# A Combinatorial Auction Protocol among Versatile Experts and Amateurs

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## Abstract

*Auctions have become an integral part of electronic commerce and a promising field for applying multi-agent technologies. Correctly judging the quality of auctioned items is often difficult for amateurs, in particular, in Internet auctions. However, experts can correctly judge the quality of items. In this situation, it is difficult to force experts to tell the truth and attain an efficient allocation since they have a clear advantage over amateurs; without some reward they cannot be expected to reveal their valuable information. In our previous work, we successfully develop such auction protocols under the following two cases: (1) a* **single***-unit auction among experts and amateurs, and (2) a combinatorial auction among* **single-skilled** *experts and amateurs. In this paper we focus on* **versatile experts***, who have interest in and expert knowledge of the qualities of several items. In the case of versatile experts, there are several problems, e.g., free riding problems, if we simply extend the previous VCG-style auction protocol. Thus, in this paper, we employ a PORF (price-oriented, rationing-free) protocol for designing our new protocol to realize a strategy-proof auction protocol for experts. In the protocol, the dominant strategy for experts is telling the truth. Also for amateurs, telling the truth is the best response when two or more experts select the dominant strategy. Furthermore, the protocol is false-name-proof.*

## 1. Introduction

Computational mechanism designs [3] have recently commanded much attention in the field of multi-agent systems. In particular, auction mechanisms are one of the most important mechanisms for realizing an efficient allocation. There have been many works on efficient task/resource allocation mechanisms [1, 5]. Also, agent-mediated electronic marketplaces [4, 12] have realized efficient auction mechanisms among agents. Furthermore, such Internet auctions as eBay.com and Yahoo.com in the real world are also becoming popular channels for the Internet economy.

Amateurs often have difficulty correctly judging the quality of auctioned items. In particular, in Internet auctions, many strangers are selling items. If amateurs misjudge the quality or buy a poor quality item at a high price, they suffer a loss. Such a situation can be avoided if the auctioneer can judge the quality correctly, but this is not always possible since it might incur too high a cost for the auctioneer.

In previous papers [6][7], we modeled the above situation by using asymmetric information from the field of game theory. For example, at art auctions, when a painting is being auctioned, it can be authentic or an imitation. There are two types of bidders: experts and amateurs. While experts can tell whether the item on sale is authentic or imitation, amateurs cannot; clearly the value of the painting depends on whether it is authentic.

It would be beneficial for an amateur if the protocol allowed such conditional bids as, "If the painting is genuine, then I'll pay up to $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 item, i.e., he is an expert, he can submit an unconditional bid, e.g., "I'm sure that the painting is real, so I am willing to pay up to $5,000." If the protocol correctly determined the quality of the item based on these declarations, an amateur could purchase the item without risk of incurring a loss, even if he is unsure of the qual-


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ity.

The difficulty in developing such a protocol is that experts have a clear advantage over amateurs, and they might not reveal such valuable information without some reward. We cannot simply apply the Clarke mechanism (a.k.a. VCG mechanism) [9] for reasons discussed in an earlier paper [6].

In a previous paper [6], we successfully designed a direct revelation protocol for a single item in which for each expert, truth-telling is a dominant or an optimal strategy, regardless of the actions of other agents. Then, in another paper [7], we designed a combinatorial auction protocol among single-skilled experts and amateurs. Briefly, the protocol can be described as follows: First, the quality of each item is decided based on experts' declarations. Then, the prices of bundles are decided using a VCG protocol.

In that paper [7], we discussed the free-riding problem among versatile experts when employing the same kind of auction protocol for single-skilled experts. Versatile experts have an interest in and expert knowledge of, multiple items. Also, in the proposed protocol, in certain cases, the protocol does not judge the quality of items. If we assume a single item or single-skilled experts, no judgment on the quality of items can work well as incentives for experts to tell the truth. However, if we assume versatile experts, this cannot work at all. Versatile experts can maliciously utilize this case to make a profit.

In this paper, we describe a combinatorial auction protocol among versatile experts and amateurs based on the PORF protocol [13], a new distinctive class of combinatorial auction protocols. We utilize the PORF protocol so that it can handle asymmetric situations. Further, by utilizing the PORF protocol, our new protocol also is false-name proof.

The outline of our new protocol can be described as follows: First, for each bundle, the protocol calculates the price. For each player, the price is defined as the maximum value of the others' evaluation values. Here, an evaluation value of each other player is carefully selected based on whether he/she is an expert or an amateur. Then, for each player, the bundle that maximizes his/her utility is assigned. Here, utilities are also calculated based on whether he/she is an expert or an amateur.

