Designing an Auction Protocol under Asymmetric Information on Nature's Selection

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ABSTRACT

Internet auctions are becoming an especially popular part of Electronic Commerce and auction protocols have been studied very widely in the field of multi-agent systems and AI. However, correctly judging the quality of auctioned goods is often difficult for non-experts (amateurs), in particular, on the Internet auctions. In this paper, we formalize such a situation so that *Nature* selects the quality of the auctioned good. Experts can observe Nature's selection (i.e., the quality of the good) correctly, while amateurs including the auctioneer cannot. In other words, the information on Nature's selection is asymmetric between experts and amateurs. In this situation, it is difficult to attain an efficient allocation, since experts have a clear advantage over amateurs and they would not reveal their valuable information without some reward. Thus, in this paper, we develop a new auction protocol in which truth-telling is a dominant strategy for each expert. This can be done by putting these experts in a situation similar to Prisoner's Dilemma. If they cooperate and tell lies, they can exclude amateurs, but betraying is a dominant strategy. By making experts to elicit their information on the quality of the good, the protocol can achieve a socially desirable, i.e., Pareto efficient allocation if certain assumptions are satisfied.

Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—*multiagent systems*; K.4.4 [**Computers and Society**]: Electronic Commerce

General Terms

Auctions, Economics, Multiagent Systems

Keywords

Auctions, Mechanism Design, Multiagent Systems

1. INTRODUCTION

Auctions have been studied very widely in the field of multi-agent systems for several reasons. First, agent-mediated electronic marketplaces [2] (e.g., eMediator[9], AuctionBot[10], and GroupBuyAuction[11]) employ auction mechanisms to realize an efficient trading mechanism among agents. Second, auction mechanisms can provide efficient task/resource allocation mechanisms in multi-agent systems[1, 3]. Third, Internet auctions such as eBay.com and Yahoo.com in the real world are becoming an especially popular part of the Internet economy.

For non-experts (amateurs), it is often difficult to correctly judge the quality of auctioned goods. In particular, on the Internet auctions, there exist many unspecified persons who are selling their goods. If we misjudge the quality of a good and purchase a poor quality item at a high price, we suffer loss by the trade. We can avoid such a situation if the auctioneer can judge the quality correctly, but this is not always the case or it might require too high cost for the auctioneer.

The situation described above can be modeled by using the notions of Nature's selection and asymmetric information in game theory. We assume Nature selects the quality of an auctioned good. Experts can observe the result of Nature's selection, while amateurs including the auctioneer cannot. In other words, the information on Nature's selection is asymmetric between experts and amateurs.

For example, in art auctions, in which a painting is auctioned, the painting can be real or an imitation. We assume Nature selects the quality of the good, i.e., real or imitation. Nature is a pseudo-player who selects random action in the auction with specified probabilities [8]. There are two types of bidders, experts and amateurs. While experts can tell whether the good on sale is real or imitation, amateurs cannot. Clearly, the value of the painting depends on whether it is real or not.

It would be beneficial for an amateur if the protocol allowed a conditional bid, e.g., "If the painting is real, then I'll pay at most $6,000. If it is an imitation, I'm not willing to pay more than $40." On the other hand, if the bidder is sure about the quality of the good, i.e., he is an expert, he can submit an unconditional bid, e.g., "I'm sure that the painting is real and am willing to pay at most $5,000." If the protocol can correctly determine the quality of the good based on these declarations, an amateur can purchase the good without the risk of incurring a loss, even if he is not sure about the quality.

The difficulty in developing such a protocol is that experts have a clear advantage over amateurs and they would not reveal their valuable information without some reward. We cannot simply apply the Clarke mechanism (a.k.a. Vickrey-Clarke-Groves mechanism) [5] since the auctioneer does not know the quality of the good and cannot determine the social surplus, i.e., the highest (or the second highest) evaluation values.

It might be possible to pay some reward or side-payment to make the experts reveal their information on Nature's selection. However, the payment must be large enough so that each expert has an incentive for telling the truth. However, if the payment becomes large, an amateur might have an incentive for pretending to be an expert to obtain the reward.

In this paper, we propose a new direct revelation protocol, in which for each expert, truth-telling is a dominant, i.e., optimal strategy regardless of the actions of other agents. In the art auction of a painting, our new protocol can be described as follows.

If two or more experts say that the painting is real, the auctioneer assumes the painting is real and applies the Clarke mechanism, i.e., the agent who declares the highest evaluation value assuming the painting is real wins and pays the value of the second highest bid. Also, if no expert says the painting is real, the auctioneer assumes the painting is an imitation and applies the same procedure using the values for an imitation. An exceptional case is when there is only one expert who says the painting is real. In this case, the protocol sells the good to that expert, if his declared value is larger than the other agents' evaluation values for an imitation.

