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Optimal auctions with multidimensional types and the desirability of exclusion

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Abstract

Within the context of a single-unit, independent private values auction model, we show that if bidder types are multidimensional, then under the optimal auction exclusion of some bidder types will occur. A second contribution of the paper is methodological in nature. In particular, we identify conditions under which an auction model with multidimensional types can be reduced to a model with one dimensional types without loss of generality. Reduction results of this type have achieved the status of folklore in the mechanism design literature. Here, we provide a proof of the reduction result for auctions.
Keywords: Optimal Auctions, Type Exclusion, Multidimensional Types.

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1 Introduction

Many results in the mechanism design literature rely heavily upon the assumption that private information is one-dimensional. What are the consequences for optimality if private information is multidimensional? The main contribution of this paper is to show that, for the case of a single-unit auction model with independent private values, if private information (in the form of bidder types) is multidimensional, then the exclusion of types is a necessary condition for optimality of the auction mechanism (see Theorem 2). A similar type of result was gotten by Armstrong in his paper on nonlinear pricing for multiproduct monopolists. In particular, Armstrong (1996) showed that if consumer utility is increasing in all arguments (i.e., in the goods vector *and* in the types vector) and convex and homogeneous of degree one in the types vector and if the set of consumer types is strictly convex with dimension greater than one, then under the optimal nonlinear pricing mechanism a set of types with positive measure will not be served (i.e., will be excluded) by the monopolist. Our main result, which requires neither convexity and homogeneity of utility with respect to types nor strict convexity of the set of types, suggests that in a wide variety of auction environments type exclusion may be general property of optimality whenever multidimensional private information is present.

The second contribution of our paper is methodological in nature. In particular, we identify conditions under which an auction model with multidimensional types can be reduced to a one-dimensional model without loss of generality. Reduction results of this type are well-known in the mechanism design literature, and are often used without proof. Here, we provide a proof of the reduction result for independent private values auctions (see Theorem 1).

2 The model

There is one object to be sold at an auction with n bidders. The i^{th} bidder bases his valuation of the object on a multidimensional parameter

$$t_i \in T = \Pi_{j=1}^{m} [a_j, b_j] \subset \mathbb{R}^m,\ m > 1$$

which summarizes his private information. We shall refer to t_i as the i^{th} bidder's type, and we shall assume that the i^{th} bidder's type t_i is distributed according to a continuous probability density $f_i : T \rightarrow \mathbb{R}_{++}$. Thus, for every (Borel) subset of types $B \subset T$, the probability that bidder i has type t_i

contained in B is given by

$$P_i(B) := \int_B f_i(t)\, d\lambda(t),$$

where λ is the Lebesgue measure on T. Bidder i values the object according to the function

$$U^i : T \to \mathbb{R}.$$

Thus, if bidder i has private information $t_i \in T$, then the value or utility that the i^{th} bidder assigns to the object is $U^i(t)$. We shall assume that the function U^i is continuously differentiable. Since the i^{th} bidder's utility function U^i is real-valued and continuous, the range of utilities (or valuations), denoted by $U^i(T)$, is given by some closed bounded interval $[\alpha_i, \beta_i]$. We shall assume the following:

Density Assumption: The distribution function

$$F_i^u(x) = P_i\left\{t \in T : U^i(t) \leq x\right\} = \int_{\{t \in T : U^i(t) \leq x\}} f_i(t)\, d\lambda(t),$$

induced by the i^{th} bidder's utility function U^i has a continuous density $f_i^u(\cdot)$ such that $f_i^u(x) > 0$ for all $x \in (\alpha_i, \beta_i)$.

The *density assumption* will be satisfied for bidder i if for every bidder type $t \in T$, the vector of partial derivatives (i.e., the gradient vector) is such that,

$$\nabla U^i(t) = \left(\frac{\partial U^i}{\partial t_1}(t), \ldots, \frac{\partial U^i}{\partial t_m}(t)\right) \neq 0.$$

For a proof, see Hoffmann-Jørgensen (1994) sections 8.10.3 and 8.12.

The following theorem is proved in the appendix.

Theorem 1 *(Reduction Result):*

The optimal auction in the multidimensional case is the same as optimal auction obtained by Myerson (1981) for the one-dimensional case. In particular, if each bidder's marginal valuation

$$u^i - \frac{1 - F_i^u(u^i)}{f_i^u(u^i)},$$

is increasing in the bidder's valuation $u^i \in [\alpha_i, \beta_i]$, given the distribution of valuation F_i^u, then the optimal auction delivers the object to the bidder with the highest marginal valuation.

Let $a = (a_1, a_2, \ldots, a_m)$. Recall that $T = \Pi_{j=1}^{m} [a_j, b_j]$. Thus, $a \in T$ is the type vector for which each component is as small as possible. Our main result is the following:

Theorem 2 *(Exclusion Result):*

If the i^{th} *bidder's utility function is such that* $\frac{\partial U^i}{\partial t_j}(a) > 0$, $j = 1, \ldots, m$, *then in the optimal auction there is exclusion of types of bidder* i.

