Chapter 1
Getting to Work

The era of putting auction theory to work began in 1993-94, with the design and operation of the radio spectrum auctions in the United States. Although the economic theory of auctions had its beginnings in the 1960s, early research had little influence on practice. Since 1994, auction theorists have designed spectrum sales for countries on six continents, electric power auctions in the US 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 economic science. In 2000, the US National Science Foundation's 50^{th} anniversary celebration featured the success of the US spectrum auctions to justify its support for fundamental research in subjects like game theory. By the end of 2001, just seven years after the first of the large modern auctions, the theorists' designs had powered worldwide sales totaling more than $100 billion. The early US spectrum auctions had evolved into a world standard, with their major features expressed in all the new designs.

It would be hard to exaggerate how unlikely these developments seemed in 1993. Then, as now, the status of game theory within economics was a hotly debated topic. Auction theory, which generated its main predictions by treating auctions as "games," had inherited the controversy. At the 1985 World Congress of the Econometric Society, a wide gulf developed between bargaining theorists, who were skeptical that game theory could explain much about bargaining or be useful for improving bargaining protocols, and researchers in auctions and industrial organization, who believed that game theory was illuminating their fields. Although game theory gained increasing prominence throughout the 1980s and had begun to influence the leading graduate textbooks by the early 1990s, there was no consensus about its relevance in 1994, when the Federal Communications Commission conducted the first of the new spectrum auctions.

The traditional foundations of game theory incorporate stark assumptions about the rationality of the players and the accuracy of their expectations which are hard to reconcile with reality. Yet, based on both field data and laboratory data, the contributions of auction theory are hard to dispute. The qualitative predictions of auction theory have been strikingly successful in explaining patterns of bidding for oil and gas[1] and have fared well in other empirical studies as well. Economic laboratory tests of auction theory have uncovered many violations of the most detailed theories, but several key tendencies predicted by the theory find significant experimental support.[2] Taken as a whole, these findings indicate that although existing theories need refinement, they capture important features of actual bidding. For real world auction designers, the lesson is that theory can be helpful, but it needs to be supplemented by experiments to test the applicability of key propositions and by practical judgments, seasoned by experience.

Whatever the doubts in the academy about the imperfections of game theory, the dramatic case histories of the new auctions seized public attention. An article in 1995 in

[1] See Hendricks, Porter and Wilson (1994).

[2] See Kagel (1995).

the New York Times hailed one of the first US spectrum auctions[3] as "The Greatest Auction Ever."[4] The British spectrum auction of 2000, which raised about $34 billion, earned one of its academic designers[5] a commendation from the Queen and the title "Commander of the British Empire." In the same period, game theorists were plying their trade on another important application as well. The National Resident Matching Program, by which 20,000 US physicians are matched annually to hospital residency programs, implemented a new design in 1998 with the help of economist-game theorist Alvin Roth. By the mid-nineties, thirty-five years' of theoretical economic research about fine details of market design was suddenly bearing very practical fruits.

Politics Sets the Stage

To most telecommunications industry commentators, the main significance of the US spectrum auctions was that a market mechanism was used at all. Spectrum rights (licenses) in the US and many other countries had long been assigned in *comparative hearings*, in which regulators compared proposals to decide which applicant would put the spectrum to its best use. The process was hardly objective: it involved lawyers and lobbyists arguing that their plans and clients were most deserving of a valuable-but-free government license.[6] With its formal procedures and appeals, a comparative hearing could take years to complete. By 1982, the need to allocate many licenses for cellular telephones in the US market had overwhelmed the regulatory apparatus, so Congress agreed to allow licenses to be assigned randomly among applicants by lottery.

The lottery sped up the license approval process, but it created a new set of problems. Lottery winners were free to resell their licenses, encouraging thousands of new applicants to apply for licenses and randomly rewarding many with prizes worth many millions of dollars. Lottery winners were often simple speculators with no experience in the telephone industry and no intention of operating a telephone business. Economic resources were wasted on a grand scale, both in processing hundreds of thousands of applications and in the consequent need for real wireless operators to negotiate and buy licenses from these speculators. The lotteries of small licenses contributed to the geographic fragmentation of the cellular industry, delaying the introduction of nationwide mobile telephone services in the United States.

A better process was needed, and in 1993, Congress authorized auctions as the answer. The question of how an auction market for radio spectrum should be designed was left to the Federal Communications Commission (FCC).

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[3] The design was based on suggestions by Preston McAfee, Paul Milgrom and Robert Wilson.

[4] William Safire, "The Greatest Auction Ever," *New York Times*, March 16, 1995, page A17, commenting on FCC Auction #4.

[5] The principal designers were Professors Ken Binmore and Paul Klemperer. It was Binmore whom the Queen of England honored with a title.

[6] The process was once characterized by an FCC Commissioner as "the FCC's equivalent of the Medieval trial by ordeal" (as quoted by Kwerel and Felker (1985)).

Designing for Multiple Goals

Congress did provide some instructions to the FCC governing the new spectrum auctions. One was that the first auctions were to be begun by July 1994. A second called for the auctions to promote wide participation in the new industry. The FCC initially responded to the second mandate by introducing bidding credits and favorable financing terms for small businesses and woman- and minority-controlled businesses, to reduce the cost of any licenses acquired by those businesses. The statute also specified that the auction process should promote "efficient and intensive use" of the radio spectrum, in contrast with the fragmented use promoted by the lottery system. The meaning of the word "efficient" was initially subject to debate, but it was eventually read in economic terms to mean, in the words of Vice President Albert Gore, "putting licenses into the hands of those who value them the most."[7]

There is a powerful tradition in economics claiming that individuals and firms, left to their own devices and operating in a sound legal framework, tend to implement efficient allocations. The argument is that when resources are allocated inefficiently, it is possible for the parties to get together to make everyone better off. So, following their mutual interests, the parties will tend to eliminate inefficiencies whenever they can. This traditional argument has its greatest force when the parties can all see what is required and have no trouble negotiating how to divide the gains created by the agreement. For radio spectrum, with thousands of licenses and hundreds of participants involved, computing just one efficient allocation can be an inhumanly hard problem and getting participants to reveal the information about their values necessary to do that computation is probably impossible. Compared to the development of a universal standard (GSM) for mobile telephones in Europe, the more fragmented system that emerged in the US highlights that the lottery system did not lead to efficient spectrum allocations. With so many parties and interests involved, the market was unable to correct the initial misallocation of the spectrum. Getting the allocation right the first time does matter. Achieving that with an auction system called for a different and innovative approach.

The Federal Communications Commission (FCC), which the law had charged with designing and running the spectrum auctions, had no previous auction experience. Within the FCC, the design task was assigned to a group led by Dr. Evan Kwerel, an economist and long-time advocate of using auctions to allocate spectrum licenses.[8]

Like any other important FCC decision, the auction design decision would need to be based on an adequate public record—a requirement that would force the FCC to go through a long series of steps. It would need to write and issue a proposed rule, allow a period for comments and another for "reply comments," meet with interested parties to discuss and clarify the points of disagreement, resolve those disagreements, issue a ruling, consider appeals, and finally run the auction. Steps like these often stifle innovation, but that is not what happened on this occasion. With no political guidance about what kind of auction to use, no in-house experts lobbying to do things their way, and no telecom with an historically fixed position about how an auction should be run, Dr. Kwerel had unusual freedom to evaluate a wide range of alternatives.