The rest of the paper is organized as follows. We first define the basic terms and explain the Price-Oriented, Rationing-Free (PORF) protocol. Then, we propose a combinatorial auction protocol among versatile experts and amateurs. Next, the important features of our protocol are presented. Furthermore, we discuss the main differences between related works, especially Eric Maskin's work, and our approach. Finally, we give concluding remarks and outline future work.


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## 2. Problem Settings

### 2.1. Basic Terms

We define the basic terms used in this paper. If you are familiar with these terms, please skip this section.

In this paper, we concentrate on private value auctions [9]. Note that *private value* in this paper has a slightly different meaning from its traditional definition. Agent $i$'s utility $u_i$ is defined as the difference between the true evaluation value $v_{i,q}$ of the allocated item for the determined Nature's selection $q$ and the payment to the seller $p_i$ for the allocated item. Namely, $u_i = v_{i,q} - p_i$.

We describe an auction protocol as Pareto efficient when the sum of all participants' utilities (including the auctioneer), i.e., the social surplus, is maximized in a dominant strategy equilibrium. In an auction setting, agents can transfer money, and the utility of each agent is quasi-linear; thus, the sum of the utilities is always maximized as a Pareto efficient allocation.

A strategy $s$ is a *dominant strategy* when it is a player's best response to any strategy that the other players might pick. In other words, whatever strategies are picked, the payoff is highest with $s$. Player $i$'s best response to the strategies chosen by the other players is the strategy that yields him/her the greatest utility [11].

In a traditional definition [9], an auction protocol is incentive compatible if declaring true type/evaluation values is a dominant strategy for each bidder: an optimal strategy regardless of the actions of other bidders. We have extended the traditional definition of incentive compatibility to address false-name bid manipulations. We define an auction protocol as incentive compatible if declaring the true type by using a single identifier is a dominant strategy for each bidder. To distinguish between traditional and extended definitions of incentive compatibility, we refer to the traditional definition as strategy-proof and to the extended definition as false-name proof.

### 2.2. Domain Definitions

In this section we define the domain model for a combinatorial auction between versatile experts and amateurs.

- A set of bidders $N = \{1, 2, \ldots, n\}$.
- A set of items $M = \{1, 2, \ldots, m\}$.
- A set of qualities is represented by $Q = \{q_I, q_R\}$. $q_I$ means "an imitation." $q_R$ means "a real item."
- A pair $j : q_k$ means that the item $j$ has the quality $q_k$.
- A set of combinations of pairs is represented by $C = \{C_0, C_1, \ldots, C_{2^m}\}$. An element of $C$ is called a bundle.

- Each bidder $i$ has his/her preferences for each bundle $B \in C$.
- Player $i$'s type $\theta_i$ is represented as a set of evaluations for bundles of items **with qualities**. For example, when $M = \{1, 2\}$, bundles are $\{\{\}, \{1\}, \{2\}, \{1, 2\}\}$, and bundles with qualities are $\{\{1 : q_I\}, \{1 : q_R\}, \{2 : q_I\}, \{2 : q_R\}, \{1 : q_I, 2 : q_I\}, \{1 : q_R, 2 : q_I\}, \{1 : q_I, 2 : q_R\}, \{1 : q_R, 2 : q_R\}, \}$. Here, $1 : q_I$ means that the quality of the item 1 is $q_I$ (imitation).
- The evaluation values of the item depends on the qualities of the items.
- The utility of player $i$, when $i$ obtains a bundle, i.e., a subset of items $B \subseteq M$, and pays $p_{B,i}$, is represented as $u_i(B, q(B), \theta_i) = v(B, q(B), \theta_i) - p_{B,i}$. $q(B)$ is a set of pairs, $j : q_k$, in the Bundle $B$.
- The number of items auctioned is more than one. Bidders are allowed to submit bids for any bundle of items.
- A set of experts is represented by $E \subset N$. Experts can observe the qualities of items. We suppose $\mid E \mid \geq 1$.
- A set of amateurs is represented by $A \subset N$. $N - A = E$. Amateurs cannot observe the qualities of items.
- The auctioneer cannot observe qualities and cannot differentiate between experts and amateurs.

