

Towards a Combinatorial Auction Protocol among Experts and Amateurs: The Case of Single-Skilled Experts

Takayuki Ito
Graduate School of Engineering
Nagoya Institute of Technology
Gokiso, Showa-ku, Nagoya 466-8555, JAPAN
itota@ics.nitech.ac.jp

Makoto Yokoo, and Shigeo Matsubara
NTT Communication Science Laboratories
NTT Corporation
2 Hikaridai, Seika-cho, Soraku-gun,
Kyoto 619-0237, JAPAN
{yokoo,matsubara}@cslab.kecl.ntt.co.jp

ABSTRACT

Auctions have recently commanded a great deal of attention in the field of multi-agent systems. Correctly judging the quality of auctioned goods is often difficult for amateurs, in particular, on the Internet auctions. We have formalized 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, we have succeeded in developing a single unit auction protocol in which truth-telling is a dominant strategy for each expert. In this paper, we focus on a combinatorial auction protocol under asymmetric information on *Nature*'s selection. Experts may have an interest in, and expert knowledge on, *Nature*'s selection for several goods, i.e., experts are versatile. However, the case of versatile experts is very complicated. Thus, as a first step, we assume experts to have an interest in, and expert knowledge on, a single good. That is, experts are single-skilled. Under these assumptions, we develop an auction protocol in which the dominant strategy for experts is truth-telling. Also, for amateurs, truth-telling is the best response when experts tell the truth. By making experts to elicit their information on the quality of the goods, the protocol can achieve a 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

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

AAMAS'03 July 14–18, 2003, Melbourne, Australia.
Copyright 2003 ACM 1-58113-683-8/03/0007 ...\$5.00.

General Terms

Algorithm, Design, Economics, Theory

Keywords

Auctions, Mechanism Design, Multiagent Systems

1. INTRODUCTION

Auctions have recently commanded much attention in the field of multi-agent systems. For example, auctions can provide efficient task/resource allocation mechanisms in multi-agent systems [1, 5]. Also, agent-mediated electronic marketplaces [3, 7, 11, 15] employ auction mechanisms to realize an efficient trading mechanism among agents. Furthermore, Internet auctions such as eBay.com and Yahoo.com in the real world are becoming especially popular channels for the Internet economy.

For amateurs, it is often difficult to correctly judge the quality of auctioned goods. In particular, on the Internet auctions, many unknown persons exist who are selling their goods. If amateurs misjudge the quality of a good and purchase a poor quality item at a high price, they 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 as it might incur too high a cost for the auctioneer.

In the previous paper [6], we modeled the situation described above 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 actions in the auction with specified probabilities [9]. There are two types of bidders: experts and amateurs. While experts can tell whether the good on sale is real or imitation, amateurs cannot, and 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 unsure of 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) [8]. The details of the reason why we can not employ the Clarke mechanism simply were discussed in the paper [6].

Thus, in the previous paper [6], we proposed a direct revelation protocol for a single good, in which for each expert, truth-telling is a dominant, i.e., an optimal strategy regardless of the actions of other agents. In this paper, we focus on a combinatorial auction protocol under asymmetric information on Nature's selection. Combinatorial auctions can be employed in multiple application areas. Recently, numerous research results on combinatorial auctions protocols have been reported [2, 10, 12, 13]. Also, there is the problem of the quality of goods in the Internet combinatorial auctions. Thus, in this paper, we develop a combinatorial auction protocol, in which for each expert, truth-telling is the dominant strategy. Also, for amateurs, truth-telling is the best response when experts tell the truth.

Experts may have an interest in, and expert knowledge on, multiple goods, i.e., experts are versatile. However, the case of versatile experts complicates the building of a combinatorial auction protocol under asymmetric information on Nature's selection. Thus, as a first step, we assume experts have an interest in, and expert knowledge on, a single good, i.e., experts are single-skilled. For example, in antique auctions, in which a painting and a traditional pot is auctioned, an expert, who is gathering paintings, have interest in, and expert knowledge on, paintings. However, he does not have interest in traditional pots.

The rest of the paper is organized as follows. We first define the basic terms in this paper. Then, we describe the model of a domain under asymmetric information on Nature's selections. Next, we explain an auction mechanism in a single-unit case under our domain to clearly present our concept. Then, we propose a combinatorial auction mechanism under asymmetric information on Nature's selections. Finally, we discuss the difficulty of realizing a combinatorial auction protocol in the case where experts are versatile.