[7] Quoted from Vice President Gore's speech at the beginning of FCC auction #4.

[8] Kwerel's initial advocacy is explained in Kwerel and Felker (1985).

Kwerel drafted a notice that proposed a complex auction rule. Industry participants, stunned by the novel proposal and with little experience or expertise of their own, sought the advice of academic consultants. These consultants generated a flood of suggestions, and the FCC hired its own academic expert, John McMillan, to help them evaluate the proposed designs. In the end, Kwerel favored a kind of simultaneous ascending auction, based in large part on a proposal by Robert Wilson and me and a similar proposal by Preston McAfee. The Milgrom-Wilson-McAfee rules called for a simultaneous multiple round ascending auction.[9] This is an auction for multiple items in which bidding occurs in a series of rounds. In each round, bidders make sealed bids for as many spectrum licenses as they wish to buy. At the end of each round the 'standing high bid' for each license is posted along with the minimum bids for the next round, which are computed by adding a pre-determined bid increment, such as 5% or 10%, to the standing high bids. These standing high bids remain in place until superceded or withdrawn.[10] An "activity rule" limited a bidder's ability to increase its activity late in the auction, thus providing an incentive to bid actively early in the auction. For example, a bidder who has been actively bidding for ten licenses may not, late in the auction, begin bidding for eleven licenses.

The theory of simultaneous ascending auctions is best developed for the case when the licenses being sold are substitutes. During the course of the auction, as prices rise, bidders who are outbid can switch their demands to bid for cheaper licenses, allowing effective arbitrage among substitute licenses. One of the clearest empirical characteristics of these auctions is that licenses that are close substitutes sell for prices that are also close—a property that is not shared by most older auction designs.

The initial reception to Kwerel's recommendation was skeptical. The proposed auction was unexpectedly complicated, and FCC Chairman Reed Hundt sought the advice of other FCC staff. He asked the economics staff: If you could pick any design you want, would this be it? He asked those who would have to run it: Can this really work? Even in the short time available to set it up? With the endorsement of his staff, Chairman Hundt decided to take the risk of adopting a new auction design.

Substitutes and Complements

Auctions are processes for allocating goods among bidders, so the challenge of auction design can only be understood by studying the demands of the participants. In the initial PCS auction, there were three groups of potential bidders. The first group included long-distance companies with no existing wireless businesses. These companies, including MCI and Sprint, were making plans to enter the wireless business on a national scale. Each wished to acquire a license or licenses that would cover the entire United States, allowing it to make its service ubiquitous and to combine wireless with its own long distance service to offer an attractive and profitable package to consumers.

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[9] The principal difference was that the Milgrom-Wilson design proposed the now-standard features that bidding on all licenses would remain open until the end of the auction, with progress ensured by Milgrom's activity rule. McAfee's design had no activity rule, and ensured the progress of the auction by closing bidding on each license separately after a period with no new bids on that license.

[10] A bidder who withdraws its bid pays a penalty equal to the difference, if positive, between the eventual sales price for the license and the amount of its withdrawn bid. If the eventual price exceeds its bid, then no penalty is payable.

A second group comprised the existing wireless companies, including AT&T, some regional Bell operating companies, and others. The companies in this group already owned or controlled licenses that enabled them to offer services to parts of the country. Their objectives in the auction were to acquire licenses that filled in the varying gaps in their existing coverage and to expand to new regions or perhaps the entire nation. These companies posed a regulatory challenge for the FCC, which wanted to allow them to meet their legitimate business needs without gaining control of enough of the spectrum to manipulate market prices. To avoid this outcome, the FCC imposed limits on the amount of spectrum that any company could control in any geographic area. These existing wireless operators would be ineligible to bid for a nationwide PCS license of the sort that had typically been awarded in European countries. From MCI's perspective, this meant that a nationwide license might be bought cheaply at auction, so it lobbied the FCC to structure the new licenses in this way.

The last group consisted mainly of new entrants without wireless businesses. Some of these companies, like Pacific Bell in California, were quite large. These companies typically sought licenses or packages covering large regional markets, but not licenses covering the entire nation.

One of the first lessons to take from this description is that the auction game begins long before the auction itself. The scope and terms of spectrum licenses can be even more important than the auction rules for determining the allocation, because a license can directly serve the needs of some potential bidders while being useless to others. For the actual PCS auctions, a license provided its owner the right to transmit and receive radio signals suitable for mobile telephone service in a particular band of radio frequencies and in a particular geographic area. These license specifications constrained the possible spectrum allocations. For example, suppose three separate licenses covering areas A, B and C were put for sale. If one bidder wanted a license covering A and half of B while the other wanted a license covering C and the other half of B, the license specifications would prevent each bidder from acquiring his optimal allocation. One task of the auction designer was to promote the best (most "efficient") possible allocation, subject to such constraints.

Achieving efficiency involves various subtle complications. A certain license may be valuable to one bidder because it helps exclude entry and increase monopoly power, while it is valuable to another because the buyer will use it to create valuable services. In comparing the efficiency of allocations, only the second kind of value counts, but bidders do not respect that difference when placing their bids. The value of a license to a bidder may depend not only on the license itself, but also on the identities of other licensees and the technologies they use, because that can affect their "roaming arrangements"—which allow their customers to use another company's services when they roam to the other company's license area. A third complication is that the bidders may need to pool information even to determine their own likely profits from various arrangements, for example because the bidders have different information about the available technology or forecasted demand.

But the fundamental barrier to efficiency that was most debated among the FCC auction designers concerned the "packaging problem." The value of a license to a bidder is not fixed; it generally depends on the other licenses the bidder receives. For example, a bidder might be willing to pay much more per license for a package of, say, five or six licenses compared to smaller packages or larger packages.[11] *Until such a bidder knows all of the licenses it will have, it cannot say how much any particular license is worth.*

Consider a situation with just two licenses. If acquiring one license makes a bidder willing to pay less for the second, then the licenses are *substitutes*. If acquiring one makes the bidder willing to pay more for the second, then the licenses are *complements*. With more than two licenses, there are other important possibilities, and these add considerable complexity to the real auction problem. For example, if there are three licenses—say A, B and C—and a certain bidder anticipates needing exactly two of them to establish its business, then A and B are complements if the bidder has not acquired C, but they are substitutes if the bidder has already acquired C. Nevertheless, most economic discussions of the auction design are organized by emphasizing the two pure cases.

Recent auctions devised by economic theorists are most distinguished from their predecessors in the ways they deal with the problems of substitutes and complements. Our later analyses will show that some of the new designs deal effectively with cases in which the items to be traded are substitutes, but that all auctions perform significantly worse in the more general case in which licenses might either be substitutes or complements. The impaired performance may take the form of loss of efficiency of the outcomes, uncompetitively low revenues to the seller, or vulnerability to collusion.

To illustrate how value interdependencies affect proper auction design, we turn to a case study in which the matter received too little attention.

New Zealand's Rights Auction

New Zealand conducted its first auctions of rights to use radio spectrum in 1990. Some of the rights took the traditional form of "*license rights*" to use the spectrum to provide a specific service, such as the right to broadcast television signals using those frequencies. Others consisted of "*management rights*" according to which the buyer may decide how to use the spectrum, choosing, for example, between television broadcasts, wireless telephones, paging, or some other service. In theory, when management rights are sold, private interests have an incentive to allocate spectrum to its most profitable uses, but the problem of coordinating uses among licensees can also become more complex.