Proof. It suffices, by continuity, to show that $f_i^u(\alpha_i) = 0$. Then every type with utility near α_i will be excluded. Let M be a bound for f_i. If $x > \alpha_i$,

$$F_i^u(x) = \int_{\{t \in T; U^i(t) \leq x\}} f(t)\, d\lambda(t) \leq M\lambda\left(\left\{t \in T; U^i(t) \leq x\right\}\right).$$

Now by the continuity of the partial derivatives, there is a $r > 0$ such that

$$\delta = \min\left\{\frac{\partial U^i}{\partial t_j}(t); 1 \leq j \leq m, t \in T, \sum_{j=1}^{m} |t_j - a_j| \leq r\right\} > 0.$$

For any $t \in T$ such that $\sum_{j=1}^{m} |t_j - a_j| \leq r$,

$$U^i(t) - U^i(a) = \int_0^1 \frac{d}{ds}\left(U^i(a + s(t-a))\right) ds =$$
$$\int_0^1 \left(U^i\right)'(a + s(t-a)) \cdot (t-a)\, ds \geq \delta \sum_{i=1}^{m} (t_i - a_i).$$

Thus, if $U^i(t) \leq x$ then for every j, $|t_j - r| \leq \sum_{i=1}^{m} (t_i - a_i) \leq \frac{x - U^i(a)}{\delta} = \frac{x - \alpha_i}{\delta}$. Therefore

$$\lambda\left(\left\{t; U^i(t) \leq x\right\}\right) \leq \lambda\left(\left\{z \in \mathbb{R}^m; |z_j - a_j| \leq \frac{x - \alpha_i}{\delta} \text{ for all } j\right\}\right) = \frac{(x - \alpha_i)^m}{\delta^m}.$$

Since

$$f_i(\alpha_i) = \lim_{x \to \alpha_i} \frac{F_i^u(x) - F_i^u(\alpha_i)}{x - \alpha_i} \leq \frac{M}{\delta^m} \lim_{x \to \alpha_i} (x - \alpha_i)^{m-1}$$

and $m > 1$ we conclude that $f_i(\alpha_i) = 0$ ending the proof. QED

Remark 1 *Consider the one dimensional case with* $T = [a, b]$. *Then type* t *is excluded if and only if* $t f_i(t) \leq 1 - F_i(t)$. *For example if the distribution is uniform on* $[a, b]$ *there is no exclusion if* $\frac{a}{b-a} > 1$ *i.e. if* $2a > b$.

Remark 2 *Also, we see from our the last remark that what drives exclusion with multidimensional types is that* $f_i(\alpha_i) = 0$ *is a general property.*

Remark 3 *The hypothesis* $\frac{\partial U^i}{\partial t_j}(a) > 0$ *is necessary for the result. For example if* $U_i(t_1, t_2) = t_1 - t_2/2$ *the conclusion will not be true in general.*

Example 1 *As an example we calculate the exclusion set in a simple case with the uniform distribution. Consider* $U^i(t) = t_1 + t_2$*. We suppose that* t *is uniformly distributed in* $[1,2]^2$*. The distribution of* U^i *given by*

$$F_i(u) = \begin{cases} \frac{(u-2)^2}{2} & \text{if } \; 2 \leq u \leq 3 \\ 1 - \frac{(4-u)^2}{2} & \text{if } \; 3 \leq u \leq 4, \end{cases}$$

$$\textit{has density } f_U(u) = \begin{cases} u-2 & \text{if } \; 2 \leq u \leq 3 \\ 4-u & \text{if } \; 3 \leq u \leq 4. \end{cases}$$

Note that the density function is continuous and it is zero for $u = 2, 4$*. Thus, the set of excluded types is* $\left[2, \frac{4+\sqrt{10}}{3}\right]$*.*

Appendix

In this appendix we prove theorem 1. For convenience the auctioneer will be bidder 0. We define $\mathcal{P}$ as the set of probability distributions on $\{0, 1, \ldots, n\}$. Thus $\mathcal{P} = \left\{(q_j)_{j=0}^n \geq 0, \sum_{j=0}^n q_j = 1\right\}$. The interpretation is that q_j is the probability that bidder j receives the object. Thus q_0 is the probability that the auctioneer keeps the object. We consider on T^n the product probability measure. The auction proceed as follows:

1. The auctioneer announces the measurable functions[1] $q : T^n \to \mathcal{P}$ and $P = (P^i)_{i=1}^n$ where $P^i : T^n \to \mathbb{R}$;

2. The bidder i confidentially announces to the auctioneer types $t_i \in T$; The auctioneer forms the vector $t = (t_i)_{i=1}^n$

3. The objects are delivered accordingly to $q(t) \in \mathcal{P}$ and bidder i pays $P^i(t)$.

For a given direct mechanism (q, P) we define

$$Q_i(t_i) = E_{-i}[q_i(t)] \text{ and } P^i(t_i) = E_{-i}\left[P^i(t)\right]. \tag{1}$$

[1] Henceforth called direct mechanisms.