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 about Nature's selection. In addition, 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 [8]. Note that *private value* in this paper has a slightly different meaning from the traditional definition. In traditional definitions [8], 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. Moreover, 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 the 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 [9].

Dominant Strategy. The strategy s is a *dominant strategy* if it is a player's 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 some other strategy s'' exists 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 [9].

3. A SINGLE UNIT AUCTION PROTOCOL

3.1 Domain Definitions for A Single Unit Auction

In this section, we define the domain model for a single unit auction. In the following, we define several relevant terms and notations.

- A set of agents is represented by $I = \{1, \dots, n\}$.
- A set of Nature's selections is represented by $Q = \{q_1, q_2, \dots, q_m\}$.
- The number of goods auctioned is one. That is, the proposed auction is a single unit auction.

- Agent i 's utility is represented by $u_i = b_{i,q} - t_i$. Here, $b_{i,q}$ is agent i 's evaluation value of the good for Nature's selection q , and 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 $\theta_i = (b_{i,q_1}, b_{i,q_2}, b_{i,q_3}, \dots, b_{i,q_m})$.
- A set of experts is represented by $E \subset I$. Experts can observe Nature's selection. We suppose $|E| \geq 1$.
- 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 a single unit 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 players if Nature's selection is higher. In other words, all players value the possible outcomes of Nature's selection in the same order. For instance, for a player, the evaluation value for a real painting is higher than that for an imitation. 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. In the protocol we present in the next section, we introduced the upper limit to solve this problem.

3.2 A Single Unit Auction Protocol

In this section, we present a single unit auction protocol [6] under asymmetric information on Nature's selection. To show our concept clearly, let us explain an example of art auctions.

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), that is, two levels of Nature's selection exist. The auction is a closed bid auction. Players submit a bid for a combination of the goods. An expert's bid consist of the observed quality and the value of the goods. Since amateurs cannot observe the quality of the good, an amateur's bid is a conditional bid, e.g., "if the quality is real, I'll pay at most \$300. If it is an imitation, I'm not willing to pay more than \$30."

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} , and we assume the upper limit is given. We classify the procedure into the following three cases:

Case A: 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 B: If the number of players 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 C: 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 anything¹. If i wins, the payment is the second highest evaluation value within $B_{E,R}$, $B_{N,R}$, and α_{q_I} .

If there is an overlap between evaluation values at two or more different Nature's selections, there is a problem in that if the item is an imitation, experts can benefit by falsely declaring that the quality is real. Thus, we introduce the upper limit in Case C to avoid this problem. The details are shown in the previous paper [6].

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 Nature's selections false are less than the threshold, truth telling is the best response. Third, our mechanism can realize Pareto efficient allocation. Fourth, even if there are irrational players, if the number of irrational players is less than the threshold, rational players do not suffer loss. The previous paper [6] provided the detailed proof for the above theorems.

3.3 Example

The following example of art auctions clarify our concepts. For simplicity, we assume that there are two types of possible Nature's selection, real or imitation. Furthermore, we assume that there are three types of participants, as shown in Table 1. Here, α means the upper limit for Nature's selection, but here, we do not use the upper limit α .

Table 1: 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	

There are two amateurs whose types are θ_1 and θ_2 , and 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

¹The case in which α_{q_I} is the maximum value in case C 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 the Pareto efficiency.

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 B. Then, this expert wins this auction, and his payment is \$40.

4. DESIGNING A COMBINATORIAL AUCTION PROTOCOL

4.1 Domain Definitions for a Combinatorial Auction

In this section, we define the domain model for a combinatorial auction under asymmetric information on Nature’s selections. In the following, we add and modify several terms and notions to the definitions in the case of a single good auction.

- The number of goods auctioned is more than one. Bidders are allowed to submit bids for any combination of the goods.
- We suppose binary Nature’s selections, i.e. real or imitation.
- A set of Nature’s selections that g_j can have is represented by $Q_{g_j} \subset Q$.
- A pair $p_{(j,k)} = (g_j, q_k)$ means that the good g_j has Nature’s selection q_k . To present a pair $p_{(j,k)}$, we use the notation $g_j : q_k$.
- A set of combinations of pairs is represented by $C = \{C_0, C_1, \dots, C_{2^j k}\}$.
- $b_i(C_x)$ is agent i ’s evaluation value of the combination C_x of pairs of a good and its Nature’s selection.
- Player i ’s utility is represented by $u_i = \sum_{C_x \in W} b_i(C_x) - t_i(C_x)$. W is a winning set of combinations. W is a set of subsets of pairs so that each pair is included in at most one of the subsets². $t_i(C_x)$ is agent i ’s payment for C_x . If an agent cannot obtain a good, we assume its utility is 0. The auctioneer i ’s utility is represented by $u_i = \sum_{C_x \in W} t_i(C_x)$.
- We suppose $|E| \geq 1$ for each good.
- We assume a single unit of each good in an auction.
- We presume the auction chooses optimal allocations that are feasible.