Acting on the advice of a consulting firm—NERA, the New Zealand government adopted a *second-price sealed-bid auction* for its first four auction sales. As originally described by Vickrey (1961), the rules of the second-price auction are these: Each bidder submits a sealed bid. Then, the license is awarded to the highest bidder for a price equal to the *second* highest bid, or the reservation price if only one qualifying bid is made. The auction gets its name from the fact that the second highest bid determines the price.

The idea of a second-price sealed-bid auction strikes many people as strange when first they hear about it, but on closer analysis, the auction is not strange at all. In fact, it

[11] An instance of this sort arose in the Netherlands spectrum auction in 1998, where most of the licenses were for small amounts of bandwidth. New entrants were expected to need five or six such licenses to achieve efficient scale and make entry worthwhile.

implements a version of the ascending ("English") auction[12] similar to the one used at Amazon auction.[13].

In an ascending auction, if a bidder has a firm opinion about what the item is worth, then he can plan in advance how high to bid – an amount that we may call the bidder's *reservation value*. At sites like eBay and Amazon, the bidder can instruct a *proxy bidder* to carry out a *reservation value strategy.* The proxy keeps beating the current highest bid on the bidder's behalf so long as that bid is less than the specified reservation value. If everyone bids that way, then the outcome will be that competition ends when the price rises to the second highest reservation value, or thereabouts (with differences due to the minimum bid increment). If everyone adopts such a reservation value strategy, then the ascending auction is almost the same as a second-price auction.

Strategic considerations in a second-price auction are easy: each bidder should set his reservation value to what the object is worth to him. If it happens that the highest bid among the other bidders is greater than this value, then he cannot do better than to bid his reservation price, because there is no bid he could make that would win the auction profitably. If, instead, it happens that the highest competing bid is less than his value, then the setting his reservation value in this way wins and fixes the price at what the competitor bid, which is the best outcome that any bid could achieve. Thus, regardless of the bids made by others, setting a reservation value equal to the bidder's actual value always earns at least as much as any other bid.

The second-price sealed-bid auction has two advantages over most other designs. First, it duplicates the outcome of an ascending bid auction with small bid increments but without requiring the bidders to be assembled together or even requiring them to hire agents to represent them in their absence. Second, it presents each bidder with a simple strategic bidding problem: each merely has to determine his reservation price and bid it. This also means that there is no need for any bidder to make estimates of the number of other bidders or their values, since those have no bearing on a rational bidder's optimal bid.

The second-price auction has a simple extension to sales of multiple identical items, and it, too, can be motivated by considering a particular ascending auction. For example, suppose there is such an auction rule with seven identical items for sale, to be awarded to the seven highest bidders in an ascending outcry auction. Again, bidders might sensibly adopt reservation value strategies, bidding just enough to be among the top seven bidders and dropping out when the required bid finally exceeds the bidder's value. An analysis much like the preceding one then leads to the conclusion that the items will be awarded to the seven bidders with the highest values for prices approximately equal to the eighth highest value. To duplicate that with a sealed-bid auction, the rule must award items at a uniform price equal to the highest rejected bid. In such an auction, the right advice to bidders is

[12] The most common form of an ascending ("English") auction is one in which the auctioneer cries out increasing bids and the bidders drop out when they are no longer willing to pay above the current price. The auction ends when there is just one remaining bidder. As the winning bidder is required to pay the current high price, it is optimal for each bidder to stay in the auction only until the current price is equal to his valuation ("reservation value") of the item and not thereafter.

[13] eBay also runs a similar auction, but its fixed ending time involves additional gaming issues as described by Roth and Ockenfels (2000).

simple: "bid the highest price you are willing to pay." A similar uniform-price rule has sometimes been used in the sale of U.S. Treasury bills.[14]

In New Zealand, the government was selling essentially identical licenses to deliver television signals to audiences in New Zealand. On the advice of its consultants, it did not adopt this "highest rejected bid" rule, but chose instead to conduct simultaneous second-price sealed-tender auctions for each license. New Zealand's second-price rules would work well in one case only: when the values of the items were independent—neither substitutes nor complements. In the actual New Zealand auction, it would have been difficult to give bidders good advice. Should a bidder bid for only one license? If so, which one? If everyone else plans to bid for just one license and picks randomly, perhaps there will be some license that attracts no bids. Bidding a small amount for every license might then be a good strategy. On the other hand, if many spread around small bids like that, then bidding a moderate amount for a single license would have a high chance of success. With interdependent values, independent auctions inevitably involve guesswork that gets in the way of an efficient allocation.

Table 1

Winning Bidders on Nationwide UHF Lots
8 MHz License Rights

Lot	Winning Bidder	High Bid (NZ$)	Second Bid (NZ$)
1	Sky Network TV	2,371,000	401,000
2	Sky Network TV	2,273,000	401,000
3	Sky Network TV	2,273,000	401,000
4	BCL	255,124	200,000
5	Sky Network TV	1,121,000	401,000
6	Totalisator Agency Board	401,000	100,000
7	United Christian Broadcast	685,200	401,000

Source: Hazlett (1998).

The actual outcome of the first New Zealand auction is shown in Table 1. Notice that one bidder, Sky Network TV, consistently bid and paid much more for its licenses than other bidders. Totalisator Agency Board, which bid NZ$401,000 for each of six licenses, acquired just one license at a price of NZ$100,000, while BCL, which bid NZ$255,000 for just one license, paid NZ$200,000 for it. Without knowing the exact values of various

[14]The Treasury rule set a uniform price equal to the lowest accepted bid.

numbers of licenses to the bidders, it is impossible to be certain that the resulting license assignment is inefficient, but the outcome certainly confirms that the bidders could not guess one another's behavior. If Sky Network, BCL, or United Christian had been able to guess the pattern of prices, they would have changed the licenses on which they had bid. The bid data shows little connection between the demands expressed by the bidders, the numbers of licenses they acquired, and the prices they eventually paid, suggesting that the outcome was inefficient.

A second problem was even more embarrassing to New Zealand's government officials.[15] McMillan (1994) described it as follows: "In one extreme case, a firm that bid NZ$100,000 paid the second-highest bid of NZ$6. In another the high bid was NZ$7 million and the second bid was NZ$5,000." Total revenue, which consultants had projected to be NZ$250 million, was actually just NZ$36 million. The second-price rules allowed public observers to get a good estimate of the winning bidders' profits, some of which were many times higher than the price. To avoid further embarrassment, the government shifted from the second-price sealed bid format to a more standard "first-price" sealed-bid format, in which the highest bidder pays the amount of its own bid. As we will see later in this book, that did not guarantee higher prices. It did, however, conceal the bidders' profits from a curious public.

The change in auction format still failed to address the most serious auction design problems. Unlinked auctions with several licenses for sale that may be substitutes or complements force a choice between the risks of acquiring too many licenses or too few, leaving a guessing game for bidders and a big role for luck. Allocations are unnecessarily random, causing licenses to be too rarely assigned to the bidders who value them the most.

Better Auction Designs

In the New Zealand case, alternative auction designs could have performed much better. For example, the government could have mimicked the design of the Dutch flower auctions. The winner at the first round would be allowed to take as many lots as it wished at the winning price. Once that was done, the right to choose next could be sold in the next auction round, and so on. No bidder would be forced to guess about which licenses to bid on with such an auction. Each bidder could be sure that, if he wins at all, he will win the number of lots or licenses anticipated by his business plan at the bid price he chose.