To calculate the price for each bundle, we employ minimal bundles defined as follows:

**Definition 1 (Minimal bundle)** *Bundle $B$ is called minimal for bidder $i$ if for all $B' \subset B$ and $B' \neq B$, $v(B', q(B'), \theta_i) < v(B, q(B), \theta_i)$ holds.*

**Assumption 1 (Versatile Experts)** *Expert $i$ has expert knowledge on and an interest in multiple items. The minimal bundle for expert $i$ includes items that $i$ has expert knowledge on and interest in. If a bundle $B$ does not include any items in $G_i$, $v(B, q(B), \theta_i) = 0$.*

For example, a painting and a traditional pot are being auctioned. If an expert has expert knowledge on and interest in both the painting and the traditional pot, he/she submits bids for the both items.

# 3. Price-oriented Combinatorial Auction Protocol among Versatile Experts and Amateurs

## 3.1. Price-Oriented, Rationing-Free Protocol

We designed a combinatorial auction protocol among versatile experts and amateurs by using a PORF protocol [13] defined as follows.

**Definition 2** *(PORF protocol)*

- *Each bidder $i$ declares his/her type $\tilde{\theta}_i$, which is not necessarily the true type $\theta_i$.*
- *For each bidder i, for each bundle $B \subseteq M$, the price $p_{B,i}$ is defined. This price must be determined independently of i's declared type $\tilde{\theta}_i$, but it might be dependent on the declared types of other bidders.*
- *We assume $p_{\emptyset,i} = 0$ holds. Also, if $B \subseteq B'$, then $p_{B,i} \leq P_{B',i}$ holds.*
- *For bidder $i$, a bundle $B^*$ is allocated where $B^* = \arg\max_{B \subseteq M} v(B, q(B), \tilde{\theta}_i) - p_{B,i}$. Bidder $i$ pays $p_{B^*,i}$. If multiple bundles exist that maximize $i$'s utility, one of these bundles is allocated.*
- *The result of the allocation satisfies allocation-feasibility. For two bidders $i$, $j$, and the bundles allocated to these bidders $B_i^*$ and $B_j^*$, $B_i^* \cap B_j^* = \emptyset$ holds.*

A PORF protocol is strategy-proof since the price of bidder $i$ is determined independently of $i$'s declared type, and he/she can obtain the bundle that maximizes his/her utility independently of the allocations of other bidders. The protocol is ration-free.

## 3.2. A Strategy-Proof Protocol for Experts $\rightarrow$ PORF protocol

The PORF protocol is very general. Thus, we can design any protocol that is strategy- proof for experts.

**Definition 3 (A PORF protocol on Experts)** *For player i who declares he/she is an expert, the price $p$ of each bundle $B$ is defined. Price $p$ does not depend on the quality or the evaluation value declared by player $i$. Using the defined prices, based on $i$'s evaluation value of his/her declared quality, the bundle that maximizes $i$'s utility is assigned to player $i$.*

**Theorem 1 (A Strategy-Proof Protocol for Experts $\rightarrow$ PORF protocol)** *Any protocol in which truth-telling is a dominant strategy for experts can be described as a PORF protocol for experts.*

**Proof** The strategy-proof protocol can be represented as $\pi(\theta, q) = (B, p)$, where $\theta$ is the type of expert $i$. The symbol $q$ is the declared quality. First, we prove that if $B$ is the same, the price is the same. We derive a contradiction assuming $\pi(\theta, q) = (B, p)$, $\pi(\theta', q') = (B, p')$, and $p' < p$. In this case, when an expert who knows his/ her true type is $\theta$ and true quality is $q$ declares falsehood that his/her type is $\theta'$ and the quality is $q'$, the expert makes a profit since he/she can win the same item with a lower price. This contradicts the assumption that in $\pi$, for experts, truth-telling is a dominant strategy.

Thus, we can represent the protocol as $\pi(\theta, q) = (B, p(B))$.

Then, we prove that $\pi$ is a price-oriented protocol, because for any $\theta$, $\pi(\theta, q) = (B, p(B))$, where $B = \arg\max_B u_i(B, q(B), \theta_i) - p(B)$ and $(B, p(B)) \in \bigcup_{\theta,q} \pi(\theta, q)$, holds. Namely, we prove that the protocol assigns bundle $B$ to player $i$, who maximizes his/her bundle under the bundle's price $p(B)$. We derive a contradiction assuming that such a protocol does not exist. Namely, we assume that $\pi(\theta', q') = (B', p(B'))$ and $u_i(B, q(B), \theta_i) - p(B) < u_i(B', q(B'), \theta_i) - p(B')$ holds. In this case, if an expert who knows that his/her true type is $\theta$ and that the true quality is $q$ declares truthfully, then his/her utility is $u_i(B, q(B), \theta_i) - p(B)$. If the expert declares falsely that his/her type is $\theta'$ and the quality is $q'$, then his/her utility is $u_i(B', q(B'), \theta) - p(B')$. There is a benefit when the expert declares falsely. This contradicts the assumption that $\pi$ is strategy-proof. □

### 3.3. Proposed Protocol

Our new auction protocol is defined as follows.