We design an auction protocol under the following assumption.

ASSUMPTION 2. For all i, q, q', g_j , where $(g_j, q) \in C_x$, $(g_j, q') \in C'_x$, $q < q'$, $b_i(C_x) \leq b_i(C'_x)$.

Assumption 2 is a combinatorial version of Assumption 1.

²Because player’s utility depends on a winning set, we can ignore implicit acquired bundles. For example, there are three bundles and their values, $\{A\} = 10, \{A, B\} = 20, \{A, B, C\} = 30$. Here, the player acquires $\{A, B, C\}$ that is in a winning set. It is not correct to consider that when the player acquires $\{A, B, C\}$, his utility may be 60 since $\{A\}$ and $\{A, B\}$ are implicitly acquired. This is not correct since $\{A\}$ and $\{A, B\}$ are not in the winning set.

ASSUMPTION 3. Expert i has expert knowledge on, and an interest in, a certain single good. Namely, if expert $i \in E$ has expert knowledge on, and an interest in, item g_j , if combination C_x includes g_j , $b_i(C_x) > 0$. If combination C_x does not include g_j , $b_i(C_x) = 0$.

For example, when a painting and a traditional pot are auctioned, if an expert has expert knowledge on, and an interest in only the painting, he submits bids only for the painting. On the other hand, if another expert has expertises on, and is interested in the traditional pot, he submits bids only on the traditional pot.

Table 2 shows a simple example. Suppose there are two goods, a and b . Also, each good can have two qualities, q_R (Real) and q_I (Imitation). The possible bids are shown in Table 2. For example, $\{a : q_R, b : q_R\}$ is a combination of a pair of good a and quality q_R and a pair of good b and quality q_R .

Table 2: An Example of Possible Combinations

$\{a : q_R\}$	$\{b : q_R\}$	$\{a : q_R, b : q_R\}$	$\{a : q_I, b : q_R\}$
$\{a : q_I\}$	$\{b : q_I\}$	$\{a : q_I, b : q_I\}$	$\{a : q_R, b : q_I\}$

Bidders can submit bids for each combination. Amateurs are allowed conditional bids, e.g., “If a is real (q_R), then I’ll pay at most \$100. If a is an imitation (q_I), I’m not willing to pay more than \$10. If a is real and b is real and they are in one set, then I’ll pay at most \$200. etc.” Table 3 shows an example.

Table 3: An Example of Amateur’s bids

	$\{a : q_R\}$	$\{b : q_R\}$	$\{a : q_R, b : q_R\}$	$\{a : q_I, b : q_R\}$
bids	100	90	200	100
	$\{a : q_I\}$	$\{b : q_I\}$	$\{a : q_R, b : q_I\}$	$\{a : q_I, b : q_I\}$
bids	10	6	20	16

An expert who is interested in g_j submits a bid that consists of the quality of an item g_j and the value of combinations that include g_j . For example, in Table 4, an expert submits a bid for good a that it contends is real (q_R) and has a value of 100.

Table 4: An Example of Expert’s Bids

	$\{a : q_R\}$	$\{b : q_R\}$	$\{a : q_R, b : q_R\}$	$\{a : q_I, b : q_R\}$
bids	100	-	100	-
	$\{a : q_I\}$	$\{b : q_I\}$	$\{a : q_R, b : q_I\}$	$\{a : q_I, b : q_I\}$
bids	-	-	100	-

4.2 A Combinatorial Auction Protocol

Based on the above bids, the auction protocol initially judges the quality of the goods, and then decides the winners and the payments.

1. For each good, the quality, real or an imitation, (i.e., Nature’s selection) is judged. Suppose the number of experts who declared the good to be real is n .

