THE CMS AUCTION: EXPERIMENTAL STUDIES OF A MEDIAN-BID PROCUREMENT AUCTION WITH NON-BINDING BIDS*

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Abstract

We report on the experimental results of simple auctions with (i) a median-bid pricing rule and (ii) non-binding bids (winning bids can be withdrawn) – the two central pillars of the competitive bidding program designed by the Centers for Medicare & Medicaid Services (CMS). Comparisons between the performance of the CMS auction and the performance of the excluded-bid auction reveal the problematic nature of the CMS auction. The CMS auction fails to generate competitive prices of goods and fails to satisfy demand. In all proposed efficiency measures, we find the excluded-bid auction significantly outperforms the CMS auction.

JEL codes: D01, D02, D03, D04, D44

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On September 30, 2010, the *New York Times* published "Fix Medicare's Bizarre Auction Program," which explained that "for the last ten years, the Centers for Medicare and Medicaid Services [CMS] has been testing an auction approach that is incredible in the inefficiency of its flawed design." The controversy stems from two central features of the CMS auction that are not part of traditional auctions: (1) The price is set at the median of the winning bids, and (2) bids may be withdrawn after the price is announced. These two features make the CMS auction substantially different from traditional procurement auctions, and the theory of how the features interact has not been fully developed. In particular, the full structure and relationships of the Nash equilibria are unknown.

Attention is drawn to the CMS auction because of its importance in terms of size and its possible influence on other governmental programs. In 2003, Congress required CMS to use auctions to price Medicare supplies as part of an effort to reduce costs and improve market efficiency. The auction, which is to replace administrative pricing, is currently in the pilot stage but the current plan is to expand the program to roughly 50% of the country in 2013 and then to 100% of the country in 2016. The results of the auction could serve as a guide to Medicare policies in the future, with its success leading to an expansion of the set of products offered and its failure leading to a belief that market methods are not suitable for Medicare. Questions exist regarding whether or not the results of the pilot will lead to well-reasoned decisions regarding expansion of the program.[1]

Critics of the proposed Medicare auction claim that the design encourages "low-ball" bids, in which suppliers submit the minimum allowable bid and then withdraw if the calculated market price is below their costs (Cramton and Katzman, 2011). We conducted simple experiments to characterize the types of behavior and outcomes that could be expected from the proposed auction and find considerable evidence for these critics' concerns. Auction architectures performing poorly in simple cases studied experimentally provide a realistic warning about problems that can surface in complex cases. Furthermore, if the behavior observed in the simple case is understandable in terms of theory, or even partial theory, then there is reason to take that theory seriously when applied to more complex cases.[2]

The absence of a fully developed theory dictates an exploratory approach to experiments in which partial theories are tested and institutional comparisons are made. Through a comparison of institutions that are understood, we seek an understanding of the performance of the CMS auction. For comparison, we examine the theoretically understood excluded-bid auction. This

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[1] For a discussion of the background of the auction and the limited experience with the pilot see the panel discussion in "Competitive Bidding Congressional Update—What You Need to Know', May 24, 2011, http://www.cramton.umd.edu/blog/2011/05/23/hill-briefing-on-medicare-auctions. Panelists report that the auctions yielded low market prices, which were not sustainable. The report also suggests that the CMS is permitted to employ a discounting rule, allowing them to modify suppliers' quantities and subsequently determine the price. Thus, the pilot results do not reflect the consequences of an auction, but instead yield a form of administered prices.

[2] This approach to the use of laboratory experimental methods for policy and systems design research is first outlined in Charles R. Plott, "Market Architectures, Institutional Landscapes and Testbed Experiments," Economic Theory, 4, 3-16, 1994. First, the methodology focuses on "proof of principle' by asking if the system in question produces the desired results. The method then shifts to the issue of "design consistency" by asking if the results are understandable in terms of the principles that lead to the design. The final focus is on robustness of the results to different and possibly extreme parameter environments. The presumption is that theory is the vehicle that gives confidence that a system will work as expected or desired in different environments and more complex than those examined in experiments.

auction has the same basic architecture as the CMS auction, but deviates by important features. In addition, we study institutions that lie “between” the CMS auction and the excluded-bid auction.

The basis of institutional comparisons is the performance of the CMS auction and other auctions in relation to four natural policy goals: (i) The auction should be successful in procuring the units demanded; (ii) The auction should be efficient from a social point of view in the sense that units are purchased from the lowest cost producers; (iii) The auction should not be wasteful from the government’s point of view; and (iv) The auction should produce a competitive price that is capable of creating a healthy supply industry. Experiments explore alternative auctions that could be used in place of the CMS auction.

The report contains five sections plus appendices. Section 1 contains a description of the auction institutions. Section 2 describes the experimental design. Section 3 outlines central aspects of theory. In particular, key Nash equilibria are identified where they are known, and special features of bidding incentives are outlined in the cases for which the Nash equilibria are not known. Section 4 contains the results. The first set of results focuses on the excluded-bid auction and establishes the fact that it performs well with reasons that are understandable. The second set of results demonstrates that the CMS auction is not a good auction. The results reveal the existence and severity of its architectural flaws. The third set of results demonstrates that the CMS auction cannot be easily fixed. These results are acquired by experiments involving auctions with variations on the central pillars of the CMS auction. The conclusions drawn from these results suggest that simply removing a faulty procedure does not correct the problems with the proposed auction and may create new problems. The collections of results in Section 4 support the robustness of the conclusions and provide an intuitive theory about why these auctions have the properties discussed. The intuitive theory is important because, presently, it is all that the science can tell us about the likely behavior when the auction is applied to environments differing in scale, complexity, and institutional features. Section 5 is a summary of the results.

1. INSTITUTIONS

The actual CMS auction has many institutional features that are not part of this study. For example, the CMS auction covers a wide range of different types of equipment, and a large number of bidders with each bidder tendering for multiple units of multiple items under some uncertainty about what the items might cost. Our experimental auctions strip away the complexities of the actual CMS auction to shed light on the basic properties of the CMS auction framework. Although simplified, it seems as if the theory can be adjusted to accommodate such complexities. The addressing of these issues must wait for new theory and experiments that might extend what is reported here[3].

Comparisons between the outcomes and behavior of the CMS auction with the excluded-bid auction provide an anchor for this study.[4] While the CMS auction shares the same basic architecture as the theoretically robust excluded-bid auction, it deviates by important features.

[3] The abstraction from multiple unit bids to single unit bids is an example. Experiments demonstrate that the general principles of auction theory can be fashioned to deal with multiple unit bids and existing work suggests that the dramatic impact of the auction architectures studied here in the single unit bid context will extend to the multiple unit bid case. However, since many institutional variables remain undecided, it is unclear exactly which of the many possible experiments should be run. For example, a model by Wilson (1979) exposes many equilibria in the continuous case, many of which would be disadvantageous to the buyer. On the other hand, Kremer and Nyborg (2004) demonstrate that when bids are tendered in discrete units the problems disappear. Or, Bresky (2008) demonstrates that bidding in the multiple unit excluded bid auction are very sensitive to the number of bids a bidder can submit and the reservation values. No doubt that more complex experiments will be possible as the relevant, alternative institutional frameworks become clearly specified.

[4] The excluded-bid auction is one of a class of auctions called uniform price auction, in which all successful bidders are paid the same, uniform, price. The excluded-bid auction is the special case in which price is set by the first excluded bid. Another popular form sets the price at the last included bid. Indeed, the CMS auction is a uniform price auction.

By perturbing these features in different experimentally controlled environments, we gauge the effects of particular design elements.

Each auction is a sealed-bid procurement auction, in which multiple units are sold at a uniform price to a single buyer with fixed demand. The institutions differ only by the pricing rule and by the bid withdrawal rule. In both institutions, bids are ordered from least to greatest. Then, a number of bids equal to the buyer's demand are accepted, and the corresponding suppliers are given the right to sell their unit at the market price. In the excluded-bid auction, the price is set at the value of the lowest bid that is not accepted. Furthermore, bids are binding commitments. In contrast, the price in the CMS auction is set at the median of accepted bids, and bids are non-binding commitments that may be withdrawn. Regardless of the number or pattern of bid withdrawals, the procurement price is determined by the original set of winning bids in the auction.

In addition to the pricing rule and bid withdrawal option, three environmental variables were manipulated to determine robustness of the institutions. Increasing the number of bidders from twelve to sixteen people studied effects of scale. Under some conditions, bidders were shown no information about the costs of other bidders; in other conditions, bidders were given full information (costs and bids of other participants). Finally, a cost of participation was added in some experimental conditions in which bidders were required to pay a fee in order to place a bid.

In total, five features (each with two different states) were manipulated, offering thirty-two possible variations of the basic auction architecture. Of these possible conditions, only ten were studied based on their ability to reveal the most about the CMS auction in terms of changes in the efficiency and robustness in response to manipulation of key auction features. Figure I contains the relationship among the institutions and environments that were studied.

2: METHODS

2.1: Experimental Procedures

We conducted four experiments using identical experimental parameters. Each experiment involved different students recruited from laboratory subject databases at the California Institute of Technology and at the University of Maryland. All experiments were done on a computer terminal in an experimental economics computer lab at their respective universities under the supervision of the experimenters. Experiments were programmed and conducted with the software z-Tree (Fischbacher 2007). Instructions were printed, distributed, and read to subjects. Following the introduction of each new auction, a short quiz was administered to check for comprehension. All costs were stated in experimental currency units (ECUs). Each experiment lasted 1.5 hours during which the number of participants was held constant.

A set of instructions are in Appendix B. The experimenters also used graphics to explain the structure of the auctions to participants. These graphics are in Appendix C.

2.2: Experimental Parameters

In all experiments, participants are sellers of a single unit with randomly assigned costs drawn from the uniform distribution [100, 1000]. The "government" is the only buyer and has a demand of seven units. The minimum allowable bid was 50 ECUs while the maximum allowable bid was 1050 ECUs. In two of the experiments, there was an entry fee of 50 ECUs and a reservation price of 1050 ECUs.

