b,-s} \leq W - W_{-b,-s} \quad \text{for all} \quad b \in \mathbb{B}, s \in \mathbb{S} \tag{8}$$

and

$$\sum_{l^*_{bs} \in L^*} (W - W_{-b,-s}) \geq W. \tag{9}$$

Condition (8) has a simple interpretation. The expressions $W_{.,-s} - W_{-b,-s}$ and $W_{.,-s} - W_{-b,-s}$ capture, respectively, the individual marginal contribution to welfare of buyer b and seller s to an economy that consists of all buyers other than b and all sellers other than s. The right side of (8) is the marginal contribution of adding the pair consisting of b and s to the economy without this pair. Condition (8) then simply states that the marginal contribution of the pair is not less than the sum of the individual marginal contributions. In other words, buyers and

[68] The proof of the Myerson-Satterthwaite (1983) impossibility result using revenue equivalence was developed by Williams (1999) and independently by Krishna and Perry (2000), with awareness of the argument evident in Makowski and Mezzetti (1994). For an alternative approach and generalization, see Makowski and Ostroy (1989) and the extension by Segal and Whinston (2012).

[69] For a given X^* (which need not be unique, as is typically the case with homogenous goods), L^* is unique because we consider different units of a homogenous goods to be different goods.

sellers are complements. Shapley (1962) shows that condition (8) holds for any model with one-to-one matching.[70]

Condition (9) states that the sum of all the pairwise marginal contributions over all the optimal trading links gives a number that is no less than total welfare. This condition is satisfied, with equality, in setups with one-to-one matchings such as the unitary framework with homogenous goods, the assignment model, or any other model in which matchings are always pairwise. Perhaps less evidently, it holds if all buyers have substitutes preferences and sellers have substitutes costs.[71]

We can now state the theorem.[72]

Theorem 1 *Assume that buyers' and sellers' types are drawn independently from distributions with positive densities everywhere on their respective supports and that conditions* (8) *and* (9) *hold. Then it is impossible to allocate goods efficiently via an incentive compatible and individ-*

[70]In one-sided setups, Bikhchandani and Ostroy (2006) show that buyers (and sellers) are substitutes. The corresponding result for a two-sided setup is an open question.

[71]Consider a component $C \in \mathbb{C}^*$ of the optimal trading network L^*, where $\mathbb{C}^*$ is the set of all components (recall that a component of a network consists of a set of nodes that are only linked to other nodes in the same component). Let $W_{-\mathbb{I},-\mathbb{J}} = \max_X \sum_{b\in\mathbb{B}\setminus\mathbb{I}} v_b(x_b) - \sum_{s\in\mathbb{S}\setminus\mathbb{J}} c_s(x_s)$. When only a set of buyers $\mathbb{I}$ or a set of sellers $\mathbb{J}$ are excluded, we write $W_{-\mathbb{I},.}$ and $W_{.,-\mathbb{J}}$, respectively. Letting W^C be the welfare created in component C, we have $W = \sum_{C\in\mathbb{C}^*} W^C$. Let $L^*(C)$ be the subset of optimal trading links in L^* that contain nodes in C, and denoted by $\mathbb{B}(C)$ and $\mathbb{S}(C)$ the sets of buyers and sellers in C. Since $W = \sum_{C\in\mathbb{C}^*} W^C$, it suffices to show that, for every $C \in \mathbb{C}^*$,

$$\sum_{l^*_{ij}\in L^*(C)} (W - W_{-i,-j}) \geq (W - W_{-\mathbb{B}(C),-\mathbb{S}(C)}) = W^C. \tag{10}$$

Noticing that the summand on the left side can be written as $W - W_{-i,-j} = W - W_{-\mathbb{B}(C),-\mathbb{S}(C)} + W_{-\mathbb{B}(C),-\mathbb{S}(C)} - W_{-i,-j}$, condition (10) can be rewritten as

$$(|L^*(C)| - 1)(W - W_{-I,-J}) \geq \sum_{l^*_{ij}\in L^*(C)} (W_{-i,-j} - W_{-\mathbb{B}(C),-\mathbb{S}(C)}) \tag{11}$$

Optimality of the allocation $X^*(\mathbf{v}, \mathbf{c})$ implies that $W_{-i,-j} - W_{-\mathbb{B}(C),-\mathbb{S}(C)} + v_i(x^*_{ij}) - c_j(x^*_{ij}) \leq W^C$, where $x^*_{ij} \in X^*(\mathbf{v}, \mathbf{c})$ is the set of goods i and j trade under $X^*(\mathbf{v}, \mathbf{c})$ because otherwise $X^*(\mathbf{v}, \mathbf{c})$ could not be optimal. Thus, a sufficient condition for (11) is $(|L^*(C)| - 1)(W - W_{-\mathbb{B}(C),-\mathbb{S}(C)}) \geq |L^*(C)|(W - W_{-\mathbb{B}(C),-\mathbb{S}(C)}) - \sum_{l^*_{ij}\in L^*(C)}(v_i(x^*_{ij}) - cj(x^*_{ij}))$, which, after eliminating terms, reads as:

$$\sum_{l^*_{ij}\in L^*(C)} (v_i(x^*_{ij}) - c_j(x^*_{ij})) \geq W - W_{-\mathbb{B}(C),-\mathbb{S}(C)} = W^C. \tag{12}$$

A sufficient condition for (12) is that each buyer has substitutes preferences and each seller has a substitutes costs, which implies that welfare is subadditive.

Two remarks are in order. First, substitutes are clearly only sufficient for (12) to hold. Cases where (12) holds despite some complementarities can easily be constructed but the more general conditions under which this is the case prove, naturally, harder to characterize concisely. Second, the inequality that leads to (12) will, generically, be strict. Therefore, (12) will typically be strict, which reinforces the notion that (9) will hold outside the domain of substitutes preferences and costs.

[72]Williams (1999, Theorem 4 and Table 1) shows that the result of Theorem 1 is sensitive to assumptions on the supports of the distributions from which buyers and sellers draw their values and costs. Recall that we assume that $\underline{v} \leq \underline{c}$ and $\overline{v} \leq \overline{c}$, guaranteeing overlapping support for the range of values and costs where trade generates surplus. This corresponds to row 1 in Table 1 of Williams (1999).

ually rational mechanism without running a deficit in expectation. Moreover, given an efficient, individually rational, and incentive compatible mechanism, there is no realization $(\mathbf{v}, \mathbf{c})$ *such that the mechanism produces a surplus for that realization.*

Proof of Theorem 1: As argued in the text, to prove the second part of the theorem it suffices to show that the VCG mechanism never runs a surplus, i.e., $R(\mathbf{v}, \mathbf{c}) \leq 0$. The first part is then an implication of the second part and the Myerson-Satterthwaite impossibility theorem.

Observe first that $\sum_{l^*_{bs} \in L^*}[W - W_{-b,.} + W - W_{.,-s}] \geq \sum_{b \in \mathbb{B}}(W - W_{-b,.}) + \sum_{s \in \mathbb{S}}(W - W_{.,-s})$ because the individual marginal contributions $W - W_{-b,.}$ and $W - W_{.,-s}$ are 0 for all agents who do not trade and every agent b or s who does trade has at least one trading link $l^*_{bs} = 1$ but may have more than one. Therefore, if we can show that $W - W_{-b,.} + W - W_{.,-s} \geq W - W_{-b,-s}$ for all b and s, we are done. To see that this is true under the conditions mentioned, assume toward a contradiction the contrary, that is, assume

$$W - W_{-b,.} + W - W_{.,-s} < W - W_{-b,-s}. \tag{13}$$

Inequality (8) is equivalent to $W_{.,-s} \leq W - W_{-b,.} + W_{-b,-s}$. We thus conclude that the left side of (13) is not less than $W - W_{-b,.} + W - (W - W_{-b,.} + W_{-b,-s}) = W - W_{-b,-s}$, which is the expression on the right side of (13) and thus delivers the desired contradiction. ■

When optimal matchings are always one-to-one, the nature of the goods (substitutes or complements) does not affect whether or not condition (9) holds because it always does.[73] Similarly, whether goods are perceived as substitutes or complements does not change that fact that condition (9) holds whenever there is only one agent on one side of the market: The marginal contribution of a monopolistic seller or monopsonistic buyer to social welfare is equal to social welfare, so, because the sum of the marginal contributions of the agents on the other side of the market is, generically, non-negative, the condition is satisfied. It is in this sense that the trading network appears to be more important than the nature of the goods being traded.[74]

[73] Beyond the unitary framework, this may be a good model when buyers have preferences over products (say, houses) that are tailored to the customer by the sellers, where each product consists of multiple components or objects (bathrooms, bedrooms, patios, and so on) and each buyer only has demand for one product and every seller can only produce one product.

[74] The network of trade does not play any role in one-sided setups with a single seller (or a single buyer) whose type is known.

3.3 Trading off Revenue and Efficiency

An implication from the preceding analysis and discussion is that in designing mechanisms for markets with two-sided private information, there is a tradeoff between revenue and efficiency. In the environment with two-sided private information, this tradeoff may be more salient than in a setup with private information on one side only because there ex post efficiency and positive revenue can be achieved. This motivates us to study this tradeoff in some detail. Our treatment is largely based on the setup and analysis in Loertscher and Niedermayer (2013, Appendix C).

Consider a Bayesian mechanism design setup, in which goods are homogenous and buyers have unit demands and sellers have unit supplies. Moreover, we assume that every buyer b draws her valuation v_b independently from some distribution F with density $f(v_b) > 0$ for all $v_b \in [\underline{v}, \overline{v}]$. Similarly, every seller s draws his cost of production c_s independently from some distribution G with density $g(c_s) > 0$ for all $c_s \in [\underline{c}, \overline{c}]$. For $\alpha \in [0, 1]$ define

$$\Phi_\alpha(v) := v - \alpha \frac{1 - F(v)}{f(v)} \quad \text{and} \quad \Gamma_\alpha(c) := c + \alpha \frac{G(c)}{g(c)}. \tag{14}$$

Observe first that $\Phi_0(v) = v$ and $\Gamma_0(c) = c$ correspond to the true types, while $\Phi_1(v) = v - (1 - F(v))/f(v)$ is the well-known concept of a buyer's virtual valuation and $\Gamma_1(c) = c + G(c)/g(c)$ is the somewhat less familiar concept of a seller's virtual cost. As noted by Bulow and Roberts (1989), $\Phi_1(v)$ and $\Gamma_1(c)$ can be interpreted, respectively, as a buyer's marginal valuation and a seller's marginal cost, treating the (change in the) probability of trade as the (marginal change in) quantity. Notice next that Φ_α and Γ_α are convex combinations of the true and the virtual types, with weight α attached to the virtual types. We restrict attention to the regular case by assuming that $\Phi_1(v)$ and $\Gamma_1(c)$ are strictly monotone in their arguments.