- (Case 1) When $n \geq 2$, the good is judged as real (q_R).
 - (Case 2) When $n = 1$, the protocol does not judge the quality of the good.
 - (Case 3) When $n = 0$, the good is judged as an imitation (q_I).
2. In terms of a good whose quality was not judged, the winner and the payment is decided as follows. Suppose an expert e_1 declares $g_j : q_R$. If e_1 's declared value is higher than the payment p_{e_1} , e_1 is the winner and pays p_{e_1} .

$$p_{e_1} = \sum_{y \neq e_1} v_y(G_{\sim e_1}) - \sum_{y \neq e_1} v_y(G), \quad (1)$$

where G is an allocation that maximizes the sum of declared values. $G_{\sim e_1}$ is an allocation that maximizes the sum of evaluation values without player e_1 . If e_1 's declared value is less than p_{e_1} , there is no trade on g_j .

3. In terms of goods whose quality was judged, based on the above judgment, the winners and the payments are decided. First, bids for the goods whose qualities are not consistent with the judged quality are rejected. The payment for winners are calculated based on Equation (2).

$$p_i = \sum_{y \neq i} v_y(G_{\sim i}) - \sum_{y \neq i} v_y(G) \quad (2)$$

An allocation G that maximizes the sum of declared values is calculated from the remaining bids. A player's value for allocation G is represented by $v(G)$. $G_{\sim i}$ means an allocation that maximized the sum of evaluation values without player i .

When calculating the first term in Equation (2), for the good g_j that was judged as real q_R , we assume there exists a dummy player for combinations that includes the good g_j . The dummy player assumes to have an evaluation value that equals the upper limit value for $g_j : q_I$. By assuming dummy players, we can guarantee that the payment of the good that was judged as real is higher than the upper limit value of its imitation.

The payment p_i is calculated based on G.V.A (Generalized Vickrey Auction) [14]. The difference is that the basic G.V.A. does not handle the quality (Nature's selection) of the good. Also, in terms of dummy players, since the first term of Equation (2) is not related to player i 's bid, the existence of dummy players does not affect incentive compatibility.

4.3 The Features of 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 when reporting the true value. The details of the proof are shown in Appendix A. \square

ASSUMPTION 4. *Two or more experts exit for each item and they correctly select a dominant strategy. In addition, no more than one irrational players exist.*

THEOREM 2. *Under Assumption 4, for amateurs, truth telling is the best response.*

PROOF (OUTLINE). Under Assumption 4, we prove that for amateur i , telling the truth is the best response. Under Assumption 4, 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. We show that there is no benefit for amateurs in the above two cases. The proof is shown in Appendix B. \square

THEOREM 3. *Under Assumption 4, our mechanism is Pareto efficient.*

PROOF.³ Under Assumption 4, the condition in Case 2 cannot be satisfied. Thus, we consider only Case 1 and Case 3. In Case 1 and 3, since the good is awarded to the player who has the maximum evaluation value, our mechanism realizes a Pareto efficient allocation. \square

THEOREM 4. *Under Assumption 4, 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 not negative. Thus, we prove that if one irrational player exists, the utilities of rational players are not negative. We have omitted the details of the proof here due to space limitation. \square

4.4 Examples

The qualities of all goods can be judged. Table 5 shows an example in which the qualities of all goods can be judged. Suppose there are experts e_1, e_2, e_3 , and e_4 , an amateur n_1 , and goods a and b . Experts e_1 and e_2 declare that good b is real q_R , i.e, $b : q_R$. Experts e_3 and e_4 declare that good a is real q_R , i.e, $a : q_R$. For each good, the upper limits are 100, i.e., $\alpha_{q_I}(a) = 100$ and $\alpha_{q_I}(b) = 100$.

Table 5: The Qualities of All Goods Can Be Judged

	$\{a : q_R\}$	$\{b : q_R\}$	$\{a : q_R, b : q_R\}$	$\{a : q_I, b : q_R\}$
e_1	-	500	500	500
e_2	-	450	450	450
e_3	400	-	400	-
e_4	350	-	350	-
n_1	100	200	300	210
	$\{a : q_I\}$	$\{b : q_I\}$	$\{a : q_R, b : q_I\}$	$\{a : q_I, b : q_I\}$
e_1	-	-	-	-
e_2	-	-	-	-
e_3	-	-	400	-
e_4	-	-	350	-
n_1	10	20	120	30

Here, in terms of good a , two experts, e_3 and e_4 , declare that good a is real (q_R). Thus, the quality of good a is judged as real (q_R). Also, in terms of good b , since two experts, e_1 and e_2 , declare good b is real (q_R), the quality of good b is judged as real (q_R). Table 6 shows combinations and their values after judging the qualities.