The experiments at Caltech involved 12 participants each and were run on October 24, 2010 (experiment 20101024) and October 27, 2010 (experiment 20101027). Both experiments at the University of Maryland involved 16 participants each and were run in the morning (experiment 20101111-a) and afternoon of November 11, 2010 (experiment 20101111-b). Combined, the experiments tested 10 different conditions listed in Table I. For convenience, Table II lists each experiment with details on logistics, parameters, exchange rates, and the sequence of conditions used.

2.3: Experimental Design

Modifications of auctions in the experiments were either institutional or environmental. Ten out of the thirty-two logically possible conditions were tested. [5] These ten conditions are listed in

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[5] The choice of experimental conditions was guided by the laboratory test bed approach to policy, which involves an assessment of the basic principles and models as opposed to measuring the influence of variables. In particular, the experimental conditions support an inquiry about the consistency of behavior with theoretical intuitions. Furthermore, the robustness of the consistency with theory is studied through changes of experimental conditions in ways that alternative theories suggest might destroy such consistency with previously supported theories.

The first set of experiments, conducted at Caltech, consisted of five experimental conditions. Twelve subjects participated under each of the four conditions: {auction architecture: excluded bid or CMS}, {binding bids or non-binding bids} under the condition of {private information about cost}. The purpose was to assess the behavior under the different architectures given the information structure best understood theoretically. A fifth experiment in the series implemented the CMS auction architecture under the condition of public information about cost. This fifth condition was imposed as a robustness check to determine if the revelation of information caused some substantial shift of behavior to a new or different type of equilibrium. The theory itself suggests that information is a powerful variable that can induce the operation of different principles.

The second set of experiments, conducted at the University of Maryland was used as a check on the robustness of the conclusions that could be drawn from the Caltech experiments. The difference in location enabled a check on the robustness of the behavior given changes to the subject pools and the experimenters. In addition, the number of subjects was enlarged by thirty-three percent from twelve to sixteen thereby permitting a robustness check on the performance as scale increases. The design reflects an assumption that evidence of models and principles continuing to work with the new subject pool at larger scale is also evidence that subject pool and experimenters are not important variables. Thus, no experiments were conducted at the University of Maryland at the smaller scale of twelve subjects.

At the University of Maryland, the excluded bid auction with private information and the CMS auction with private information were conducted without an entry fee. These four experiments allowed the study of the impact of the bidding fee in addition to serving as the robustness test discussed above. The robustness test was supplemented by an experiment with the CMS auction under the condition of public information about costs (with no entry fee) like the experiment conducted at Caltech with twelve subjects. A total of five experiments were conducted at the University of Maryland.

Of the 32 logical possibilities of the variables the ten experiments described above were conducted. The remaining 22 treatments were excluded from the experiment because they did not contribute to the goals of the study. The study revolves around two main auction frameworks: the excluded bid-auction with binding bids and the CMS auction with non-binding bids both, which have the conditions of private information, and no entry fee. Subsequent treatments served as comparison to one of these two auctions. For example, only two treatments of the 16 possibilities

Table I and were chosen because they reveal the most about the properties and robustness of the central pillars in the CMS auction.

The experiments are named by the date they were conducted. Experiments 20101024 and 20101027 contained six separate auctions, but looked at five conditions. The six auctions were (in order): the excluded-bid auction, the CMS auction with binding bids, the CMS auction, the CMS auction with full information, the CMS auction, and the excluded-bid auction with non-binding bids.

As a control, the excluded-bid auction was conducted to establish a baseline for expected behavior in a theoretically understood auction. Subsequent auctions modified only one rule at a time to ease the transition between conditions for the participants. The CMS auction was conducted twice, with the full information CMS auction in between. This design exists to gauge the effects of learning for this auction mechanism. The experiments explore both central pillars (first the pricing rule, then the bid withdrawal rule). Furthermore, it also tests whether the performance of an auction with well-known properties remains unimpaired when either of the pillars is imposed on it.

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with the public information condition were included because they revealed properties of the standard CMS auction when bidders had more information. Treatments with public information in the excluded-bid auction were not included because such experiments would not reveal further information regarding the performance of the CMS auction. Those account for 14 of the 22 missing logical possibilities.

Treatments with bidding fees were in response to results from the experiments at Caltech where entry fees were not imposed. This accounts for 4 of the missing experiments bringing the total count to 18. The Caltech experiments showed participants submitting low-ball bids and the possibility that the behavior reflected the operations of a completely different theory based on special attitudes. Thus, an entry fee was introduced as a modification to the standard excluded-bid and CMS auctions. The last four excluded were CMS binding-bid auctions with private information (fee and no fee) and the non-binding excluded bid auction (fee and no fee) in the 16 person condition. Binding-bids was an interesting comparison to the non-binding bid case, which was already revealed in the 12 person condition. Effects of scale were gauged using the standard treatments. This accounts for the last 4 remaining treatments, which bring the total up to 22 excluded treatments from the study.

Experiments 20101111-a and 20101111-b were designed with the intent to determine whether results from the experiments at Caltech held given environmental changes. Both experiments at the University of Maryland planned for six auctions within the 1.5 hours. However, due to time constraints and difficulties in conducting long-distance experiments, only the first four were completed in Experiment 20101111-a and the first five in Experiment 20101111-b. The five auctions were (in order): the excluded-bid auction, the CMS auction, the CMS auction with full information, the excluded-bid auction with an entry fee, and the CMS auction with an entry fee (Experiment 20101111-b only).

3. THEORIES AND MODELS

A complete theory for the CMS auction and variations of the CMS auction does not exist. However, the theory that does exist is able to provide hints towards the effects of independent features of the auctions. We start with the excluded-bid auction, which has a well-defined Nash equilibrium before turning to the CMS auction, in which we identify one family of Nash equilibria in our experimental environment. Because the CMS auction has a family of equilibria, it lacks uniqueness, which leads to some ambiguity about which equilibrium, if any, is a foundation for the observed behavior. Nevertheless, the family of equilibria provides insights to the behaviors observed. The following discussion focuses on variations of the CMS and excluded-bid institutions and the currently existing theories of behavior.

3.1 The Excluded-Bid Auction with Binding Bids

The excluded-bid auction has market price determined by the first excluded-bid. All bids below the market price are accepted and bidders receive the market price for the unit. Bids are binding commitments in the sense that accepted bids must be sold at the market price. Because the excluded-bid auction is well understood, it was chosen to serve as a reference point. According to theory, it produces competitive revenue, encourages suppliers to reveal their true costs, and assigns goods efficiently. The auction satisfies *voluntary participation* because at the Nash equilibrium bidders are guaranteed a non-negative payoff.

When suppliers have only one unit to sell, the auction has a single Nash equilibrium. The auction institution is a truthful mechanism—every bidder maximizes his payoff by bidding his true cost, regardless of the other bids submitted. In theory, this auction should achieve consistently high efficiencies regardless of the experience of the bidders, the extent of information available, or the scale of application.

3.2 The Median-Bid Auction with Non-Binding Bids (CMS)

The CMS auction has two key features: the price is determined by the *median winning bid*[6] and *bids are non-binding*. This auction is not truthful—at the Nash equilibrium suppliers' bids do not equal their costs. However, this auction does satisfy voluntary participation because suppliers may withdraw their bids if the calculated market price is below their cost.

The CMS auction has multiple Nash equilibria, including the extreme case of every supplier submitting the minimum allowable bid (Cramton and Katzman, 2011). For one family of Nash equilibria in the CMS auction, a number of bidders greater than the median of the number of demanded units ($n > median$) bid the minimum allowable, thereby setting the price at the

[6] For k demanded units, the median is defined as (k+1)/2 if k is odd and k/2+1 if k is even.

minimum allowable bid. No single bidder can improve his payoff by submitting a different bid, so it is a Nash equilibrium.

When costs and bids are common knowledge (public information) in the CMS auction, a different class of Nash equilibria emerges. Let $n(B)$ be the set of bidders with costs at most B. Choose any bid B for which $0 < median \leq \ |n(B)| \leq k$, for k demanded units. Let all bidders in the set $n(B)$ bid B, and all other bidders bid at least B (and withdraw if they "win"). In these equilibria, the price is set at B and no single bidder can change the price.

It is of interest to note that another equilibrium exists in which the bidders in $n(B)$ bid B and withdraw their bids if the resulting price is below their cost while all other bidders bid the minimum allowable and withdraw.

An observation about non-binding bids is useful, especially in the context of the CMS auction. If a bid can be withdrawn and if the bid does not determine the price, such as in median-bid price auctions, then the bid only works to determine whether the bidder is among the winners or not. If the price is below the bidder's cost, the bidder can withdraw his bid. A low-ball bid that ensures the bidder will be among the winners is an option that gives the bidder the right to sell at the market price.

An alternative theory based on bidder attitudes suggests that the bidders have malicious intent to hurt the other bidders by forcing the price down. To test that theory we add a cost to bid in two of the experiments. If malicious intentions exist, then this behavior will continue at some price in the form of the low-ball bids. If on the other hand, the low-ball bids reflect strategic bidding, the addition of the entry fee will remove it from behavior.

3. 3 The Excluded-Bid Auction with Non-Binding Bids

One variation of the CMS architecture changes the pricing rule from the median price rule to the excluded-bid rule. This produces an auction with the excluded-bid pricing rule and non-binding bids. Similar to the CMS auction, this variation satisfies voluntary participation because participants have the option to withdraw bids. Similar to the excluded-bid auction, this auction has an equilibrium bid function $bid(cost) = cost$. However, due to the withdrawal option, the family of equilibria identified for the CMS auction also extends to this auction: if a number of bidders greater than the number of demanded units $(n > k)$ bid the minimum allowable, then the price is set at the minimum and no single bidder can improve his payoff by submitting a different bid.