- Each bidder $i$ declares his/her type $\tilde{\theta}_i$, which is not necessarily true.
- For each bidder $i$ and for each bundle $B \subseteq M$, the price $p_{B,i}$ is defined as follows:

  For expert $i$, the price $p_{B,i}$ for a bundle $B$ is defined as follows:

  $p_{B,i} = \max_{j,B'} v(B', q(B'), \theta_j)$, where $v(B', q(B'), \theta_j)$ is another bidder $j$'s evaluation value for bundle $B'$. $B'$ is a minimal bundle (defined in definition 1), and $B' \cap B \neq \emptyset$.

  When bidder $j$ is an expert, then the evaluation value of bundle $B$ is utilized for calculating $i$'s price which is based on $j$'s submitted evaluation values and qualities.

  When bidder $j$ is an amateur, for each item, if one or more experts (besides $i$) declare that the item is genuine, then it is judged genuine for $j$. If no expert declares it genuine, then the item is judged an imitation for $j$. Then, the evaluation value of bundle $B$ is utilized for calculating $i$'s price based on the above qualities and his/her submitted evaluation values.

  For amateur $i$, the price $p_{B,i}$ is defined as follows:

  $p_{B,i} = \max_{j,B'} v(B', q(B'), \theta_j)$, where $v(B', q(B'), \theta_j)$ is another bidder $j$'s evaluation value for bundle $B'$. $B'$ is a minimal bundle (defined in definition 1), and $B' \cap B \neq \emptyset$.

  When bidder $j$ is an expert, then the evaluation value of bundle $B$ is utilized for calculating $i$'s price based on his/her submitted evaluation values and qualities.

  When bidder $j$ is an amateur, for each good, if one or more experts declares it genuine, then the item is judged genuine for $j$. If no expert declares the item genuine, then it is judged to be an imitation for $j$. Then, the evaluation value of bundle $B$ is utilized for calculating $i$'s price based on the above qualities and his/her submitted evaluation values.

  (Exceptional case) When bundle $B$ includes an item that only one expert has declared genuine, the price of the bundle $B$ is $\infty$. This gives an incentive to experts to reveal that they are experts, helping to discourage experts from pretending to be amateurs.
- We assume $p_{\emptyset,i} = 0$ holds. Also, if $B \subseteq B'$, $p_{B,i} \leq P_{B',i}$ holds.
- For bidder $i$, a bundle $B^*$ is allocated where $B^* = \arg\max_{B \subseteq M} v(B, q(B), \tilde{\theta}_i) - p_{B,i}$. Here, the bundle $B$ in $v(B, q(B), \tilde{\theta}_i)$ is selected based on the quality of each item. If $i$ is an expert, his/her declared qualities are selected. If $i$ is an amateur, the quality of an item is genuine if one or more experts declares it genuine, and an item is considered an imitation if there is no expert declares that it is genuine. Bidder $i$ pays $p_{B^*,i}$. If multiple bundles exist that maximize $i$'s utility, one of them is allocated.