An interesting point of this protocol is that the experts are in a situation similar to Prisoner's Dilemma. Let us assume the painting is real. If they cooperate and tell lies, i.e., the painting is an imitation, they can exclude amateurs from the auction, but betraying, i.e., declaring the painting is real, is a dominant strategy for an expert. More specifically, assuming there are only two experts, 1 and 2. When expert 2 cooperates, i.e., declares that the painting is an imitation, expert 1 would be better off betraying, since the exceptional case would then be applied and expert 1 could buy the painting without paying the price for a real good. When expert 2 betrays, then expert 1 has no chance to win the good if he declares the painting is an imitation, thus he would be better off betraying. In either case, expert 1 would be better off betraying. By making experts to elicit their information on the quality of the good, the protocol can achieve a socially desirable, i.e., Pareto efficient allocation if certain assumptions are satisfied.

The rest of the paper is organized as follows. We first describe the model of a domain under asymmetric information on Nature's selections and present the difficulty of applying the Clarke mechanism to this problem. Next, we explain an auction mechanism in a simple case under our domain in order to clearly present our concept. Then, we propose a generalized auction mechanism under asymmetric information on Nature's selections. Finally, we discuss how in our mechanism experts are confronted with the Prisoner's Dilemma, and compare our mechanism with other related work.

2. PRELIMINARIES

Below, we define the basic terms used in this paper.

Participants. We assume two types of participants, *experts* and *amateurs*. The expert is the player who has *correct* information on Nature's selection. The amateur is the player who does not have an idea on Nature's selection. Also, we define *irrational players*. Irrational players may not select a dominant strategy when it exists.

Private Value Auctions. In this paper, we concentrate on private value auctions[5]. Note that *private value* in this paper has a slightly different meaning from that in traditional definition. In traditional definitions[5], in private value auctions, each agent knows its own evaluation values of a good, which are independent of the other agents' evaluation values. Agent i's utility u_i is defined as the difference between the true evaluation value b_i of the allocated good and the payment to the seller t_i for the allocated good. Namely, $u_i = b_i - t_i$. Such a utility is called a *quasi-linear* utility.

In this paper, if an agent cannot observe Nature's selection (i.e., an amateur), there is a dependency between his utility and other agents' evaluation values. If an agent can observe Nature's selection (i.e., an expert), his utility is independent of the other agents' evaluation values and has no uncertainty. Further, once an amateur learns Nature's selection, his utility is independent of the other agents' evaluation values and has no uncertainty. Formally, agent i's utility u_i is defined as the difference between the true evaluation value $b_{i,q}$ of the allocated good for the determined Nature's selection q and the payment to the seller t_i for the allocated good. Namely, $u_i = b_{i,q} - t_i$.

Pareto Efficiency. We say an auction protocol is Pareto efficient when the sum of all participants' utilities (including that of the auctioneer), i.e., the social surplus, is maximized in a dominant strategy equilibrium. In a more general setting, Pareto efficiency does not necessarily mean maximizing the social surplus. In an auction setting, however, agents can transfer money among themselves and the utility of each agent is quasi-linear; thus the sum of the utilities is always maximized in a *Pareto efficient* allocation. If the number of goods is one, in a Pareto efficient allocation, the good is awarded to a bidder having the highest evaluation value corresponding to the quality of the good.

Best Response. Player i's best response to the strategies chosen by the other players is the strategy that yields him the greatest utility[8].

Dominant Strategy. The strategy s is a *dominant strategy* if it is a player's strictly best response to any strategies the other players might pick, in the sense that whatever strategies they pick, his payoff is highest with s. In addition, strategy s' is *weakly dominated* if there exists some other strategy s'' for player i which is possibly better and never worse, i.e., yielding a higher payoff in some strategy and never yielding a lower payoff[8].

3. DOMAIN DEFINITIONS UNDER ASYMMETRIC INFORMATION ON NATURE'S SELECTIONS

In this section, we define the domain model under asymmetric information on Nature's selections. In the following, we define several terms and notations.

- A set of agents is represented by $I = \{1, \ldots, n\}$.
- A set of Nature's selection is represented by $Q = \{q_1, q_2, \ldots, q_m\}$.
- The number of goods auctioned is one. Namely, the proposed auction is a single-unit auction.
- Agent i's utility is represented by $u_i = b_{i,q} - t_i$. $b_{i,q}$ is agent i's evaluation value of the good for Nature's selection q. t_i is agent i's payment. This type of utility is called a *quasi-linear* utility. If an agent cannot obtain a good, we assume its utility is 0.
- The evaluation value of the good depends on Nature's selection.
- Player i's type θ_i is represented by a vector $\theta_i = (b_{i,q_1}, b_{i,q_2}, b_{i,q_3}, \ldots, b_{i,q_m})$.
- A set of experts is represented by $E \subset I$. Experts can observe Nature's selection. We suppose $\mid E \mid \geq 1$.
- A set of amateurs is represented by $N \subset I$. $I - N = E$. Amateurs cannot observe Nature's selection.
- The mechanism designer cannot observe Nature's selection and cannot differentiate between experts and amateurs.