3.4 The Median-Bid Auction with Binding Bids

A second variation of the CMS architecture retains the median-bid pricing rule and removes the bid withdrawal option, thereby changing the rule to binding bids. Similar to the CMS auction, this auction is not a truthful mechanism; participants have an incentive to bid above their cost. For this auction, Cramton and Katzman (2011) show that there are no strictly increasing bid functions. Instead, they suggest that suppliers with high costs will attempt to avoid negative payoffs by bidding the maximum allowable bid. Suppliers cannot be guaranteed non-negative payoffs regardless of their bids, so this auction does not satisfy voluntary participation.

3.5 *Entry Fees*

In the excluded-bid auction with an entry fee, if fewer suppliers enter than units demanded, then each entering supplier receives a previously disclosed reservation price. Otherwise, this auction operates exactly as the excluded-bid auction described in Section 3.1. As developed in Appendix

D, theory suggests that suppliers will enter the market and bid if and only if their cost is below a particular cutoff cost dependent on the parameters of the experimental environment.[7] In this symmetric equilibrium, entering suppliers place "truthful" bids as would be the case in the excluded-bid auction without an entry fee. Due to the uncertainty of participants' costs, the probability of a perfect procurement decreases. For the parameters outlined in Section 2.2 with 16 suppliers, the cutoff cost would be 626 ECUs, the probability of perfect procurement would be 92.5%, and the average price would be 588 ECUs.

In the CMS auction, the introduction of an entry fee creates an incentive for those who expect to be excluded to opt out of the bidding process. The Nash equilibrium is unknown to us since suppliers who do not expect to be excluded may still choose to opt out if they believe that the median cost will be below their cost plus the entry fee. However, the bidding patterns are of interest. First, bidders would seem to have the same incentive to place low-ball bids as they would have in the absence of an entry fee. If low-ball bids reflect attitudes of spite or attempts to punish other bidders, then the low-ball bids would remain. Secondly, sensible strategies exist. The decision theory principles from game theory suggest that bidders will choose to enter if profits given expected market price are sufficient to cover the entry fee. Even if the game theoretic bidding strategies are unknown, the decision theoretic property is suggested by special parts of the general theory.

[7] Previous studies indicate that entry is governed by expected profits. In auctions, the focus has been on first price auctions (Palfrey and Pevnitskaya, 2008) or comparisons of auction institutions (Ivanova-Stenzel and Salmon, 2011). To our knowledge the extension and testing of the theory of entry for excluded bid auctions that we offer here, is new.

Section 4: RESULTS

The research is summarized by the following 10 results. Results 1 – 3 collectively argue that procurement auctions satisfying CMS's four policy goals exist and can be compared to the CMS auction mechanism. In particular, the excluded-bid auction performs well in the sense that the performance is understandable from a theoretical point of view, efficient, and satisfies the natural policy objectives. Results 4 – 6 reveal, however, that the proposed CMS auction does not perform as satisfactorily. Results 7 and 8 report on the individual features that make the CMS auction unusual. Results 9 and 10 explain the effects of adding an entry fee. Measures of efficiency are summarized in Table III, while regressions are summarized in Table IV.

4.1 Good Procurement Auction Architectures Exist.

Results 1-3 establish the properties of the excluded-bid auction. The auction demonstrates that the capacity to create successful auctions is not beyond the available science.

RESULT 1: *In the excluded-bid auction, suppliers tend to reveal their costs.*

Support. Figures IV and X display the bidding behavior for the excluded-bid auction. Theory suggests that it is a dominant strategy for suppliers to bid their costs. Indeed, three out of every four bids (78.1%) approximately[8] follow this strategy in Experiments 20101024 and 20101027. As the number of suppliers increase in Experiments 20101111-a and 20101111-b, the adherence to this strategy drops to 54.0% and 68.3% respectively. These results are comparative to previous experimental findings (Isaac 2008). A third of suppliers consistently submit bids equal to their

[8] We define "approximately" as ±30 ECUs (10¢) to take into account the tendency of participants to round their cost to the nearest 5, 10 or 25. To give some perspective, in Experiments 20101024 and 20101027, 40.0% follow the dominant strategy exactly, 58.7% are within ±2 ECUs, and 70.8% are within ±15 ECUs.

costs while the remaining suppliers, on average, tend to overbid when they have low costs. This observation is captured by a simple linear regression of the model $bid = \alpha + \beta \times cost$, which reveals a relatively small intercept $\hat{\alpha} = 123$ ($se = 12.5$) and a slope $\hat{\beta} = .856$ ($se = .020$). These parameters also suggest that suppliers are more likely to bid truthfully as their costs approach the expected competitive price.

RESULT 2: *Prices generated in the excluded-bid auction approximate the competitive price.*

Support. In the excluded-bid auction, 22 out of the 52 total periods generate prices within 1% of the competitive price; 36 out of 52 are within 5%. As depicted in Figures II and III, the prices that differ greatly from the competitive price are located both above and below the competitive price and result largely from untruthful bidding by one or two bidders (who either received negative payoffs or lost the right to sell). Consequently, the average market price generated is 102.2% ($se = 13.1$) of the competitive price. Similar to the model for bidding behavior, a simple linear regression for the model $Market\ Price = \alpha + \beta \times (Competive\ Price)$ returns an intercept $\hat{\alpha} = 111$ ($se = 35.5$) and a slope $\hat{\beta} = .824$ ($se = .057$) that is significantly greater than zero, with a p-value $< 10^{-18}$. If α is constrained to 0, then $\hat{\beta} = 1.00$ ($se = .014$), closely matching the ideal $\beta = 1$.

RESULT 3: *Outcomes in the excluded-bid auction are consistent with policy objectives: the auction has perfect procurement with near-perfect efficiency levels.*

Support. As is true for all binding bids auctions with sufficient participation, the excluded-bid auction has perfect procurement in every period. From the government perspective, perfect procurement at prices that approximate the competitive price (as reported in Result 2) lead to an efficiency level of 100.3% ($se = 14.8\%$). Efficiency from the supplier perspective is more variable due to untruthful bidding, but still high on average at 93.7% ($se = 42.3\%$). Social efficiency – how well the auction allocates units to suppliers with the lowest costs – is near-perfect at 96.1% ($se = 4.7\%$).

4.2 The CMS Auction Performs Poorly

Results 4 – 6 suggest that the CMS auction performs poorly in absolute terms and relative to the excluded-bid auction. The CMS auction fails to provide a sufficient disincentive for perverse bidding behavior that leads to low efficiency and poor performance.

RESULT 4: *In the CMS auction, suppliers with high costs submit "low-ball" bids. The prevalence of this activity increases with experience, information, and scale.*

Figures V and XI display the bidding behavior for the CMS auction with private information; Figures VIII and IX display the bidding behavior for those with public information. In each figure, there is a collection of bids at the minimum allowable level for suppliers with primarily high costs. Across all CMS auctions, one out of every five bids is a low-ball bid. The prevalence of this behavior more than doubles with experience (from 12% to 26%), and is exacerbated by information (to 24%), and scale (to 18%). In general bidding behavior exhibits substantial variability. In Experiments 20101024 and 20101027, many of the remaining bids are scattered above the supplier's cost. There is less of a discernible trend in the CMS auctions of Experiments 20101111-a and 20101111-b. Simple linear regressions of the model $bid = \alpha + \beta * cost$ describe the data poorly as illustrated by the standard errors reported in Table IV.

RESULT 5: *Prices generated in the CMS auction do not approximate the competitive price. They are significantly and consistently lower than the competitive price.*

Support. Figures II and III show that the CMS auction generates prices that are consistently lower than the competitive price – only 5 out of the 138 total periods generate prices within 15% of the competitive price. The average market price generated differs greatly with experience, information, and scale. For 12 suppliers and private information in CMS Iteration I, the average price is 69.5% ($se = 19.5\%$) of the competitive price, which drops with the introduction of public information to 39.2% ($se = 29.8\%$) and drops slightly further with experience to 34.9% ($se = 25.2\%$) in CMS Iteration II. Scaling up to 16 suppliers, the average price begins low at 33.4% ($se = 18.6\%$) for private information and rises to 46.1% ($se = 23.1$) for public information. This information is summarized in Table III. For each CMS auction, the econometric model $Market\ Price = \alpha + \beta \times (Competive\ Price)$ returns a slope $\hat{\beta}$ that is not statistically significantly greater than 0, suggesting that the underlying competitive price has no bearing on the observed market price.

RESULT 6: *Outcomes in the CMS auction are not consistent with policy objectives: the auction fails to obtain adequate procurement and has poor efficiency levels relative to the excluded-bid auction.*

Support. In the CMS auction, one out of five periods procured no units at all and only 3 of the 138 total periods had perfect procurements. On average, the CMS auction with 12 bidders and private information procured 4.2 units ($se = 1.7$) out of the 7 units demanded in Iteration I, which declined to 2.2 units ($se = 2.2$) for Iteration II. As the auction increased in scale to 16 bidders, the average dropped to 1.7 units ($se = 1.8$). When valuations were public information, an average of 2.2 units ($se = 2.4$) and 2.4 units ($se = 1.8$) were procured for 12 and 16 bidders respectively. A consequence of low prices and poor procurements, efficiency from the supplier perspective suffered dramatically with 29.3% at best and 1.1% at worst. Although the government benefited from low prices, inadequate procurements led to efficiency levels (73.9%, 52.0%, 37.2%, 47.5%) that were poor relative to the near-perfect efficiency reported in Result 2. Social efficiency in the CMS auction is also much lower (53.8%, 35.3%, 25.3%, 37.1%) than the in the excluded-bid auction because not all units are procured. See Table III for more details.

4.3 The CMS Auction Cannot be Easily Fixed

Results 7 and 8, suggest that the CMS auction cannot be fixed by marginal changes. The problems exist at the foundations of the auction design. The policy of non-binding bids can independently make an otherwise well-functioning auction perform poorly. Similarly, the median-bid pricing rule has the independent ability to disrupt well-functioning auctions.