There are other designs, as well, that limit the guesswork that bidders face. A common one in US on-line auctions allows bidders to specify both a price and a desired quantity. The highest bidders (or, in case of ties, those who bid earliest) get their orders filled in full, with only the last winning bidder running the risk of having to settle for a partial order. As with the Dutch design, efficiency is enhanced because bidders do not have to ponder over which licenses to bid on, and such rules reduce the "exposure" risk that a bidder may wind up acquiring licenses at a loss, because it buys too few to build an efficiently scaled system.

[15] For a detailed account, see Mueller (1993).

The FCC Design and Its Progeny

In the circumstances of the FCC's big PCS auction, it was obvious that some licenses would be substitutes. For example, there would be two licenses available to provide PCS service to the San Francisco area. Since the two licenses had nearly identical technical characteristics and since, for antitrust reasons, no bidder would be allowed to acquire more than one, these licenses were necessarily substitutes. The argument that some licenses were complements was also made occasionally, but the force of the argument was reduced by the large geographic scope of the licenses.[16]

As in the New Zealand case, the main design issue was to minimize guesswork, allowing bidders to choose among substitute licenses based on their relative prices. When substitute goods are sold in sequence, either by sealed bids or in an ascending auction, a person bidding for the first item must guess what price he will have to pay later if he waits to buy the second, third, or fourth item instead. Incorrect guesses can allow bidders with relatively low values to win the first items, leading to an inefficient allocation. With this problem in mind, the final rules provided that the licenses would be sold all at once, in a single open ascending auction. The openness of the process would eliminate the guesswork, allowing bidders to switch among substitute licenses, and guaranteeing equal prices for perfect substitutes as well as an efficient outcome.

In order for the auction to work in this idealized way, bidding on all licenses would need to remain open until no new bids were received for any license. In a worst case scenario, the auction might drag on interminably as each bidder bid on just one license at a time, even when it was actually interested in eventually buying, say, 100 licenses. To mitigate this risk, the FCC adopted my "*activity rule*." The general application of an activity rule involves two key concepts: eligibility and activity. A bidder's activity in any round is the "quantity" of licenses on which it has either placed new bids in the round or had the high bid at the beginning of the round. In the example cited earlier, the quantity is just the number of licenses on which a bid is placed, but other quantity measures, including the total bandwidth of the licenses bid or the bandwidth multiplied by the population covered, have also been used. The rule specifies that a bidder's total activity in a round can never exceed its eligibility. A bidder's initial eligibility, applicable to the first round of the auction, is established by filing and application paying a deposit before the bidding begins. Its eligibility in each later round depends on its recent bidding activity. One simple form of the rule specifies that a bidder's eligibility in any round after the first is equal to its activity in the preceding round. Thus, bidders who are not active early in the auction lose eligibility to place bids later in the auction. This rule speeds the auction and helps bidders to make reliable inferences about the remaining demand at the current prices.

The FCC rules have evolved since the original 1994 design, but larger changes have been made to adapt the simultaneous ascending auction to other applications. One

[16] Dr. Mark Bykowsky of the National Telecommunications and Information Administration (NTIA) was a forceful advocate that licenses could be complements and proposed a complex package auction design to accommodate the possibility. His case that complementarity was important is more convincing for the later auctions in which smaller licenses were sold. Nonetheless, the short time available to run the first auction led to a near-consensus that the package auction proposal involved too many unspecified details and unresolved uncertainties to evaluate and adopt immediately.

common variation arises when there are many units of each kind of item, such as auctions involving the sale of electricity contracts. In these auctions, for each item, each bidder bids his quantity demanded at the current price indicated on a “clock” visible to all bidders. The clock starts at a low price and keeps raising the price at any point at which the current total demand of all bidders exceeds the supply of that item. When demand equals supply on all items, the auction ends. A series of such clocks record the current prices for the various goods, and the rate of movement in these clocks determine the progress of the auction. A similar clock auction was used in March 2002 by the British government to buy 4 million metric tons of CO_2 emission reductions proposed by British businesses.

Clock auctions share several key characteristics with their FCC ancestor. Bidding on all items takes place simultaneously, so bidders can respond to changing relative prices. Prices rise monotonically, ensuring that the auction progresses in an orderly and predictable way. All bids are serious and represent real commitments. There is an activity rule that prevents a buyer from increasing its overall demand on all items as prices increase. Finally, bidding ends simultaneously on all the lots, so that opportunities for substitution do not disappear during the auction until all final prices are set.

New variations based on the same principles continue to be created to solve a wide range of economic problems. Electricité de France (EDF) used a particularly interesting one in 2001 in a sale of electrical power contracts. The sale involved power contracts of different lengths, ranging from three months to two years, but all beginning at the same time—January 2002 for the first sale. Because different buyers wanted different mixes of contract lengths and because all contracts covered the first quarter of 2002, EDF regarded the different kinds of contracts as substitutes.

Larry Ausubel and Peter Cramton developed the auction design. The first step was to assist EDF in developing a standard for comparing bids on contracts of different lengths. Using recent price data, it determined that, for example, a six-month contract awarded only if its price was X higher than the price of a three-month contract, where X is a number that varies from time to time. During the auction itself, the price clocks were controlled to maintain this relationship, that is, the price of a six- month contract was at all times X higher than the price of the three-month contract. Prices for contracts of all lengths continued to rise until total remaining demand exhausted the total power available.[17] Such an auction creates competition among bidders for contracts of different lengths, increasing both efficiency and sales revenue compared to more traditional auction designs.

Comparing Seller Revenues

The question most frequently asked of auction designers is: What kind of auction leads to the highest prices for the seller? The answer, of course, depends on the particular circumstances, but even the thrust of the answer surprises many people: There is no systematic advantage of either sealed bids over open bid auctions, or the reverse.

[17] For example, in the sale of power beginning January 2002, when the total demand exceeded the power available for the first quarter of 2002, the auction ended. Any remaining unsold power for, say, the second quarter of 2002 was then included in subsequent sales.

A particular formal statement of this conclusion is known as the *payoff equivalence theorem*. It holds that in an important class of idealized situations, the average revenues from an auction and the payoffs of bidders are exactly the same. To illustrate the logic of the idea, suppose you are selling an item that is worth $10 to bidder A and $15 to bidder B. If you sell the item using an ascending bid auction with both bidders in attendance, then bidder A will stop bidding at a price close to $10 and B will acquire the item for that price. If you use sealed bids instead and sell the item to the highest bidder, then the outcome will depend on what the bidders know when they bid. If they know all the values, then in theory B will bid just enough to ensure that it wins—around $10 or $10.01 and A will likely bid just under $10. If they behave that way, the price will be just the same as in the ascending auction. As William Vickrey first observed, a similar conclusion holds on average for a much wider class of auction rules and in a more realistic set of situations than the one described here. For forecasting average revenue, it is irrelevant which auction is used, within a certain class of standard auction designs.