³This proof relies on Theorem 1 and Assumption 2.

Table 6: After Judging the Qualities

	$\{a : q_R\}$	$\{b : q_R\}$	$\{a : q_R, b : q_R\}$
e_1	-	500*	500
e_2	-	450	450
e_3	400*	-	400
e_4	350	-	350
n_1	100	200	300

The auctioneer calculates allocation G that maximizes the sum of the values. In this example, $G = \{\{a : q_R\}, \{b : q_R\}\}$ maximizes the sum of values. Thus, the good a is assigned to e_3 , and the good b is assigned to e_1 . Based on G , the auctioneer decides the payments for each participant according to equation (2).

The payment by e_1 can be calculated as follows.

$$\begin{aligned}
 p_{e_1} &= \sum_{y \neq e_1} v_y(G_{\sim e_1}) - \sum_{y \neq e_1} v_y(G) \\
 &= 850 - 400 = 450
 \end{aligned} \tag{3}$$

Also, the payment by e_3 is $p_{e_3} = 850 - 500 = 350$. The payments by e_2 , e_4 , and n_1 are 0 since they are not assigned any goods.

The qualities of some goods cannot be judged. Table 7 shows an example in which the quality of some goods cannot be judged. Suppose there are experts e_1 , e_2 , e_3 , and e_4 , an amateur n_1 , and goods a and b . Expert e_1 declares that good a is real q_R , i.e., $a : q_R$. Experts e_2 , e_3 , and e_4 declare that good b is real q_R , i.e., $b : q_R$. $\alpha_{q_I}(a) = 10$ and $\alpha_{q_I}(b) = 10$.

Table 7: The Qualities of Some Goods Cannot Be Judged

	$\{a : q_R\}$	$\{b : q_R\}$	$\{a : q_R, b : q_R\}$	$\{a : q_I, b : q_R\}$
e_1	100	-	100	-
e_2	-	50	50	50
e_3	-	115	115	115
e_4	-	105	105	105
n_1	50	80	130	100
	$\{a : q_I\}$	$\{b : q_I\}$	$\{a : q_R, b : q_I\}$	$\{a : q_I, b : q_I\}$
e_1	-	-	100	-
e_2	-	-	-	-
e_3	-	-	-	-
e_4	-	-	-	-
n_1	20	30	80	50

Here, the number of experts who declare good a is real (q_R) is one (only e_1 declares good a is real). Thus, the protocol does not judge the quality of good a . Since the quality of good a cannot be judged, combinations $\{a : q_R, b : q_R\}$, $\{a : q_I, b : q_R\}$, $\{a : q_R, b : q_I\}$, and $\{a : q_I, b : q_I\}$ are removed from the winner candidates. On the other hand, in terms of good b , three experts, e_2 , e_3 , and e_4 , declare good b is real (q_R). Thus, good b is judged as real q_R . Table 8 shows combinations and values after judging the quality of goods.

In terms of good a , expert e_1 is a winner who declared that the quality of good a is real q_R . The payment is \$20.

Table 8: After Judging the Quality of Goods

	$\{a : q_R\}$	$\{b : q_R\}$	$\{a : q_I, b : q_R\}$
e_1	100*	-	-
e_2	-	50	50
e_3	-	115*	115
e_4	-	105	105
n_1	50	80	100
	$\{a : q_I\}$		
e_1	-		
e_2	-		
e_3	-		
e_4	-		
n_1	20		

In terms of combination $\{b : q_R\}$ that includes good b , the winner and the payment is decided by the same method as the Vickrey auction protocol. Thus, expert e_3 is the winner. The payment is \$105.

5. DISCUSSION

In this paper, Assumption 3 limits the range of the strategies for experts. Toward a general combinatorial auction protocol among experts and amateurs, we discuss the case in which we do not employ Assumption 3, i.e., the case in which experts can declare the qualities of multiple goods. We can call these experts versatile experts.

Table 9 shows an example free-riding problem among versatile experts. Suppose there are experts e_1 , and e_2 , an amateur n_1 , and goods a and b . Here, e'_1 represents e_1 's false declaration. The qualities of goods a and b are imitation and real, respectively. Here, expert e_1 falsely declares that goods a and b are real q_R . In fact, expert e_1 knows that good a is an imitation as shown by e'_1 . Expert e_2 also declares that goods a and b is real q_R . We can recognize e_2 also declares falsehood.