RESULT 7: *In the excluded-bid auction with non-binding bids, suppliers submit "low-ball" bids, causing lower prices, procurement, and efficiencies than those observed in the excluded-bid auction.*

Support. Similar to the low-ball bids reported in Result 4 in the CMS auction, Figure VI shows that suppliers in the excluded-bid auction with non-binding bids submit bids at the minimum allowable level. The remaining suppliers tend to bid above their cost, perhaps accounting for the low-ball bidders. Figure II depicts that the resulting market prices are often lower than the competitive price, but greater than the prices observed in the CMS auction and reported in Result 5. On average, the price is 83.9% ($se = 17.9\%$) of the competitive price. Out of the 24 total periods, 9 have perfect procurement, 5 procure six, 7 procure five, and the remaining 3 procure four units. Thus, this auction averages 5.8 units. Efficiency from the perspective of government is 112.0% ($se = 30.5\%$) because the government is procuring all or nearly all demanded units at prices lower than the competitive price. Consequently, the low prices and low procurements cause efficiency from the supplier perspective to be 68.5% ($se = 32.9\%$), lower than in the excluded-bid auction. Social efficiency remains high at 87.9% ($se = 11.5\%$).

RESULT 8: *In the median bid auction with binding bids, suppliers consistently bid above their cost. This auction procures the demanded number of units at prices below the competitive price at high levels of efficiency for the government, but at low levels of efficiency for suppliers.*

Support. As shown in Figure VII, suppliers in the median-bid auction with non-binding bids submit bids above their costs. In contrast to the auctions with non-binding bids reported on in Results 4 and 7, no supplier with a high cost submits a low-ball bid. Instead, suppliers are bidding at the maximum allowable level, as predicted by the incomplete theory. A simple linear regression of the model $bid = \alpha + \beta \times cost$ reveals an intercept $\hat{\alpha} = 170$ ($se = 19.7$) and a slope $\hat{\beta} = 1\ .00$ ($se = .032$). These parameters suggest that, on average, suppliers submit bids that are 170 greater than their cost. As shown in Figure II, these bids translate into prices that approximate the competitive price better than the CMS auctions but are still lower than the competitive price on average at 88.7% ($se = 13.7\%$). However, binding bids and sufficient (in this case, mandatory) participation implies perfect procurement, even if suppliers are forced to sell at a loss (at prices below their bids). This leads to above-perfect levels of efficiency from the government perspective at 124.6% ($se = 30.2\%$), near-perfect social efficiency at 97.4% ($se = 3.1\%$), but poor efficiency for suppliers at 68.6% ($se = 34.6\%$).

4.4 Elimination of low-ball bidding behavior with an entry fee reveals properties of auction robustness and absence of malicious intent.

Results 9 and 10 discuss an additional attempt to isolate and clarify the principles at work in the excluded-bid and CMS auctions. Imposing an entry fee evokes a subtle property in which bidders enter if and only if they believe that they can profit. Consequently, the entry fee discourages low-ball bidding and reveals the suppliers' beliefs about the expected price. These results reinforce the claim that the theory underlying simple cases also extends to complex classes and invites further exploratory approaches.

RESULT 9: *Imposing an entry fee predictably changes behavior in the excluded-bid and CMS auctions according to theory. Furthermore, the decline of low-ball bidding behavior opposes the suggestion that bidders use spiteful or punishing bidding strategies.*

Support: As shown in Figure XII, behavioral change in the excluded-bid auction is closely aligned with the theoretical predictions. Theory predicts that individuals choose not to pay the fee and bid if their cost is at or above the cutoff cost of 626 and this theory is supported in the data. Indeed, suppliers with costs of 625 or above are more likely to opt out than to bid. A decline in entry begins at a cost of 525, with 96% of suppliers entering, and drops to 22% at costs of 650. Following that, the percent of suppliers entering the auction trends toward zero. At first entering suppliers have a tendency to submit bids greater than their costs. However, this inflation of bids decreases with experience. A regression of the first five periods indicates significant overbidding with intercept $\hat{\alpha} = 290.9$ $(se = 41.1)$ and slope $\hat{\beta} = .34$ $(se = .11)$, and a regression of the last five rounds indicates a progression towards the Nash bidding strategy[9], with intercept $\hat{\alpha} = 118.9$ ($se = 25.7$) and slope $\hat{\beta} = .87$ ($se = .06$).

As predicted, low-ball bids are eliminated in the CMS auction. As shown in Figure XIII, a stable configuration of bidding appears to emerge, with over half of the entering suppliers submitting bids equal to their cost plus the fee and the remaining bids clustering around 325. Consequently, suppliers begin to opt out much sooner—only 7 out of the170 potential bids are submitted by suppliers with costs above 400.

RESULT 10: *The introduction of entry fees does not change the relative system performance of the excluded-bid auction and the CMS auction along the major measures of performance. The excluded-bid auction consistently performs better than the CMS auction.*

Support: The excluded-bid auction with an entry fee better approximates competitive prices, results in better procurements, and yields higher levels of social efficiency than the CMS auction with an entry fee. Market price in the excluded-bid auction with an entry fee is 132% ($se = 42\%$) of the competitive price, whereas the comparative CMS auction resulted in 67% ($se = 16\%$) of the competitive price. Although the variance for the excluded-bid auction is high, Figure III shows that pricing in the excluded-bid auction converges towards the competitive price as bidders gain experience.

The excluded-bid auction with an entry fee allocates units efficiently to the suppliers with the lowest costs, as indicated by a near-perfect social efficiency of 95.5% ($se = 5.8\%$). As a result

[9] This is comparable to the truthful cost revelation in Result 1. Although the Nash bidding strategy is to bid cost, bidding cost + fee is an understandable mistake, even for those who recognize the truth revealing properties of the second price auction.

of prices sometimes set at the reservation price, the government's value of each unit, government efficiency is low at 66.5% ($se = 37.8\%$) and supplier efficiency is high at 162.5% ($se = 77\%$). Comparatively, the CMS auction allocates units poorly, with a lower social efficiency at 59.9% ($se = 19.3\%$), and performs poorly from the perspective of suppliers at 34.4% ($se = 23.1\%$) and the government at 74.6% ($se = 24.9\%$).

Procurement in the excluded-bid auction with an entry fee is perfect in all but 3 out of the 28 trials, and the reservation price is paid to participants in 6 out of the 28 trials[10]. The average number of units procured was 6.86 $units$ ($se = .45\ units$), which is close to the theoretical prediction of 6.86. In the CMS auction, procurement was 3.75 $units$ ($se = 1.6\ units$). While the government may appear to benefit from lower prices in the CMS auction with entry fees, it fails to procure the units it demands. Ultimately, these results preserve the relative performance of the excluded-bid and CMS auctions despite the introduction of an entry fee.

5. SUMMARY AND CONCLUSION

The central issues explored in this paper are motivated by the architecture of the CMS auction and by the policy goals the auction was designed to address. An assessment of the performance is based on an institutional comparison of the CMS auction with its variations and on applications of theory. Evidence suggests that the withdrawal option contributes to the presence of low-ball bidding behavior and that the median-bid pricing rule reliably generates prices lower than the competitive price, deterring suppliers from submitting bids when participation is not

[10] Theory predicts imperfect procurement in 7.5% of the trials and exactly 7 bids submitted in 9% of the trials given bidding behavior in response to the cutoff cost. Given 28 trials, we expect on average 2 imperfect trials and an average of 5 trials where the reservation price is paid.

mandatory. Hence, the CMS auction rests on an architecture that constrains its efficiency below the levels at which existing, well-known auctions are capable of performing.

In the classical uniform price auction, the price is determined by the first excluded-bid and bids are binding commitments. Comparing this excluded-bid auction with the CMS auction under controlled, laboratory conditions reveals the superior performance of the excluded-bid auction. The excluded-bid auction performs as predicted by theory: the prevalent bidder strategy is to reveal costs (Result 1), and as a consequence, prices emerge near the competitive equilibrium price (Result 2) and the social efficiency is nearly perfect (Result 3). Furthermore, the auction behavior remains consistent with theory regardless of scale or experience.

In contrast to the excluded-bid auction, the CMS auction performs poorly as a procurement auction. A pervasive bidding strategy is to bid at the minimum allowable level (Result 4), driving down prices (Result 5) and generating a low efficiency on each dimension (Result 6). Furthermore, the poor performance of the CMS auction is exacerbated by experience, information, and scale.

Analysis of select features from the CMS auction architecture help isolate independent contributions to the poor performance and suggest that "slight" adjustments to the CMS auction will not improve performance to the standards set by the excluded-bid auction. In particular, replacing the median-bid pricing rule with the first-excluded-bid pricing rule (while maintaining the right to withdraw) allows for the independent study of the impact of the withdrawal option. The resulting increase in the number of equilibria introduced by the withdrawal option removes the opportunity to produce any "crisp" test of theory, but reveals the option's effect on bidding behavior. In general, suppliers were observed to either place bids near their cost (except those with low costs, who safely bid above their cost without risking their right to sell) or at zero, two of the equilibria identified (Result 7). Removal of the bid withdrawal feature while retaining the pricing rule dramatically (but predictably) increased prices and procurement, but the prices observed were reliably lower than the prices in the excluded-bid auction and contributed to low supplier efficiency. With the bid withdrawal feature removed, bidders must trade at the price set by the median bid, which may be substantially below their cost. Thus, attempting to avoid such a result, there was evidence that bidders with costs above the expected market price attempted to exclude themselves by submitting a bid at the maximum allowable level (Result 8).

The imposition of an entry fee demonstrates the robustness of the theory and results. Furthermore the fee eliminated low-ball bidding (Result 9), suggesting that bidders are not malicious, but rather that auction architecture does not provide sufficient disincentives for underbidding. Furthermore, for suppliers with medium to high costs, the CMS auction with an entry fee deters participation because the prices generated do not approximate the competitive price (Result 10).