The mechanisms must satisfy incentive compatibility and individual rationality constraints:

$$Q_i(t_i)\,U^i(t_i) - P^i(t_i) \geq Q_i(t_i')\,U^i(t_i) - P^i\left(t_i^{'}\right), \forall t_i', t_i \in T, \tag{IC}$$

$$Q_i(t_i)\,U^i(t_i) - P^i(t_i) \geq 0. \tag{IR}$$

Let us define the auxiliary function, $V^i : T \to \mathbb{R}$,

$$V^i(t_i) = Q_i(t_i)\,U^i(t_i) - P^i(t_i).$$

The compatibility of incentives constraints can be rewritten as

$$V^i(t_i) - V^i(t_i') \geq Q_i(t_i')\left(U^i(t_i) - U^i(t_i')\right), \forall t_i, t_i' \in T_i. \tag{IC'}$$

The following lemma is important:

Lemma 1 *There exists a convex function $\phi_i : R^i \to \mathbb{R}$ such that $V^i = \phi_i \circ U^i$. Moreover $Q_i(t_i) \in \partial\phi_i(U^i(t_i))$.*

Proof: Note first that if a and c are elements of $(U^i)^{-1}(r), r \in R^i$ then (IC') implies $V^i(a) - V^i(c) \geq Q_i(c) \cdot 0 = 0$. Analogously, $V^i(c) - V^i(a) \geq 0$. Thus $V^i(a) = V^i(c)$. Therefore

$$\phi_i : R^i \to \mathbb{R}, \phi_i(r) := V^i(x_r), \text{where } x_r \in \left(U^i\right)^{-1}(r), r \in R^i$$

is well defined. Since

$$\phi_i(\gamma) = V^i(x_\gamma) = \sup_{x' \in T_i} Q_i(x')\,\gamma - P^i(x')$$

it follows that ϕ_i is a convex function. Moreover, if $\eta = U^i(t_i)$

$$\phi_i(\gamma) - \phi_i(\eta) \geq Q_i(t_i)(\gamma - \eta), \text{for all } \gamma, \eta \in R^i.$$

Thus, we have that $Q_i(t_i) \in \partial\phi_i(U^i(t_i))$. QED

For every $u = (u^1, \ldots, u^n) \in R = \prod_{i=1}^m R^i$ define

$$\vec{q_i}(u) = E\left[q_i(x) \middle| u = \left(U^j(x_j)\right)_{j=1}^n\right] \text{ and}$$
$$\vec{P^i}(u) = E\left[P^i(x) \middle| u = \left(U^j(x_j)\right)_{j=1}^n\right].$$

Remark 4 *The conditional expectation is only defined almost everywhere. For the step above we need to use a regular conditional distribution, so that the conditional expectation is defined everywhere (see Hoffmann-Jørgensen 10.3, page 120).*

Note first that $\sum_{i=0}^{n} \vec{q}_i(u) = 1$. Let us calculate $\vec{Q}_i(u^i) = E[\vec{q}_i(u) | u^i]$. We calculate first

$$E\left[\vec{q}_i(u) | u^i\right] = E\left[E[q_i(x) | u] | u^i\right] = E\left[q_i(x) | u^i\right] =$$
$$E\left[E[q_i(x) | x_i] | u^i = U^i(x_i)\right] = E\left[Q_i(x_i) | u^i = U^i(x_i)\right] \in \partial\phi_i\left(u^i\right).$$

The last relation is true since $Q_i(x_i) \in \partial\phi_i(u^i) = [\phi^-(u^i), \phi^+(u^i)]$ and

$$\phi^-\left(u^i\right) = E\left[\phi^-\left(u^i\right)|u^i\right] \le E\left[Q_i(x_i)|u^i = U^i(x_i)\right] \le E\left[\phi^+\left(u^i\right)|u^i\right] = \phi^+\left(u^i\right).$$

The incentive compatibility constraints can be rewritten as

$$\vec{Q}_i\left(u^i\right)u^i - E\left[\vec{P}^i(u)\middle| u^i\right] \ge \vec{Q}_i(u')\,u^i - E\left[\vec{P}^i(u)\middle| u'\right], \tag{IC'}$$

The individual rationality constraint can be rewritten

$$\vec{Q}_i\left(u^i\right)u^i - E\left[\vec{P}_i(u)\,|u^i\right] \ge 0.$$

The auctioneer expected revenue is

$$E\left[\sum_{i=1}^{n} P^i(x)\right] = E\left[E\left[\sum_{i=1}^{n} P^i(x)\middle| u\right]\right] = E\left[\sum_{i=1}^{n} \vec{P}^i(u)\right].$$

Thus the optimal auction problem is reduced to the one-dimensional optimal auction solved by Myerson. There is one twist however. Myerson's assumptions require that the density function have a positive minimum (i.e., have positive values everywhere). Already we have seen here simple examples where Myerson's everywhere positivity assumption is not satisfied. One can easily see, however, that Myerson's proof works as long as the density is positive and continuous in the *interior* of R^i and this is an assumption that is satisfied by many examples including the ones considered here.

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