We design an auction protocol under the following assumption.

Assumption 1. *For all i, q, q', where $q < q'$, $b_{i,q} \leq b_{i,q'}$.*

This assumption means that it is not worse for agents if Nature's selection is higher. In other words, all agents value the possible outcomes of Nature's selection in the same order. For example, for a player, the evaluation value for a real painting is higher than the evaluation value for an imitation. Although this assumption is very realistic, there is a difficulty in realizing an auction mechanism in which the experts' dominant strategy is telling the truth. This assumption allows overlap between evaluation values at two or more different Nature's selections

However, if there is an overlap between evaluation values at two or more different Nature's selection, there is a problem. Table 1 shows an example in which there are overlaps of evaluation values between different Nature's selections. θ_2's evaluation value for an imitation, \$500, is higher than θ_1's evaluation value for a real item, \$400.

We assume that an expert declares a pair composed of the observed Nature's selection and his private evaluation value of the good. An amateur declares only his private evaluation value of the good. Also, let us assume the mechanism first judges Nature's selection. Then, the mechanism uses the second price scheme (Vickrey auction) within evaluation values in the judged Nature's selection. Namely, if the mechanism judges that Nature's selection is an imitation, the winner is the bidder who submitted the highest bid in that Nature's selection and the payment is the second highest bid for that Nature's selection.

Table 1: Example of Overlapped Evaluation Values

	q_I: imitation	q_R: real
θ_1	\$300	\$400
θ_2	\$500	\$650
θ_3	\$700	\$800

There are three players whose types are θ_1, θ_2, and θ_3. Suppose that there is an amateur whose type is θ_1 and experts whose types are θ_2 and θ_3. Suppose that expert θ_2 submits the bid (θ_2, q_R), \$650, i.e., declares that the good is real. Suppose that expert θ_3 submits the bid (θ_3, q_I), \$700, i.e., declares that the good is an imitation. Since the amateur cannot observe Nature's selection, his payment depends on the true Nature's selection. If the mechanism believes expert θ_2's judgement that Nature's selection is real and sells the good at \$400 (the second highest bid in *real* within \$400 and \$650), expert θ_2 can benefit if the good is an imitation. While expert θ_2's evaluation for an imitation is \$500, he can purchase the good at \$400. If the mechanism believes expert θ_3's judgement that Nature's selection is an imitation and sells the good at \$300 (the second highest bid in real within \$300 and \$700), he can benefit if the good is real. While expert θ_3's evaluation for real is \$800, he can purchase the good at \$300.

To solve the above problem, in the next section, we present an auction mechanism under asymmetric information on Nature's selections. In this mechanism, we successively make experts declare the true Nature's selection and the true evaluation value for a good.

The Clarke mechanism (a.k.a. Vickrey-Clarke-Groves mechanism)[5] is a well-known mechanism in which truth-telling is the dominant strategy for each player and the obtained allocation is Pareto efficient.

However, we cannot employ the Clarke mechanism in our problem settings. In the Clarke mechanism, the allocation that maximizes the social surplus is chosen, and each agent i pays the decreased amount of the social surplus for other agents caused by the participation of agent i. Since the auctioneer does not know Nature's selection, he cannot know the social surplus of possible allocations.

We can modify the Clarke mechanism so that the auctioneer simply assumes that the largest declared Nature's selection is true. In the case of Table 1, suppose that there is an amateur whose type is θ_3 and experts whose types are θ_1 and θ_2. Suppose that expert θ_1 submits the bid (θ_1, q_I), \$300, i.e., declares that the good is an imitation. Suppose that expert θ_2 submits the bid (θ_2, q_R), \$650, i.e., declares that the good is real. Suppose that amateur θ_3 submits a conditional bid. The auctioneer assumes the good is real, i.e., the maximum Nature's selection, and chooses the allocation that maximizes the social surplus, i.e., allocating the good to θ_3. The payment of θ_3 is \$650, i.e., the second highest value. This result looks fine. However, we are faced with a difficulty when calculating the payment/reward of θ_2. If θ_2 did not participate, the auctioneer would assume that

Nature's selection is imitation and allocate the good to θ_3, and the social surplus would be considered to be \$700. If we assume θ_2 increases the social surplus to \$800, i.e., the evaluation value of θ_3 for a real good, by its participation, we need to pay compensation money, say \$100, to θ_2.

However, paying such compensation money causes more difficulties. First, the amount of compensation money can be larger than the payment, thus the auctioneer might lose money. Second, by paying compensation money, the mechanism gives an agent an incentive for over-declaring Nature's selection and obtaining compensation. For example, if the good is an imitation and θ_2 tells the truth, it can obtain nothing and its utility is 0, but if θ_2 says the good is real, it can obtain the compensation. Thus, in this modification of the Clarke mechanism, truth telling is not a dominant strategy.

