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**Unbundling Truthful Revelation when  
Auctioning Bundled Goods**

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# Unbundling Truthful Revelation when Auctioning Bundled Goods\*

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## Abstract

We study truthful revelation when a seller auctions bundles of goods and is interested in learning the buyer's valuations for each individual good. We generalize the auction rules for the Becker-DeGroot-Marschak mechanism and the Vickrey auction to induce truthful revelation.

*Keywords:* Auction; truthful revelation; Becker-DeGroot-Marschak mechanism; Vickrey auction.

*JEL Classification:* D44, D47, Q23, Q28.

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# 1 Introduction

This paper proposes auction rules to sell bundles of goods when the seller wants to learn the buyer's valuations for each good in the bundles. Truthful revelation is important in a number of situations. For example, the seller may wish to use the information obtained on the value of the goods in other markets, for internal transactions, policy evaluation, or to design subsequent auctions. The research question was in fact posed in the context of public timber sales where data from auctions is used to estimate the parameter values of forestry economics models, and provide benchmarks for other lots sold elsewhere at fixed prices. Similar needs exist in procurement auctions when a buyer outsources complex projects that involve multiple components (e.g. design, engineering, production and installation). We study sales to a single buyer using a generalization of the Becker-DeGroot-Marschak (BDM) mechanism (Becker et al. 1964), as well as to multiple buyers in a Vickrey auction (Vickrey 1961). We show that with appropriate modifications, both mechanisms can achieve truthful revelation of the value of each good in the bundle.

## 2 Model

A seller auctions bundles of  $N$  goods. Each bundle is denoted by quantity vector  $Q' = (q_1, \dots, q_N)$  where  $q_n \geq 0$  is the quantity of good  $n$  and the prime symbol denotes the transpose operator. The composition of these bundles may be exogenously given or chosen by the seller. In both interpretations, the bundles are fixed for the auction and cannot be unbundled or divided by buyers. This is the case, for example, in many timber auctions where once the lot boundaries are determined, separation of species is impractical or too costly. Lot boundaries, however, could be exogenous (e.g. constrained by geography) or a choice variable. The seller may offer a single or multiple bundles  $Q'_k = (q_{k,1}, \dots, q_{k,N})$  for  $k = 1..K$ .

A buyer has a private value vector  $v' = (v_1, \dots, v_N)$  where  $v_n$  denotes the per-unit willingness to pay for good  $n$ . The buyer is thus willing to pay  $\bar{v}_k \equiv Q'_k v$  for bundle  $Q_k$ . Linearity simplifies the analysis but rules out, for example, complementarity between quantities  $q_{k,n}$  and  $q_{k',n'}$ . Vectors of private values are drawn from a distribution with full support over the  $N$ -dimension space  $V = \Pi_{n=1}^N [v_{0,n}, v_{1,n}]$  where  $v_0 \ll v_1$  and  $v_i = (v_{i,0}, \dots, v_{i,N})$  for  $i \in \{0, 1\}$ .  $S = [Min_k Q'_k v_0, Max_k Q'_k v_1]$  is the resulting support for bundle values. The objective is to develop a mechanism that truthfully



reveals the buyer's valuation  $v$ .

### 3 Single Bundle ( $K = 1$ ): No Truthful Revelation

When a single bundle is offered, truthful revelation of  $v$  as a strictly dominant strategy is not possible.

**Proposition 1.** *There is no direct truthful mechanism that reveals  $v$  in strictly dominant strategy.*

*Proof:* A direct mechanism is denoted  $(x(b), t(b))$  where the buyer sends signal  $b \in V$  and the functions  $x()$  and  $t()$  map  $b$  respectively into a probability to obtain the bundle and a transfer to the seller.