It is natural to call an allocation rule constrained efficient if it maximizes expected welfare subject to some (expected) revenue target, and subject to agents' incentive and individual rationality constraints. It can be shown that all constrained efficient allocation rule are as follows (see Loertscher and Niedermayer (2013) for details). For any realization of $(\mathbf{v}, \mathbf{c})$ and any $\alpha \in [0, 1]$, let $\mathbb{B}^*_\alpha$ and $\mathbb{S}^*_\alpha$ be the sets of buyers and sellers that would trade under efficiency if the true types were $\Phi_\alpha(v_b)$ for all $b \in \mathbb{B}$ and $\Gamma_\alpha(c_s)$ for all $s \in \mathbb{S}$.[75] Under the constrained efficient allocation rule with weight $\alpha \in [0, 1]$ on revenue, expected welfare W_α and revenue R_α

[75] Letting λ be the solution value of Lagrange multiplier for the problem of maximizing expected welfare subject to some revenue constraint, the number α is given as $\alpha = \lambda/(1 + \lambda)$. As the revenue target increases, so does λ and hence α.

are then given as

$$W_\alpha = E\left[\sum_{b\in\mathbb{B}^*_\alpha} v_b - \sum_{s\in\mathbb{S}^*_\alpha} c_s\right] \quad \text{and} \quad R_\alpha = E\left[\sum_{b\in\mathbb{B}^*_\alpha} \Phi_1(v_b) - \sum_{s\in\mathbb{S}^*_\alpha} \Gamma_1(c_s)\right], \tag{15}$$

where expectations are taken with respect to the densities $f(v_1)\cdot\ldots\cdot f(v_B)$ and $g(c_1)\cdot\ldots\cdot g(c_S)$. For $\alpha\in[0,1]$, W_α is strictly decreasing in α while R_α is strictly increasing in α. This is the trade-off between efficiency and revenue. Observe also that W_0 is maximal welfare, while R_1 is maximal revenue in the setup with two-sided private information. As an illustration, consider the bilateral trade problem of Myerson and Satterthwaite (1983) with F and G uniform on $[0,1]$. Then $\Phi_\alpha(v)=(1+\alpha)-\alpha$ and $\Gamma_\alpha(c)=(1+\alpha)c$, and so $W_\alpha=\int_{\alpha/(1+\alpha)}^{1}\int_0^{v-\alpha/(1+\alpha)}(v-c)dcdv=\frac{1+3\alpha}{6(1+\alpha)^3}$ and $R_\alpha=\int_{\alpha/(1+\alpha)}^{1}\int_0^{v-\alpha/(1+\alpha)}(2v-2c-1)dcdv=\frac{-1+3\alpha}{6(1+\alpha)^3}$. Thus, $W_0=1/6=R_1=-R_0$ and $W_1=1/12$.

Next we substantiate the notion that this tradeoff is more salient in allocation problems with two-sided private information than in problems with private information on one side only. For the purpose of comparing the two allocation problems, we first need to determine the tradeoff between revenue and welfare in the one-sided problem. Without loss of generality, assume that sellers have no private information, but that each seller still draws his cost c_s independently from G. In order to induce seller s to sell, we therefore only have to pay him c_s. All other assumptions remain the same. For any $\alpha\in[0,1]$, let $\mathbb{B}^{\text{one}}_\alpha$ and $\mathbb{S}^{\text{one}}_\alpha$ be the sets of buyers and sellers that would trade under efficiency if the true types of the buyers were $\Phi_\alpha(v_b)$ for all $b\in\mathbb{B}$ and while the seller types are given by their true types c_s for all $s\in\mathbb{S}$. Denoting by W^{one}_α and R^{one}_α the expected welfare and revenue in the one-sided problem under a constrained efficient allocation rule, we have

$$W^{\text{one}}_\alpha = E\left[\sum_{b\in\mathbb{B}^{\text{one}}_\alpha} v_b - \sum_{s\in\mathbb{S}^{\text{one}}_\alpha} c_s\right] \quad \text{and} \quad R^{\text{one}}_\alpha = E\left[\sum_{b\in\mathbb{B}^{\text{one}}_\alpha} \Phi_1(v_b) - \sum_{s\in\mathbb{S}^{\text{one}}_\alpha} c_s\right]. \tag{16}$$

As in the two-sided setup, revenue R^{one}_α is increasing in α while welfare W^{one}_α is decreasing in α for $\alpha\in[0,1]$. Observe then that $W^{\text{one}}_0=W_0$ and $W^{\text{one}}_1>W_1$. We thus have established the following result.

Theorem 2 *The cost in terms of welfare lost by increasing revenue from the level under an ex post efficient allocation rule to maximum revenue is larger in environments with two-sided private information than in one-sided ones.*

To illustrate, reconsider the bilateral trade problem with F and G uniform on $[0,1]$. We now have $W_\alpha^{\text{one}} = \int_{\alpha/(1+\alpha)}^1 \int_0^{(1+\alpha)v-\alpha} (v-c)dcdv = \frac{1+2\alpha}{6(1+\alpha)^2}$ and $R_\alpha^{\text{one}} = \int_{\alpha/(1+\alpha)}^1 \int_0^{(1+\alpha)v-\alpha} (2v - c - 1)dcdv = \frac{\alpha}{3(1+\alpha)^2}$. Thus, $W_0^{\text{one}} = 1/6 = W_0$ and $W_1^{\text{one}} = 1/8 > 1/12 = W_1$ and $R_0^{\text{one}} = 0$ and $R_1^{\text{one}} = 1/12$. Thus, in this illustrative example, the percentage of welfare lost, as a fraction of maximum welfare, as one goes from minimal to maximal revenue is 25% for the one-sided problem and 50% for the two-sided problem.

This is depicted in Figure 3, where the efficient frontier is the thicker solid line for the two-sided problem and the thinner solid line for the one-sided problem. The dashed lines correspond to the (the inefficient part of) the maximum revenue frontiers, which give the maximum revenue that can be obtained for a given level of welfare.[76]

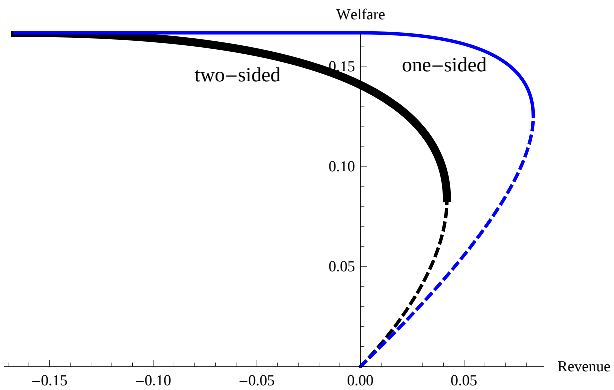


Figure 3: Efficient frontiers for one-sided and two-sided problems illustrating Theorem 2. The figure is drawn for the bilateral trade problem with uniform distributions.

According to Theorem 2, adjusting an allocation mechanism so as to increase expected revenue is more costly in terms of lost welfare with private information on both sides of the market than on just one. This is possibly an important insight for ongoing public debates. Commissioners and members of Congress are calling for the FCC's incentive auction to deliver substantial revenues, but it appears their thinking is grounded in the historical FCC auctions involving one-sided private information, where the revenue-efficiency tradeoff is not as severe, and so they do not fully appreciate the tradeoff as it applies to incentive auctions.

For example, as described in Section 2.2, although the FCC's upcoming incentive auction is only required by the authorizing legislation to break even, plus cover the costs of the auction and certain costs associated with reallocating spectrum, there is an ongoing policy debate over the extent to which the auction should be designed with revenue maximization in mind. All of

[76] This is inefficient because the same level of revenue can be achieved with higher welfare.

the FCC Commissioners have agreed that the auction should be designed to raise at least $7 billion, and Commissioner Ajit Pai has stated that "we should focus on maximizing revenue."[77] Members of Congress and public interest groups have made it clear that substantial revenue is expected from the auction. A member of Congress has stated that "we want the FCC to design the rules to get us at least $24 billion" and another has interpreted the authorizing legislating as requiring that the auction be designed to maximize revenue.[78] It is important to inform this debate about the steeper tradeoff between revenue and efficiency in auctions with two-sided private information. Prior FCC auctions have raised substantial amounts of money for the U.S. Treasury with little evidence of substantial efficiency losses.[79] However, this experience has been in environments with one-sided private information, which as shown by Theorem 2, allows one to be more aggressive than in incentive auctions in terms of generating revenue without severely sacrificing efficiency.

Given the clear legislative requirement that the FCC's incentive auction must at least break even, the tradeoff between revenue and efficiency is something that auction designers must address in light of the lesson from Theorem 1, which implies zero or negative expected revenue from a fully efficient mechanism. More generally, there is a broad consensus in public finance that non-distortionary lump-sum transfers, such as would be required to finance ex post efficient trade whenever revenue in the efficient mechanism is negative, are not plausible in the real world. Indeed, there is a notion (albeit one that is rarely formalized) that requiring public projects to be self-financed creates just about the right incentives for public servants to select projects appropriately (for a discussion of these issues, see, for example, Hellwig (2003, Section 7)). This raises the question of what (Bayesian) mechanism maximizes welfare subject to budget balance.

Second-best mechanisms As mentioned, the expected revenue from the mechanism placing weight α on revenue, R_α, is increasing in α and satisfies $R_0 < 0$ under fairly general conditions. Moreover, under assumption (4), $R_1 > 0$ holds. This implies that there is a unique number

[77] Congressional Hearing on "Keeping the New Broadband Spectrum Law on Track" (U.S. House Energy and Commerce Committee, 12 Dec. 2012). The amount $7 billion is related to estimates of the cost to develop a nationwide interoperable public safety network.

[78] See footnote 60.

[79] Total bids have exceeded $50 billion according to FCC Commissioner Jessica Rosenworcel's statements at the Congressional Hearing on "Keeping the New Broadband Spectrum Law on Track" (U.S. House Energy and Commerce Committee, 12 Dec. 2012) despite the FCC's generally conservative approach to setting reserve prices (see footnote 35). Fox and Bajari (2013) provide evidence of inefficiencies in spectrum license allocations related to the geographic coverage of the licenses offered being inefficiently small. See also the references in footnote 47.