4. DESIGNING THE AUCTION PROTOCOL

4.1 Protocol: two levels of Nature's selection

In this section, we present an auction protocol in which truth telling is a dominant strategy. First, in order to clearly show our concept, we present a protocol in the simple example of an art auction. Then, in the next section, we generalize the protocol.

In art auctions, the quality of the good is Nature's selection. Let us assume two qualities, q_R (i.e., real) and q_I (i.e., imitation). Namely, there exist two levels of Nature's selection. The sets of the evaluation values for q_R and q_I submitted by experts are represented by $B_{E,R}$ and $B_{E,I}$, respectively. The sets of the evaluation values for q_R and q_I submitted by amateurs are represented by $B_{N,R}$ and $B_{N,I}$, respectively. The upper limit for Nature's selection q_I is represented by α_{q_I}. Evaluation values in q_I cannot exceed the upper limits α_{q_I}. We assume the upper limit is given. We classify the procedure into the following three cases:

- case 1: If nobody declares q_R (i.e. real), the mechanism determines that the quality of the good is q_I. The winner is the bidder i who submits the maximum evaluation value within $B_{E,I}$ and $B_{N,I}$. If i wins, i's payment is the second highest evaluation value within $B_{E,I}$ and $B_{N,I}$.
- case 2: If the number of agents who declare q_R (i.e. real) is one, the mechanism does not determine the quality of the good. If b_{i,q_R}, the evaluation value of the expert i who declares q_R, is higher than the maximum evaluation value within $B_{E,I}$ and $B_{N,I}$, the winner is i. The payment is the maximum evaluation value within $B_{E,I}$ and $B_{N,I}$. If not, the mechanism does not trade anything.
- case 3: If two or more experts declare q_R (i.e. real), the mechanism determines that the quality of the good is q_R. The winner is the bidder i who submits the maximum evaluation value in $B_{E,R}$, $B_{N,R}$, and α_{q_I}. If α_{q_I} is the maximum value, the mechanism does not trade anything[1]. If i wins, the payment is the second highest evaluation value within $B_{E,R}$, $B_{N,R}$, and α_{q_I}.

[1]The case in which α_{q_I} is the maximum value is an extremely rare case. This case happens when an auctioneer fails to set an appropriate upper value, e.g., extremely high value and for every participants there is no evaluation value that is larger than α_{q_I}. However, in this case, the mechanism cannot satisfy Pareto efficiency.

4.2 Examples

The following examples of art auctions clarify our concepts. For simplicity, we assume that there are two types of possible Nature's selection, real or imitation. Also, we assume that there are three kinds of participant types, as shown in Table 2. α means the upper limit for Nature's selection. In Example 1 and Example 2, α can be ignored.

Table 2: Example of Simple Cases

	q_I : imitation	q_R : real
θ_1	\$30	\$11,000
θ_2	\$40	\$12,000
θ_3	\$50	\$15,000
α	\$100	

Example 1. There are two amateurs whose types are θ_1 and θ_2. Also, there is an expert whose type is θ_3. In this case, the amateurs submit the bids $(\theta_1, 0)$ and $(\theta_2, 0)$. The second argument, 0, in each pair declares that they are amateurs. If the expert declares this good is real, he submits (θ_3, q_R). In this case, since there is only one expert, we employ case 2. Then, this expert wins this auction, and his payment is \$40.

Example 2. There is an amateur whose type is θ_1. Also, there are two experts whose types are θ_2 and θ_3. In this case, the amateur submits the bid $(\theta_1, 0)$. If both of the experts declare this good is real, they submit the bids (θ_2, q_R) and (θ_3, q_R). Since there are two experts, we employ case 3. Then, the expert whose type is (θ_3, q_R) wins the good, and his payment is \$12,000.

Table 3 shows the information from Table 1 with upper limits. For each Nature's selection, we provide upper limits. The upper limits are given before an auction starts. By using the upper limits we can make experts tell the truth.

Table 3: Example of Overlapped Evaluation Values with Upper Limits

	q_I : imitation	q_R : real
θ_1	\$300	\$450
θ_2	\$500	\$850
θ_3	\$800	\$1000
α	\$800	

Example 3. Let us assume this good is an imitation. The experts whose types are θ_1 and θ_2 declare that this good is real. They submit the bids (θ_1, q_R), \$450 and (θ_2, q_R), \$850. The expert whose type is θ_3 declares that this good is an imitation. He submits the bid (θ_3, q_I), \$800. Namely, this expert tells the truth.