Assume the buyer has valuation  $v$ . Let  $IC(v, \tilde{v})$  denote the incentive compatibility constraint ensuring that buyer type  $v$  truthfully reports  $b = v$  instead of  $\tilde{v} \in V$

$$x(v)Q'v - t(v) \geq x(\tilde{v})Q'v - t(\tilde{v}) \tag{1}$$

Take a pair of valuations  $(v, \tilde{v})$  such that  $Q'v = Q'\tilde{v}$ . Such a pair exists since the distribution of  $v$  has full support on  $V$ . From (1), the two incentive compatibility constraints  $IC(v, \tilde{v})$  and  $IC(\tilde{v}, v)$  imply

$$x(v)Q'v - t(v) = x(\tilde{v})Q'v - t(\tilde{v}).$$

Thus, buyer type  $v$  is indifferent between revealing  $v$  or  $\tilde{v}$ . QED

The only relevant issue to the buyer is the value and price of the bundle as a whole. Nothing in the problem provides incentives to consider individual goods separately.

It is possible to reveal  $v$  as a weakly dominant strategy. We demonstrate this point using a modified BDM where the buyer bids vector  $b \in (\mathfrak{R}^+)^N$  and the seller draws a random value  $r$  with CDF  $G()$ , PDF  $g()$  and support  $R$  such that  $S \subsetneq R$ . Any bid  $b \notin S$  can be ignored because there exist a  $b' \in S$  that dominates  $b$ . For bid  $b \in S$ , the buyer wins the bundle and pays  $r$  when  $Q'b \geq r$ .

The buyer maximizes:

$$\int_0^{Q'b} (Q'v - r) dG(r).$$

The FOC for  $b_n$  gives:

$$Q'(v - b)q_n g(Q'b) = 0.$$

When  $q_n > 0$ , the FOC simplifies to  $Q'(v - b) = 0$  which is independent of  $n$ . Any bid such that  $Q'b = Q'v = \bar{v}$  is weakly dominant. As previously indicated, individual bids on goods do not matter as long as the total bid equals the value of the bundle. Therefore, the mechanism can only reveal the bidder's aggregate valuation  $\bar{v}$ ; not her vector of valuations  $v$ .

## 4 Truthful Revelation with Generalized BDM (GBDM)

We now consider a simple extension of the BDM with multiple bundles in order to establish truthful revelation as a strictly dominant strategy.

**Definition 1.** *In a GBDM, the buyer bids  $b \in (\mathfrak{R}^+)^N$ . The seller draws a random price  $r$  with CDF  $G()$ , PDF  $g()$  and support  $R$  such that  $S \subsetneq R$ . The bidder receives bundle  $k$  and pays  $r$  if  $Q'_k b \geq r$ .*

The same bid vector and price are used to allocate *all* bundles.

**Proposition 2.** *The GBDM achieves truthful revelation of  $v$  in strictly dominant strategy as long as there are  $K \geq N$  linearly independent bundles.*

*Proof:* A buyer who bids  $b$  obtains bundle  $k$  if  $Q'_k b \geq r$ . As above, we ignore any  $b \notin S$ . The bidder's profits from placing bid  $b \in S$  is

$$\sum_k \int_0^{Q'_k b} (Q'_k v - r) dG(r)$$

The first order condition with respect to  $b_n$  gives

$$\sum_k \alpha_k Q'_k (v - b) q_n^k g(Q'_k b) = 0$$

which can be written together in matrix form as

$$\left( \sum_k g(Q'_k b) Q_k Q'_k \right) (v - b) = 0 \tag{2}$$

Denote  $\tilde{Q}_k = g(Q'_k b)^{1/2} Q_k$  and  $X = (\tilde{Q}_1, \dots, \tilde{Q}_K)$  so that (2) becomes

$$XX'(v - b) = 0.$$

Since  $b \in R$ , we have  $g(Q'_k b) > 0$  and matrix  $X$  is of rank  $N$  if there are  $K \geq N$  linearly independent bundles. When this is the case, matrix  $XX'$  is also of rank  $N$  and the unique solution to the  $N$  first order conditions is  $b = v$ . QED

The GBDM is strongly incentive compatible because it is always optimal to submit a total bid equal to the total value for each bundle, and with  $K \geq N$  linearly independent bundles, the unique solution achieving this goal is to submit a truthful bid for each good.