Table 9: An Example of Free Riding Problems

	$\{a : q_R\}$	$\{b : q_R\}$	$\{a : q_R, b : q_R\}$	$\{a : q_I, b : q_R\}$
n_1	500	-	-	-
e'_1	10	400	410	-
(e_1	-	400	-	401)
e_2	200	100	600	-
	$\{a : q_I\}$	$\{b : q_I\}$	$\{a : q_I, b : q_I\}$	$\{a : q_R, b : q_I\}$
n_1	200	-	-	-
e'_1	-	-	-	-
(e_1	1	-	-	-)
e_2	-	-	-	-

If expert e_1 declares truth, goods a and b are awarded to e_2 who declared a value of 600 for the combination of a and b . If expert e_1 falsely declares e'_1 , amateur n_1 wins good a and e_1 wins good b . That is, expert e_1 is unfairly awarded the good. This is an example of a free riding problem. In this paper, by assuming single-skilled experts, we avoid free riding problems. Solving free-riding problems is one of the most important issues relating to combinatorial auction protocol among versatile experts and amateurs.

6. CONCLUSIONS

In this paper, we proposed a combinatorial 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. Experts may have an interest in, and expert knowledge on, multiple goods. In other words, experts are versatile. However, the case of versatile experts complicates the building of a combinatorial auction protocol under asymmetric information on nature's selection. Thus, as a first step, we assumed experts have an interest in, and expertised knowledge on, a single good, i.e., experts are single-skilled. Under these assumptions, we developed an auction protocol that has the following features. (1) A dominant strategy for experts is truth-telling. (2) For amateurs, truth-telling is the best response when experts tell the truth. (3) Our mechanism realizes a Pareto efficient allocation. (4) If the number of irrational players is 1 or less for each good, the utilities of rational players are not negative.

Regarding a generalized combinatorial auction, the free-riding problem among versatile experts we discussed in this paper is the one of the most important issues. Thus, one of our future work is to realize a protocol that can handle the free-riding problem among versatile experts.

Also, in G.V.A. a problem in terms of preference elicitation has received plenty of attention. In G.V.A., expressing one's preferences requires bidding on all bundles. Our protocol may make this problem worse because it allows bidders to submit conditional bids. However, several methods to elicit preference have been proposed [4]. We believe that this problem in our protocol can be mitigated by applying these methods.

7. REFERENCES

- [1] C. Boutilier, M. Goldszmidt, and B. Sabata. Sequential auctions for the allocation of resources with complementarities. In *Proc. of the sixteenth International Joint Conference on Artificial Intelligence*, pages 524–534, 1999.
- [2] Y. Fujishima, K. Leyton-Brown, and Y. Shoham. Taming the computational complexity of combinatorial auctions: Optimal and approximate approaches. In *Proc. of the 16th International Joint Conference on Artificial Intelligence (IJCAI99)*, pages 548–553, 1999.
- [3] R. H. Guttman, A. G. Moukas, and P. Maes. Agent-mediated electronic commerce: A survey. *The Knowledge Engineering Review*, 13(2):147–159, 1998.
- [4] B. Hudson and T. Sandholm. Effectiveness of preference elicitation in combinatorial auctions. In *Proc. of AAMAS02 Workshop on Agent Mediated Electronic Commerce IV (AMEC IV)*, 2002.
- [5] L. Hunsberger and B. J. Grosz. A combinatorial auction for collaborative planning. In *Proc. of the 4th International Conference on Multi-Agent Systems*, pages 151–158, 2000.
- [6] T. Ito, M. Yokoo, and S. Matsubara. Designing an auction protocol under asymmetric information on nature's selection. In *Proc. of the 1st International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS02)*, pages 61–68, 2002.
- [7] C. Li and K. Sycara. Algorithm for combinatorial

coalition formation and payoff division in an electronic marketplace. In *Proc. of the 1st International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS02)*, pages 120–127, 2002.