$\alpha^* \in (0,1)$ such that $R_{\alpha^*} = 0$ holds. Because W_α is strictly decreasing in α, it follows that a mechanism that implements the α^*-allocation rule is a second-best mechanism in the sense of maximizing ex ante expected surplus subject to budget balance (in expectation) (and incentive compatibility and individual rationality). Myerson and Satterthwaite (1983) derived such a second-best mechanism for the bilateral trade problem and noticed that when values and costs are drawn from a common uniform distribution, it can be implemented by the linear equilibrium of the double auction of Chatterjee and Samuelson (1983). On the existence and efficiency of equilibria in the double auction, see Satterthwaite and Williams (1989). More generally, Loertscher and Niedermayer (2013) observe that with possibly many buyers and one seller, any α-allocation rule can be implemented with a fee-setting mechanism, according to which the seller sets a (reserve) price in a second-price auction and, upon trade at the transaction price t, the market maker receives the fee $t - E_v[\Gamma_\alpha^{-1}(\Phi_\alpha(v))|v \geq t]$. Lastly, Gresik and Satterthwaite (1989) analyzed the convergence of welfare toward full efficiency under second-best mechanisms as the markets become large.[80]

3.4 Deficit-free Mechanisms for Practical Implementation

The analysis and discussion above lead naturally to the question of whether there are practical mechanisms that implement "almost" efficient allocation rules that do not run a deficit.[81] To address this question, we begin with practical mechanisms for centralized secondary markets in the unitary framework and then discuss the case of buyers with multi-unit demands and sellers with multi-unit supplies. Lastly, we analyze briefly the scope for improving efficiency, without running a deficit, by combining primary and centralized secondary market allocation mechanisms.

[80] For convergence results in similar veins, see also Rustichini, Satterthwaite, and Williams (1994) and Cripps and Swinkels (2006) for double auctions and Tatur (2005) for VCG mechanisms with participation fees.

[81] Starting with the work by Smith (1962) and Smith (1964), a large experimental literature has documented the remarkably efficient performance of the continuous-time double-auction, which is an open auction format similar to the New York Stock Exchange. In terms of efficiency and convergence to the competitive equilibrium, this format typically outperforms other auction formats such as the uniform price double auction and posted offer markets (Smith, Williams, Bratton, and Vannoni (1982); Cason and Friedman (2008); Walker and Williams (1988); McCabe, Rassenti, and Smith (1993)). The success of two-sided markets in laboratory settings has led to a number of centralized 'smart' markets that facilitate exchange in homogeneous goods markets with network externalities such as electricity, gas, and water (Rassenti, Smith, and Wilson (2003); Wilson, Rassenti, and Smith (2003); McCabe, Rassenti, and Smith (1990); and Murphy, Dinar, Howitt, Rassenti, and Smith (2000)).

3.4.1 An Almost Efficient Dominant Strategy Double Auction

Unit Case McAfee (1992) introduces the following dominant strategy double auction for the unitary framework with homogenous goods. All buyers and sellers submit bids simultaneously. Let k be the efficient quantity defined with respect to the submitted bids $(\mathbf{v}, \mathbf{c})$. Letting $v_{(h)}$ denote the h-th highest bid submitted by a buyer, $c_{(h)}$ the h-th lowest bid submitted by a seller and setting $v_{(B+1)} = \underline{v}$ and $c_{(S+1)} = \overline{c}$, the quantity traded is $k-1$ if $v_{(k+1)} < c_{(k)}$ or $c_{(k+1)} > v_{(k)}$. All buyers who trade pay $v_{(k)}$ and all sellers who trade are paid $c_{(k)}$. Observe that $v_{(k)} \geq c_{(k)}$ by construction. Thus the mechanism runs no deficit in these instances. If both $v_{(k+1)} \geq c_{(k)}$ and $c_{(k+1)} \leq v_{(k)}$ hold, the efficient quantity k is traded at the uniform price $p_0 = (v_{(k+1)} + c_{(k+1)})/2$; that is, buyers who receive a unit pay p_0 and sellers who sell a unit are paid p_0.[82] Thus, the mechanism runs no deficit in these instances either. That it endows all agents with dominant strategies to bid their types follows from the second-price nature of the mechanism: No agent can affect the price he pays or get, given that he trades.

A lesson from the analysis above is that under fairly general conditions some surplus has to be sacrificed in order to avoid deficits in markets with two-sided private information. The α^*-mechanisms, which were first analyzed by Myerson and Satterthwaite (1983) and Gresik and Satterthwaite (1989), achieve this by inducing trade only for the traders that belong to the efficient sets defined with respect to $\Phi_{\alpha^*}(v_b)$ and $\Gamma_{\alpha^*}(c_s)$. However, these concepts, and thus the α^*-mechanisms, are Bayesian notions that depend on the fine details of the design problem at hand. They thus violate the robustness requirement often associated with the Wilson Doctrine, which postulates that in order to be practical mechanisms should be free of such details (Wilson, 1987). The postulate of the Wilson Doctrine is particularly relevant when the design problem at hand is a one-shot allocation mechanism in which learning and convergence to the true parameters cannot occur. McAfee's mechanism, in contrast, sacrifices efficiency by preventing trade by the least efficient pair of traders, if it prevents any trade at all. As this pair is well-defined for any submitted bids regardless of the process that determines agents' types, the mechanism is in line with the Wilson Doctrine.[83]

[82] The choice of p_0 as the mean of $v_{(k+1)}$ and $c_{(k+1)}$ is somewhat arbitrary. More importantly, the restriction that both $v_{(k+1)} \geq c_{(k)}$ and $c_{(k+1)} \leq v_{(k)}$ has to hold for the efficient quantity k to be traded is a source of inefficiency. Without affecting the dominant strategy properties, it could be replaced by the condition that if either (i) $v_{(k+1)} \geq c_{(k)}$ or (ii) $c_{(k+1)} \leq v_{(k)}$ (or both), the quantity traded is k. If only (i) holds, the uniform price paid by buyers who trade and received by sellers who sell is $v_{(k+1)}$; if only (ii) holds, it is $c_{(k+1)}$; while if both (i) and (ii) are satisfied, it is p_0, or any other selection from $[v_{(k+1)}, c_{(k+1)}]$. This mechanism never runs a deficit either.

[83] However, the price p_0 depends on the bounds of the distribution in case $k = \min\{B, S\}$. This is for example

An important question that McAfee (1992) leaves open is how or to what extent the mechanism can be generalized to the empirically often more relevant case where buyers have multi-unit demands and sellers have multi-unit supplies. Such a generalization faces two challenges: The efficient trades that must be foregone need to be identified, and demand and supply of those agents who trade has to be balanced. (Observe that the latter constraint is automatically satisfied in the unit case.) Loertscher and Mezzetti (2013) show that both challenges can be overcome by identifying the marginal buyer and seller (as opposed to the marginal trade) and then using them to dissect the two-sided problem into two one-sided problems.[84]

3.4.2 Connected Primary and Centralized Secondary Market Design

It has been argued that combining primary and centralized secondary markets may be a source of inefficiency by inducing speculative bidding (Garratt and Tröger, 2006) and facilitating collusion (Garratt, Tröger, and Zheng, 2009). In the following, we provide arguments to the effect that carefully connecting allocation mechanisms for primary and centralized secondary markets can improve outcomes.[85] The main idea is simple and based on the insight that efficient mechanisms that run a surplus exist for primary markets but not for centralized secondary markets. Therefore, by combining the two, it may be possible to achieve efficiency in both markets without running a deficit in expectation. In many real-world applications, the designer or market maker will typically also participate as an organizer and seller in a primary market. Consequently, the option of combining primary and centralized secondary markets in the way outlined below is a practical possibility in these instances.

Illustration To illustrate, consider a situation with $B = 2$ buyers who draw their values for a homogenous good independently from the distribution F with support $[0, 1]$ and density f and one private seller whose cost c is drawn from the distribution G with the same support and density g. The mechanism designer owns one unit of the good, which he values at 0. Consider the following mechanism. In the primary market, which is run first, the designer's unit is offered for sale using a second-price auction without reserve. After the primary market

the case in the bilateral trade problem whenever $v_b > (\underline{v} + \overline{c})/2 > c_s$. In this way, the mechanism depends on some details of the design problem although it is independent of any other assumptions about distributions. It should also be noted that in exactly the same vein the VCG-mechanism is not detail free (in the two-sided setup) despite being independent of distributional assumptions.

[84] We refer the reader to Loertscher and Mezzetti (2013) for details. Interestingly, only the marginal trader on the long side of the market will not trade and inframarginal traders may trade less than the efficient quantities.

[85] Kwerel and Williams (2002) propose a two-sided auction for spectrum licenses that includes unassigned spectrum held by the FCC.

closes, the centralized secondary market is run in which the remaining unit is allocated efficiently. With two bidders, this means that the runner up from the primary market allocation participates in the centralized secondary market together with the private seller. All of this is common knowledge. The resulting equilibrium allocation will be efficient if there is a monotone equilibrium bidding strategy for the primary market. We show next that this is the case. Due to the revenue equivalence theorem, this implies that our focus on this specific mechanism is without loss of generality.

Let $u(v) := \int_0^v (v-c)g(c)dc = \int_0^v G(c)dc$ be the expected payoff of participating in the centralized secondary market for a bidder whose value is v and who is a runner up in the primary market. Let $\beta(v) = v - u(v)$ be the expected value of winning in the primary market, net of the option value of participating in the centralized secondary market. Observe that bidding $\beta(v)$ in the primary market is a weakly dominant strategy and that $\beta'(v) = 1 - G(v) > 0$. Therefore, the bidding strategy in the primary market is indeed monotone. Denoting by $f_{N,k}$, the density of the distribution of k-th highest out of N independent draws from F, the expected revenue from this mechanism can be written as

$$\begin{aligned} R &= \int_0^1 b(v) f_{2,2}(v)dv + \int_0^1 \int_0^c (c-v) f_{2,2}(v) g(c) dc dv \\ &= \int_0^1 (v - 2u(v)) f_{2,2}(v) dv = \int_0^1 \left(v - 2\int_0^v G(c)dc \right) f_{2,2}(v) dv, \end{aligned}$$

where the second integral in the first line stems from the dominant strategy implementation in the Myerson-Satterthwaite bilateral trade problem when the distributions are $f_{2,2}(v)$ and $g(c)$. A simple geometric argument reveals that $2\int_0^v G(c)dc < v$ for any distribution G that first-order stochastically dominates the uniform distribution.[86] Thus, a sufficient condition for expected revenue to be positive is $G(c) \leq c$ for all $c \in [0,1]$. However, this condition is clearly only sufficient.[87]

Decreasing costs of greed The assumption that the designer's units have zero costs may be appropriate in some instances but may seem stark in others. To make a comparison between one-sided and two-sided setups meaningful, assume that the designer draws his opportunity

[86] The argument is this: For G uniform, $\int_0^v G(c)dc$ is equal to the symmetric triangle with length and height v, whose size is thus $v^2/2 < v$. For any distribution that stochastically dominates the uniform, $\int_0^v G(c)dc$ will be smaller than this triangle.

