"UNAVOIDABLE MECHANISMS"

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ABSTRACT

This paper is an attempt to explain the frequent use of some allocation mechanisms, like the open English auctions and the sealed-bid discriminating auctions. Given a criterion for the allocation of resources, a mechanism is called unavoidable within a range of environments if it must be embedded in any allocation mechanism that does as well or better in these environments. When the criterion is the planner's payoff, classes of environments can be identified where the commonly observed auctions are unavoidable.

SOMMAIRE

Cet article propose une explication de l'usage fréquent de certains mécanismes d'allocation de ressources, tels que l'enchère ouverte anglaise ou les enchères à offres scellées. Etant donné un critère pour l'allocation des ressources, un mécanisme est dit inévitable sur un horizon d'environnements s'il doit être encastré dans tout autre mécanisme mieux ou plus performant dans ces environnements. Si le critère choisi est le revenu du planificateur, on peut identifier des classes d'environnements où les enchères communément observées sont inévitables.

1. INTRODUCTION

Some economic institutions seem to prevail consistently. Auctions, for example, have been held since antiquity, and are still widely used to allocate various kinds of goods (see Cassady [3]). Moreover, although one can conceive a huge variety of auctions, the commonly observed auctions take essentially one of the following "standard" forms:[1]

(i) an <u>open ascending-bid (English) auction</u>

Starting at a very low price, the auctioneer lets it increase until all bidders but one - the winner - drop out.

(ii) a <u>first-price sealed-bid auction</u>

Only one sealed bid is submitted by each agent. The agent announcing the highest bid wins and pays the amount he bids.

(iii) a <u>second-price sealed-bid auction</u>

Each agent submits only one sealed bid. The agent announcing the highest bid wins but pays an amount equal to the second highest bid.

One conventional approach to justify the prevalence of certain resource allocation processes is mechanism design (Hurwicz [8]). Applied to auctions this approach has lead to the construction of optimal auctions (Harris and Raviv [8], Myerson [16], Riley and Samuelson [18], Maskin and Riley [11]). The conclusion was that any of the above standard auctions, with a reserve price, should indeed prevail when bidders are risk neutral and have independently identically distributed private valuations ([8], [16],

[18]), but the optimal auctions in other, more general, circumstances (see [11] and [4]) would sharply amend the commonly observed auctions. Hence, the mechanism design approach did not fully support the standard auctions.

Another attempt at explaining why auctions are used was recently made by Milgrom [13]. He asserted that auctions might be used because they are efficient, relatively simple and robust institutions, the last adjective meaning that they remain desirable within a large range of circumstances. Milgrom supported this claim by showing that, with no uncertainty about the agents' characteristics, auction outcomes coincide with core allocations, and a weak seller - one with little bargaining power -, or an agent with the possibility of resale, almost prefers to offer to sell by auction regardless of other available options. In the important case where some of the agents' characteristics are privately known, however, Hagerty and Rogerson [6] showed that the only robust trading mechanisms are posted-price mechanisms.[2] Thus, the frequent use of auctions still remains largely unjustified.

This paper constitutes one further attempt at explaining the wide diffusion of economic institutions like auctions. Given a criterion for the allocation of resources, a mechanism is called unavoidable within a range of environments if it must be embedded in (i.e., homomorphic to) any allocation mechanism that performs as well or better in these environments. Let the criterion be the planner's payoff; then

1) The second-price sealed-bid and the open auctions are unavoidable when bidders are strictly risk averse and their private valuations have a strong common value element.

2) The first-price sealed-bid auction is unavoidable when bidders are extremely risk averse and have identically independently distributed private valuations.

Before defining unavoidability, some notation is developed in the next section. The third section is then devoted to embeddings of allocation mechanisms, the fourth to the environments and the fifth to unavoidability. In section 6 circumstances are described where the first-price sealed-bid, the second-price sealed-bid, and the open ascending-bid auctions are unavoidable. Finally, the notion of unavoidability is rephrased in section 7 in the language of category theory, indicating how this mathematical field might be useful for the analysis of allocative systems.

