PUTTING AUCTION THEORY TO WORK

This book provides a comprehensive introduction to modern auction theory and its important new applications. It is written by a leading economic theorist whose suggestions guided the creation of the new spectrum auction designs. Aimed at graduate students and professionals in economics, the book gives the most up-to-date treatments of both traditional theories of "optimal auctions" and newer theories of multi-unit auctions and package auctions, and shows by example how these theories are used. The analysis explores the limitations of prominent older designs, such as the Vickrey auction design, and evaluates the practical responses to those limitations. It explores the tension between the traditional theory of auctions with a fixed set of bidders, in which the seller seeks to squeeze as much revenue as possible from the fixed set, and the theory of auctions with endogenous entry, in which bidder profits must be respected to encourage participation. It shows how seemingly different auction designs can lead to nearly identical outcomes if the participating bidders are the same – a finding that focuses attention on (1) attracting bidders and (2) minimizing the cost of running the auction and bidding in it. It shows how new auction designs can accommodate complicated procurement settings and sales with many interrelated goods.

Paul Milgrom is Leonard and Shirley Ely Professor of Humanities and Social Sciences and Professor of Economics at Stanford University. He has also taught at Harvard University and MIT. A Fellow of the American Academy of Arts and Sciences and the Econometric Society, Professor Milgrom has served on the editorial boards of the *American Economic Review*, *Ecometrica*, the *Journal of Economic Theory*, the *Journal of Economics and Management Strategy*, and *Games and Economic Behavior.* He is coauthor with John Roberts of the 1992 landmark text *Economics, Organization, and Management.*

Professor Milgrom's research has been published in the leading journals in economics, including the *American Economic Review*, *Econometrica*, the *Journal of Political Economy*, the *Quarterly Journal of Economics*, the *Journal of Economic Theory*, the *Journal of Economic Perspectives*, and the *Journal of Mathematical Economics.* His current research interests are in incentive theory, planning, and auction market design. Professor Milgrom is internationally known for his work in spectrum auction designs.

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Peter Diamond, *On Time*, 1994
Douglas Gale, *Strategic Foundations of General Equilibrium: Dynamic Matching and Bargaining Games, 2000*
Ariel Rubinstein, *Economics and Language*, 2000

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PAUL MILGROM
Stanford University

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Preface

This book synthesizes the insights I have found from my teaching, research, and consulting about auction design. For me, the three have long been intertwined. I wrote my Ph.D. thesis about auction theory under the guidance of Robert Wilson, who was then already advising bidders about how to bid and governments about how to design auctions. Fifteen years later, Wilson and I together made proposals that became the basis for the design of the Federal Communications Commission (FCC) spectrum auctions – the most influential new auction design of the twentieth century. The FCC design was copied with variations for spectrum sales on six continents. In the intervening years, I had often taught about auction theory, though not yet as the practical subject that it was to become.

Work on this book began in spring of 1995, when I delivered the Churchill lectures at Cambridge University. Those lectures emphasized the history and design of the spectrum auctions run by the FCC beginning in 1994, as well as the bidders' experiences in the auctions. Wilson and I had only a few weeks in which to form our design and make recommendations, and my "Churchill project" was to complete the analysis of those recommendations by identifying the kinds of environments in which our new design was likely to be effective. Events caused the project to be delayed, but the project received a boost and a twist when I delivered lectures about auction theory in courses at Stanford in 1996 and 2000, in Jerusalem in 1997, and at Harvard and MIT in 2001 and 2002.

In my 1978 dissertation, I had written that there were seven main results of auction theory. Two decades later, there are many more and many views about what is most important and how best to synthesize this exceptionally beautiful theory. What is distinctive about my synthesis here and what makes it both more encompassing and more practical than earlier attempts is that it is rooted both in traditional demand theory and in real-world experiences.[1] I unify auction theory with demand theory partly by using familiar techniques and concepts: the envelope theorem, comparative statics methods, and demand theory concepts like substitutes and complements.