[87] Assuming, for example, that F is uniform and $G(c) = c^\sigma$ with $\sigma > 0$, expected revenue can be shown to be positive for any $\sigma > 0.44$.

costs for selling each unit he owns independently from the same distribution G as the private sellers. Let $K \in \{0, .., S\}$ be the number of units owned by the designer, and assume that the number of private sellers is $S - K$. Let $W_\alpha^{\text{con}}(K)$ be expected welfare under a constrained efficient allocation rule in a connected setup where the designer owns K units with $S-K$ private sellers.[88] The following simple but possibly valuable result is then an immediate corollary to Theorem 2.

Corollary 1 *The welfare loss from revenue maximization decreases in* K. *That is,* $W_0^{con}(K) - W_1^{con}(K)$ *is decreasing in* K.

A Connected Market with Dominant Strategies that never runs a deficit In practice, a designer might not only face the constraint that there must be no deficit in expectation but also that there must be no deficit ex post. In the following, we briefly describe a hybrid, detail-free mechanism (i.e., a mechanism that does not rely on knowledge of the distributions from which bidders draw their values and costs) that achieves this objective.

Consider the following setup within the unitary framework. All buyers and all private sellers have unit demands and supplies. Let $K \geq 1$ be the number of units owned by the government seller who values them at 0. There are M private sellers and N buyers with $N \geq K + M$ for simplicity. As usual, let $v_{N+1} = \underline{c}$ and $c_{M+1} = \overline{v}$, where $\underline{c}$ is the lowest possible cost of a private seller (typically 0) and $\overline{v}$ is the highest possible valuation of a buyer.

Letting $k \in \{K, K + M\}$ be the quantity traded and v_i be the i-th highest bid of a buyer and c_j be the j-th lowest bid by a private seller, the private sellers who trade are paid the price $p_S(k) := \min\{c_{k+1}, v_k\}$ and the buyers who trade pay $p_B(k) := \max\{v_{k+1}, c_k\}$. This induces dominant strategies for the usual reasons for any given k. The net revenue that accrues to the mechanism designer as a function of k is $R(k) = kp_B(k) - (k - K)p_S(k)$. Now choose k such that $R(k) \geq 0 > R(k + 1)$.[89]

[88] When the quantity traded is Q, a private seller s now sells if and only if his cost c_s is such that $\Gamma_\alpha(c_s)$ is smaller than the Q-th smallest element of the K cost draws of the designer and of the $\Gamma_\alpha(c_j)$ of his $S - K - 1$ competitors j.

[89] Efficiency could be further increased, at the cost of additional complexity, if one changed the pricing rule to the following element in the spirit of McAfee (1992). If the efficient quantity is k and $v_{k+1} \geq c_k$ and $c_{k+1} \leq v_k$, let the price be $p = p_B = p_S = (v_{k+1} + c_{k+1})/2$. (One could still do a little better than that because the mean is somewhat arbitrary).

4 Complications and Open Issues

In this section, we discuss additional issues that are likely to arise in the design of centralized markets with privately informed buyers and sellers. Sections 4.1 and 4.2 discuss issues pertaining to the choice of open versus closed auction formats, which dominated much of the discussion regarding the structure of the FCC format. In Section 4.1, we discuss the extension of the linkage principal to the two-sided environment and show that the linkage principle is less general in this setting. In Section 4.2, we discuss collusion in two-sided markets. Section 4.3 discusses how complexity is likely to impact two-sided design while Section 4.4 discusses the relative welfare implications of policies intended to promote downstream competition by precluding strong bidders from the auction in one-sided and two-sided settings.

4.1 Common Values

In this section, we depart from the assumption of private values and costs that we maintained thus far in order to discuss issues that are specific to environments where values and costs are interdependent and bidders' information is affiliated. Under these assumptions, Milgrom and Weber (1982) show that for one-sided auctions with single unit demand and symmetric bidders, there is a close connection between the expected revenue generated in open and closed formats of an auction and the linkage principle.

For a one-sided auction, the linkage principle asserts that when the mechanism designer (here the seller) possesses private information that is affiliated with the signals of all other agents, expected revenues are increased when the designer commits to a policy of always revealing his private information. This implies that under a broad set of auction environments, an open format that provides signals to all parties generates more expected revenue than closed formats. The logic of this result stems from the fact that winners, when bidding naively, overestimate the other bidders' signals and suffer from the winners' curse. Rational bidders will reduce their bids in order to avoid the problem of the winner's curse. New information that is affiliated with the other bidders' valuations reduces the expected magnitude of overestimation from a winning bid and increases every bidder's bid on average.

An analogue in the two-sided symmetric setting would assert that when the mechanism designer possesses private information that is affiliated with the signals of all other agents, then the expected revenue is increased when he commits to a policy of revealing such information. As payment rules in the two-sided settings are generated by the difference in bids across sets of buyers and sellers, however, information that leads all bidders to raise their expected bids on average does not necessarily lead to decreases in deficits. Rather, as discussed below, the role of information in a two-sided setting is more nuanced.

Beginning with a modification of Krishna (2002, Chapter 7), consider an environment with $B+S$ market participants: B buyers who have unit demand and S sellers who have unit supply.[90] Each bidder $i \in \{1,\ldots,B,B+1,\ldots,B+S\}$ receives a signal X_i regarding the value of the object. We assume the valuation to each bidder depends on his own observed signal and symmetrically upon the unobserved signals of the other bidders (so that the signals of the other bidders can be interchanged without affecting a given bidder's value). More specifically, assume all signals X_i are drawn from the interval $[0,\omega]$ and that for all i we can write bidder i's value for having the good at the end of the auction as $v_i(\mathbf{X}) = u(X_i, \mathbf{X}_{-i})$, where the function u is symmetric in the last $B+S-1$ arguments.[91] As it will be convenient to distinguish between buyers and sellers, we will sometimes reindex the sellers by $j = i - B$ and denote their signals as $C_j \equiv X_{j+B}$.

We further assume that bidders' information is affiliated.[92] Affiliation implies that for any signals $x_1^{'} > x_1^{''}$ and $x_2^{'} > x_2^{''}$,

$$\frac{f(x_1^{'}|x_2^{'})}{f(x_1^{''}|x_2^{'})} \geq \frac{f(x_1^{'}|x_2^{''})}{f(x_1^{''}|x_2^{''})}, \tag{17}$$

and that $F(x_1|x_2^{'}) \leq F(x_1|x_2^{''})$ and $E[x_1|x_2^{'}] > E[x_1|x_2^{''}]$ for all x_1, where $f(y|z)$ denotes the conditional density of y conditional on z, $F(y|z)$ the corresponding conditional distribution and $E[y|z]$ the conditional expectation.

We now define other random variables and mappings with respect to bidder 1, but because of the assumed symmetry, they are the same for all bidders. Let the random variables $Y_1, Y_2, ..., Y_{B+S-1}$ be the largest, second largest, etc., from among $X_2, X_3, ..., X_{B+S}$ and note that $X_1, Y_1, Y_2, ..., Y_{B+S-1}$ are affiliated.

We let $v(x,y) = E[V_1 \mid X_1 = x, Y_S = y]$ be the expectation of the value to a bidder when the signal he or she receives is x and the Sth highest signal among the other bidders, Y_S, is y. We assume that v is nondecreasing in y and strictly increasing in x and that $v(0,0) = 0$.

[90] As shown in Perry and Reny (1999), the linkage principle does not hold in multi-unit auctions.

[91] As shown in Krishna (2002), the linkage principle does not hold with asymmetric bidders. In these asymmetric environments, revealing information can change the order of bidders' valuations and influence the allocation. See Milgrom (2004) for a simple example and Board (2009) for a more general discussion.

[92] As stated by Klemperer (1999, p.254): "Loosely, two signals are affiliated if a higher value of one signal makes a higher value of the other signal more likely, *and* this is true on every subspace of the variables' domain. Thus affiliation is stronger than correlation which is just a global summary statistic; affiliation can be thought of as requiring local positive correlation everywhere."

Define a *standard* two-sided mechanism to be one in which if k buyers and sellers trade, then it is the k buyers with the highest bids and the k sellers with the lowest bids who trade. For each standard two-sided mechanism I, suppose that the mechanism has a symmetric and increasing equilibrium β^I, which is a mapping from a bidder's observed signal to his or her bid. Let $\tau^{b,I}(z,x)$ denote the expected payment by a buyer if she is a winning bidder when she receives a signal x but bids as if her signal were z, i.e., she bids $\beta^I(z)$. Let $\tau_1^{b,I}(z,x)$ denote the derivative of $\tau^{b,I}(z,x)$ with respect to its first argument and $\tau_2^{b,I}(z,x)$ the derivative with respect to its second argument, evaluated at (z,x). Let $\tau^{s,I}(z,c)$ be the expected payment received by a seller if he sells his unit when he receives a signal c, with derivatives defined as above.

Proposition 1 *Let I and II be two standard two-sided mechanisms, each having a symmetric and increasing equilibrium such that (i) for all x, $\tau_2^{b,I}(x,x) \geq \tau_2^{b,II}(x,x)$; (ii) for all c, $\tau_2^{s,I}(c,c) \leq \tau_2^{s,II}(c,c)$; (iii) $\tau^{s,I}(0,0) = \tau^{s,I}(0,0) = 0 = \tau^{b,II}(0,0) = \tau^{s,II}(0,0)$. Then the expected revenue in I is at least as large as the expected revenue in II.*

Proof. Let $F_{S,1}(\cdot \mid x)$ denote the distribution of Y_S conditional on $X_1 = x$, i.e., $F_{S,1}(z \mid x) \equiv \Pr(Y_S < z \mid X_1 = x)$, and let $f_{S,1}(\cdot \mid x)$ be the associated density.