When we employ the protocol with the upper limit, case 3 is applied since there are two experts who declare the good is real. In case 3, the winner is the bidder who declares the maximum bid in $B_{E,R}$, $B_{N,R}$, and α. In this example, the expert who declares (θ_2, q_R),\$850 is the winner. The payment is the second highest value, \$800, among $B_{E,R}$, $B_{N,R}$, and α.

In the following, we demonstrate that there is the problem when we employ the same protocol without the upper limit. Namely, In case 3, the winner is the bidder who declares the maximum bid in $B_{E,R}$ and $B_{N,R}$. The payment is the second highest value among $B_{E,R}$ and $B_{N,R}$. In this case, the winner is θ_2 and the payment is 450. If θ_2 declares the truth, case 2 is applied. In case 2, θ_2 has no chance to win the good. As same as the example, if θ_2 declares a falsehood, the payment is 450. The problem is that, in this case, since θ_2's evaluation value for an imitation is 500, he profits $50(= 500 - 450)$. Thus, θ_2 profits from declaring a falsehood.

To solve the above problem, we employ the upper limit $\alpha = 800$. By using the upper limit, even if θ_2s tell a falsehood, he can not make a profit.

4.3 Dominant Strategy for Experts

In this section, we demonstrate that for experts truth telling is a dominant strategy in our protocol.

THEOREM 1. *In our mechanism, truth telling is a (weakly) dominant strategy for the experts.*

PROOF (OUTLINE). In the proof, we confirm that false bids must not result in positive utility for expert i or must result in a payment that equals the payment that he makes at the true value. The details of the proof are shown in Appendix A. □

4.4 Best Response for Amateurs

ASSUMPTION 2. *There exist two or more (in the generalized case, there exist k, where k is a given threshold, or more) experts and they correctly select a dominant strategy. In addition, there exist one or less (in the generalized case, there exist $k-1$ or less) irrational players.*

THEOREM 2. *Under assumption 2, for amateurs, truth telling is the best response.*

PROOF (OUTLINE). Under assumption 2, we prove that for amateur i, telling the truth is best response. Under assumption 2, amateurs have the following two strategies, **telling the truth**, i.e., declaring they are amateurs, or **telling a falsehood**, i.e., declaring they are experts.

First, when the amateur declares truth, obviously there is no benefit even if he declares false evaluation values. Next, in the following, we prove that even if the amateur tells a falsehood, there is no benefit for him. (1)We prove that if case 1 or case 3 is satisfied without amateur i, his utility is not positive if he declares, as an expert, a larger Nature's selection than the true Nature's selection. (2)We prove that if case 2 is satisfied without amateur i, there is no benefit for him. In this case, there is obviously another amateur who declares he is an expert.

We show the details of the proof in the generalized case in Appendix B. □

THEOREM 3. *Under assumption 2, our mechanism is Pareto efficient.*

PROOF (PROOF OF THEOREM 3). Under assumption 2, the condition in case 2 cannot be satisfied. Thus, we consider only case 1 and case 3. In case 1 and case 3, since the good is awarded to the player who has the maximum evaluation value, our mechanism realizes a Pareto efficient allocation. □

4.5 Robustness against Irrational Players

In this section, we present robustness against irrational players. First, we define irrational players.

THEOREM 4. *Under assumption 2, even if there exist irrational players, if their number is 1 (in the generalized case smaller than the threshold), the utilities of rational players are not negative.*

PROOF (OUTLINE). We demonstrate that when rational players can win the good, the payment is determined based on the correct Nature's selection. When they cannot win the good, the utility is 0 and is not negative. Thus, we prove that if there exists one irrational player, the utilities of rational players are not negative. We have omitted the details of the proof here due to the limitation of space. In Appendix C, we show the details in the generalized case. □

5. GENERALIZED PROTOCOL

5.1 Protocol: multiple levels of Nature's selection

In this section, we present a generalized protocol. q_x means that Nature's selection is x. The maximum and second Nature's selections submitted are represented by $q_{\max}$ and q_{second}, respectively. The number of experts who declare $q_{\max}$ is represented by p. The set of the evaluation values for q_x submitted by experts is represented by B_{E,q_x}. The set of the evaluation values for q_x submitted by amateurs is represented by B_{N,q_x}. The upper limit for Nature's selection q_x is represented by α_{q_x}. We assume the upper limit is given. k is a threshold value. In the basic idea, if the number of experts who declare the same Nature's selection q is larger than k, we assume that Nature's selection is q.