- [8] A. Mas-Colell, M. D. Whinston, and J. R. Green. *Microeconomic Theory*. Oxford University Press, 2nd edition, 1995.
- [9] E. Rasmusen. *Games and Information*. Blackwell Publishers Ltd, 2nd edition, 1994.
- [10] T. Sandholm. An algorithm for optimal winner determination in combinatorial auctions. In *Proc. of the 16th International Joint Conference on Artificial Intelligence (IJCAI'99)*, pages 542–547, 1999.
- [11] T. Sandholm. eMediator: A next generation electronic commerce server. In *Proc. of the International Conference on Autonomous Agents (AGENTS00)*, pages 341–438, 2000.
- [12] T. Sandholm. Improved algorithms for optimal winner determination in combinatorial auctions and generalizations. In *Proc. of 17th National Conference on Artificial Intelligence (AAAI2000)*, pages 90–97, 2000.
- [13] T. Sandholm, S. Suri, A. Gilpin, and D. Levine. Winner determination in combinatorial auction generalizations. In *Proc. of the 1st International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS02)*, pages 69–76, 2002.
- [14] H. R. Varian. Economic mechanism design for computerized agents. In *Proc. of the First Usenix Workshop on Electronic Commerce*, 1995.
- [15] P. R. Wurman, M. P. Wellman, and W. E. Walsh. The Michigan internet auctionbot: A configurable auction server for human and software agents. In *Proc. of the 2nd International Conference on Autonomous Agents (AGENTS98)*, 1998.

APPENDIX

A. THE PROOF OF THEOREM 1

In this section, 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. Here, the Nature's selections are real, q_R , or an imitation, q_I . q_T represents true Nature's selection observed by expert i . q_{max} represents the maximum Nature's selection submitted without i . q_F represents expert i 's false declaration on Nature's selection. For the following cases, we prove that if i declares q_F , there is no benefit for i . According to Assumption 3, we assume that expert i has an interest in, and expert knowledge on, good g_j only. Here, i does not have positive utility if he submits bids on combinations that do not include g_j . Thus, i submits his bids in combinations that include g_j .

Expert i has two strategies in terms of his expertise, (1) and (2). (1) To declare that he is an expert. (2) To declare that he is an amateur. When expert i declares that he is an amateur, i.e, strategy (2), obviously there is no benefit for him. When expert i declares that he is an expert, i.e, strategy (1), there are the following three cases, (I), (II), and (III). For each case, we prove that if i declares Nature's selection false, q_F , for good g_j , or submits false evaluation values, there is no benefit for i .

(I) $q_T < q_{\max}$, $q_T = q_I$ (an imitation) and $q_{\max} = q_R$ (Real). In this case, there are two cases, (a) and (b).

(a) If i declares true Nature's selection, q_T , i has no chance to award the item. Obviously, there is no benefit from declaring false evaluation values.

(b) If i declares Nature's selection false, $q_F = q_{\max}$, case 1 ($n=2$) is applied. A dummy player is represented by x . Here, i 's utility is represented by the following equation.

$$\begin{aligned} u'_i &= v_i(G') + \sum_{j \neq i} v_j(G') - \sum_j v_j(G'') \\ &= \sum_j v_j(G') - \sum_j v_j(G'') \end{aligned}$$

Where, I represents a set of players. G' represents an allocation that maximizes the sum of evaluation values in I , and G'' represents an allocation that maximized the sum of evaluation values $I + \{x\} - \{i\}$. G' can be seen as an allocation that maximized the sum of evaluation values in $I + \{x\} - \{x\} (= I)$. That is, G' maximizes the sum of evaluation values in a set that removes $\{x\}$ from $I + \{x\}$, and G'' maximized the sum of evaluation values in a set that removes $\{i\}$ from $I + \{x\}$. Note that while we consider true evaluation values for i and dummy player x , we consider declared evaluation values for other bidders since we are considering i 's utility. Thus, dummy player x 's evaluation value, i.e., the upper limit for q_I , is larger than i 's true evaluation value, i.e., the evaluation value for $g_k : q_I$. Thus,

$$\sum_j v_j(G') \leq \sum_j v_j(G'')$$

When the goods are not assigned to i and x , $\sum_j v_j(G') = \sum_j v_j(G'')$, i.e., $u'_i \leq 0$. Thus, there is no benefit for i , even if he declares Nature's selection false.

(II) $q_T = q_{\max}$, There are two cases, (c) and (d). (c) If $q_T = q_{\max} = q_R$ (Real), There are two cases, [c-1] and [c-2]. [c-1] When i declares Nature's selection true $q_T = q_R$, the number of experts who declare q_R is larger than 2, so Case 1 is applied. Obviously, there is no benefit from declaring false evaluation values because of G.V.A. [c-2] When i declares Nature's selection false $q_F = q_I (< q_{\max} = q_R)$, Case 1 or Case 2 is applied. Since $q_{\max} > q_F$, i has no chance of winning the good.