2. ALLOCATION GAME FORMS

The problem of allocating some resource among a group of self-interested agents having relevant private information boils down to specifying a set of policies that the agents can choose, and an allocation function or distribution rule matching the chosen policies into a distribution of the resource among the agents. Accordingly, let $A = [(\Sigma^a)^n, (\pi_i^a; \beta_i^a, \alpha_i^a)_{i=1,\ldots,n}]$ denote an (possibly non-deterministic) allocation game form with $n \geq 2$ agents: $(\Sigma^a)^n$ is a symmetric set of policies $(\sigma_1,\ldots,\sigma_n)$, where σ_i is agent i's offering policy; $\pi_i^a:(\Sigma^a)^n \longrightarrow [0,1]$ is the probability that agent i gets the resource, $\pi_1^a + \ldots + \pi_n^a \leq 1$; $\beta_i^a:(\Sigma^a)^n \longrightarrow (-\infty,+\infty)$ and $\alpha_i^a:(\Sigma^a)^n \longrightarrow (-\infty,+\infty)$ are functions indicating agent i's expense if he does or does not receive the resource respectively.

Throughout this paper the functions π_i^a, β_i^a, α_i^a are assumed to be symmetric, i.e. invariant under any permutation of their arguments other than i and

$$\pi_i^a(\ldots\sigma_i,\ldots,\sigma_j\ldots) = \pi_j^a(\ldots\sigma_j,\ldots,\sigma_i\ldots),$$
$$\beta_i^a(\ldots\sigma_i,\ldots,\sigma_j\ldots) = \beta_j^a(\ldots\sigma_j,\ldots,\sigma_i\ldots),$$
$$\alpha_i^a(\ldots\sigma_i,\ldots,\sigma_j\ldots) = \alpha_j^a(\ldots\sigma_j,\ldots,\sigma_i\ldots).$$

Note that, in this setting, an agent's policy can be a function of his competitors' offers. Hence, strictly speaking, an offering policy is not an offer. It is also not a strategy since an environment (agents' preferences and types) has not yet been specified. Strategies will be introduced in section 4.

The standard auction game forms can now be defined.

DEFINITION 2.1: A is a <u>first-price sealed-bid auction game form</u> (FP) if

(i) Σ^a (now written Σ^{fp}) = $[c,d]$, $d > c \geq 0$.

(ii) Let $M = \{i | \sigma_i = \max(\sigma_1,\ldots,\sigma_n)\}$. Then $\pi_i{}^a(\sigma_1,\ldots,\sigma_n)$ (now written $\pi_i{}^{fp}(\sigma_1,\ldots,\sigma_n)$) = 0 when i does not belong to M.

(iii) $\pi_1{}^{fp} +\ldots+ \pi_n{}^{fp} = 0$ or 1.

(iv) $\beta_i{}^{fp}(\sigma_1,\ldots,\sigma_n) = \sigma_i$.

(v) $\alpha_i{}^{fp}(\sigma_1,\ldots,\sigma_n) = 0$.

DEFINITION 2.2: A is a <u>second-price sealed-bid auction game form</u> (SP) if

(i) Σ^a (now written Σ^{sp}) = $[c,d]$, $d > c \geq 0$.

(ii) Let $M = \{i | \sigma_i = \max(\sigma_1,\ldots,\sigma_n)\}$. Then $\pi_i{}^a(\sigma_1,\ldots,\sigma_n)$ (now written $\pi_i{}^{sp}(\sigma_1,\ldots,\sigma_n)$) = 0 when i does not belong to M.

(iii) $\pi_1{}^{sp} +\ldots+ \pi_n{}^{sp} = 0$ or 1.

(iv) $\beta_i{}^{sp}(\sigma_1,\ldots,\sigma_n) = \max_{j\neq i} \{\sigma_j,\sigma_*\}$.

(v) $\alpha_i{}^{sp}(\sigma_1,\ldots,\sigma_n) = 0$.

Note that the above specifications allow for a reservation price σ_*. Part (i) of the definitions, however, precludes unbounded bidding policies. This should not constitute a practical restriction, since auctioneers are usually careful in drawing only bidders who have a reputation for being "financially competent" (see Cassady [3]).