We classify the procedure into four cases based on the number of experts who declare $q_{\max}$. The protocol proposed in this paper is defined as follows.

case 1: If $q_{\max}$ equals to q_1, the mechanism determines that Nature's selection is q_1. The winner is the bidder i who submits the maximum evaluation value within $B_{N,q_{\max}}$ and $B_{E,q_{\max}}$. The payment is the second highest evaluation value within $B_{E,q_{\max}}$ and $B_{N,q_{\max}}$.

case 2: If $p = 1$, the mechanism does not determine Nature's selection. If $b_{e,q_{\max}}$, the evaluation value of the expert e who declares $q_{\max}$, is higher than the maximum evaluation value within $B_{E,q_{second}}$, $B_{N,q_{second}}$, and $\alpha_{q_{second-1}}$, the winner is the expert e. The payment is the maximum evaluation value within $B_{E,q_{second}}$, $B_{N,q_{second}}$, and $\alpha_{q_{second-1}}$, If not, the mechanism does not trade anything.

case 3: If $2 \leq p \leq k-1$, the mechanism does not determine Nature's selection. If $b_{e,q_{\max}}$, the evaluation value of the expert e who declares $q_{\max}$, equals the maximum evaluation value within $B_{E,q_{\max}}$, $B_{N,q_{\max}}$, and $\alpha_{q_{\max}-1}$, then the winner is the expert e. The payment is the second highest evaluation value within $B_{E,q_{\max}}$, $B_{N,q_{\max}}$, and $\alpha_{q_{\max}-1}$. If not, the mechanism does not trade anything.

case 4: If $p \geq k$, the mechanism determines that Nature's selection is $q_{\max}$. The winner is the bidder i who submits the maximum evaluation value within $B_{E,q_{\max}}$, $B_{N,q_{\max}}$, and $\alpha_{q_{\max}-1}$. The payment is the second highest evaluation value within $B_{E,q_{\max}}$, $B_{N,q_{\max}}$, and $\alpha_{q_{\max}-1}$.

5.2 Dominant Strategy for Experts

In this section, we show that, in the generalized case, for experts truth telling is a dominant strategy. Truth telling means an expert submits his true Nature's selection and its evaluation value.

THEOREM 5. *In our mechanism, truth telling is a (weakly) dominant strategy for the experts.*

PROOF (OUTLINE). In the proof, we confirm that false bids must not result in positive utility for expert i or must result in a payment that equals the payment that he makes at the true value. The main idea for this proof is the same as in proof 4.3. Since the details of the full proof are fairly long, we provide the proof at our Web site (http://www.jaist.ac.jp/~itota/AAMAS2002/). □

5.3 Best Response for Amateurs

ASSUMPTION 3. *There exist k, where k is a given threshold, or more experts, and they correctly select a dominant strategy. In addition, there exist $k-1$ or less irrational players.*

THEOREM 6. *Under assumption 3 for amateurs, truth telling is the best response.*

PROOF (OUTLINE). The outline of this proof is almost the same as proof of theorem 2 in the simple case, i.e., where $k = 2$ and there exist two levels of Nature's selection. The details of the proof in the generalized case are shown in Appendix B. □

THEOREM 7. *Under assumption 3, our mechanism is Pareto efficient.*

PROOF (PROOF OF THEOREM 7). The proof is the same as proof of theorem 3. □

5.4 Robustness against Irrational Players

In this section, we describe robustness against irrational players in the generalized case.

THEOREM 8. *Under assumption 3, even if there exist irrational players, if their number is smaller than the threshold k, the utilities of rational players are not negative.*

PROOF (OUTLINE). The outline of this proof is almost the same as proof of theorem 4 in the simple case. The details are shown in Appendix C. □

6. DISCUSSION

6.1 Prisoner's Dilemma among Experts

One of the interesting aspects of our mechanism is that experts are confronted with the Prisoner's Dilemma situation[4]. Suppose there is an art auction and the painting is real. Experts have two strategies: telling the truth, i.e., the painting is real, q_R, or telling a lie, i.e., the painting is an imitation, q_I. This corresponds to the case in which the number of levels is two and $k = 2$ (described in Section 4.1). For example, suppose there exist two experts and their evaluation value for real is \$101, (\$101,q_R). Also, suppose there exist some amateurs who evaluate real as \$60, (\$60, 0) and imitations as \$0, (\$0, 0). Table 4 shows an example of a payoff matrix for this setting.

In this example, if experts can cooperate, i.e., together declare that the painting is an imitation, they have a chance to win the painting at a lower price, i.e., higher utilities. Namely, if they cooperatively declare (\$1,q_I), i.e., tell a falsehood, then they can win the painting at the price of \$1. The expected utilities are (50,50) (we assume, here, in the case of a tie-break that they share the utility). If one of the two experts betrays, and declares (\$101, q_R), then this expert can win the good at the price \$1. Its expected utility is 100. If both of the experts betray, i.e., tell the truth, and declare (\$101, q_R), then the experts can win the good at the price \$101. The expected utilities are (0,0). In our mechanism, for each expert, telling the truth, i.e., declaring the painting is real, is a dominant strategy.