Practical people tend to feel puzzled when presented with Vickrey's irrelevance conclusion. Auctioneers who conduct ascending auctions often say that they generate more excitement and more competition than sealed bids. After all, they argue, no bidder is willing to bid close to its value unless pushed to do so by the open competition of the ascending auction design. Those who favor sealed-bids counter by arguing that ascending auctions never result in more being paid than is absolutely necessary to win the auction; there is no money "left on the table." Sealed bids frequently result in lots of money left on the table. For instance, in the December 1997 auction for licenses to provide wireless telephone services in Brazil, an international consortium including Bellsouth and Splice do Brazil bid $2.45 billion in that auction to win the license covering the Sao Paulo concession. This bid was about 60% higher than the second highest bid, so 40%, or about $1 billion, was left on the table.[18]

Similar arguments among practitioners arise quite frequently, sometimes with variations. In the United States, the staff of the Treasury Department have periodically argued the relative merits of two alternative auction schemes for selling bills. In one scheme, each bidder pays the amount of its own bid for each bill it buys while in the other all bidders pay the same "market-clearing price," identified by the lowest accepted bid. Advocates of the first ("each-pays-its-own-bid") scheme say that the government will get more money from the auction, since winning bidders are by definition people who have bid more than the lowest acceptable bid. Advocates of the second ("uniform price") scheme counter that bidders who know they must pay their own bid when they win will naturally bid less, reducing market clearing price and leading to lower revenues.

Informal arguments like these show that the matter is subtle, but they do not settle the issue. A formal analysis based on the *payoff equivalence theorem* discussed in chapter 3 helps to cut through the confusion. Under certain idealized conditions, if the allocation of lots among bidders is the same for two different designs, then the average payoffs to all parties, including the average prices obtained by the seller, must also be *exactly the same*.

[18] While the 60% overbid may be atypical, the ordinary amounts of money left on the table are still impressive. For example, in the Brazilian band A privatization, the median overbid was 27%. That is, for half the licenses, the winning bidders bid *at least* 27% more than the second highest bid.

One cannot conduct a meaningful analysis of average prices alone, without also studying how the designs affect the distribution of the lots among the winning bidders.

The practical uses of the payoff equivalence theorem are similar in kind to the uses of the Modigliani-Miller theorems in financial economics, the Coase theorem in contract theory, and the monetary neutrality theorems in macroeconomics. All of these theorems assert that under idealized conditions, particular effects cannot follow from identified causes.[19] For example, according to the Modigliani-Miller theorems, if decisions about debt-equity ratios and dividend policies merely slice up the total returns to a firm's owners without affecting the firm's operations, then those decisions cannot affect the firm's total market value. Today, financial economists explain financial decisions by focusing on how financial decisions might affect a firm's operations—its taxes, bankruptcy costs and managerial incentives. Similarly, according to the Coase theorem, if there were no costs or barriers to transacting, then the default ownership of an asset established by the legal system could not affect value. Today, economic theorists explain features of organization in terms of costs and barriers to transacting, including incomplete information and incomplete contracts. The payoff equivalence theorem is similar: the payment terms of an auction do not affect the seller's total revenue unless they are associated with a change in the allocation of the goods. Today, analysts focus more attention on how assumptions of the theorem are violated and the consequences of those violations or, for government regulators, about the implied trade-offs between their allocation and revenue objectives.

The planning for a sale of electrical power in Texas in 2002 illustrates how the payoff equivalence theorem has been applied in practice. According to the planned auction design, the auctioneer would gradually raise the prices for any products with excess demand and would accept quantity demands from the bidders, in much the fashion that Leon Walras once described. The auctioneer would not tell the bidders the quantities demanded by others. The rules called for the auctioneer to stop raising the price for a product when its total demand falls to the level of available supply. Texas ratepayers benefit from the revenues of this power sale, and the ratepayers' advocate argued that the auctioneer should continue to raise prices until demand is actually *less than* supply, and should then roll back the price by one increment. The idea was to sell power for the *highest* market clearing price, rather than the lowest one. This rule was problematic for a variety of reasons relating to the details of the auction, and the design team cited the payoff equivalence theorem to argue that there was little reason to expect that the proposed change would lead to higher prices. Bidders would bid differently if the payment rules were changed. A bidder who knows that it may acquire power at a lower price if it withdraws demand early will be more inclined to do that than a bidder who knows that it cannot cause a price rollback. The net effect on revenues is hard to predict,

[19] According to the Modigliani-Miller theorems, under its idealized "frictionless markets" conditions, a firm's financial structure and dividend policy cannot affect its market value. According to the Coase theorem, under other idealized conditions, the initial allocation of ownership rights cannot alter the efficiency of the final allocation. Monetary neutrality theorems hold that under yet other idealized conditions, monetary policy cannot change real outcomes in an economy. The payoff equivalence theorem holds that under its idealized conditions, changing payment rules cannot affect the participants' final payoffs.

because it depends on how the proposed new rule changes the allocation. Eventually, the ratepayer advocate agreed not to oppose the auction design.

The Academic Critics

Economists who work at putting auction theory to work encounter a dazzling array of issues, from ideological to theoretical to practical. Recognizing the complexity of the problems and the short times available to solve them, the engineering work for auctions sometimes entails guesses and judgments that cannot be fully grounded in a complete economic analysis. Auction designers generate ideas using theory, test those ideas when they can, and implement them with awareness of their limitations, supplementing the economic analysis with worst-case analyses and other similar exercises.

The idea that economic theorists can add value through this mixture of auction theory and practical judgment has come under attack from some members of the economics profession. Some of the more frequent attacks, and my responses to them, are expressed below.

Resale and the Coase Theorem

One of the most frequent and misguided criticisms of modern auction design comes in the form of the remarkable claim that the auction design does not matter at all. After all, say the critics, once 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 went even farther, arguing on this basis that the only proper objective of the government is to raise as much money as possible in the sale, since it should not and cannot control the final allocation.

To justify this argument, the critics relied on the Coase Theorem, which holds that if there are no laws or frictions to block trades in the market and no wealth effects on preferences, then the initial allocation of property rights cannot affect the final allocation of property rights, which will necessarily be efficient. Coase reasoned that so long as the allocation remains inefficient, the parties will continually find it in their interests to buy, sell and swap as necessary to eliminate the inefficiency.

Whatever merits the Coasian argument may have in other situations, it plainly leads to the wrong conclusion in this case.[20] The history of the US wireless telephone service offers direct evidence that the initial fragmented distribution of rights was inefficient. Despite demands from consumers for nationwide networks and the demonstrated successes of similarly wide networks in Europe, such networks were slow to develop in the United States.

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[20] The Coase theorem has includes a variety of assumptions that may fail in this application, such as the assumption that the parties values reflect social value—not market power, the assumption that the parties have unlimited budgets, so spending on spectrum rights does not impair the ability to invest in infrastructure, and the assumption that rights have no “externalities,” that is, that bidders don’t care about which competitors get license rights. The importance of the last assumption is analyzed by Jehiel and Moldovanu (2001).

As I argued during the deliberations at the FCC, the conclusion that initial allocations *do* matter follows by juxtaposing two well-known propositions from economic theory.[21] The first is that, as explained in chapter 2, auction mechanisms exist that achieve efficient license allocations for any number of available licenses, provided the government uses the auction from the start. With just one good for sale, the English auction is such a mechanism. The generalized Vickrey auction, which works even in the case of multiple goods, is analyzed in detail in chapter 2. The second proposition is that, even in the simplest case with just a single license for sale, there exists *no* mechanism that will reliably untangle an initial misallocation. Intuitively, in any two-sided negotiation between a buyer and seller, the seller has an incentive to exaggerate its value and the buyer has an incentive to pretend its value is lower. These misrepresentations can delay or scuttle a trade. According to a famous result in mechanism design theory—the Myerson-Satterthwaite theorem—there is no way to design a bargaining protocol that avoids this problem: delays or failures are inevitable in private bargaining if the good starts out in the wrong hands.