My perspectives on auction theory differ in emphasis and method from those of several recent contributors. In chapter 1, I describe how one can use the stylized results of auction theory in practical design. Chapter 2 presents my distinctive treatment of the Vickrey auction, which explains how the striking theoretical advantages of the auction are offset by equally striking disadvantages, which too often go unremarked.

Chapters 3 and 4 develop the classical results of auction theory using the tools of ordinary demand theory: the envelope theorem and the comparative statics techniques. This is in sharp contrast to graduate microeconomics textbooks that emphasize the distinctive "revelation principle" as the basic tool of mechanism design theory (Mas Colell, Whinston, and Green (1995)) – a tool that has no analog in or relevance for demand theory.

In chapter 5, I revisit the models of auctions with interdependent values and correlated information to recast them in the same terms. These new treatments show that parts of auction theory that had seemed difficult can be treated simply by using the same methods.

My experience in auction consulting teaches that clever new designs are only very occasionally among the main keys to an auction's success. Much more often, the keys are to keep the costs of bidding low, encourage the right bidders to participate, ensure the integrity of the process, and take care that the winning bidder is someone who will pay or deliver as promised. Chapter 6 emphasizes those considerations. It particularly emphasizes the consequences of free entry and the instruments available to the designer to encourage entry of the right kinds.

Chapters 7 and 8 deal with an area of auction design in which scholarly input can add enormous value. This is in the area of multi-unit

[1] In the years after the first FCC auctions, I contributed to spectrum auction designs in the United States, Germany, Australia, and Canada, electricity auction designs in New Jersey and Texas, asset sales in the United States and Mexico, and internet procurement auctions. My suggestions were also the principal basis of the FCC's design for auction #31 – its first package or "combinatorial" auction design.

auctions. Such auctions have been used for radio spectrum, electrical power, Treasury bills, and other applications. The design problems for these auctions include not just the usual ones about getting incentives and allocations right, but also limiting the complexity so that costs incurred by bidders are not too high and the reliability of the system is maintained. Unlike auctions for a single object, in which efficiency and revenue objectives are usually at least roughly aligned, multi-item auctions can involve radical trade-offs between these two objectives. Chapter 8, especially, highlights such trade-offs and explains how the new Ausubel–Milgrom design tries to reach a practical compromise.

I owe debts to many people not only for their help in preparing this book, but for helping me to reach this point in my understanding of auctions. Robert Wilson introduced me to auction theory in graduate school, directed my Ph.D. research, and joined me in the work of creating the FCC auction for our joint client, Pacific Bell. I have dedicated this book to him. The folks at Pacific Bell, particularly James Tuthill, had the patience and courage to support my applied research and to help me advocate it to the FCC. Evan Kwerel and the FCC team repeatedly showed the courage to be innovators, trying out radical new ideas. The colleagues with whom I have consulted on auction designs – Larry Ausubel, Peter Cramton, Preston McAfee, John McMillan, Charles Plott, and again Robert Wilson – inspired me with their ideas, enthusiasm, and inspiration.

Many people have directly supported my efforts in writing this book. I am especially grateful to five students and colleagues who read the entire manuscript and made helpful suggestions. Professor Valter Sorana's detailed and very thoughtful comments are reflected throughout the book. My research assistant, Hui Li, often sat next to me at my computer, insisting that certain passages or arguments needed further detail and prodding me to make the text, as she would say, "easy enough for me." The Harvard graduate students Parag Pathak and Siva Anantham and the Stanford graduate student Paul Riskind all read the entire manuscript and made hundreds of suggestions. The undergraduate Dan Kinnamon read and commented on parts of the manuscript and provided research assistance for the buy-price model of chapter 6. I also had invaluable discussions about particular parts of the subject matter with many colleagues, including Susan Athey, Larry Ausubel, Jeremy Bulow, Peter Cramton, Paul Klemperer, Evan Kwerel, Benny Moldovanu, Noam Nisan, Motty Perry, Leo Rezende, John Roberts, Al Roth, David Salant, Ilya Segal,

Padmanhabhan Srinagesh, Steve Tadelis, Bob Wilson, Lixin Ye, and Charles Zheng.