We begin on the seller side. The expected payoff of the seller with signal c who bids $\beta^I(z)$ is

$$[1 - F_{S,1}(z \mid c)]\tau^{s,I}(z,c) + \int_{-\infty}^{z} v(c,y) f_{S,1}(y|c) dy.$$

In equilibrium, it is optimal to choose $z = c$ and the resulting first-order condition implies that

$$[1 - F_{S,1}(z \mid c)]\tau_1^{s,I}(z,c) = f_{S,1}(c|c)\tau^{s,I}(c,c) - f_{S,1}(c|c)v(c,c),$$

which we can rewrite as

$$\tau_1^{s,I}(z,c) = \frac{f_{S,1}(c|c)}{1 - F_{S,1}(z \mid c)}\tau^{s,I}(c,c) - \frac{f_{S,1}(c|c)}{1 - F_{S,1}(z \mid c)}v(c,c). \tag{18}$$

Letting $\Delta(c) = \tau^{s,II}(c,c) - \tau^{s,I}(c,c)$. and noting that

$$\Delta'(c) = (\tau_1^{s,II}(c,c) - \tau_1^{s,I}(c,c)) + (\tau_2^{s,II}(c,c) - \tau_2^{s,I}(c,c)), \tag{19}$$

we can see that

$$\Delta'(c) = \frac{f_{S,1}(c|c)}{1 - F_{S,1}(c|c)}\Delta(c) + [\tau_2^{s,II}(c,c) - \tau_2^{s,I}(c,c)]. \tag{20}$$

By hypothesis (ii), the second term on the right side is positive, and by hypothesis (iii), which implies $\Delta(0) = 0$, it follows that $\Delta(c)$ and $\Delta'(c)$ cannot be of different signs. This implies that for all c, $\Delta(c) \geq 0$.

A similar argument holds for the buyers. The expected payoff of a bidder with signal x who bids $\beta^I(z)$ is

$$\int_{-\infty}^{z} v(x, y) f_{S,1}(y \mid x) dy - F_{S,1}(z \mid x)\tau^{b,I}(z, x).$$

In equilibrium, it is optimal to choose $z = x$ and the resulting first-order conditions imply that

$$v(x, x) f_{S,1}(x \mid x) - f_{S,1}(x \mid x)\tau^{b,I}(x, x) + F_{S,1}(x \mid x)\tau_1^{b,I}(x, x) = 0,$$

which we can rewrite as

$$\tau_1^{b,I}(x, x) = \frac{f_{S,1}(x \mid x)}{F_{S,1}(x \mid x)} v(x, x) - \frac{f_{S,1}(x \mid x)}{F_{S,1}(x \mid x)} \tau^{b,I}(x, x).$$

Letting $\Delta(x) = \tau^{b,I}(x, x) - \tau^{b,II}(x, x)$, and replacing for $\tau_1^{b,I}(x, x)$ as done above,

$$\Delta'(x) = -\frac{f_{S,1}(x \mid x)}{F_{S,1}(x \mid x)} \Delta(x) + \left(\tau_2^{b,I}(x, x) - \tau_2^{b,II}(x, x)\right).$$

By similar arguments as above, this function is strictly positive. ■

Proposition 1 allows for a partial ranking of alternative one-sided and two-sided mechanisms by comparing the statistical linkages between (i) a buyer's own signal and the price she would pay upon winning and (ii) a seller's own signal and the price he would receive upon selling. In a one-sided setting, where the seller's transfer is independent of his signal, the proposition along with the assumption of affiliation implies that any information that increases the statistical link between the buyer's signal and his payment increases revenue. For example, starting with a first-price mechanism in an environment with $S < B$ sellers, $\tau_2^{b,FP}(x, x) = 0$ since a winning buyer's payment is based only on his bid. The release of a public signal, which is affiliated with both Y_S and x, implies that a higher signal is likely when x is high and thus that a winning buyer's expected payment under the release of the public signal is greater than or equal to zero.

In a two-sided setting, by contrast, information that increases the statistical link between the buyer's signal and the buyer's payment will also increase the statistical link between the seller's signal and the seller's payment. This implies that when (i) holds, (ii) typically will not. The following counterexample shows that the release of information may be revenue decreasing in a two-sided setting even for symmetric buyers and sellers.

Example 1 *Consider a VCG mechanism with two buyer (indexed by 1 and 2) and one seller (indexed by 3) with a single object. Both buyers and the seller attach a value to the object as follows:*

$$V_i(x_1, x_2, x_3) = x_i - \frac{1}{2}\min\{x_1, x_2, x_3\}, \tag{21}$$

where X_1, X_2, and X_3 are affiliated values. Suppose that the mechanism designer can design a mechanism that perfectly reveals the value of $\min\{x_1, x_2, x_3\}$ prior to the VCG. We will show that it is not in the interest of the designer to reveal this information.

Let $\psi(x) \equiv E[Y_2|X = x, Y_1 = x]$ and note that by the affiliation $\psi(x)$ is increasing in x. In the case of no information, each bidder bids $\beta^{NI}(x_i) = x_i - \frac{1}{2}\psi(x_i)$, which is equivalent to $v(x_i, x_i)$ defined above. For a given realization of signals $\mathbf{x} = \{x_1, x_2, x_3\}$ over all buyers and sellers, let $\hat{x}_k$ be the kth highest signal. Over all states where there is trade, the expected revenue is equal to the difference in bids of the second highest and highest signals, which can be expressed as $\beta^{NI}(\hat{x}_2) - \beta^{NI}(\hat{x}_1) = \hat{x}_2 - \hat{x}_1 + \frac{1}{2}[\psi(\hat{x}_1) - \psi(\hat{x}_2)]$. Note that by affiliation, the last term is positive.

If the designer reveals the value of $\min\{x_1, x_2, x_3\}$, each bidder now bids $\beta^I(x_i) = x_i - \frac{1}{2}\min\{x_1, x_2, x_3\}$. Over all states where there is trade, expected revenue is now equal to $\beta^{NI}(\hat{x}_2) - \beta^{NI}(\hat{x}_1) = \hat{x}_2 - \hat{x}_1$, which is smaller than in the case with no information. As the states in which trade occurs is the same with and without information, expected revenue decreases after releasing information.

In the example above, the release of information increases the payments that the buyer pays from $\hat{x}_2 - \frac{1}{2}\psi(\hat{x}_2)$ to $\hat{x}_2$ in each state for which there is trade. Thus, just as in the one-sided auction, expected transfers from the buyers are increasing when information is revealed. However, the release of information also increases the payments that the sellers receive from $\hat{x}_1 - \frac{1}{2}\psi(\hat{x}_1)$ to $\hat{x}_1$. For the given interdependent value structure, the increase in transfers to sellers is larger than the increase in transfers from the buyers. This leads to an overall decrease in revenue in all states for which trade occurs.

Despite the existence of interdependent value structure where the linkage principle does not hold, it is not the case for all interdependent value structures. For VCG mechanisms, for example, the expected revenue is determined by the difference between the bids of the last buyer to receive a good and the last seller to sell a good. If information makes the difference in the bids of these two bidders smaller, the designer's revenue will increase.

As an example where an open format unambiguously leads to higher revenue than a closed format, we consider a setting with a single seller where each bidder has a value based on his own private signal and the average of all bidders' signals. The mechanism designer has the choice between running a VCG mechanism and a clock proxy auction. The clock proxy auction runs an ascending clock auction up to the point where there are two remaining bidders and then runs a sealed-bid second-price auction.[93] As the optimal strategy in the clock proxy auction is symmetric, the value of all but the highest two values will be know prior to the second-price auction. We will show for an additive interdependent value structure, it is in the interest of the designer to reveal such information.

Example 2 *Consider a VCG mechanism with B buyer and one seller with a single object. All buyers and the seller attach a value to the object as follows:*

$$V_i(\mathbf{x}) = x_i + \frac{1}{B+1}\sum_{i=1}^{B+1} x_i, \tag{22}$$

where $X_1, X_2, \ldots, X_{B+1}$, are affiliated values. For a given realization of signals $\mathbf{x} = \{x_1, x_2, \ldots, x_{B+1}\}$ over all buyers and sellers, let $\hat{x}_k$ be the kth highest signal. We will show that it is in the interests of the designer to credibly reveal $\hat{x}_k$ for $k > 2$.

Let $\psi_j(x) \equiv E[Y_j|X = x, Y_1 = x]$ for $j > 1$ and note that by the affiliation $\psi_j(x)$ is increasing in x. In the case of no information, each bidder bids $\beta^{NI}(x_i) = x_i + \frac{2x_i}{B+1} + \frac{1}{B+1}\left[\sum_{j=2}^{B+1}\psi_j(x_i)\right]$. Over all states where there is trade, expected revenue is given by:

$$[\hat{x}_2 - \hat{x}_1]\left[1 + \frac{2}{B+1}\right] + \frac{1}{B+1}\sum_{j=2}^{B+1}[\psi_j(\hat{x}_2) - \psi_j(\hat{x}_1)]. \tag{23}$$

When $\hat{x}_k$ is known for $k > 2$, the highest and second highest bidders will bid $\beta^I(x_i) = x_i + \frac{2x_i}{B+1} + \frac{1}{B+1}\left[\sum_{j=2}^{B+1}(\hat{x}_i)\right]$. Over all states where there is trade, the expected revenue is given by:

$$[\hat{x}_2 - \hat{x}_1]\left[1 + \frac{2}{B+1}\right]. \tag{24}$$

As $\psi_j(\hat{x}_1) - \psi_j(\hat{x}_2) > 0$ by affiliation, expected revenue increases with information.

The short analysis above suggests that information revelation in the two-sided problem is more nuanced than in its one-sided counterparts. While the linkage principle does not extend

[93]It would also be possible to use an ascending clock to capture every bidders value. However, once the first B bidders have dropped out, the winning bidder knows the price at which he can win the object and waiting until his own valuation is only a weak best response.

in full generality to the two-sided problem, public information can be deficit reducing for at least some interdependent value models. Research into identifying the environments in which the original linkage principle holds and into identifying types of information that are increase revenue in a broader set of environments is likely to be useful moving forward.

While we have restricted ourselves to the symmetric case where the linkage principle holds in the one-sided case, we note that two-sided markets typically involve additional asymmetries that may be important for assessing the impact of public information on the distribution of bids. For example, buyers and sellers are likely to have different value functions and signals of different precision.