Mechanism Design Theory

A second line of criticism emerges from a part of game theory called "*mechanism design theory*." A "mechanism" is essentially a set of rules to govern the interactions of the parties. For example, it may specify the rules of an auction. Are there to be sealed or ascending bids? If sealed bids, how will the winner and price be determined? And so on.

Once the rules of the mechanism and the designer's objective have all been specified, the designer applies some criterion or "*solution concept*" to predict the outcome and then evaluates the outcome according to the objective. In the theory's purest and most elegant form, the aim is to identify the mechanism that maximizes the performance according to the specified objective. For example, one might try to find the auction that maximizes the expected selling price or the expected efficiency of the outcome. We will treat parts of this theory at length later in this book.

Mechanism design theory poses this challenge to practical auction designers: how can you incorporate the use of theory without, at the same time, applying the mechanism design approach? If you believe the theory accurately describes the behavior of players, you should use it to optimize the mechanism performance!

There is a longstanding joke about the arbitrage theory in financial economics that applies equally to mechanism design theory. Two people are walking along a street when one spots a $100 bill on the ground. "Pick it up," says one. "Why bother?" replies the other. "If it were real, someone would have picked it up already!"

Like arbitrage theory, the equilibrium analysis of game theory is an abstraction based on a sensible idea. Just as arbitrage theory implies that people don't leave real $100 bills lying on the street, equilibrium theory says that players in a game do not overlook ways to increase their payoffs. Both theories are useful idealizations—not reasons to leave $100 bills lying on the ground! Theories like these, based on ubiquitous awareness and thoroughly rational calculations, are obviously inexact models of real behavior, and one

[21] The theory described here applies to *private values* models, in which a bidder's maximum willingness to pay for any good or package of goods is independent of what other bidders know about that good.

should be especially careful about applying them to choices that are complex and subtle, or when players are inexperienced, or when the time and other resources to support effective decision-making are limited.

Despite their simplicity and incompleteness, equilibrium models can be very valuable to real-world mechanism designers. Just as a mechanical engineer whose mathematical model assumes a frictionless surface treats those calculations as inexact, an economic designer whose model assumes that the players adopt equilibrium strategies may do the same. Just as the real-world mechanical engineer pays attention to factors that increase friction and builds in redundancy and safety margins, the real-world mechanism designer pays attention to timing and bidder interfaces to make rational decisions easier, and plans to accommodate worst-case scenarios, in case bidders make mistakes or simply behave contrary to expectations.

At the present state of the art, academic mechanism design theory relies on stark assumptions to reach theoretical conclusions that can sometimes be fragile. One such assumption is that bidder types are statistically independent. It is well known (Cremer and McLean (1985)) that relaxing this assumption leads to optimal mechanisms that have implausibly strange designs, in which bidders are forced to make side-bets with the auctioneer about how much others are likely to bid. Game theoretic equilibrium models also assume not only that bidders maximize accurately but also that they are themselves completely confident that others will maximize accurately. Moreover, they cling to these beliefs even when their best strategies are very sensitive to small mistakes by other bidders.[22] Practical auction designers must treat these analyses with skepticism. Real players in mechanism are rarely if ever so confident about their competitors' behavior, and analyses that rely too sensitively on their assumptions are not reliable. Useful, real-life mechanisms need to be robust. Those that are too fragile should be discarded, while a robust mechanism can sometimes be confidently adopted even if, in the corresponding mechanism design model, it is not provably optimal.[23]

Besides the very demanding behavioral assumptions that characterize the theoretical mechanism design approach, the existing formal models of mechanism design theory capture and analyze only a small subset of the issues that a real auctioneer faces. Some of the important issues that are usually omitted from mechanism design models are listed below. While none of these are incompatible with mechanism design theory in principle, accounting for all in a single optimization model is far beyond the reach of present practice.

- *What to sell?* If a farmer dies, should the entire farm be sold as a unit? Or should some fields be sold to neighbors? The house and barn as a holiday and weekend home? How should the FCC cut up the radio spectrum? Should power

[22] For example, see Dasgupta and Maskin (2000) or Perry and Reny (2002).

[23] The view expressed here is a variation of the "Wilson doctrine," which holds that practical mechanisms should be simple and designed without assuming that the designer has very precise knowledge about the economic environment in which the mechanism will operate. Here, we further emphasize that even given a very complete description of the economic environment, the behavior of bidders cannot be regarded as perfectly predictable.

suppliers be required to bundle regulation services, or should that be priced separately?

- *To whom and when?* Marketing a sale is often the biggest factor in its success. Bidders may need approval or may need to line up financing to participate. Conditions may change: financing may be more easily available at one time than another; uncertainties about technology or demand may become partly resolved; etc. Bidders may actively try to discourage others from bidding, hoping to get a better price.[24] Auctioneers may seek to screen bidders to encourage participation by those who are most qualified.
- *How?* For example, if the deal is complicated and needs to be individually tailored for each bidder, a seller might prefer to engage in a sequence of negotiations to economize on costs. If an auction is to be used, the right kind can depend, as we have already seen, on whether the items are substitutes or complements.
- *Interactions?* Decisions about what to sell, to whom, when, and how are not independent ones. What to sell depends on what buyers want, which depends on who is bidding, which may depend on how and when the auction is conducted.
- *Mergers and Collusion?* The European spectrum auctions of 2000, with their very high stakes, provided some interesting examples of before-the-auction actions to reduce competition. In Switzerland, last minute mergers among potential bidders resulted in only four bidders showing up for four spectrum licenses. The auction was postponed, but the licenses were eventually sold for prices close to the government-set minimum. Similar problems of valuable spectrum attracting few bidders and resulting in prices near the minimum occurred in Germany, Italy, and Israel.
- *Resale?* Most of the theory of mechanism design starts with a given set of bidders who keep whatever they buy. The possibility of resale not only affects auction strategy, it may also attract speculators who buy with the intention of reselling. Should the seller encourage speculators, as additional bidders create more competition in the auction? Or should the seller discourage them, since value captured by speculators must come from someone else's payoff—possibly the seller's?

The mechanism design purist's view, which holds that the only consistent approach is to develop theoretically "optimal" mechanisms, is not useful in practice. Even if we could incorporate all the features described above, our models of human behavior are not nearly accurate enough for use in optimization. Behavior is neither perfectly stable over time, nor the same across individuals, nor completely predictable for any single individual. Useful analyses must be cognizant of these realities.

[24] On the eve of the FCC PCS spectrum auction #4, the author made a television appearance on behalf of Pacific Bell telephone, announcing a commitment to win the Los Angeles telephone license, and successfully discouraging most potential competitors from even trying to bid for that license.