### 3.4. Examples

Tables 1 and 2 show an example of our proposed protocol. We assume there are two experts, $e_1$ and $e_2$, and one amateur, $a_1$. Also, there are 2 items, 1 and 2. Bundles with qualities are $\{1{:}q_R\}$, $\{1{:}\ q_I\}$, $\{2{:}\ q_R\}$, $\{2{:}\ q_I\}$, $\{1{:}q_R, 2{:}q_R\}$,$\{1{:}q_R, 2{:}q_I\}$,$\{1{:}q_I, 2{:}q_R\}$, and $\{1{:}q_I, 2{:}q_I\}$. Table 1 presents evaluation values of the bundles. Based on these evaluation values, the protocol chooses the price of each bundle for each player as shown in the left of Table 2. Based on evaluation values and prices, utilities are calculated as shown in the right of Table 2. The procedure to calculate $e_1$'s price of $\{1\}$ is as follows. First, $e_2$'s and $a_1$'s minimal bundles are $\{$1,2$\}$. Then, the $e_1$' s price of $\{1\}$ is 600, since $e_2$'s and $a_1$'s evaluation values are 600 and 100 for the minimal bundle, and $\{1\}$ is included in $\{$1,2$\}$. Note that $a_1$ considers both 1 and 2 genuine when $e_1$ does not exist. Thus, $a_1$'s evaluation value of $\{$1,2$\}$ is 100 (for $\{1 : q_R, 2 : q_R\}$). Similarly, $e_2$'s price of $\{1\}$ is 800, since $e_1$'s and $a_1$'s evaluation values for $\{$1,2$\}$ are 800 and 100, respectively. Note that $a_1$ considers both 1 and 2 genuine when $e_2$ does not exist. The maximum value is 800. Thus, $e_2$'s price of $\{1\}$ is 800. Based on these prices, we can calculate utilities for each bundle. The right half of Table 2 shows the utility for players. Consequently, $e_1$ achieves the bundle $\{$1,2$\}$.

Tables 3 and 4 show a second example of our proposed protocol. Here, we create a case in which an amateur needs to employ the exceptional case in the protocol. Table 3

| | {1:$q_R$} | {1: $q_I$} | {2: $q_R$} | {2: $q_I$} | {1:$q_R$, 2:$q_R$} | {1:$q_R$, 2:$q_I$} | {1:$q_I$, 2:$q_R$} | {1:$q_I$, 2:$q_I$} |
|---|---|---|---|---|---|---|---|---|
| $e_1$ | 300 | - | 400 | - | 800 | - | - | - |
| $e_2$ | 100 | - | 500 | - | 600 | - | - | - |
| $a_1$ | 50 | 10 | 50 | 30 | 100 | 80 | 60 | 40 |

**Table 1. Example 1: Evaluation Values**

| | {1} | {2} | {1, 2} | | {1} | {2} | {1, 2} |
|---|---|---|---|---|---|---|---|
| $e_1$ | 600 | 600 | 600 | $e_1$ | 0 | 0 | 200 |
| $e_2$ | 800 | 800 | 800 | $e_2$ | 0 | 0 | 0 |
| $a_1$ | 800 | 800 | 800 | $a_1$ | 0 | 0 | 0 |
| | Prices | | | | Utilities | | |

**Table 2. Example 1: Prices and Utilities**

presents evaluation values for bundles. Based on these evaluation values, the protocol decides the price of each bundle for each player. Prices are shown on the left of Table 4. For example, the following is the decision procedure of $e_1$'s price of each bundle. First, $e_2$'s and $a_1$'s minimal bundles are {1,2}. Second, $e_1$' s price of {1} is 150 since $e_2$'s and $a_1$'s evaluation values are 150 for the minimal bundle and {1} is included in {1,2}. Note that $a_1$ considers 2 an imitation when $e_1$ does not exist. Thus, $a_1$'s evaluation value of {1,2} is 150 (for $\{1 : q_R, 2 : q_I\}$). Similarly, $e_2$'s price of {1} is 300 since $e_1$'s and $a_1$'s evaluation values for {1,2} are 300 and 190, respectively. Note that $a_1$ considers 2 genuine when $e_2$ does not exist. The maximum value is 300. Thus, $e_2$'s price of {1} is 300. Based on these prices, we calculate utilities for each bundle. The right half of Table 4 shows the utility for players. Consequently, $e_1$ achieves bundle {1,2}.

| | {1} | {2} | {1, 2} | | {1} | {2} | {1, 2} |
|---|---|---|---|---|---|---|---|
| $e_1$ | 150 | 150 | 150 | $e_1$ | 0 | 0 | 150 |
| $e_2$ | 300 | 300 | 300 | $e_2$ | 0 | 0 | 0 |
| $a_1$ | 300 | $\infty$ | $\infty$ | $a_1$ | 0 | 0 | 0 |
| | Prices | | | | Utilities | | |

**Table 4. Example 2: Prices and Utilities**

## 4. Features of the Protocol

**Theorem 2 (Dominant Strategy for Experts)** *For experts, truth telling is a (weak) dominant strategy.*

**Proof** For experts, the prices of bundles do not depend on their declared qualities and evaluation values. Thus, their utilities do not increase how they declare falsehood on their qualities and evaluation values either. Even if an expert pretends to be an amateur and the case is the exceptional, the price becomes $\infty$. If not, the price does not change. □