4.2 Collusion

In thin two-sided settings, collusion across buyer and seller pairs may be quite lucrative to the pair and quite costly to the designer. Consider, for example, the bilateral trade problem in an independent private values environment with value and cost drawn from the uniform distribution on $[0, 1]$. In a VCG mechanism, the designer's expected payment is 1/6 if the buyer and the seller bid truthfully. If the two parties collude by having the buyer always submit a value of 1 and the seller always submit a bid of 0, however, the object is always traded and the designer pays 1 regardless of the realized types.[94]

As buyer and seller pairs may have strong incentives to collude, concerns for collusion in two-sided markets have understandably been raised in the literature and are likely to be important for the open versus closed format debate.[95] For example, Rothkopf (2007, p.192) raises the issue of "conspiracies in two-sided markets between bidders offering to sell and those offering to buy," while Hobbs, Rothkopf, and O'Neill (2000) discusses how to construct such conspiracies in two-sided electricity markets. The LIBOR scandal, where reports by potential buyer and seller trading pairs guided the prices paid in transactions with a third party, demonstrates that such concerns are likely important in practice.[96]

[94] This example is particularly severe due to the use of the VCG mechanism, where truth-telling is only a weak best response. We use it only as an example to highlight the additional incentives for collusion that may be possible when deficits are paid by a third party. See Ausubel and Milgrom (2006) for a broader discussion of this issue.

[95] The concern for collusion in open formats stems from the potential of individuals in the auction to condition their future actions on past events. This argument was first put forth in Mead (1967) and first analyzed formally in Robinson (1985). Theoretical arguments supporting the relative susceptibility of open formats can be found in Klemperer (2002), Brusco and Lopomo (2002), Marshall and Marx (2007), and Marshall and Marx (2009). Empirical evidence that collusion may be easier to sustain in open formats can be found in Athey, Levin, and Seira (2011). Experimental evidence directly related to this issue can be found in Hu, Offerman, and Onderstal (2011) and Hinloopen and Onderstal (2010).

[96] The industrial organization and contracting literature has also been concerned with collusion when third

The potential for collusion between buyers and sellers and its effect on the efficiency of the market appears to depend on the mechanism used and the degree of efficiency this mechanism achieves in equilibrium.[97] For example the mechanism provided in McAfee (1992) appears to be relatively robust to buyer and seller collusion. Recall that in this mechanism, when $v_{(k+1)} < c_{(k)}$ or $c_{(k+1)} > v_{(k)}$, the mechanism trades $k-1$ units, the buyer pays $v_{(k)}$ and the seller pays $c_{(k)}$. However, when both $v_{(k+1)} \geq c_{(k)}$ and $c_{(k+1)} \leq v_{(k)}$ hold, the efficient quantity k traded at the uniform price $p_0 = (v_{(k+1)} + c_{(k+1)})/2$. In cases where $c_{(k+1)} \leq v_{(k)}$ but $v_{(k+1)} < c_{(k)}$, the kth seller and the $k+1$ (or higher) buyer have an incentive to form a coalition and have the buyer submit a bid equal to $c_{(k)}$. This bid will lead to the kth unit being traded and leads to a trade price which is lower for all buyers and higher for all sellers. Likewise in cases where $v_{(k+1)} \geq c_{(k)}$ but $c_{(k+1)} > v_{(k)}$, the $k+1$th (or higher) seller and the kth buyer have an incentive to form a coalition and have the buyer submit a bid equal to $v_{(k)}$. These coalitions will lead to higher surplus for all trading parties at the same time as encouraging efficiency. As a buyer and seller pair cannot generate more total surplus by distorting their paired bids in any other circumstance, collusion between buyers and sellers under this almost efficient mechanism work in favor of increasing efficiency.[98]

The transition from one-sided mechanisms to two-sided mechanisms may also have implications for the ability of one side of the market to collude or tacitly collude with one another. As noted by Milgrom (2004, Section 7.2), for instance, a key concern in the design of uniform price auctions in settings where bidders can demand multiple units is the possibility of equilibrium prices that are very far away from the competitive levels. In cases where demand is known and inelastic, low-price equilibria exist for a variety of both sealed bid and clock auctions where the revenue is very close to the sellers reserve. When supply is elastic, by contrast, the worst auction outcome resembles the results of Cournot competition among buyers. Green and Newbery (1992) and Klemperer and Meyer (1989) find that prices lie between prices in the

parties play the role of budget-balancers. See Eswaran and Kotwal (1984) and Holmstrom (1982) for early papers in this literature.

[97] There is a small experimental literature that supports this conjecture. The double oral auction typically used in the experimental literature, for instance, does not appear to be particularly susceptible to collusion relative to posted offer formats (Isaac and Plott (1981); Clauser and Plott (1992)). In one-sided settings with buyers, ascending bid auctions and first-price clock auctions appear to be sensitive to tacit collusion, while descending clock auctions do not appear to have this feature (Li and Plott (2009)). Experimental work also suggests that sealed-bid markets can be vulnerable to collusion if certain types of communication are allowed (Isaac, Ramey, and Williams (1984); Isaac and Walker (1985); Saijo, Une, and Yamaguchi (1996); Artale (1997); Kwasnica (1998)).

[98] This is in contrast to the VCG mechanism noted above. In the homogeneous goods VCG mechanism, the inframarginal buyer and seller pair always have an incentive to collude. This collusion can be deficit increasing and efficiency decreasing.

Cournot equilibrium and the competitive equilibrium when supply is elastic and uncertain. In their models, the competitive equilibrium is the only equilibrium that exists when uncertainty of supply is sufficiently large. Thus, in a two-sided setting where uncertainty over the sellers valuations generates both uncertainty and elastic supply, there are reasons to believe that some non-competitive equilibria may disappear.[99]

As discussed in Section 2.2, the FCC has taken steps within SMR auction design to limit the ability of bidders to collude. Presumably similar steps would be of value in the design of a centralized market with privately informed buyers and sellers. The question remains whether such two-sided markets are more or less susceptible to collusion than their one-sided counterparts.

4.3 Complexity

As is the case with the broadcast incentive auction, it is likely that many of the settings for which two-sided markets must be designed will be ones where goods are heterogeneous and individuals perceive some objects as complementary. A major concern in the design of mechanisms in such settings is whether potential bidders are able to understand the auction and whether bidders act in these environments in a way predicted by theory and intended by the designer. Such concerns may be heightened in two-sided settings where complementarities between buyers and sellers and uncertainty over available supply may lead to greater complexity in analyzing potential bids and developing optimal strategies.[100]

While auction complexity is a nascent field, one clearly emerging pattern is that bidders fail to analyze the full set of potential bids even in simplified combinatorial settings. In Kagel, Lien, and Milgrom (2010), for example, bidders participated in a Porter, Rassenti, Roopnarine, and Smith (2003) style combinatorial clock auction that allows for multiple package bids in each period and use an 'XOR' bidding language to allocate objects. Despite having many packages that were potentially profitable, bidders typically concentrated their bids on one or two packages each round that maximized current period profit. When these packages did not correspond with packages that were predicted by theory to be "efficiency relevant," overall

[99]See Rassenti, Smith, and Wilson (2003) for experimental evidence of these effects as they relate to electricity markets.

[100]As stated by FCC Commissioner McDowell Congressional Hearings on the incentive auction, for instance, "Quite simply, the incentive auctions will be the most complex in world history and the entire process may take the greater part of a decade. I urge the Commission to work in a deliberate and transparent manner, with an eye toward simplicity, humility and restraint." ("Keeping the New Broadband Spectrum Law on Track" (U.S. House Energy and Commerce Committee, 12 Dec. 2012), pp.2–3)

revenue and efficiency fell.[101] A similar result is found in Scheffel, Ziegler, and Bichler (2012) and Bichler and Shabalin (2013), who study the clock-proxy auction of Ausubel, Cramton, and Milgrom (2006). In the clock-proxy auction, bidders are allowed to submit a single bid in each round of the clock round, followed by a supplementary sealed-bid phase, where bidders can submit bids over all packages. The authors find that in environments with a large number of packages, bidders analyze and bid on only a small set of supplementary bids. This leads to a decrease in overall efficiency.[102]

In two-sided settings, where there is an inherent complementarity between buyers and sellers, bidding on only a subset of profitable packages may have profound effects on the efficiency of the auction. As was seen in section 3.2, the trading network can be quite intricate and omitted bids can lead to a substantial (or complete) change of the network of trades. For example, if sellers have multiple goods and are willing to sell all of them or none of them, an incomplete set of bids by buyers on some goods may lead sellers to retain others. This inherent threshold problem is not present in most one-sided problems where supply is static.

In many of the common iterative auction formats, straightforward bidding is a Nash equilibrium when goods are substitutes. Thus, the complexity of bidding in an auction can be strongly related to the complementarities that exist across goods. In one-sided settings, potential complementarities can often be eliminated through careful prepackaging of objects. For example, in the sale of 700 MHz spectrum, most countries sold licenses in pairs. These paired licenses were ideal for LTE-based 4G networks, which used one frequency for transmitting information and another license for transmitting.[103] In two-sided auctions, the ability for the designer to prepackage licenses may be limited. Uncertainty over supply and the potential of very different goods being sold may make it difficult for the designer to fully eliminate complementarities. This implies that designs that can facilitate complementarities may be of greater importance with two-sided private information.

[101] Brunner, Goeree, Holt, and Ledyard (2010) also find that individuals do not bid on all packages in a simultaneous multi-round format that uses an 'XOR' bid language and allows for package bidding (SMRPB). They find that this design hurts efficiency in environments where complementarities are low.

[102] Testing the VCG mechanism, Chen and Takeuchi (2010) and Scheffel, Ziegler, and Bichler (2012) also find that profitable packages are not bid on. Similar to the results for second-priced sealed bid auctions, they also find underbidding and overbidding across packages.

[103] Most countries also sell licenses as generic lots and assign specific licenses only at the end of the auction to avoid frequency fragmentation. The proposed rules for the broadcast incentive auction propose selling all spectrum as generic lots and then having the FCC optimize the resulting spectrum for the bidders after the auction.

4.4 Exclusion of buyers

In reply comments to the FCC on the design of the incentive auction, multiple commenters have suggested that strong buyers should be restricted in their ability to acquire spectrum at the auction.[104] The discussion has focused on whether restrictions should be placed on the ability of largest wireless services providers, Verizon and AT&T, to purchase spectrum licenses in the incentive auction. Without wading into the details of this debate, we consider the effect of excluding a strong buyer from a one-sided versus a two-sided mechanism. For comparability, we consider a one-sided VCG mechanism versus a two-sided VCG mechanism.