In policy analysis experiments play a role in understanding and in developing confidence in the accuracy and robustness of theory. It is the resulting theory that must be relied upon when decisions are made about the more complex and uncontrolled field environments. The chain of logic is made difficult in the case of the CMS auction because the theory is incomplete. Nevertheless, partial theories contribute to our understanding of particular observed behaviors and institutional comparisons allow us to assess the performance of novel auction architectures. The challenge, for those who are unconvinced by the evidence that the CMS auction will perform poorly, is to explain why the principles seen operating so clearly in the laboratory environment will not operate when the auction is deployed in the field.

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Figure I:
Experimental Design

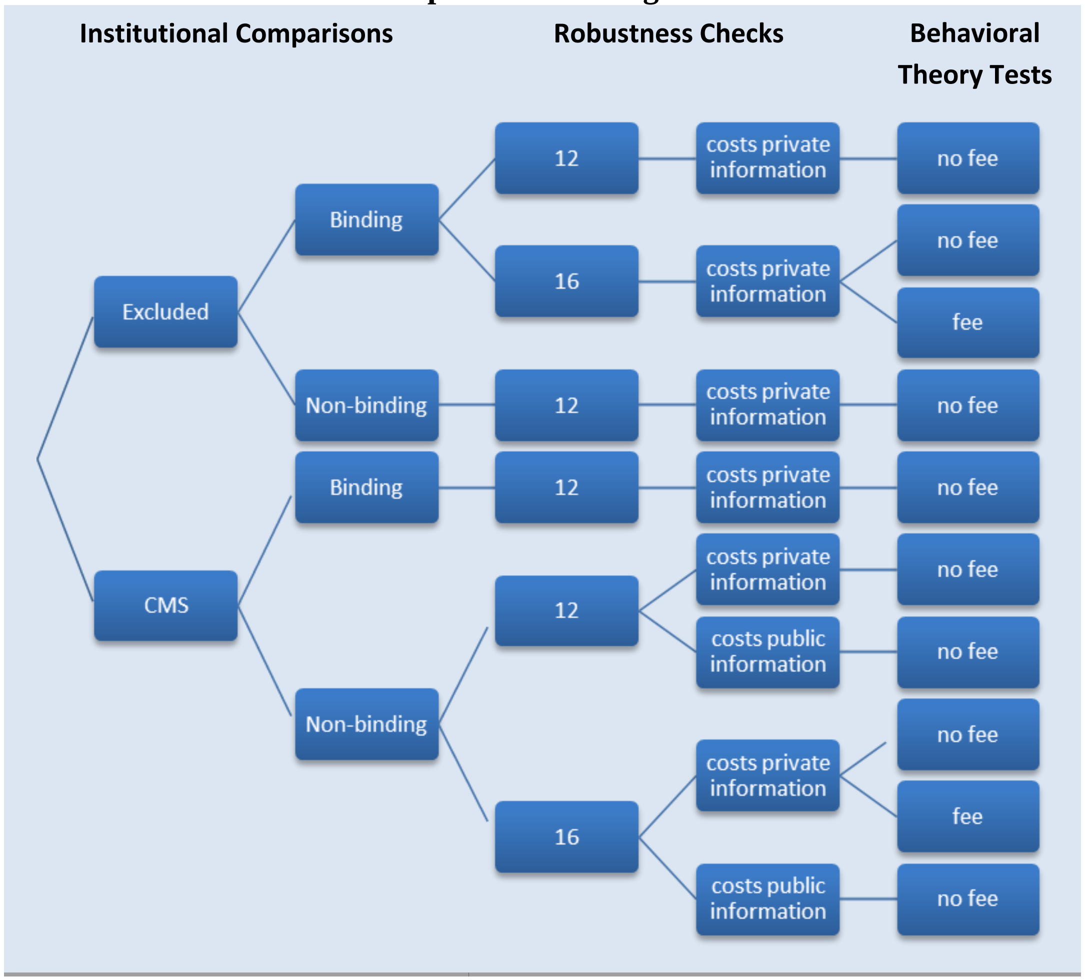


Figure II
Experiments 20101124 and 20101127: Pricing Success

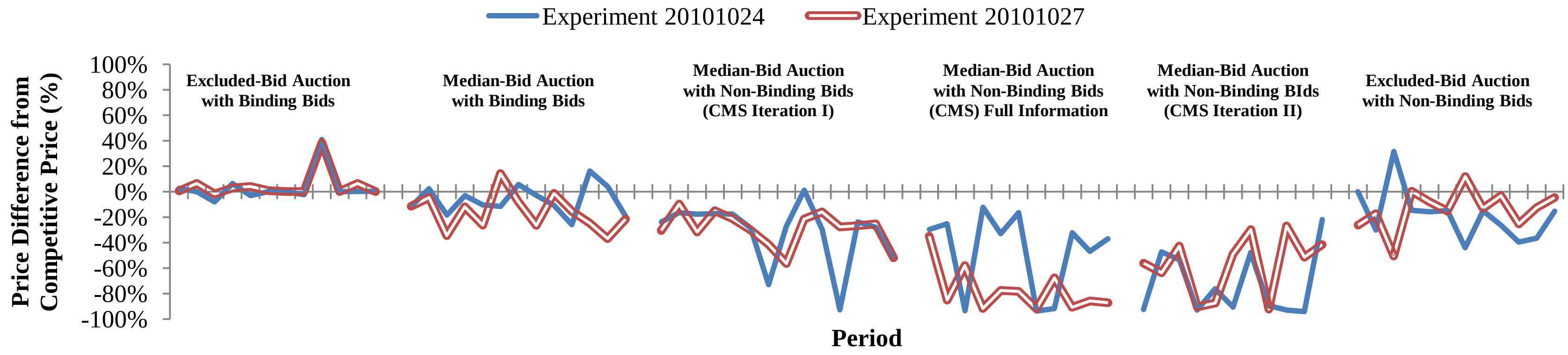


Figure III
Experiments 20101111-a and 20101111-b: Pricing Success

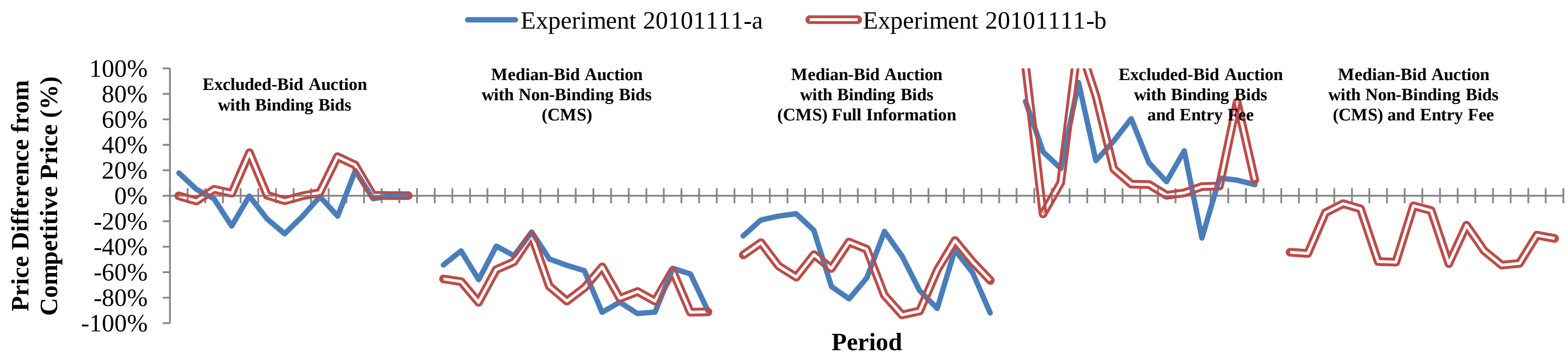


Figure IV:
Excluded-Bid Auction with Binding Bids

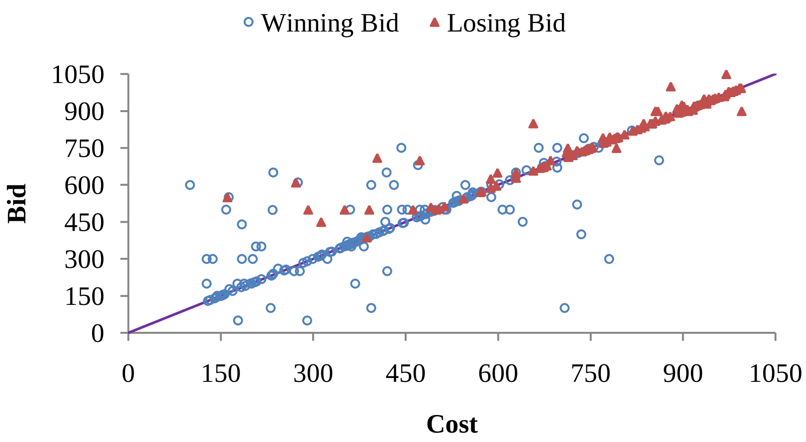


Figure V:
Median-Bid Auction with Non-Binding Bids (CMS)