**Theorem 3 (Allocation Feasibility)** *The result of the allocation by the protocol satisfies allocation feasibility.*

**Proof** For items that two or more experts declare genuine, and for items that no expert declares genuine, we can prove that it is impossible for two or more players to win the same bundle. If one or more bids are submitted to a bundle, the bid that has the largest evaluation value wins. There is no contradiction on the quality of items for each player. This means that there is no situation in which experts calculate their own evaluation values with different judged qualities of the same item. The player who wins the bundle maximizes his/her utilities on the bundle and has the largest evaluation value on the bundle. Thus, the other players cannot maximize their utilities on the bundle. Alternatively, the other players can maximize their utilities on the bundle, but their evaluation values are smaller than the winner's evaluation value. Therefore, there is no case in which two or more players (contradictorily) win the same bundle.

If there is an item that only one expert declares genuine, then only experts have a chance to win it. Namely, there is no chance for amateurs. If one or more bids are submitted to the bundle, the bid that has the largest evaluation value wins. There is no contradiction on the quality of items for each expert.

□

**Theorem 4 (Ex-post Equilibrium for Amateurs)** *For amateurs, truth telling is the best response if two or more experts select dominant strategies for a good.*

**Proof** Since two or more experts select dominant strategies for an item, there is no chance to select the exception. Thus, there is no profit in an amateur pretending to be an expert. For amateurs, the prices of bundles do not depend on their declared evaluation values. Thus, their utilities do not increase how they declare falsehood on their evaluation values. □

**Theorem 5 (False-Name Proof)** *The protocol is false-name proof.*

**Proof** (Outline) We can prove this in the same way as the symmetric version [13][15]. Due to space limitations, we omit the details of the proof.

| | {1:$q_R$} | {1: $q_I$} | {2: $q_R$} | {2: $q_I$} | {1:$q_R$, 2:$q_R$} | {1:$q_R$, 2:$q_I$} | {1:$q_I$, 2:$q_R$} | {1:$q_I$, 2:$q_I$} |
|---|---|---|---|---|---|---|---|---|
| $e_1$ | 100 | - | 100 | - | 300 | - | - | - |
| $e_2$ | 100 | - | - | 50 | - | 150 | - | - |
| $a_1$ | 80 | 50 | 110 | 70 | 190 | 150 | 160 | 120 |

**Table 3. Example 2: Evaluation Values**

# 5. Discussion

## 5.1. Efficiency of Allocation

We cannot guarantee that our protocol (or the PORF protocol) realizes efficient allocation. The following is an example in which our protocol failed to achieve efficient allocation. To simplify the discussion, we assume that each expert selects his/her dominant strategy. Each amateur also selects his/her best response. Furthermore, for simplicity, we assume that there are two items, 1 and 2, and that their quality is genuine.

Table 5 shows evaluation values. Here, $e_2$ wins bundle $\{1\}$. $e_1$ does not have a chance to win. Thus, $\{2\}$ is not assigned to any player. The social surplus is 9. Here, our protocol fails to allocate the items efficiently. On the other hand, in VCG, $\{1\}$ is assigned to $e_2$, $\{2\}$ is assigned to $e_1$, social surplus is 17, and the goods are efficiently assigned to players.

| | {1} | {2} | {1, 2} |
|---|---|---|---|
| $e_1$ | 6 | 8 | 8 |
| $e_2$ | 9 | 10 | 10 |

**Table 5. Failure of Efficient Allocation**

Here, the problem is caused because it is difficult for our protocol to handle situations in which one player has the maximum evaluation values for two or more substitutional items. In this case, our protocol tries to assign both of the items to the player. However, the player does not need both of the substitutional goods. Thus, the social surplus decreases. Although VCG cannot realize strategy-proof protocol for experts, it can handle the above case.

In fact, the above case is very exceptional. Thus, we show that the difference in social surplus between our new protocol and the VCG protocol is small. We conducted the following experiment to present the difference in social surplus between our new protocol and VCG. In the experiment we assumed that each expert selects his/her dominant strategy. Also, each amateur selects his/her best response. Thus, there is no chance that an exceptional case occurs. Furthermore, for simplicity, we assume that there are two items, 1 and 2, and that the quality of all items is genuine.

In our protocol, we expect that the social surplus will vary according to the probability that the items are substitutional. In this experiment, we present how the social surplus of our protocol and VCG changes according to the probability that the items are substitutional. We determine the evaluation values of agent $i$ by the following method utilized in [14].