The period since I began this work was an especially difficult one for me personally and for my family, and I thank them, too. Without the love and support of my wife, Eva Meyersson Milgrom, and my children, Joshua and Elana, I could not have finished this book.

Foreword

Paul Milgrom has had an enormous influence on the most important recent application of auction theory for the same reason you will want to read this book – clarity of thought and expression. In August 1993, President Clinton signed legislation granting the Federal Communications Commission the authority to auction spectrum licenses and requiring it to begin the first auction within a year. With no prior auction experience and a tight deadline, the normal bureaucratic behavior would have been to adopt a "tried and true" auction design. In 1993, however, there was no tried and true method appropriate for the circumstances – multiple licenses with potentially highly interdependent values. I had been advocating the use of auctions to select FCC licensees since 1983, when I joined the staff of the FCC's Office of Plans and Policy. When auction legislation finally passed, I was given the task of developing an auction design.

One of the first auction design issues the FCC considered was whether to use an ascending bid mechanism or a single round sealed bid. The federal government generally used sealed-bid auctions, especially for high-valued rights such as offshore oil and gas leases. FCC staff felt reasonably confident that we could implement a sealed-bid auction – keep the bids secure, open the bids, and select the high bids. There were doubts whether we could do anything more complex. In the end, the FCC chose an ascending bid mechanism, largely because we believed that providing bidders with more information would likely increase efficiency and, as shown by Milgrom and Weber (1982a), mitigate the winner's curse.

The initial design the FCC proposed in September 1993 was a hybrid of an ascending bid and a first-price sealed-bid auction. It was intended to address the contentious policy issue of the appropriate geographic scope of the licenses for broadband personal communications services (PCS). Some companies argued that the FCC should issue nationwide licenses. Other companies, especially incumbent cellular providers that were barred from holding both a cellular and a PCS license in the same geographic area, argued for regional licenses. For each of two nationwide spectrum blocks, the FCC proposed conducting a single round sealed-bid auction for all 51 licenses as a group, followed by a series of open outcry auctions for the same licenses individually. The sealed bids would be opened at the conclusion of the open outcry auctions, and the spectrum awarded to the highest sealed bid only if it exceeded the sum of bids on the individual licenses.

The initial FCC proposal also discussed the possibility of a simultaneous auction mechanism. Had AirTouch, a large cellular operator, not advocated this approach, it might not have been mentioned in the FCC's September *Notice of Proposed Rule Making*. In a meeting with me, AirTouch pointed out that in my 1985 FCC working paper written with Lex Felker I had suggested a simplified system of simultaneous bidding where parties simultaneously placed independent bids on several licenses.

In 1985 I had no idea how to run such a simultaneous auction, and in 1993 I was very skeptical of the possibility of anyone developing and the FCC implementing a workable simultaneous auction within the one year provided by the legislation; but Paul Milgrom and Bob Wilson (working for Pacific Bell) and Preston McAfee (working for AirTouch) completely changed my thinking. Both the Milgrom–Wilson and the McAfee proposals were mindful of the limits on the complexity of any proposal that the FCC could or would implement. Both proposed simultaneous ascending bid auctions with discrete bidding rounds. This approach promised to provide much of the operational simplicity of sealed-bid auctions with the economic efficiency of an ascending auction.