Consider an environment with 1 object/seller, $n \geq 2$ normal buyers, and 1 strong buyer, where the cost is drawn from distribution G, normal buyers draw their values from distribution F, and the strong buyer draws its value from distribution H, where all distributions have support $[0, 1]$ and $H = F^a$ for some $a > 0$. (We assume continuous distributions with densities that are positive on the interior of the support.) For $a = 1$, the strong buyer is symmetric with the normal buyers. For $a > 1$, distribution G first-order stochastically dominates F and one can view the strong buyer as, loosely, a times as strong as a normal buyer in the sense that the strong buyer can be viewed as equivalent to a coalition of a normal buyers. If $a < 1$, then the "strong" buyer is actually weaker than the normal buyers.

In this example with one object, when there is trade, the payment made by the buyer is the maximum of the second-highest value and the seller's cost, and the payment made to the seller is the highest value.

Let J and $\hat{J}$ be the cumulative distributions for the highest value among the n normal buyers and for the combined n normal buyers plus the strong buyer, respectively, with j and $\hat{\jmath}$ being the respective densities.[105] Note that $\hat{J}$ first-order stochastically dominates J. Let J_t and $\hat{J}_t$ be the joint distributions of the first and second highest values excluding and including

[104] As reported in the communications trade press, "Among the areas of continuing disagreement is whether the FCC should impose a cap on the ability of Verizon Wireless and AT&T to buy spectrum in the auction." ("Sharp Disagreements Remain on Incentive Auction Rules," *Communications Daily*, March 15, 2013) See, for example, the comments by T-Mobile: "One of the strongest deterrents to widespread participation in the 600 MHz auction is the prospect that bidding will be pointless if the nation's two largest carriers – each of which has a market capitalization roughly ten times that of its next largest competitor – are given an unfettered ability to acquire all of the spectrum offered. Most commenters, therefore, support imposing a cap on spectrum acquisitions...." (Reply Comments of T-Mobile USA, Inc., GN Docket No. 12-268, March 12, 2013, pp.iv–v, available at http://apps.fcc.gov/ecfs/document/view?id=7022130363, accessed March 20, 2013) Other examples include the reply comments of the Competitive Carriers Association and Cellular South, Inc. in the same docket.

[105] Excluding the strong buyer, the cumulative distribution for the highest value among the n buyers is $J(x) = F(x)^n$, and the density is $j(x) = nF(x)^{n-1}f(x)$. Including the strong buyer, the cumulative distribution for the highest value among the $n+1$ buyers is $\hat{J}(x) = H(x)F(x)^n$, and the density is $\hat{\jmath}(x) = nH(x)F(x)^{n-1}f(x) + F(x)^n h(x)$.

the strong buyer, with j_t and $\hat{j}_t$ being the respective densities.[106]

In both the one-sided and two-sided VCG mechanisms, the change in the expected number of units transacted from excluding the strong buyer is

$$\int_0^1 \int_0^{v_1} g(c)\left(j(v_1) - \hat{j}(v_1)\right) dc dv_1 \leq 0,$$

and the change in social welfare from excluding the strong buyer is

$$\Delta\mathcal{H} = \int_0^1 \int_0^{v_1} (v_1 - c) g(c)\left(j(v_1) - \hat{j}(v_1)\right) dc dv_1 \leq 0,$$

where the inequalities follow from first-order stochastic dominance. Thus, the expected number of units transacted and expected social welfare decrease when the strong buyer is excluded.

In the one-sided VCG, the highest-valuing buyer pays $\max\{v_2, c\}$ whenever $v_1 > c$, so the change in expected revenue from excluding the strong buyer is:

$$\begin{aligned} \Delta\mathcal{R}_1 &= \int_0^1 \int_0^{v_1} \int_0^{v_2} v_2\left(j_t(v_1, v_2) - \hat{j}_t(v_1, v_2)\right) g(c) dc dv_2 dv_1 \\ &+ \int_0^1 \int_0^{v_1} \int_{v_2}^{v_1} c\left(j_t(v_1, v_2) - \hat{j}_t(v_1, v_2)\right) g(c) dc dv_2 dv_1 \\ &\leq 0, \end{aligned}$$

where the inequality again follows from first-order stochastic dominance. Expected revenue in the one-sided mechanism decreases when a buyer is excluded.

The corresponding expression for the two-sided VCG mechanism, which takes into account payments received from buyers minus payments made to sellers, is:

$$\begin{aligned} \Delta\mathcal{R}_2 &= \int_0^1 \int_0^{v_1} \int_0^{v_2} (v_2 - v_1)\left(j_t(v_1, v_2) - \hat{j}_t(v_1, v_2)\right) g(c) dc dv_2 dv_1 \\ &+ \int_0^1 \int_0^{v_1} \int_{v_2}^{v_1} (c - v_1)\left(j_t(v_1, v_2) - \hat{j}_t(v_1, v_2)\right) g(c) dc dv_2 dv_1. \end{aligned}$$

As one can see in the expression for $\Delta\mathcal{R}_2$, in the two-sided VCG, excluding a strong buyer can affect the payment by the buyer as well as the payment to the seller. There are four possible effects on revenue of the exclusion of a buyer. First, the exclusion of a buyer with a value that is between the first and second-highest values among the normal buyers can decrease the amount paid by the buyer, but it does not affect the payment to the seller. Second, the exclusion of a strong buyer with a value that is greater than but close to the highest value among the normal

[106] Excluding the strong buyer, the joint distribution of the first and second highest values is $J_t(y, x) = n(F(y) - F(x))F(x)^{n-1} + F(x)^n$, with density $j_t(y, x) = n(n-1)F(x)^{n-2} f(x) f(y)$. Including the strong buyer, the joint distribution is $\hat{J}_t(y, x) = (H(y) - H(x))F(x)^n + n(F(y) - F(x))H(x)F(x)^{n-1} + H(x)F(x)^n$ and the density is $\hat{j}_t(y, x) = nF(x)^{n-1}\left(f(x)h(y) + f(y)h(x)\right) + n(n-1)H(x)F(x)^{n-2} f(y) f(x)$.

buyers decreases revenue because it decreases the amount paid (from the highest to the second highest among the normal buyers) with little effect on the amount paid to the sellers (from the value of the strong buyer to the highest among the normal buyers, which are assumed to be close in this case). Third, the exclusion of a strong buyer with a value that is significantly greater than the highest among the normal buyers can increase revenue because, although it decreases the amount paid by the winning buyer, it can decrease the amount paid to the seller by more. Fourth, if the exclusion of a strong buyer causes the object not to be sold when it would have otherwise, this increases revenue from a negative amount (the efficient mechanism runs a deficit) to zero.

Considering these four effects, the first and second effect, in which the exclusion of the strong buyer decreases revenue are more likely when the strong buyer is not too much stronger than the highest valuing buyer from among the normal buyers, i.e., in our example, as long as a is not too much larger than n. The third and fourth cases, in which the exclusion of the buyer increases revenue are more likely when the strong buyer is stronger than the highest valuing buyer from among the normal buyers, i.e., in our example, for a sufficiently greater than n. Thus, in our example, if n is larger, a larger value of a is required in order for the exclusion of a buyer to potentially increase revenue.

In summary, excluding a strong buyer is likely to decrease revenue unless the buyer is sufficiently strong relative to the highest valuing normal buyer. With sufficiently many normal buyers, excluding a strong buyer is likely to decrease revenue.[107]

Within this framework, we can compare the sensitivity of the one-sided mechanism to the exclusion of a strong buyer with the sensitivity of the two-sided mechanism to the exclusion of a strong buyer. Given our focus in this subsection on efficient mechanisms, the welfare loss $\Delta\mathcal{H}$ is the same for both the one-sided and two-sided mechanisms. Because we view both welfare and revenue as relevant criteria, and because the sum of welfare and revenue is positive, which facilitates the interpretation of results, we consider the effect of excluding a strong buyer on the sum of social welfare and revenue. In Figure 5, we compare $\Delta\mathcal{R}_1 + \Delta\mathcal{H}$ with $\Delta\mathcal{R}_2 + \Delta\mathcal{H}$, as a percentage of welfare plus revenue when the strong buyer is included.[108]

[107] Although Figure 4 assumes that the values of the normal buyers are drawn from the uniform distribution, numerical robustness checks indicate that the qualitative result holds for values drawn from any beta distribution except those that are highly positively skewed, in which case the normal buyers' values are, in expectation, close to zero, so excluding the strong buyer actually decreases the expected distance between the first and second highest values, conditional on both exceeding the cost, as well as decreasing the expected distance between the highest value and the cost, conditional on only the highest value exceeding the cost.

[108] Although Figure 5 assumes that the values of the normal buyers are drawn from the uniform distribution,

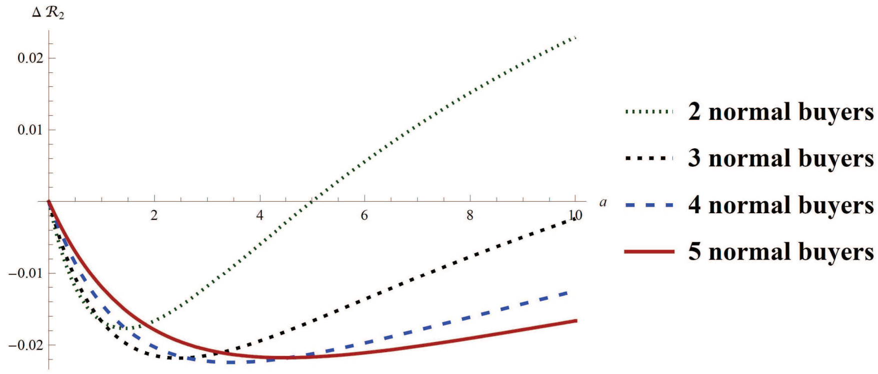


Figure 4: Change in expected net revenue in a two-sided VCG mechanism from the exclusion of the strong buyer as a function of the strength of the strong buyer, as measured by a, for varying numbers of normal buyers (assumes F and G are uniform)