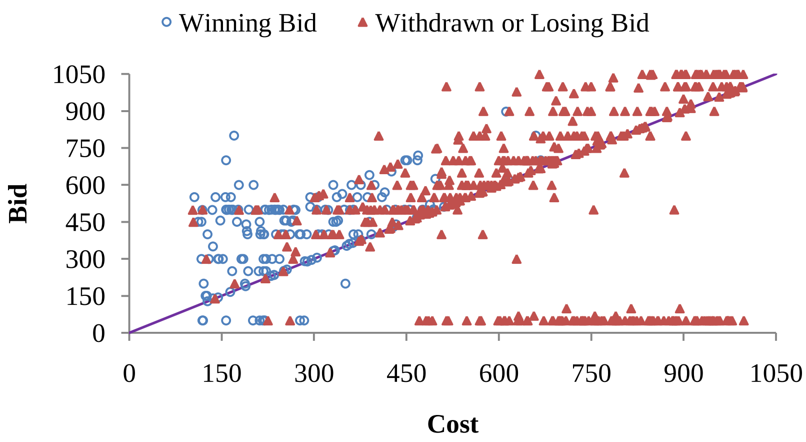


Figure VI:
Excluded-Bid Auction with Non-Binding Bids

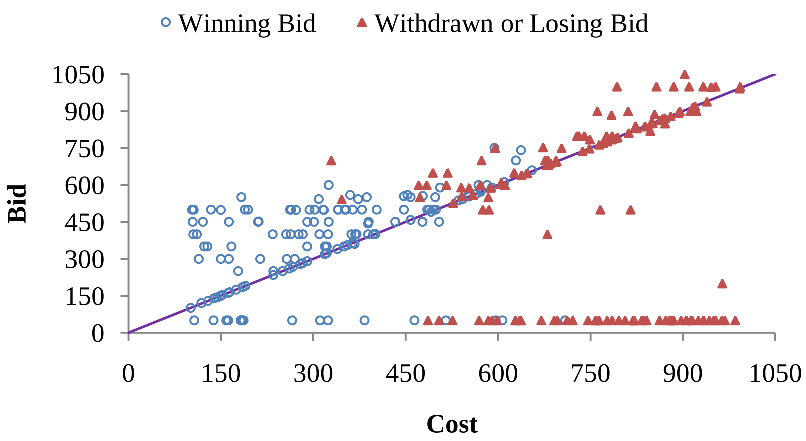


Figure VII:
Median-Bid Auction with Binding Bids

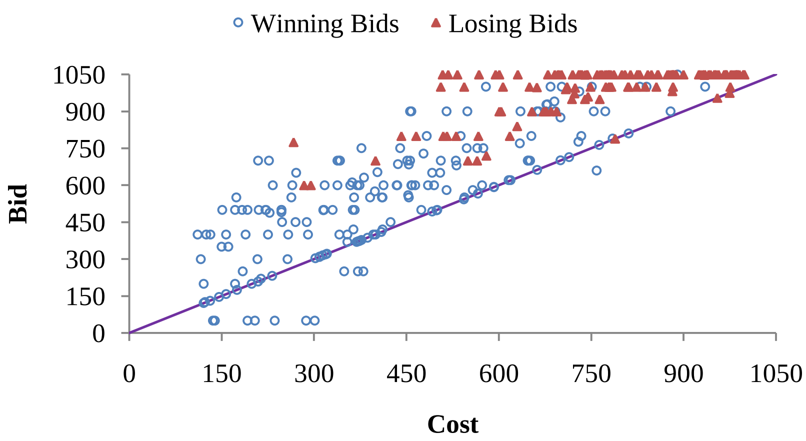


Figure VIII:
Median-Bid Auction with Non-Binding Bids (CMS):
Full Information

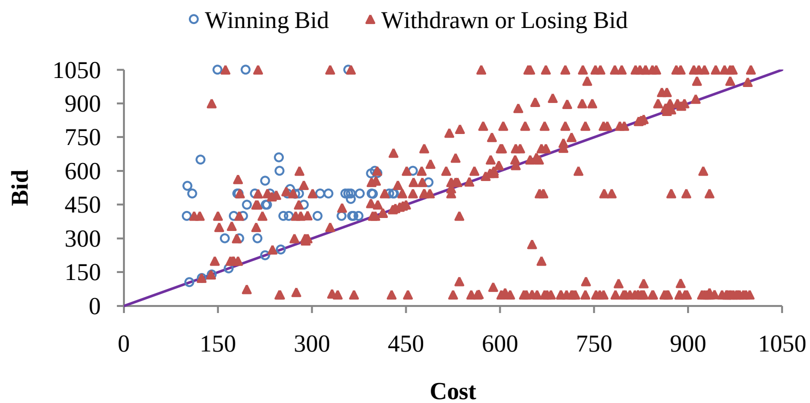


Figure IX:
Median-Bid Auction with Non-Binding Bids (CMS):
Full Information and 25% More Bidders

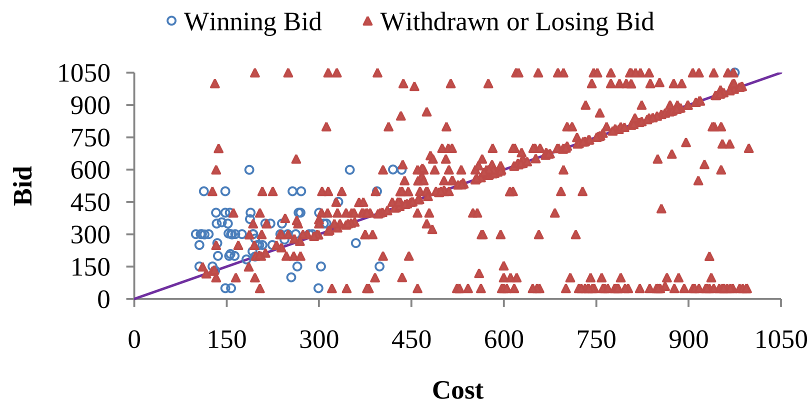


Figure X:
Excluded-Bid Auction with Binding Bids:
25% More Bidders

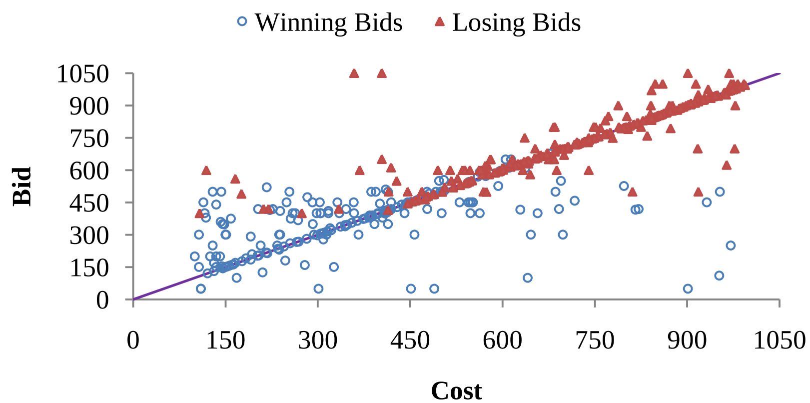


Figure XI:
Median-Bid Auction with Non-Binding Bids (CMS):
25% More Bidders

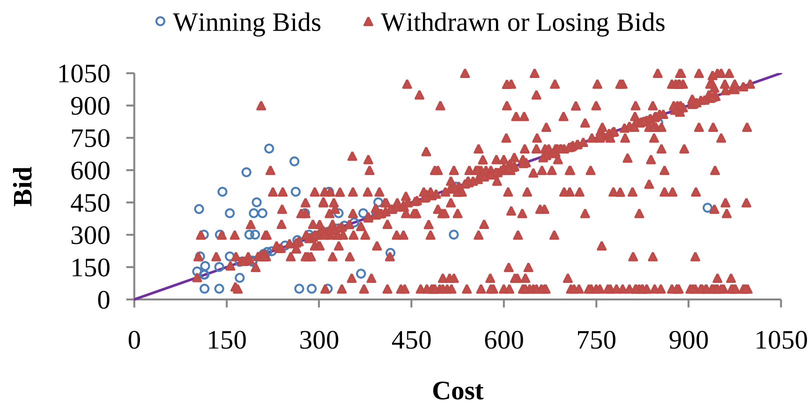


Figure XII:
Excluded-Bid Auction with Binding Bids:
Entry Fee and 25% More Bidders

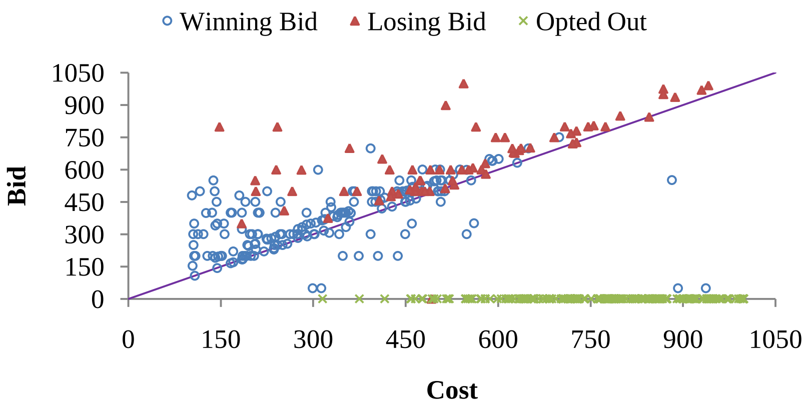


Figure XIII:
Median-Bid Auction with Non-Binding Bids (CMS):
Entry Fee and 25% More Bidders

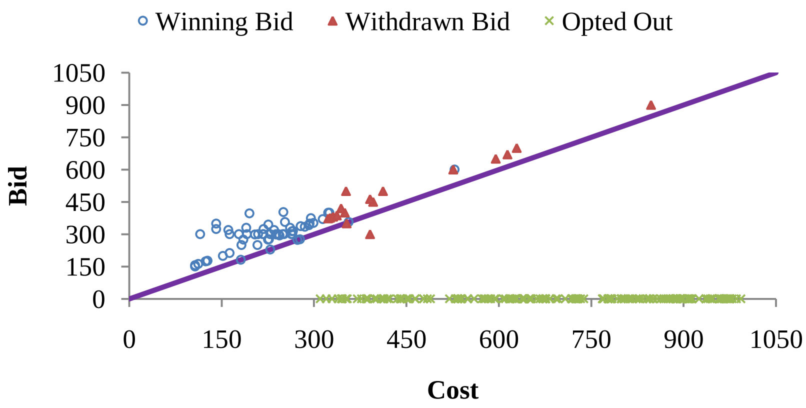


Table I:
Summary of Treatments

Condition	Pricing Rule	Bid Withdrawal Rule	Number of Participants	Nature of Information	Entry Fee
1	Excluded-Bid	Binding	12	Private	No
2	Excluded-Bid	Binding	16	Private	No
3	Excluded-Bid	Binding	16	Private	Yes
4	Excluded-Bid	Non-Binding	12	Private	No
5	CMS	Binding	12	Private	No
6	CMS	Non-Binding	12	Private	No
7	CMS	Non-Binding	12	Public	No
8	CMS	Non-Binding	16	Private	No
9	CMS	Non-Binding	16	Private	Yes
10	CMS	Non-Binding	16	Public	No