The 1993 legislation required that the FCC develop auction rules within 7 months and begin auctions within another 4 months. The FCC could have met the legislative mandate by beginning a sealed-bid auction or an oral outcry auction. So why was it so important to begin a simultaneous auction within the legislative deadline? It was my view that whatever method was used in the first FCC auction, if it appeared successful, would become the default method for all future auctions, including broadband PCS. So I spent considerable effort looking for a set of licenses for our first auction that the FCC could successfully auction using the simultaneous multiple round design. I proposed to senior FCC staff that we auction 10 narrowband PCS licenses. This was a small enough number that we could successfully implement a simultaneous auction, and the licenses were valuable enough that a success would be considered important, but not so valuable that a failure would impose an unacceptably large loss.

The closing rule was one of the major design issues for a simultaneous auction. McAfee proposed a market-by-market closing rule with adjustments in bid increments to foster markets closing at approximately the same time. In contrast, Milgrom and Wilson proposed a simultaneous closing rule whereby the auction closes on all licenses only after a round has passed with no bidding on any license. Until then, bidding remains open on all licenses. McAfee proposed the market-by-market closing rule because of its operational simplicity. The FCC could surely run a number of separate ascending bid auctions in parallel. Milgrom argued however, that market-by-market closing could potentially foreclose efficient backup strategies. (For example, you might be the high bidder on a license for several rounds while a license that is a substitute for you closed. If you were then outbid on your license, you would not have the opportunity to place a bid on the substitute.) Milgrom's argument prevailed, and the FCC adopted a simultaneous closing rule, but not before addressing a closely related issue.

Would an auction with the simultaneous closing rule proposed by Milgrom and Wilson ever end? This was the worst case scenario that troubled me when I first met Paul Milgrom. He had come to the FCC to explain their auction design. The simultaneous multiple round auction with a simultaneous closing rule struck me as the most elegant solution I had seen for auctioning multiple licenses that could be both substitutes and complements. But might bidders each have an incentive to hold back while observing the bids made by others? If so, how could the FCC be sure that the auction would close in a timely fashion? I asked Milgrom this question. He clearly had thought about the problem and responded that with no loss of efficiency, bidders could be required to be active on at least one license in every round. Any serious bidder must either have a high bid or place an acceptable new bid. With only 20 days between Comments and the deadline for Reply Comments, Milgrom and Wilson developed this insight into the activity rule that the FCC has used in all its simultaneous multiple round auctions. The Milgrom–Wilson activity rule was an elegant, novel solution to a difficult practical auction design issue. It imposed a cost on holding back by tying a bidder's level of eligibility in future rounds to its activity level in the current round. If a bidder is not active on a minimum percentage of the quantity of spectrum for which it is eligible to bid, it suffers a permanent loss of eligibility. This discourages bidders from holding back, whether to "hide in the grass" or to collusively divide up the market.

The activity rule was critical to the FCC adopting the Milgrom–Wilson auction design. The FCC could not tolerate the risk that the auction would drag on indefinitely with little bidding. The activity rule, with the ability to increase the activity requirement during the action, provided the FCC with a mechanism to promote a reasonable auction pace without subjecting bidders to the risk of an unanticipated close when they still wished to make additional bids. Without this feature the broadband PCS auction might have ended after only 12 rounds with revenue at 12% of the actual total. Because of less than anticipated initial eligibility in the auction, the initial level of the activity requirement put little pressure on bidders to make new bids once there were bids on most licenses. Bidding almost ended after 10 rounds but dramatically increased after the FCC raised the activity requirement in round 12.

The elegance and the coherence of the proposal were not sufficient to make it an easy sell at the FCC. Many staff had little taste for taking the chance on an auction design that had never been used and seemed far more complex than any auction they had heard of. Chairman Reed Hundt's legal advisor, Diane Cornell, argued that the mechanism, especially the activity rule, was much too difficult for bidders to understand. I promised her that we would develop bidding software that would automatically calculate activity requirements and make it easy for bidders to participate. At the time, no such software existed, but fortunately we were able to develop user friendly interfaces in time for the first auction. A more serious concern was that the auction might be an operational fiasco. If that happened, the argument that the design had theoretical beauty would not carry much weight in a congressional oversight hearing. My boss was quite frank when he told me that he did not want the FCC to be a "beta test site" for new auction designs.