Despite these limitations, a large portion of this book focuses on mechanism design and related analyses. The theory is useful in practice for thinking through some issues and guiding some decisions. Among the decisions that the theory can illuminate are ones about *information policy* (what information to reveal to bidders), how to structure *split awards* (in which a buyer running a procurement auction splits its business between two or more suppliers), how to create *scoring rules* (in which bids are evaluated on dimensions besides price), and when and how to implement *handicapping* (in which the auctioneer treats bids unequally in order to encourage more effective competition, for example, promote small businesses or those run by women and minorities). The mechanism design approach also helps answer important questions about when to use auctions at all. Purchasing managers sometimes pose this question by asking whether particular goods and services are "auctionable," that is, whether the most effective procurement process is to run a formal bidding process.

Theory and Experiment

In sharp contrast to mechanism design purists, some economic experimenters raise an opposite objection: why should any attention be paid to auction theory at all, now that we have the capability to test alternative auction designs in experimental economics laboratories? Theories sometimes fail badly. The rest of the time, they explain only some of the data, so why rely on theory at all?

The possibility of experimental tests has, indeed, fundamentally shifted the way auctions can be designed. In the FCC auction design, successful tests conducted by Charles Plott in his laboratory at Caltech helped convince the FCC to adopt the theoretically motivated Milgrom-Wilson design. Working software demonstrating the design was another important element.[25] Yet, the experiments to date have been very far from replicating the actual circumstances of high value auctions.

In practice, it is unlikely that anyone will ever test a range of actual proposals in a completely realistic setting. The amounts at stake in experiments are necessarily much smaller, and the preparation time for bidders will normally be much less. Because experimental settings differ so much from the auctions they simulate, the role of theory is indispensable. Theory guides the design of experiments, suggests which parts of any experimental results might be generalized, and illuminates the economic principles at work, enabling further predictions and improvements upon the original design.

The philosopher Alfred North Whitehead, when asked whether theory or facts was more important, answered famously: "theory about facts." Indeed, theories that are incompatible with facts are useless, but there can be no experimental designs and, indeed, no reporting of experimental results without a conceptualization of the issues. Theory will always play a key role in answering engineering questions, including questions about auction design.

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[25] Working software demonstrating the feasibility of the new design was another important element. Implementation issues also played a huge role in the debate. The very possibility of running the computer implemented simultaneous auction drew hackles from critics in 1994. To rebut the critics, my assistant, Zoran Crnja, programmed a flawless small-scale version of the software in a set of linked Excel spreadsheets. His software convinced the FCC that a reliable system could be created using our proposed rules even in the short time available.

Practical Concerns

The final criticism is that, in the real world, the whole mechanism design approach is irrelevant for several reasons. First, the auction rules themselves are subject to bargaining: there is no single mechanism designer. Second, the rules are rarely even a first tier concern in setting up and running a complex auction. Several other issues are more important.

One such issue is marketing: an auction cannot succeed without participants. This interacts with the first observation: bidders may simply refuse to participate in designs that they strange or unfair.[26] This very observation, however, emphasizes that good design can be affirmative way to attract more and better participants.

There are many examples of auctions and other competitions that get poor results because the rules are rigged to favor particular bidders and so discourage others from participating. One is the earlier description of MCI's attempts to rig the US spectrum auctions in its favor by making the "lot" a single national license. When different bidders want different kinds of lots, a package auction design, such as the ones often used in bankruptcy sales, may enable wider participation.

Another example is the initial public offering (IPO) of shares in a young company. In the past, the investment banks that organize the IPOs have often reserved shares in "hot" offerings for the bank's biggest and best customers, and that discourages small investors from participating. Trying to buck this trend, investment bank WR Hambrecht has introduced its "Open IPO" product, which is a uniform price auction in which large and small investors are all subject to the same auction rules. The company tries actively to attract small investors to increase demand for shares and create an alternative to the existing auction system, although its success will also depend on attracting larger investors, too, and companies willing to experiment with a new system.

A second important practical issue concerns the property rights being allocated. For example, if auctions are to be used to allocate take-off and landing rights at a congested airport, then the rights themselves need to be carefully defined. What is to happen to a plane that is delayed for mechanical reasons and cannot depart in its assigned slot? What are the airline's rights if weather delays decrease the capacity of the airport? While no sophisticated auction rule can lead to a good outcome unless these practical issue are resolved, an auction system that fails to coordinate all the resources needed by the airlines—takeoff slots, landing slots, rights through *en route* choke points, gate access, and so on—cannot succeed regardless of how well rights are defined. Real problems require comprehensive solutions, and the auction rules are a part whose importance varies across applications.

Another important practical detail for electronic auctions is the interface used by bidders. The original FCC auction software made it easy for bidders to make mistakes. On several occasions, bidders made what came to be called "fat finger bids." For example, when trying to bid $1,000,000, a bidder might accidentally enter a bid of

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[26] My own experience designing a procurement auction system for Perfect Commerce, Inc, revealed the seriousness of this concern. Sellers do often refuse to participate in auctions that are not structured to their liking.

$10,000,000—an error encouraged by the fact that the early interfaces could not accept commas in the bid field.

The FCC's solution for this problem, however, was one that considered more than the ease of bidding. Under the FCC's initial rules, bidders found it easy to communicate messages, including threats, with their bids in the auction. Suppose, for example, that bidder A wishes to discourage competitor B from bidding on a particular license, say #147, in a particular auction. If B bids on that license, A might retaliate by raising the price of another license on which B has the current high bid of, say, $9,000,000 by bidding $10,000,147, where the last three digits send a none-too-subtle message about its motivations. Such bids were frequently observed in some of the early FCC auctions.

Both the "fat finger" and the signaling problems were solved when the FCC changed the auction interface to require that a bidder select its bid from a short drop-down menu on its bidding screen. All bids on the menu used round numbers, being the minimum bid plus one or more increments. This system eliminated typos involving one or more extra digits and simultaneously made it much harder for bidders to encode messages in their bids.

Some critics respond to such anecdotes with the claim that while these do show that rules matter, they mainly show the dangers in electronic auctions or auctions using novel rules. However, even familiar, low-tech auctions can perform badly on account of problematic rules. In 1998, the Cook County, Illinois, tax collector conducted a traditional oral outcry auction to sell the right to collect certain 1996 property taxes that were two years overdue. In that "1996 tax sale" auction, a bid specified the *penalty rate* that the winning bidder could charge in addition to the taxes due, as compensation for its collection services. The auction was conducted in an ordinary meeting room, with the auctioneer sitting in the front. The auctioneer would read a property number and the bidding instantly began with the bidders shouting penalty amounts. The maximum opening bid was 18% and successively lower bids were shouted until a winning low bidder was determined.

The trouble occurred when several bidders simultaneously opened with bids of the maximum amount. Under the Cook County rules for that year, in the event of such a tie, the auctioneer was to assign the properties to winning bidders essentially at random. A bidder tied with, say, five others at 18% then faced a simple choice. He could bid less than 18%, having roughly a one in six chance to win the auction at a much lower rate than 18%. Or, he could sit quietly and enjoy a one in six chance to win at a rate of 18%. Most bidders chose to sit quietly, and about 80% of the properties sold at the maximum rate of 18%.

How can we be sure it was the faulty rules, rather than collusion among (more than a dozen) bidders, that accounted for this outcome? A few days after the auction began, the county auctioneer announced a change in the rules. In the future, a tie bid at 18% would result in withdrawal of the property from the auction. After the change, penalty rates quickly collapsed to a lower level, providing some initial evidence that the treatment of ties does matter. Immediately after the rule change, some bidders sought a court order to restrain the auctioneer from changing its rules during the auction. The court agreed and issued the order. After the order was issued and the original rules restored, the winning bids quickly returned to 18%.