The variant of the open ascending-bid auction that will be specified is similar to the one studied by Milgrom and Weber [14]. In this variant the price level and the number of active bidders is constantly displayed. Bidding policies are bounded non decreasing step functions $\tau:[0,+\infty) \longrightarrow [0,+\infty)$ - at each price level p, $\tau(p) \geq p$ means "stay active" and $\tau(p) < p$ says "withdraw". Each n-tuple $(\tau_1(\cdot),\ldots,\tau_n(\cdot))$ of bidding policies fulfills the following assumption.

CONSISTENCY ASSUMPTION: Given an interval $[c,d]$, $0 \leq c < d$, for each $(\tau_1(\cdot),\ldots,\tau_n(\cdot))$ there must exist a bounded function $g:\{1,\ldots,n\} \times [c,d]^n \longrightarrow [0,+\infty)$ and a vector $(p_1,\ldots,p_n)$ in $[c,d]^n$ such that if, say, $c \leq p_n < \ldots < p_1$, then

$\tau_i(p) = g_1(p_i,\ldots,p_i)$ when $p \leq g_1(p_n,\ldots,p_n)$,

$\tau_i(p) = g_1(p_i,\ldots,p_i,p_n)$ for $g_1(p_n,\ldots,p_n) < p \leq g_1(p_{n-1},\ldots,p_{n-1},p_n$

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$\tau_i(p) = g_1(p_i,p_i,p_3,p_4,\ldots,p_n)$ when $g(p_3,p_3,p_3,p_4,\ldots,p_4) < p$.

Each function $g_i(\cdot)$ is non-decreasing and must satisfy:

(i) Invariance under any permutation of its arguments other than the ith one.

(ii) $g_i(\ldots p_i,\ldots,p_j\ldots) = g_j(\ldots p_j,\ldots,p_i\ldots)$.

(iii) $g_1(p_1,p_2,\ldots,p_n) = g_1(p_2,p_2,\ldots,p_n)$ if $p_n \leq \ldots \leq p_2 \leq p_1$.

The consistency assumption comes naturally when one wants to add more structure to the set of bidding policies allowed in an open ascending-bid auction game form. It is not very restrictive, for the set of bidding policies remains quite big. Requirements (i) and (ii) on $g(\cdot)$ simply say that this function must be symmetric. Condition (iii) implies that each $g_i(\cdot)$ is determined only by its n-1 smallest arguments. In theorem 6.6 the function $g_i(\cdot)$ and the vector $(p_1,\ldots,p_n)$ will coincide with a valuation function and a vector of types respectively.

DEFINITION 2.3: A is an <u>open ascending-bid auction game form</u> (OB) if

(i) $(\Sigma^a)^n$ (now written $(\Sigma^{ob})^n$) is the set of n-tuples of bidding policies $(\tau_1(\cdot),\ldots,\tau_n(\cdot))$ that satisfy the consistency assumption.

(ii) Let M be the set of bidders who quit last, that is,
$M = \{i \mid \inf_p [p \mid \tau_i(p) < p] = \max_j \inf_p [p \mid \tau_j(p) < p]\}$. Then
$\pi_i^{ob}(\tau_1(\cdot),\ldots,\tau_n(\cdot)) = 0$ if $(\tau_1(\cdot),\ldots,\tau_n(\cdot))$ does not belong to $(\Sigma^{ob})^n$ or i is not in M.

(iii) $\beta_i^{ob}(\tau_1(\cdot),\ldots,\tau_n(\cdot)) = \max_{j\neq i} [\inf_p \{p \mid \tau_j(p) < p\}, p_*]$, where $p_* \geq 0$ is a reserve price.

(iv) $\alpha_i^{ob}(\tau_1(\cdot),\ldots,\tau_n(\cdot)) = 0$.

The policy set $(\Sigma^{ob})^n$ of the open ascending-bid auction game form is much larger than the policy sets $(\Sigma^{fp})^n$ and $(\Sigma^{sp})^n$. It clearly illustrates the distinction between offers and policies. In some sense the open ascending-bid auction game form embeds or contains the second-price sealed-bid auction game form. This statement will now be made precise.