The statement in Proposition 2 can be generalized in a number of ways. First, if there are only  $K < N$  linearly independent bundles, the seller can reveal  $K$  linear combinations of the goods' prices. This matters to an auctioneer who cares only about the value of a few relevant bundles. Second, the proposition follows under the alternative scheme where the auctioneer draws a random vector of per-unit prices  $r \in R'$  such that  $V \subsetneq R'$  (instead of a single bundle price) and allocates bundle  $k$  if  $Q'_k b \geq Q'_k r$ . Doing so, the auctioneer can set random prices that better describe the assessed value of each bundle. Finally, the auctioneer does not always have to actually proceed with the sale of all of the  $K$  bundles offered at auction. The bundles could be presented to the buyer with arbitrarily small probabilities that the sale will proceed. This may be a useful design feature or necessary, for example, if the physical quantities in the bundles are not mutually exclusive quantities. For instance, a seller interested in the value of two tree species on a single piece of land could offer two bundles, each allowing for the harvesting of different quantities of each of the types of trees. Once the bid is received, the seller would then randomly select which of the two bundles is actually auctioned off.

## 5 Truthful Revelation with Vickrey Auctions

$M > 1$  bidders with i.i.d. valuation vectors  $v_m$ , for  $m = 1, \dots, M$  each submit a bid  $b'_m = (b_{1,m}, \dots, b_{N,m})$ . Denote  $\hat{B}$  the highest bid value, that is,  $\hat{B} = \text{Max}_m Q' b_m$ , and  $\hat{\hat{B}}$  the second highest value. In a Vickrey auction, the bidder who bids  $\hat{B}$  wins the bundle and pays  $\hat{\hat{B}}$ . A similar argument as the one presented in Proposition 1 shows that it is a weakly dominant strategy for

bidder  $m$  to reveal any  $b$  such that  $Q'b = Q'v_m$ . In contrast with the one-good dimensional case, there is a continuum of Nash equilibria in weakly dominant strategy. Truthful revelation is only one equilibrium. We extend the analysis to multiple bundles to demonstrate the possibility of eliminating all Nash equilibria in weakly dominant strategy other than the truthful one.

**Definition 2.** *In a generalized Vickrey auction, each buyer bids vector  $b \in (\mathbb{R}^+)^N$ . The bidder with bid  $\hat{B}_k$  receives bundle  $k$  and pays  $\hat{B}_k$ . Ties are broken by random allocation.*

**Proposition 3.** *Assume there are  $K \geq N$  linearly independent bundles. In a random Vickrey auction, truthful revelation is the unique weakly dominant strategy for all bidders.*

*Proof:* Consider a bidder with valuation  $v_m$  who bids  $b_m$ . Take bundle  $k$ . Let  $\bar{v}_{k,m} = Q'_k v_m$  and  $V_{k,m} = \{x : Q'_k x = \bar{v}_{k,m}\}$ . The standard argument that truthful revelation is a weakly dominant strategy in the scalar case (see, for example, Proposition 1 in Levin (2004)) applies here in the following sense: the set of weakly dominant strategies in auction  $k$  is  $V_{k,m}$ . This holds for all  $k = 1..K$ . The set of bidder  $m$ 's weakly dominant strategy is  $\bigcap_{k=1}^{k=K} V_{k,m}$ . When there are  $K \geq N$  linearly independent bundles, we have  $v_m = \bigcap_{k=1}^{k=K} V_{k,m}$ . QED

The Proposition implies that there exists a unique Nash equilibrium in weakly dominant strategy.<sup>1</sup>

## 6 Summary

The paper derives three results:

1. An impossibility theorem stating that truthful revelation of each goods' valuation is *not* possible in strictly dominant strategies when the seller offers a single bundle containing multiple goods;
2. Proofs that when  $K \geq N$  linearly independent bundles are offered, truthful revelation of each goods' valuation can be achieved:
  - (a) as a strictly dominant strategy in a generalized BDM; and
  - (b) as the unique equilibrium in weakly dominant strategies in a Vickrey auction.

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<sup>1</sup>There may also exist other equilibria that do not involve weakly dominated strategies (Blume and Heidhues 2004).

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