Why did the FCC adopt the basic Milgrom–Wilson auction design despite these concerns? First, it was good policy. It seemed to provide

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bidders sufficient information and flexibility to pursue backup strategies to promote a reasonably efficient assignment of licenses, without so much complexity that the FCC could not successfully implement it and bidders could not understand it. Just having a good idea, though, is not enough. Good ideas need good advocates if they are to be adopted. No advocate was more persuasive than Paul Milgrom. He was so persuasive because of his vision, clarity and economy of expression, ability to understand and address FCC needs, integrity, and passion for getting things right. He was able to translate his theoretical vision into coherent practical proposals and explain in plain English how all the pieces fit together. He took the time to learn relevant institutional facts and to listen. He was willing and able to modify his proposals to address FCC concerns about auction length and destructive strategic behavior. He never used hard sell or oversold his results, and thus he engendered the trust of FCC staff. He was always responsive to the frenetic time pressures under which the FCC often operates – willing to talk about auction rules while he was on vacation, take desperate calls late at night, and visit the FCC on very short notice during that first year it was developing its auction design.

As persuasive as Milgrom was, the FCC might not have been willing to risk adopting such a novel auction design without additional outside supporters. One was John McMillan, whom the FCC hired as a consultant to provide independent analysis of alternative auction designs. His report to the FCC (a revised version published in the *Journal of Economic Perspectives* in 1994) provided strong support for the Milgrom–Wilson design. And his calm manner and articulate explanations were reassuring to FCC staff that we were going in the right direction.

Another ally was Preston McAfee, who helped solidify support for the Milgrom–Wilson design when he said that he preferred it to the simpler simultaneous design he had developed at a time when he underestimated the FCC's ability to implement anything but the simplest auction design. More important was his suggestion to modify the Milgrom–Wilson proposal to permit bid withdrawals subject to a penalty. In a conference organized by Barry Nalebuff in January 1994 to help the FCC sort out alternative auction designs, McAfee proposed a simple way to reduce the exposure risk faced by bidders for licenses with strong complementarities. To discourage strategic insincere bidding, the Milgrom–Wilson design had not allowed for any bid withdrawals. However, when a collection of licenses is worth more than the sum of the licenses individually, bidders face the risk of paying too much for part of a package of licenses when the rest of the package is won by other bidders. The National Telecommunications and Information Administration (NTIA), whose role includes advising the White House on telecommunications policy, had proposed combinatorial auction mechanism to address this concern. The design, based on the work of Banks, Ledyard, and Porter (1989) and developed in a NTIA staff paper by Mark Bykowsky and Robert Cull, seemed far too complex for the FCC to implement in the time available. As an alternative, McAfee proposed permitting bid withdrawals subject to a payment equal to the difference between the withdrawn bid and the subsequent high bid.

Though the FCC did not adopt the NTIA proposal, the fact that the NTIA proposed a simultaneous auction design was helpful in building support for the Milgrom–Wilson design. It made that mechanism look like a reasonable middle ground between sequential ascending bid auctions and simultaneous ascending auctions with package bidding. In addition to their written comments, in January 1994, the NTIA jointly sponsored with Caltech a PCS auction design conference that brought FCC staff together with academic experimentalists as well as game theorists. Proposed and organized by Mark Bykowsky and John Ledyard, the conference provided additional support for the use of a simultaneous auction mechanism. The demonstration by David Porter of the combinatorial auction mechanism proposed by NTIA helped show the feasibility of some form of electronic simultaneous auction. Perhaps most important was a presentation by Charles Plott of experimental evidence on the relative performance of sequential, simultaneous, and combinatorial auction designs. This research sponsored by PacTel at Paul Milgrom's suggestion, offered experimental evidence that when there were strong synergies among items, simultaneous auctions were better than sequential auctions, and combinatorial bidding was even better. Based on both the theory and experimental evidence, Ledyard persuasively argued that though it would be nice if the FCC implemented the combinatorial mechanism he had helped design, the FCC could achieve most of the benefits with a simpler simultaneous design along the lines proposed by Milgrom and Wilson.