Table 4: Example of Payoff Matrix in Our Auction

		Expert 1	
		q_I : imitation	q_R : real
Expert 2	q_I : imitation	(50,50)	(0,100)
	q_R : real	(100,0)	(0,0)

6.2 Related Work

As related work, in a previous paper one of the authors investigated information revelation in ascending-bid auctions[6]. In Internet auctions, we can observe bidders engaging in the behavior called last minute bidding, namely, a large fraction of the bids for a good are submitted in the closing seconds of the auction. Thus, this causes a problem of information revelation failure, namely, bidders cannot obtain information about the target good from the other bidders' bidding behavior in open-bid auctions. This results in an inefficient allocation. To solve this problem, that paper[6] proposed a method that induces informed bidders to reveal their information about the good by paying compensation money.

Let us discuss the following differences between this work and the previous work[6]. First, in the previous work[6], the mechanism was based on an open cry auction and an indirect revelation mechanism. Also, the mechanism pays compensation money to experts. Our mechanism is a direct revelation mechanism and does not have to pay compensation money. This is an advantage of the newly developed mechanism. Second, while the previous work assumes a rather simple situation, this paper assumes a fairly complicated situation in our mechanism. More specifically, the previous work assumes that there are only two levels of Nature's selection, high-quality and low-quality, and that there is no overlaps in players' evaluation values between different Nature's selections. On the other hand, in this mechanism, we assume an arbitrary number of levels of Nature's selections and allow overlap in the players' evaluation values between different Nature's selections. Third, the previous work defined player's utility with a special assumption. In this work, we allow a player's utility to have a quasi-linear form. A quasi-linear form is a very common assumption and widely used in much literature.

In general, in order to handle a situation under asymmetric information on Nature's selections, it is a common and widely used method to have the auctioneer or the seller guarantee the quality of the good. In the general affiliated value model[7], it is strategically dominant for the auctioneer or the seller to tell the truth about the quality of the good. Namely, if the good is a high-quality good, the auctioneer or the seller announces this. Conversely, if the good is a low-quality good, the auctioneer or the seller announces this without hiding any bad information. The result can be a higher expected revenue for the seller. However, forming contracts to guarantee the quality is troublesome because agreements need to be made on how to measure quality. Moreover, in an auction among consumers, the seller, as well as the buyers, is not always an expert on the quality of the good. Therefore, this solution is not always feasible.

7. CONCLUSIONS

In this paper, we proposed an auction mechanism under asymmetric information on Nature's selections. The main issue is how the mechanism makes experts reveal their information on Nature's selection to attain an efficient allocation of the good. In order to design an information revelation mechanism, the Clarke mechanism has been widely used in much literature. However, we cannot simply employ the Clarke mechanism since, in this setting, even the auctioneer cannot decide Nature's selection. Therefore, in this paper, we proposed an auction protocol under asymmetric information on Nature's selections. The following advantages of the mechanism were found. First, in our mechanism, for experts, truth telling is a dominant strategy. Second, under the assumption that the number of experts is larger than (or equal to) a given threshold and the number of irrational players who declare false Nature's selections are less than the threshold, truth telling is best response. Third, our mechanism can realize Pareto efficient allocation. Fourth, even if there exist irrational players, if the number of irrational players is less than the threshold, rational players do not suffer loss.

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APPENDIX

A. DOMINANT STRATEGY FOR EXPERTS

We confirm that false bids must not result in positive utility for expert i or must result in a payment that equals the payment that he makes at the true value. q_i represents Nature's selection observed by expert i. $q_{m'}$ represents the maximum Nature's selection submitted without i. q'_i represents expert i's false Nature's selection. For the following cases, we prove that if i declares q'_i, there is no benefit for i.

1. When $q_i < q_{m'}$, q_i equals to q_I. $q_{m'}$ equals to q_R. If i declares the **truth**, this is case 2 or case 3, and he does not have the chance to win the good. If i declares a **falsehood**, $q'_i = q_{m'}$ and i wins, this is case 3. The payment t_i is the maximum evaluation value within $B_{E,R}$, $B_{N,R}$, and α_{q_I}. Since $\alpha_{q_I} \geq b_{i,q_I}$, $t_i > b_{i,q_I}$. Namely, i's utility $u_i = b_{i,q_I} - t_i \leq 0$. Thus, if i declares a false bid, i cannot get positive utility.

2. When $q_i = q_{m'}$, **in the case of** $q_i = q_{m'} = q_R$**,** if i declares the **truth**, since the number of bidders who declare $q_{m'}$ is more than two, case 3 is applied. The payment is the maximum evaluation value within $B_{E,R}$, $B_{N,R}$, and α_{q_I}. Obviously, there is no benefit from declaring false evaluation values. If i declares a **falsehood**, if $q'_i = q_I < q_{m'} = q_R$, case 2 or case 3 is applied. Since i does not declare the maximum Nature's selection $q_{m'}$, i has no chance to win the good. Thus, there is no benefit from declaring a false bid.