- Determine whether the items are substitutional or complementary for agent $i$; with probability $p$, the items are substitutional, and with probability $1 - p$, the they are complementary.
  - When the items are substitutional, randomly choose evaluation value of each item from within a range of $[0, 1]$ based on uniform distribution. The evaluation value of the set is the maximum of the evaluation value of A and that of B ( having only one item is enough).
  - When the items are complementary, the evaluation value of A or B is 0. Randomly choose the evaluation value of the set from within the range of $[0, 2]$ (all- or-nothing).

Figure 1 shows an experimental result where the number of players was 10. We created 1,000,000 different problems and showed the average of the social surplus by varying the probability that the items are substitutional. For comparison, we show the surplus of the VCG, i.e., the Pareto efficient social surplus.

When the probability that the items are substitutional is 0, i.e., items are complementary, and the social surplus of our protocol is identical to VCG. Even when the probability that the items are substitutional is 1.0, the social surplus of our protocol is 95% of VCG.

## 5.2. Impossibility of Pareto Efficient Protocol

The proposed protocol does not guarantee a Pareto efficient allocation. However, no protocol guarantees a Pareto efficient allocation.

**Theorem 6 (Impossibility of Pareto Efficient Protocol)** *No protocol guarantees a Pareto efficient allocation and satisfies strategy-proof for experts, even if two or more experts exist against all items.*

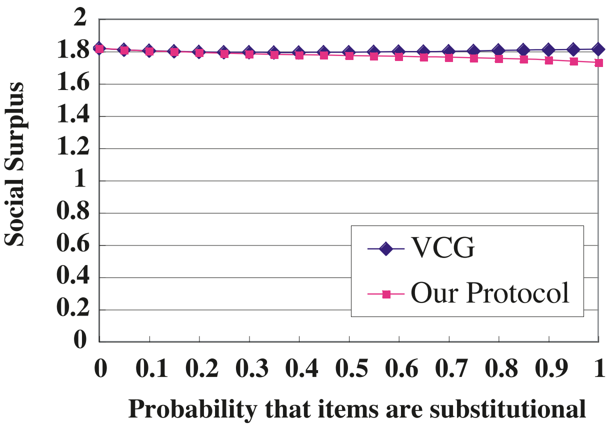


**Figure 1. Experimental Results**

**Proof** We derive a contradiction assuming that there exists a protocol that can guarantee a Pareto efficient allocation and that is strategy-proof for experts when two or more experts exist against all items. Assume that there are two items, 1 and 2, and the item 2 is genuine. There are two experts, $e_1$ and $e_2$, and one amateur, $a_1$. Each player declares the evaluation values in Table 6.

| | $\{1{:}q_R\}$ | $\{1{:}q_I\}$ | $\{2{:}q_R\}$ | $\{1{:}q_R, 2{:}q_R\}$ | $\{1{:}q_I, 2{:}q_R\}$ |
|---|---|---|---|---|---|
| $e_1$ | 6 | 5 | 6 | 6 | 6 |
| $e_2$ | 0 | 0 | 0 | 12 | 11 |
| $a_1$ | 7 | 0 | 5 | 7 | 5 |

**Table 6. Counter-example**

If item 1 is an imitation, in a Pareto efficient allocation, both items are assigned to $e_2$, and the VCG payment is 10. If item 1 is genuine, in a Pareto efficient allocation, item 1 is assigned to $a_1$, and item 2 is assigned to $e_1$. The VCG payments are 6 for $a_1$ and 5 for $e_1$. The contradiction can be derived when the experts' opinions are different. From the point of view of mechanism design, we need to consider the following:

First, let us discuss $e_1$'s price. To realize a Pareto efficient allocation, if item 1 is genuine, we need to adjust the pricing mechanism. When $e_2$ declares that item 1 is real (since item 1 is real), for $e_1$ the price of item2 is less than 5, since as long as $e_1$'s evaluation value is more than 5, a Pareto efficient allocation does not change. Also, the price of other items needs to be high enough that $e_1$ wins item 2.

Now, let us consider the $e_2$'s price. To realize a Pareto efficient allocation, if item 1 is an imitation, we need to adjust the pricing mechanism. When $e_1$ declares that item 1 is an imitation, for $e_2$ the price of the bundle $\{1,2\}$ is less than 10. Also, the price of other items needs to be high enough that $e_2$ wins the bundle $\{1,2\}$.

