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CHAPTER ONE

Getting to Work

The era of putting auction theory to work began in 1993–1994, 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 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 economic science. In 2000, the US National Science Foundation's fiftieth 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 debate erupted between researchers studying bargaining, who were skeptical that game theory could explain much about bargaining or be useful for improving bargaining protocols, and those investigating in auctions and industrial organization, who believed that game theory was illuminating their studies. 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 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 the 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.

[1] See Hendricks, Porter, and Wilson (1994).
[2] See Kagel (1995).
[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. They give their account of the auction in Binmore and Klemperer (2002). It was Binmore whom the Queen of England honored with a title.

1.1 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 United States 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).

1.2 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

[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)).

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 United States highlights that the lottery system did not lead to efficient spectrum allocations. 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. Achieving that with an auction system called for a different and innovative approach.

The 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]

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).

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.

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 superseded 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 that

[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 that withdraws its bid pays a penalty equal to the difference, if positive, between the eventual sale price for the license and the amount of its withdrawn bid. If the eventual price exceeds its bid, then no penalty is payable.

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.

1.2.1 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.

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 up 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 its 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, but be 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. For example, the licensee identities 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 than for smaller 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 differ 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 when licenses might either be substitutes or complements. The impaired performance may take various forms including a loss of efficiency of the outcomes, uncompetitively low revenues to the seller, vulnerability to collusion, complexity for the bidders, and long times to completion.

[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.

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

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

[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).

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 value, 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 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 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 value 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, for 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