   In the case of $q_i = q_{m'} = q_I$**,** if i declares the **truth** and i wins, the payment is the maximum evaluation value within $B_{E,I}$ and $B_{N,I}$. Obviously, there is no benefit from declaring false evaluation values. If i declares a **falsehood**, i.e., if $q_i' = q_R > q_{m'} = q_I$, case 2 is applied. The payment is the maximum evaluation value within $B_{E,I}$ and $B_{N,I}$. This is the same as or larger than the payment when i tells the truth. Thus, there is no benefit from declaring a false bid.

3. When $q_i > q_{m'}$, q_i equals to q_R. $q_{m'}$ equals to q_I. If i declares the **truth**, this is case 2. If i wins, the payment is the maximum evaluation value within $B_{E,I}$ and $B_{N,I}$. If i declares a **falsehood**, this is case 1. If i wins, the payment is the maximum evaluation value within $B_{E,I}$ and $B_{N,I}$. This is the same as or larger than the payment if i tells truth. Thus, there is no benefit from declaring a false bid.

B. BEST RESPONSE FOR AMATEURS

Suppose that the number of experts is larger than k, and experts take a dominant strategy. Also, there exist $k-1$ or less irrational players. Under this assumption, we prove that for amateur j, telling the truth is the best response. Here, j has two strategies, declaring that he is an amateur or declaring that he is an expert.

When j truthfully declares that he is an amateur. Obviously there is no benefit even if he declares a larger/smaller false evaluation. Since this is case 4, j can win if the following is satisfied. $b_{j,q_{m'}} = \max\{B_{E,q_{m'}}, B_{N,q_{m'}}, \alpha_{q_{m'-1}}, b_{j,q_{m'}}\}$. The payment is $t_j = \max\{B_{E,q_{m'}}, B_{N,q_{m'}}, \alpha_{q_{m'-1}}\}$ (1).

When j declares he is an expert

- When case 1 or case 4 is satisfied without j the payments are the same even if j declares a larger Nature's selection than the true Nature's selection.

  When case 1 is satisfied without j, when j can win, the payment is the same as payment (1).

  When case 4 is satisfied without j,

  1. When j declares $q_{i'} = q_{m'}$, the number of bidders who declare $q_{m'}$ equals $k+1$, and case 4 is applied. The payment if j wins is the same as payment (1).
  2. When j declares $q_{i'} > q_{m'}$, case 2 is applied. The payment if j wins is the same as payment (1).

- When case 2 or case 3 is satisfied without j, another amateur obviously declares that he is an expert, i.e., tells a lie. We show that there is no benefit for j.

  When case 2 is satisfied without j,

  1. When j declares $q_{i'} = q_{m'}$, the number of bidders who declare $q_{m'}$ is two. If $k > 2$, then case 3 is applied. If k_2, then case 4 is applied. For each case, the payment if j wins is the same as payment (1).
  2. When j declares $q_{i'} > q_{m'}$, only j declares $q_{\max}$, and case 2 is applied. In the above, we show that when case 2 is applied, the payment if j wins is the same as payment (1).

  When case 3 is satisfied without j,

  1. When j declares $q_{i'} = q_{m'}$, the number of bidders who declare $q_{m'}$ equals k, and case 4 is applied. The payment if j wins is the same as payment (1) when j declares the truth.
  2. When j declares $q_{i'} > q_{m'}$, only j declares $q_{\max}$, and case 2 is applied. In the above, we show that when case 2 is applied, the payment if j wins is the same as payment (1).

C. ROBUSTNESS AGAINST IRRATIONAL PLAYERS

Let us assume $q_{\max}$ is the true Nature's selection. $q_{m'}$ represents the maximum Nature's selection among declared Nature's selections. Since experts take a dominant strategy, they inevitably declare $q_{\max}$,

When $q_{m'} > q_{\max}$, rational players have no chance to win. Namely, their utility is not less than 0.

When $q_{m'} = q_{\max}$, this means that irrational players take a dominant strategy. In this case, the dominant strategy equilibrium is satisfied. Thus, the utilities of rational players are not less than 0.

When $q_{m'} < q_{\max}$, case 2, case 3, or case 4 is applied. When case 2 is applied, if rational player i wins, the payment is $t_i = \max\{B_{E,q_{\max}-1}, B_{N,q_{\max}-1}, \alpha_{q_{\max}-2}\}$.
When case 3 is applied, if rational player i wins, the payment is $t_i = \max\{B_{E,q_{\max}}, B_{N,q_{\max}}, \alpha_{q_{\max}-1}\}$.
When case 4 is applied, if rational player i wins, the payment is $t_i = \max\{B_{E,q_{\max}}, B_{N,q_{\max}}, \alpha_{q_{\max}-1}\}$.

In the above three cases, since the payment is based on the true Nature's selection $q_{\max}$, the utilities of rational players are not less than 0.