(d) $q_T = q_{\max} = q_I$ (An imitation), There are two cases, [d-1] and [d-2]. [d-1] When i declares Nature's selection true $q_T = q_I$, case 3 is applied. i 's utility u_i is

$$u_i = v_i(G) + \sum_{j \neq i} v_j(G) - \sum_{j \neq i} v_j(G_{\sim i})$$

Obviously, there is no benefit from declaring false evaluation values. [d-2] When i declares Nature's selection false $q_F = q_R (> q_{\max} = q_I)$, Case 2 is applied. i 's utility u'_i is

$$u'_i = v_i(G') + \sum_{j \neq i} v_j(G') - \sum_{j \neq i} v_j(G'_{\sim i})$$

Here, we confirm $u'_i \not\geq u_i$.

$$\begin{aligned} u'_i - u_i &= v_i(G') + \sum_{j \neq i} v_j(G') - \sum_{j \neq i} v_j(G'_{\sim i}) \\ &\quad - \{v_i(G) + \sum_{j \neq i} v_j(G) - \sum_{j \neq i} v_j(G_{\sim i})\} \end{aligned}$$

Here, both $G_{\sim i}$ and $G'_{\sim i}$ represent an optimal allocation without i . Thus, $G_{\sim i} = G'_{\sim i}$.

$$= (v_i(G') - v_i(G)) - \left(\sum_{j \neq i} v_j(G) - \sum_{j \neq i} v_j(G') \right)$$

Suppose $a = (v_i(G') - v_i(G))$ and $b = (\sum_{j \neq i} v_j(G) - \sum_{j \neq i} v_j(G'))$. Here, a is i 's increased utility by declaring Nature's selection false, and b is other members' utility lost by i 's false declaration. Here, if $a > b$, (even if i did not declare Nature's selection false) G' was selected as an optimal allocation. However, G was selected as an optimal allocation. Thus, $a \leq b$. Therefore,

$$u'_i - u_i = a - b \leq 0. \quad (4)$$

In other words, There is no benefit for i even if he declared Nature's selection false. The above Equation (4) cannot hold if experts are versatile. Intuitively, even if an expert lost his utility in terms of a certain good, he can make a benefit from another good.

(III) $q_T > q_{\max}$, In this case, $q_T = q_R$ and $q_{\max} = q_I$. There are two cases, (e) and (f). (e) When i declares Nature's selection true $q_T = q_R$, Case 2 is applied. There is no benefit from declaring false evaluation values. (f) When i declares Nature's selection false $q_F = q_I$, Case 1 is applied. The proof of this case is same as (I)(b).

B. THE PROOF OF THEOREM 2

In this section, we prove Theorem 2. Amateur i has two strategies, (I) and (II). (I) To declare the truth that he is an amateur. (II) To declare a falsehood that he is an expert. We classify the cases into (1), (2), and (3) according to the bids without i , and prove that for each case, the strategy (II) does not result in a benefit.

(1) For the good g_j , Case 1 ($n=2$) is satisfied without i . In this case the quality of g_j is q_R , since experts declare the truth. There are two cases, (1-I) and (1-II)

(1-I) If i declares a truth, i.e., i declares i is an amateur, there is no benefit for i because of G.V.A.

(1-II) If i declares a falsehood, i.e., i declares i is an expert, there are two cases, [1-II-a] and [1-II-b]. [1-II-a] When i declares q_R , Case 1 is applied. Here, i 's utility is the same as the case (1-I) in which he declares the truth. Thus, there is no benefit for i . [1-II-b] When i declares q_I , Case 1 is applied since there are two or more experts who declare q_R . There is no chance of i winning the good.

(2) For the good g_j , case 2 ($n=1$) is satisfied without i . In this case, since experts declare the truth, the true quality is q_I . There is obviously one amateur who falsely declares he is an expert. There are two cases, (2-I) and (2-II).

(2-I) When i declares a truth, i.e., i declares he is an amateur, i has no chance of winning g_j since one amateur, who falsely declares he is an expert and the quality is q_R , wins the good.

(2-II) When i declares a falsehood, i.e., i declares he is an expert, there are two cases, [2-II-a] and [2-II-b]. [2-II-a] When i declares q_I , there is no chance of winning the good. [2-II-b] When i declares q_R , Case 1 is applied. This case is almost the same as the proof (I)(b) in appendix A.

(3) For the good g_j , Case 3 ($n=0$) is satisfied without i . In this case, since experts declare the truth, the true quality is q_I . This case is almost the same as the proof (II)(d) in appendix A.