Table II:
Summary of Experimental Details

Experiment #	1	2	3	4
Date	10-24-2010	10-27-2010	11-11-2010	11-11-2010
Location	California Institute of Technology		University of Maryland	
Exchange Rate (ECUs/$)	300		125	
Conditions Run (in order)	1, 5, 6, 7, 6, 4		2, 8, 10, 3	2, 8, 10, 3, 9

Table III:
Summary of Auction Performances

	Procurement (units)		Pricing Success		Social Efficiency		Government Surplus		Supplier Surplus	
Treatment	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Excluded-Bid (12)	7	0	103.9%	11.4%	97.7%	4.2%	96.9%	10.1%	101.6%	31.3%
Excluded-Bid (16)	7	0	100.8%	14.6%	94.7%	4.9%	103.2%	14.8%	86.9%	49.5%
Excluded-Bid (16), Fee	6.66	.45	132.3%	41.5%	95.5%	5.8%	66.5%	37.8%	162.5%	77.0%
Excluded-Bid (12), Non-B	5.83	1.09	83.9%	17.9%	87.9%	11.5%	112.0%	30.5%	68.5%	32.9%
CMS (12), Binding	7	0	88.7%	13.7%	97.4%	3.1%	124.6%	30.2%	68.7%	34.6%
CMS (12), Public Info.	2.19	2.40	39.3%	29.8%	35.3%	36.8%	52.0%	54.2%	17.8%	23.3%
CMS Iteration I (12)	4.21	1.77	69.5%	19.5%	56.2%	24.8%	70.8%	31.4%	42.3%	23.3%
CMS Iteration II (12)	2.23	2.22	34.9%	25.2%	36.6%	35.2%	61.1%	69.4%	12.8%	15.7%
CMS (16), Public Info.	2.37	1.77	46.1%	23.1%	37.1%	26.5%	47.5%	33.7%	13.4%	21.4%
CMS (16), Fee	3.75	1.57	66.5%	15.8%	59.9%	19.3%	74.6%	24.9%	34.4%	23.0%
CMS (16)	1.72	1.84	33.4%	18.6%	25.3%	26.8%	37.2%	40.9%	0.7%	8.3%

Table IV:
Tests of prices and bid functions

Treatment	*Market Price = α + β×Competitive Price* Estimate for a	Estimate for b	*Bid = α + β×Cost* Estimate for a	Estimate for b
Excluded-Bid (12)	130.91	.83	72.63	.90
	(44.20)	(.06)	(14.03)	(.02)
Excluded-Bid (16)	167.13	.69	116.78	.81
	(53.05)	(.09)	(14.75)	(.02)
Excluded-Bid (16), Fee	-142.20	1.60	177.37	.71
	(245.03)	(.47)	(18.85)	(.04)
Excluded-Bid (12), Non-B	330.52	.33	38.67	.70
	(137.44)	(.20)	(15.41)	(.04)
CMS (12), Binding	138.33	.67	169.50	1.00
	(103.31)	(.15)	(19.68)	(.03)
CMS (12), Public Info.	536.49	-0.43	424.61	.10
	(211.58)	(.31)	(42.95)	(.07)
CMS Iteration I and II (12)	276.41	.10	319.36	.36
	(151.16)	(.23)	(28.41)	(.05)
CMS (16), Public Info.	221.58	.02	263.47	.41
	(112.38)	(.21)	(30.13)	(.05)
CMS (16), Fee	266.45	.14	94.12	.91
	(80.39)	(.14)	(12.44)	(.04)
CMS (16)	173.21	.01	184.19	.48
	(129.49)	(.23)	(29.94)	(.05)
Excluded-Bid (12 and 16) †	111.28	.82	123.56	.86
	(35.54)	(.06)	(12.54)	(.02)
CMS (12 and 16) †	62.65	.35	260.28	.41
	(106.34)	(.17)	(20.77)	(.03)
CMS (12 and 16), Public Info. †	297.68	-.10	327.77	.28
	(112.38)	(.15)	(25.06)	(.04)

†Results for these auctions in the text reported regression of the combined data from both 12 and 16 bidder conditions.

Appendix A: Instructions

<u>Excluded-bid:</u>

In this auction, you are going to participate in **an excluded-bid auction** in which you will be a SELLER of a commodity. In this auction with 12 participants, the participants submitting the lowest 7 bids will sell the item at the price of the 8th lowest bid.

You are selling a single item. Your cost of production for the single item is drawn from a uniform distribution [100, 1000]. Your task is to submit bids for the opportunity to sell your item. In each period you will be randomly assigned a different cost of production. You are not to reveal this information to anyone. It is your own private information. The minimum bid you may submit is 50; the maximum bid you may submit is 1050.

$$Profit = \begin{cases} if\ you\ submit\ one\ of\ the\ 7\ lowest\ bids: & (market\ price) - (cost\ of\ production) \\ otherwise: & 0 \end{cases}$$

$$market\ price = 8^{th}\ lowest\ bid$$

Questions

Suppose for example, the bids are: 100, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, and 220.

What is the highest accepted bid? ______

What is the price that all bidders will receive? ______

If Participant A's bid is 160 and his cost of production is 185. What is his profit? ______

If you bid *below* your value, can you lose money? Yes No

If you bid your value, can you lose money? Yes No

If you bid *above* your value, can you lose money? Yes No

<u>Median Price Auction with Cancellation:</u>

Participants with the 7 lowest bids will be offered the right to sell the item at the valued price. When you are offered the right to sell your item, you can also opt to 'cancel your bid' and not sell the item at the market price. A bid cancellation *will not* affect the valued price of the item. You will all choose to accept or cancel simultaneously, but if a cancellation occurs, then the person with the next highest bid who has accepted the market price will sell the item.

$$Profit = \begin{cases} if\ you\ one\ of\ the\ 7\ lowest\ bidders\ that\ \boldsymbol{accept}: & (market\ price) - (cost\ of\ production) \\ otherwise: & 0 \end{cases}$$

$$market\ price = median\ of\ 7\ lowest\ bids$$

<u>Median Price Auction with Cancellation</u> [with public information]:
However, in this auction, you will be able to see the costs of all participants. Once all participants have bid, you will also be able to see their bids and whether they are one of the lowest 7 bidders. The minimum bid you may submit is 50; the maximum bid you may submit is 1050.

<u>Entry Fee</u>:

For the remaining auctions, after learning your cost, you will first decide whether to bid in the particular auction. **To bid in the auction, you must pay an entry fee of 50 ECUs.** Thus, your profit in Experimental Currency Units (ECUs) will be determined by:

$$Your\ profit\ = \begin{cases} if\ you\ do\ not\ bid: & 0 \\ if\ you\ sell\ the\ item: & (market\ price) - (cost\ of\ production) - 50 \\ if\ you\ don't sell\ the\ item: & -50 \end{cases}$$

<u>Entry Fee and Excluded-bid</u>:
In this auction, you are going to participate in **an excluded-bid auction** in which you will be a SELLER of a commodity. **To bid in this auction, you must pay an entry fee of 50 ECUs.** Bidders submitting the lowest 7 bids will sell the item at the price of the 8th lowest bid. If there are fewer than 7 bidders, the item will be sold at 1050 ECUs.

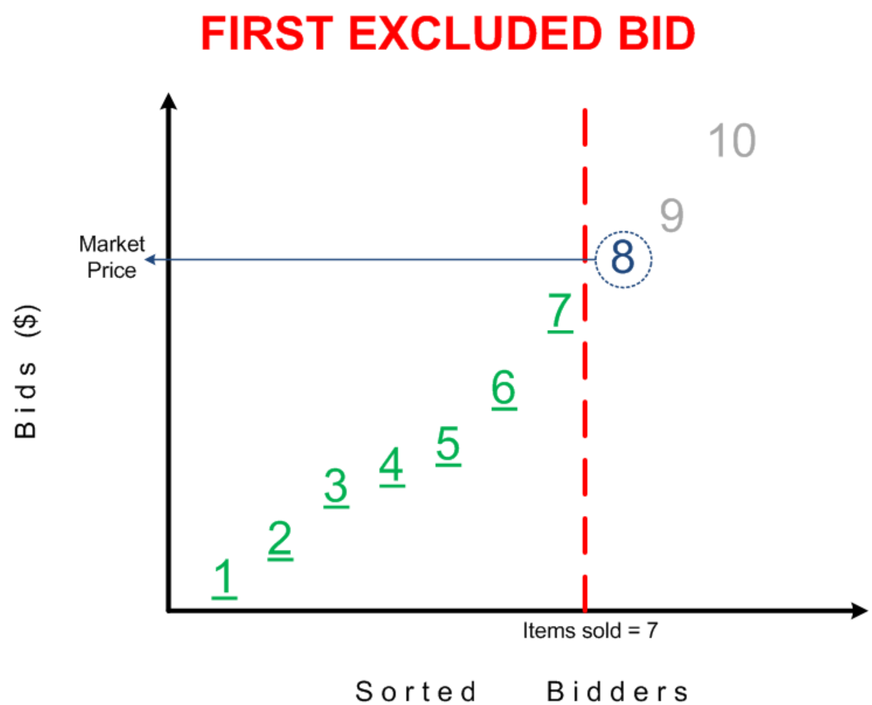
$$market\ price = \begin{cases} if > 7\ bidders: & 8^{th}\ lowest\ bid \\ if \le 7\ bidders: & 1050 \end{cases}$$