Part of the explanation for the successful collaboration between outside economists and the FCC in designing spectrum auctions was that the initial responsibility for a design was given to the FCC's Office of Plans and Policy (OPP), which has a tradition of applying economics to public policy and tends to be far more open to new approaches than the operating bureaus. The OPP had been advocating the use of auctions for more than 10 years prior to the passage of the auction legislation, and was a logical home for a small team drawn from throughout the agency.

One of the pillars of that team was Karen Wrege, an auction project manager, whom the FCC recruited from the Resolution Trust Corporation. In 1993, it was not enough to convince FCC Chairman Reed Hundt that simultaneous multiple round auction was the best auction design. He had to be convinced that the FCC could implement it with the year mandated by Congress. Karen was able to visualize how the auction might work, convince Don Gips on Hundt's staff that it could work, and – as part of a remarkable FCC team – make it work. Jerry Vaughan led the team with indomitable courage through many harrowing moments, such as a complete system failure the night before the start of FCC auction #3. The team was too large for me to mention here all who deserve credit, but some who deserve particular mention for making the Milgrom–Wilson auction design proposal a reality are the lawyers Kent Nakamura, Jonathan Cohen, and Jackie Chorney, the information technology specialist John Giuli, the contracting officer Mark Oakey, and the economist Greg Rosston.

Much credit for implementing the FCC auctions goes to the contractors and consultants. Most of the programming for the electronic auction system was performed by outside contractors. After the first auction, the FCC hired a second economic theorist, Peter Cramton, to provide advice on refining the auction design and to develop a tool to help bidders and the FCC track the progress of the auction. We also contracted with a team of experimental economists from Caltech: Charlie Plott, John Ledyard, and Dave Porter. Without the help of Plott and Antonio Rangel, a first year graduate student, the contractor for the FCC's first auction might not have succeeded in translating the FCC auction rules into software code. Caltech also tested the software used in the first and second FCC narrowband PCS auctions. As part of their "torture testing" they paid experiment participants a bonus for any error they could find in the software. Caltech also developed a clever method for manually checking all the calculations during the first FCC auction. Run by Rangel in parallel with the electronic auction system, this also provided a manual backup that could have been put into service if the electronic system had failed. Fortunately it did not.

The first FCC simultaneous multiple round auction began on July 25, 1994 in the Blue Room of the Omni Shoreham Hotel in Washington, DC. Bidding was conducted electronically on site. Despite the testing of the software, there was some trepidation about whether it would work. There was particular concern about the software for stage II of the activity rule. The chief programmer for the contractor that developed the software and would run it during the auction said, in essence, "I am completely confident that the software will work properly in stage II, but do not try it." We never found out, because the auction closed successfully in stage I. Every round, the FCC decided on how to set the bid increments on each license. We had a committee of three consultants to advise us: John McMillan, a theorist; Charlie Plott, an experimentalist; and Bill Stevenson, an auctioneer. We had five days to complete the auction before we would be kicked out of the ballroom so it could be used for a wedding. There was vigorous discussion about how large to make the bid increments, how long to make the rounds, and whether to deploy stage II of the activity rule. As it turned out, with few licenses, vigorous competition, and bidders on site, the auction closed after 47 rounds and five days, in time for the wedding in the Blue Room.

Perhaps the biggest hero of the story of putting auction theory to work is FCC Chairman Reed Hundt. He defied the traditional tendency of government bureaucracies to do the safe thing even if it is not the best thing. He always wanted to know: "What does economic theory tell us?" He always tried to put into practice his favorite motto, "Do the right thing." But without economic theorists like Paul Milgrom, he would not have known what that was.

Evan Kwerel
January 2003

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