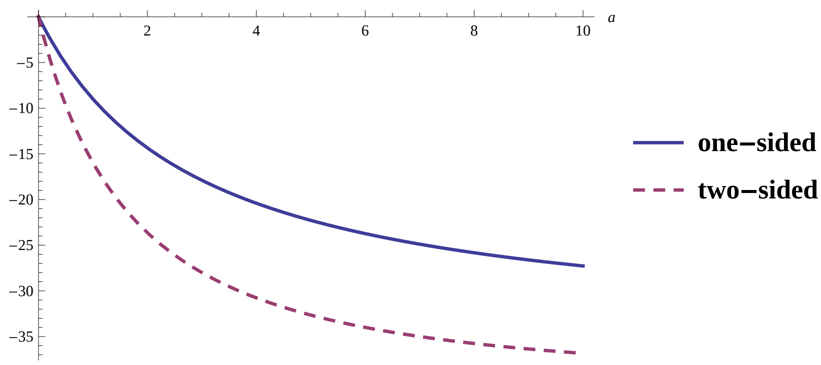


Figure 5: Percentage change in the sum of social welfare plus net revenue from the exclusion of the strong buyer as the strength of the strong buyer, as measured by a, varies, assuming 4 normal buyers (assumes F and G are uniform)

As shown in Figure 5, the two-sided mechanism is more sensitive in percentage terms to the exclusion of the strong buyer. The loss from excluding a strong buyer in terms of the percentage reduction in the sum of welfare plus revenue is greater in the two-sided setup than in the one-sided setup.[109] For example, when there are four normal buyers and the strong buyer is four times as strong as a normal buyer, then excluding the strong buyer reduces welfare plus

numerical robustness checks indicate that the qualitative result holds for values drawn from any beta distribution. The percentage changes are smaller for lower variance symmetric distributions, and they are smaller for negatively skewed than for positively skewed distributions.

[109] Conditional on trade occurring, the two-sided VCG mechanism generates lower revenue than the one-sided VCG mechanism because of the need to compensate the seller by an amount that exceeds his actual cost. Thus, even a similar decrease in revenue from excluding the strong buyer results in a greater percentage decrease. As shown in Figure 4, the negative impact of exclusion on revenue increases rapidly for values of a less than n, but then levels out. This is reflected in the decreasing but convex curves in Figure 5. The effect is initially greater for the two-sided VCG because the exclusion of the strong buyer can affect both the amount paid by buyers and the amount paid to the seller, whereas in the one-sided mechanism, the amount paid to the seller is equal to the seller's cost.

revenue in the one-sided mechanism by slightly more than 20% but in the two-sided mechanism by more than 30%. The effect is more pronounced the stronger is the strong buyer and, one can show, less pronounced as the number of participating normal buyers increases.

In addition to the negative effects from excluding a strong buyer that are described above, in the context of the incentive auction, the reduction in the amount of spectrum transacted has broader implications because it means that less spectrum will be reassigned from broadcasters to providers of mobile wireless services and could potentially affect the repacking of the remaining broadcast licenses. In reply comments to the FCC, AT&T states: "*This* auction is different, and there is *no* room for regulatory error, because the consequences of such error would be much more severe: less (or no) spectrum would be reassigned to providers of mobile wireless services in the first place."[110]

5 Conclusion

The possibility for economists to contribute to the practical design of centralized markets with privately informed buyers and sellers has been a long way coming. Recent calls for an incentive auction for spectrum licenses coupled with increasing demands for centralized platforms for the exchange of landing-slots, port slots, and electricity trade suggest that the need and opportunity for developing such markets is on the rise. Just as spectrum license auctions mobilized economists in the study of one-sided auctions, we expect that theoretical, experimental, and empirical research will develop to meet this new challenge.

Most of the theoretical research relating to market design has been predominantly on mechanisms for primary markets. We have shown that in many relevant dimensions, results from one-sided problems do not carry over to two-sided setups. This suggests that intuition that is based on one-sided problems may be misleading, and it underscores the importance of understanding where the key differences lie. This paper shows that focusing on the complementarity inherent between buyers and sellers in a two-sided mechanism is likely to be one of the keys to developing new theoretical insights.

Additional experimental research, possibly with tighter ties to theory, is also likely to be valuable. The experimental literature has found that the continuous-time double auction is a highly efficient mechanism in homogeneous goods markets. Research into whether such mech-

[110] Reply Comments of AT&T Inc., GN Docket No. 12-268, March 12, 2013, p.4, available at http://apps.fcc.gov/ecfs/document/view?id=7022130222, accessed March 20, 2013, italics in original.

anisms can be extended to environments with heterogeneous goods with and without complementarities across these goods is likely to be valuable moving forward. Likewise, experiments that aim to better understand how individuals deal with complexity in two-sided markets is likely to be important to optimal design.

In this paper, we have reviewed the existing literature on the design of centralized secondary markets with privately informed buyers and sellers and provided a number of new results. The design of incentive auctions will likely stimulate research on this topic. The research program is articulated in Satterthwaite and Williams (2002, p.1841), where they say, "This is part of an effort to develop a theory of market mechanisms that is analogous to the theory of auctions. Currently, economic theory provides little guidance to financial exchanges in the selection of computer algorithms and floor procedures for trading. A theory of market mechanisms would provide such guidance and also complement the rich literature on markets in experimental economics, which is currently the main source of guidance in the design of market mechanisms." We expect the time may be ripe for the advancement of this research program.

A Appendix: The Linkage Principle

In this appendix, we provide a statement of the linkage principle following the presentation of Krishna (2002, Chapter 7). Define a *standard* auction format to be one in which the high bidder wins. Suppose that each bidder $i \in \{1, ..., N\}$ receives a signal X_i regarding the value of the object. Assume the valuation to each bidder depends on its own observed signal and symmetrically upon the unobserved signals of the other bidders, with all signals X_i are drawn from the interval $[0, \omega]$ and bidder i's value given by $v_i(\mathbf{X}) = u(X_i, \mathbf{X}_{-i})$, where the function u is symmetric in the last $N-1$ components.

Define random variables $Y_1, Y_2, ..., Y_{N-1}$ to be the largest, second largest, etc., from among $X_2, X_3, ..., X_N$. Let $G(\cdot \mid x)$ denote the distribution of Y_1 conditional on $X_1 = x$, i.e., $G(z \mid x) \equiv \Pr(Y_1 < z \mid X_1 = x)$, and let $g(\cdot \mid x)$ be the associated density. We let $v(x, y) = E(V_1 \mid X_1 = x, Y_1 = y)$ be the expectation of the value to a bidder when the signal he receives is x and the highest signal among the other bidders, Y_1, is y. We assume that v is nondecreasing in y and strictly increasing in x and that $v(0, 0) = 0$.

For each standard auction format A, suppose that the auction has a symmetric and increasing equilibrium β^A, which is a mapping from a bidder's observed signal to its bid. Let $W^A(z, x)$ denote the expected payment by a bidder if he is the winning bidder when he receives a signal x but bids as if his signal were z, i.e., he bids $\beta^A(z)$. Let $W_1^A(z, x)$ denote the derivative of W^A with respect to its first argument and $W_2^A(z, x)$ the derivative with respect to its second argument, evaluated at (z, x).

In a first-price sealed-bid auction, labeled I, where the high bidder wins and pays the amount of his bid, we have $W^I(z, x) = \beta^I(z)$, and in a second-price auction, labeled II, where the high bidder wins and pays the amount of the second-highest bid, we have $W^{II}(z, x) = E\left[\beta^{II}(Y_1) \mid X_1 = x, Y_1 < z\right]$.

The linkage principle can then be stated as follows:

Proposition 2 *(Krishna,* 2002*, Proposition* 7.1*) Let A and B be two standard auctions, each having a symmetric and increasing equilibrium such that* (i) *for all x, $W_2^A(x, x) \geq W_2^B(x, x)$;* (ii) $W^A(0, 0) = 0 = W^B(0, 0)$. *Then the expected revenue in A is at least as large as the expected revenue in B.*

Proof. The expected payoff of a bidder with signal x who bids $\beta^A(z)$ is

$$\int_{-\infty}^{z} v(x,y)g(y \mid x)dy - G(z \mid x)W^A(z,x).$$

In equilibrium, it is optimal to choose $z = x$ and the resulting first-order conditions imply that

$$v(x,x)g(x \mid x) - g(x \mid x)W^A(x,x) + G(x \mid x)W_1^A(x,x) = 0,$$

which we can rewrite as

$$W_1^A(x,x) = \frac{g(x \mid x)}{G(x \mid x)}v(x,x) - \frac{g(x \mid x)}{G(x \mid x)}W^A(x,x).$$

Letting $\Delta(x) = W^A(x,x) - W^B(x,x)$, we conclude that

$$\Delta'(x) = -\frac{g(x \mid x)}{G(x \mid x)}\Delta(x) + \left(W_2^A(x,x) - W_2^B(x,x)\right).$$

By hypothesis (i), the second term is positive, and by hypothesis (ii), which implies $\Delta(0) = 0$, it follows that $\Delta(x)$ and $\Delta'(x)$ cannot be of different signs, implying that for all x, $\Delta(x) \geq 0$. Q.E.D.

To use this proposition to rank, for example, the second-price and first-price auctions, we need to assume that the bidders signals are *affiliated* (see Milgrom and Weber, 1982, Appendix on Affiliation, pp.1118–1121), which implies that $G(z \mid \cdot)$ is decreasing and that $W_2^{II}(x,x) \geq 0$. Note that $W_2^I(x,x) = 0$. Thus, under the assumption of affiliation, $W_2^{II}(x,x) \geq W_2^I(x,x)$. In addition, $W^{II}(0,0) = 0 = W^I(0,0)$, so the linkage principle implies that expected revenue from a second-price auction is at least as great as that from a first-price auction. To show that expected revenue is greater when public information is made available, consider the first-price auction. Let S be a random variable denoting the information available to the seller and suppose a symmetric equilibrium strategy $\hat{\beta}(S,X_1)$ that is increasing in both variables. Then let $\hat{W}^I(z,x) = E\left[\hat{\beta}(S,z) \mid X_1 = x\right]$ be the expected payment of a winning bidder when he receives signal x but bids as if it were z. Assuming S and X_1

are affiliated, so that $\hat{W}_2^I(z,x) \geq 0$, then $\hat{W}_2^I(x,x) \geq W_2^I(x,x)$ and the linkage principle implies that expected revenue is at least as great when information is revealed as when it is not. To see that an ascending-bid auction has greater expected revenue than a second-price auction, note that in an ascending-bid auction, the observed points at which other bidders cease to be active provide additional signals that are also affiliated with X_1 and so the logic for information revelation increases expected revenue applies.

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