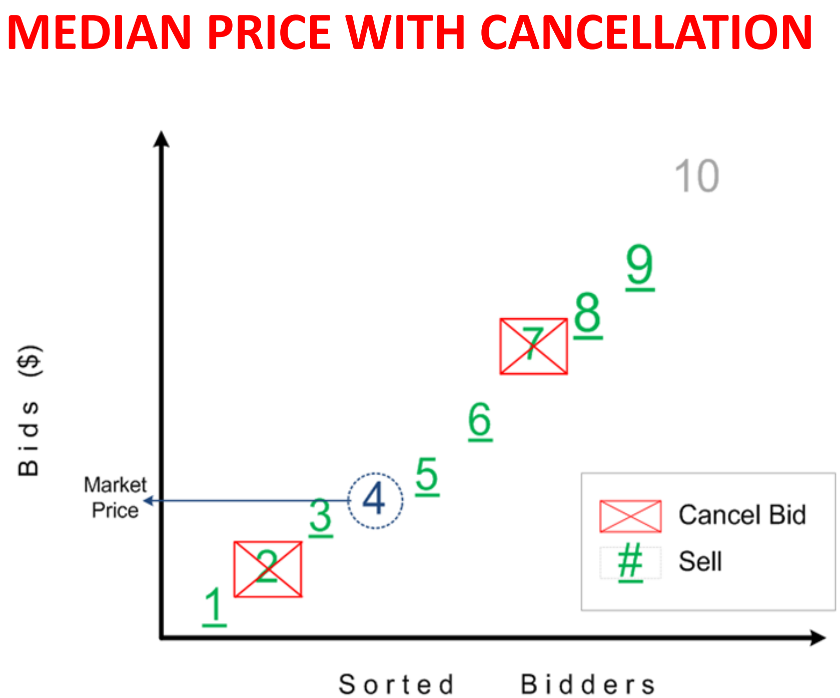
<u>CMS with an Entry Fee</u>:
In this auction, you are going to participate in **a median price auction with cancellation** in which you will be a SELLER of a commodity. **To bid in this auction, you must pay an entry fee of 50 ECUs.** After all bidders submit bids, the median of the lowest 7 bids will be calculated and **set *irrevocably*** as the market price. If there are fewer than 7 bidders, then the market price is **set irrevocably** at the median among all submitted bids (if there are an even number of bidders, the price is the higher of the two middle bids).

$$market\ price = \begin{cases} if \ge 7\ bidders: & median\ of\ 7\ lowest\ bids \\ if < 7\ bidders: & median\ of\ bids \end{cases}$$

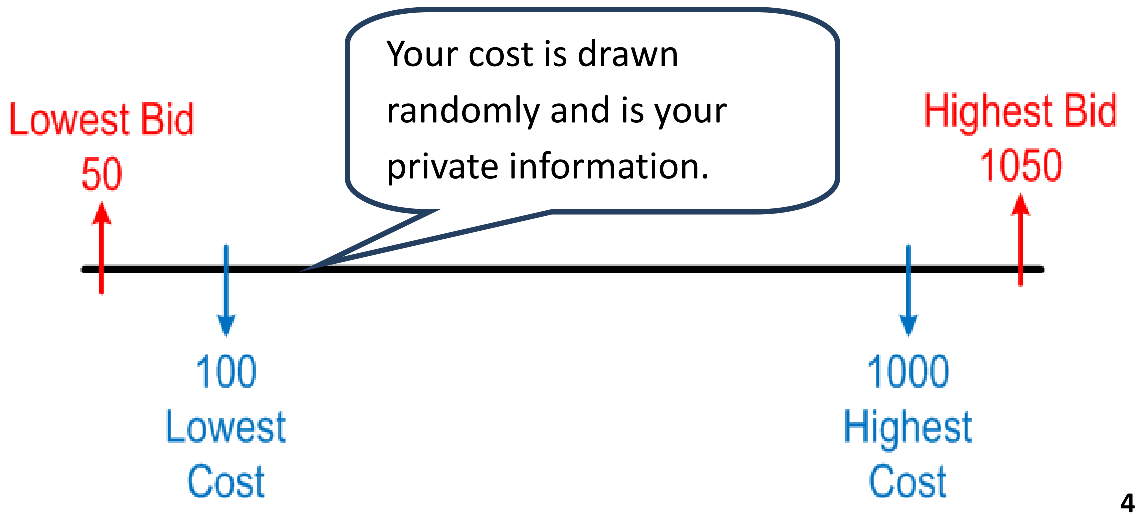
Appendix B: Graphics

The following were used as visual aids when explaining the instructions in the experiments. Images at Caltech were hand-drawn on the white board, while those at the University of Maryland were produced by Peter Cramton and are shown below:





Possible Costs and Admissible Bids



Appendix C:

The Equilibrium of an Excluded-Bid Procurement Auction with an Entry Fee and Reservation Price

The additions of an entry fee and a reservation price have an impact on the Nash equilibrium of a first-excluded price procurement auction. Participation is voluntary but those who bid must pay a fee. Hence, the number of bidders is variable. If fewer suppliers enter than units demanded, a reservation price is paid to all those that enter. The following is common knowledge:

- The number of bidders $n = 16$
- The entry fee $f = 50$
- The number of units demanded $k = 7$
- reservation price $r = 1050$
- The distribution of costs: Costs are integers drawn independently from a uniform distribution with support $[\underline{c}, \overline{c}] = [100{,}1000]$. Costs are known to suppliers before they decide to bid or opt out and suppliers bid if and only if they pay the entry fee.

What follows is a proof that a symmetric Nash equilibrium exists for truthful bidders (i.e. they bid their cost) in the form of a "cutoff cost" c^* such that a suppliers bid if and only if their costs fall below the cutoff cost. This cutoff cost will be computed so the assumption of its existence is justified. Further, we assume that a supplier with an expected profit, given their cost, of zero does not bid. By these assumptions, suppliers bid only when they believe that their expected profit upon entry, given their cost, is positive and the expected profit given a cost equal to the cutoff cost is zero:

$$Enter\ if\ E(Profit \mid cost) > 0 \qquad (1)$$

$$E(Profit \mid cost = Cutoff) = 0 \tag{2}$$

The expected profit can be calculated by computing three terms: (a) if the number of suppliers that enter is less than or equal to the number of units demanded, then all winners are paid the reservation price; (b) if more suppliers enter than units demanded, then all winners (the k lowest bids) are paid the value of the first excluded bid; (c) if more suppliers enter than units demanded then, those with bids above the k^{th} lowest bid do not sell and receive zero. All suppliers who enter pay and thus incur the fee, including those who do not sell a unit. Using the notation $\Pr(\cdot)$ to indicate probability of a price:

$$E(Profit \mid cost) = -f + (r - cost)\Pr(r) + \sum_{p=cost}^{\bar{c}} (p - cost)\Pr(p) + \sum_{p=\underline{c}}^{cost} (0)\Pr(p) \tag{3}$$

Note that the last term in (3) is equal to zero. For symmetric agents that do not bid above the cutoff cost, the probability of the price being above the cutoff cost but not equivalent to the reservation price is zero. That is, $\Pr(p) = 0$ over the range $[c^*, \bar{c}]$ for cost c^*. Using this property, and recalling that $Pr(r)$ is the probability that the number of bidders is less than or equal to the number of units demanded, equation (3) simplifies to equation (4):

$$E(Profit \mid cost = c^*) = -f + (r - cost)\Pr(r) = 0 \tag{4}$$

$$where \Pr(r) = \sum_{m=0}^{k-1} \binom{n-1}{m} \left(\frac{c^* - \underline{c}}{\bar{c} - \underline{c}}\right)^m \left(\frac{\bar{c} - c^*}{\bar{c} - \underline{c}}\right)^{n-m-1} \tag{5}$$

Substituting in our values for $n, k, f, r, \overline{c},$ and $\underline{c}$, we can determine $c^* \approx 626.117$.

The probability in (5) that the reservation price is paid to a participant that enters is not dependent on their cost; rather, it is dependent only on the number of participants, the number of units demanded, the distribution of costs, and the cutoff cost. Stated explicitly, (5) is the probability that between 0 and $k-1$ suppliers (out of $n-1$ total suppliers) have costs below c^* and the remaining suppliers have costs above c^*. The binomial coefficient accounts for all the different combinations of participants.

Consequently, we can calculate the probability that fewer than k units are procured (by determining the probability that fewer than k suppliers have costs below c^*), the probability that reservation price will be paid to participants (by determining the probability that k or fewer suppliers have costs below c^*), the expected number of units procured (by weighting the probability that m units are procured by the number of units procured), and the expected price (by weighting the probability that m units are procured by the expected price for m submitted bids):

$$\Pr(\#\ Procured < k) = \sum_{m=0}^{k-1} \binom{n}{m} \left(\frac{c^* - \underline{c}}{\bar{c} - \underline{c}}\right)^m \left(\frac{\bar{c} - c^*}{\bar{c} - \underline{c}}\right)^{n-m} \tag{6}$$

$$\Pr(r) = \sum_{m=0}^{k} \binom{n}{m} \left(\frac{c^* - \underline{c}}{\bar{c} - \underline{c}}\right)^m \left(\frac{\bar{c} - c^*}{\bar{c} - \underline{c}}\right)^{n-m} \tag{7}$$

$$\mathrm{E}(\#Units\ Procured) = (7)\Pr(\#Procured \geq k) + \sum_{m=0}^{k-1} (m) \binom{n}{m} \left(\frac{c^* - \underline{c}}{\bar{c} - \underline{c}}\right)^m \left(\frac{\bar{c} - c^*}{\bar{c} - \underline{c}}\right)^{n-m} \tag{8}$$

$$\mathrm{E}(Price) = \sum_{m=0}^{k} (1050)\Pr(\#\ Procured = m) + \sum_{m=k+1}^{n} \left(\left(c^* - \underline{c}\right)\Pr(\#\ Procured = m) + \underline{c}\right) \tag{9}$$

Substituting in our values for $n, k, \overline{c}, \underline{c}$, and c^*, we can determine $\Pr(\#\ Procured < k) = 7.5\%$, $\Pr(r) = 17.3\%$, $\mathrm{E}(\#Units\ Procured) = 6.89$, and $E(Price) = 587.551$.