Understanding auction theory is helpful for more than just avoiding obviously bad designs. Well-designed auctions that link the allocation of related resources can perform much better than traditional auction sales. In the New Zealand case described earlier, if the novel second-price auction rules had been replaced with more traditional pay-as-bid rules, any simultaneous sealed-bid auction would still be prone to misallocation, because bidders would still need to guess about which TV licenses to bid on. Computational experiments suggest that 25-50% of the value might have been lost simply because the allocation was so poorly coordinated. In similar circumstances, the current world-standard for spectrum auctions, the simultaneous ascending auction, can theoretically lead to an efficient or nearly efficient outcome.

The simultaneous ascending auction has limitations too, which can be particularly important when the items for sale are ones that different bidders prefer to package in different ways, or when there are complicated constraints on the collection of acceptable offers. In such cases, a package auction design can both attract a wider set of bidders and vastly increase the likelihood that the right packages emerge from the auction. The design of these auctions is, however, subject to many pitfalls, to which we return in section II of this book.

There are many more examples of the importance of the detailed auction rules. One is from a Mexican sealed-bid auction for a road construction contract, in which the bidders were asked to submit a total bid and to break down the bid into three pieces in case part of the project was delayed or canceled. Although each bidder was required to specify four numbers, the project was to be awarded based only on the total price. The winning bidder submitted a bid in which the "total" was less than the sum of the three parts. As matters transpired, the sum of the three was low enough to win, and the winner claimed that he had simply made an "arithmetic mistake" and that the price must, of course, be the sum of the three component parts. It seems more likely that this device was used to place two bids, allowing the bidder to withdraw the lower one if the higher bid was a winner. That could be a useful option in a competitive setting, but even more so if the bidders were colluding, because the low "total price" bid would prevent a deviator from cheating on the agreement and placing a lower than expected bid. Indeed, if the auctioneer had intended to facilitate collusion in the bidding, this would have been quite a clever design for accomplishing that!

Another example of how the details matter is drawn from the German experience in a 1999 spectrum auction. In that auction, Mannesmann and T-Mobil managed to divide the market between themselves without engaging in intense price competition. With ten licenses for sale and a 10% price increment, Mannesmann opened the bidding by jumping to prices of DM20 million for five licenses and DM18.18 million for the other five, effectively suggesting to T-Mobil that the ten licenses be divided five-and-five at a price of DM20 million. In the event, T-Mobil bid DM20 million for the five licenses and that ended the auction. The facts that equal division was possible and that the bidder could make such jump bids are design elements that contributed to this outcome. The risk was predictable. Indeed, the danger that such rules posed had been previously been pointed out in a 1997 report commissioned by the US spectrum authorities.[27]

In the US electricity markets, ill-considered market rules frequently contributed to high prices by making too easy for power suppliers to manipulate the system. In a famous example, energy traders at the Enron Corporation manipulated the California power market by scheduling transmissions on congested links that were far in excess of those Enron had actually planned. That led the California Power Exchange to try to mitigate the expected congestion by paying the company to reduce its transmissions, resulting in massive profits for the company. Only after repeated failures did these designs evolve to produce more reasonable results, yet all of these defects are instantly revealed by a game theoretic analysis of the market designs.

The most careful statistical evidence of the importance of design comes not from auction markets *per se* but from the closely related "matching" markets, such as the ones by which most new US doctors are matched to hospital residency programs. Roth (1991) provides evidence that a particular characteristic of the matching rules—whether the rules lead to a "stable" match—is an important determinant of whether organized markets succeed in attracting participants over a long period of years. A match is stable if no medical student strictly prefers to be matched to another program as compared to the one he is currently matched with while this other program simultaneously strictly prefers this medical student to one of those with whom it is matched. The analogous criterion for auctions is that no group of participants should be able to do better by rejecting the auction outcome and making a side-deal of their own. Auctions that do not have this theoretical property are likely to run into trouble in practice, as some participants try to void the auction outcome to reach a better deal among themselves.

Successful auction programs need to be well designed in every important respect, of which auction rules are one. Applying the perspective of auction theory can be valuable in many ways. It can enable an auctioneer to avoid mistakes like those that marred the 1993 spectrum auction in New Zealand and the 1996 tax auction in Cook County. It can help the auctioneer to pursue multiple objectives, like promoting minority participation, encouraging alternative suppliers, and enhancing competition among bidders with diverse advantages. Finally, rules can be designed to accommodate complicated preferences and constraints for the bidders and the auctioneer. We will see some examples of this later in this book.

Plan for this Book

This book integrates two projects, which are presented in the next two sections. The first section gives a review of traditional auction theory and is based on courses that I have given over a period of years at Stanford, Jerusalem, Harvard, and MIT. Traditional auction theory is based largely on the theory of mechanism design and the chapter organization follows certain principles of that theory. Much of the analysis is focused on auctions in which each buyer wants only a single object—a condition called *singleton demand*.

[27] See Cramton, McMillan et al. (1997).

My treatment of the material differs from other treatments in two ways. First, it emphasizes practical applications where possible and makes an effort to include the issues that are most important in practice. Second, the treatment reflects my personal view that incentive theory is a mysterious new part of economics but is closely related to standard demand theory. Rather than taking a too-specialized view that obfuscates the connections, I approach the material using general perspectives and techniques that, I believe, prove their worth by delivering some difficult results in short, intuitive arguments.

The second section of the book differs from the first in its questions and methods. The questions mainly concern the design of auctions for environments in which there are multiple heterogeneous goods. These environments are fundamentally more complex than ones with singleton demand. One reason is that the number of possible allocations is exponentially larger, which leads to serious issues about the practical feasibility of auction algorithms and bidder strategies. For example, in an auction with five bidders and one item, there are only five theoretically possible allocations of the item and each bidder bids over just a single item. However, in an auction with five bidders and five items, there are $5^5 = 3125$ theoretically possible allocations. A second way in which singleton demand is special is that it eliminates much of the tension between promoting efficient allocations and ensuring competitive revenues for the seller. In the general case of section II, where multiple heterogeneous goods are sold with complementarities among the items, that tension can be severe. For example, the Vickrey auction, noted for its ability to promote efficient outcomes, can leads to zero low revenues in relevant examples. A third difference concerns the problem of *value discovery*. With singleton demand, bidders have only one allocation to evaluate, but in the general case the exponentially larger number of allocations can force a bidder to reduce its valuation activities, which can limit both efficiency and price competition.

Because the Vickrey mechanism plays a significant role in both parts of the theory, we begin by studying this mechanism in the next chapter.

Auction theory has grown into a huge area of research, and this book reports on only those parts of the theory research that are relatively settled and that, in my opinion, have promise to be helpful to auction designers. With these criteria in mind, I have given only light coverage to some of the elegant formal treatments of how auctions perform when there are very many bidders[28] as well as much of the recently developing literature about one or more of these topics: auctions with “interdependent” valuations, collusion among bidders, corrupt auctioneers, purchases for resale, and information processing during auctions. Readers who wish to follow the frontiers of auction theory are encouraged to read about these subjects in the new auction literature.

[28] This research begins with Wilson (1977) and includes Milgrom (1979) and the especially beautiful results by Pesendorfer and Swinkels (1997), Pesendorfer and Swinkels (2000), Swinkels (2001).

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