When $e_1$ declares that item 1 is an imitation and $e_2$ declares that it is genuine, $e_1$'s price for item 2 is less than 5, and $e_2$'s price for the bundle $\{1,2\}$ is less than 10. Namely, while $e_1$ prefers to win item 2, $e_2$ prefers to win bundle $\{1,2\}$. Thus, the protocol cannot satisfy allocation feasibility. □

### 5.3. Revising the Earlier Auction Protocols

We can improve the earlier auction protocols [6][7] by utilizing a PORF protocol. In previous works, we proposed a single unit auction protocol among experts and amateurs[6], and a combinatorial auction protocol among single-skilled experts and amateurs[7]. In protocol [6], the number of level of quality is 2 to n. Also, in protocols [6][7], we assumed the existence of irrational players who do not adopt rational strategies. These earlier protocols [6][7] employed the upper values or dummy players in [7] for imitations. When the auctioneer fails to set a suitable upper value and there is no evaluation value of a real item under the upper limit, there is the possibility that items cannot be efficiently allocated. By utilizing a PORF protocol, we can construct protocols that do not need an upper limit and that can handle multiple levels of quality and irrational players. Due to the space limitations, we only show the case a single-unit auction which can be also applied to a combinatorial auction among single-skilled experts and amateurs [7].

*Case of a Single-unit Auction:* The number of item is 1 with two levels of quality: genuine and imitation.

The value of a bid for an expert is determined as follows: When one or more experts declares that the item is genuine, the price is defined as the maximum value among the amateurs' evaluation values for real and experts' evaluation values for the qualities they declare. When there is no expert who declares that the item is genuine, the price is defined as the maximum value among evaluation values for an imitation.

The value of a bid for an amateur is determined as follows: When two or more experts declare that an item is genuine, the price is defined as the maximum value among amateurs' evaluation values for real and experts' evaluation values for the qualities they declare. When only one expert declares that the item is genuine, the price is $\infty$. When no expert declares that the item is genuine, the price is defined as the maximum value among evaluation values for an imitation.

By using this system, the protocol allocates an item to a bidder who is willing to buy the items at that price. For an expert, the protocol uses the evaluation value for the qual-


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ity he declares. For an amateur, we use the evaluation value for genuine items if there exists at least one expert who declares that the item is genuine. Otherwise, we use the evaluation value for imitations.

This protocol satisfies allocation feasibility since only one bidder has a positive utility by obtaining the item. Also, for an expert, truth-telling becomes a dominant strategy because his price is determined independently from his declared value and quality. Furthermore, an expert has no incentive to pretend to be an amateur since his price increases. If more than two experts use this dominant strategy, the allocation is Pareto efficient.

## 6. Related Work

We have been designing auction protocols under asymmetric situations. Maskin[10][2][8], whose work is close to our approach, first demonstrated the impossibility of efficient allocation if buyers have multi-dimensional information and interdependent values. Dasgupta and Maskin [2] showed a very strong necessary condition for allocating efficiently under multi-dimensional information and interdependent values. Krishna claims that this condition is rarely satisfied (Chapter 17.2 in [8]). This means that designing an efficient auction protocol is almost impossible if buyers have multi-dimensional information and interdependent values.

Maskin's formalization is very general and can formalize the situation handled in this paper when a single item is auctioned. He presented impossibility results of general cases. We are dealing, however, with a special case in which one signal (type) is fully independent but anther signal (quality) is totally correlated. Our setting provides a special case that can avoid Maskin's impossibility results, yet retaining enough generality to formalize realistic situations. We are currently investigating how our results can be further generalized while avoiding the impossibility results.

## 7. Conclusions

In this paper, we designed a combinatorial auction protocol among **versatile** experts and amateurs. Versatile experts have an interest in and expert knowledge of the qualities of several items. In [6] we found a free-rider problem in versatile experts. Thus, in this paper, we utilized a PORF protocol to realize our new protocol which has several advantageous features: (1) For experts, truth-telling is the dominant strategy. (2) For amateurs, truth-telling is the best response if two or more experts select a dominant strategy. (3) The protocol is false-name proof.

In this paper we showed that the difference between the social surplus of VCG and our protocol is quite small. We also proved that no protocol guarantees a Pareto efficient allocation and satisfies the strategy-proof condition for experts when multiple experts exist against all items. Then, by using the PORF protocol, we revised our previous asymmetric auction protocols so that they did not need to employ upper limits.

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