3. SIMPLENESS

Let I_Ω be the indicator function of a set Ω, i.e. $I_\Omega(x) = 1$ if x belongs to Ω, and $I_\Omega(x) = 0$ otherwise.

DEFINITION 3.1: A game form $B = [(\Sigma^b)^n, (\pi_i{}^b; \beta_i{}^b, \alpha_i{}^b)_{i=1,\dots,n}]$ <u>embeds</u> (or <u>is homomorphic to</u>) an allocation game form A if there exists an injective function Φ from Σ^a into Σ^b such that, for all $(\sigma_1,\dots,\sigma_n)$ in $(\Sigma^a)^n$,

(i) $\pi_i{}^a(\sigma_1,\dots,\sigma_n) = \pi_i{}^b(\Phi(\sigma_1),\dots,\Phi(\sigma_n))$.

(ii) $\beta_i{}^a(\sigma_1,\dots,\sigma_n)\ I_{\{\pi_i^a(\sigma_1,\dots,\sigma_n)>0\}} =$

$$\beta_i{}^b(\Phi(\sigma_1),\dots,\Phi(\sigma_n))\ I_{\{\pi_i^b(\Phi(\sigma_1),\dots,\Phi(\sigma_n))>0\}}.$$

(iii) $\alpha_i{}^a(\sigma_1,\dots,\sigma_n)\ I_{\{\pi_i^a(\sigma_1,\dots,\sigma_n)<1\}} =$

$$\alpha_i{}^b(\Phi(\sigma_1),\dots,\Phi(\sigma_n))\ I_{\{\pi_i^b(\Phi(\sigma_1),\dots,\Phi(\sigma_n))<1\}}.$$

almost surely with respect to some probability measure.[3] One can then also say that A <u>is embedded</u> in B.

We insist here in having an injective function $\Phi:\Sigma^a \longrightarrow \Sigma^b$, because we want the cardinality of Σ^b not to be lower than the cardinality of Σ^a in order for the statement "B embeds A" to make intuitive sense. This requirement also nicely tunes the definition, as the following proposition illustrates.

PROPOSITION 3.2: <u>The first-price sealed-bid auction game form does not embed the second-price sealed-bid auction game form</u>.

PROOF: Suppose it can. Without losing generality, consider the second-price sealed-bid auction game form without reservation price, i.e. $\pi_1^{sp} + \ldots + \pi_n^{sp} = 1$.

Note that $\pi_1^{fp}(\Phi(c),\ldots,\Phi(c)) = \pi_1^{sp}(c,\ldots,c) = 1/n$ by symmetry. Then the requirement $\beta_1^{fp}(\Phi(c),\ldots,\Phi(c)) = \beta_1^{sp}(c,\ldots,c) = c$ implies that $\Phi(c) = c$.

It must also be true that $\pi_1^{fp}(\Phi(d),\Phi(c),\ldots,\Phi(c)) = \pi_1^{sp}(d,c,\ldots,c) = 1$. Therefore, $\beta_1^{fp}(\Phi(d),\Phi(c),\ldots,\Phi(c)) = \beta_1^{sp}(d,c,\ldots,c) = c$ must hold. But this implies that $\Phi(d) = c$, so that $\Phi(\cdot)$ is not injective. <u>Q.E.D</u>.

The next statement shows in turn that the above definition of simpleness is not vacuous.

PROPOSITION 3.3: <u>An open ascending-bid auction game form can embed the second-price sealed-bid auction game form</u>.

PROOF: Let the interval [c,d] of the consistency assumption coincide with Σ^{sp}. Take $p_* = \sigma_*$. Since the set of bidding policies Σ^{ob} contains constant functions, the desired injective function $\Phi:\Sigma^{sp} \longrightarrow \Sigma^{ob}$ is just defined as $\Phi(\sigma_i) = \sigma_i$. <u>Q.E.D.</u>

One could strengthen the notion of embedding by asking for a bijective function $\Phi:\Sigma^a \longrightarrow \Sigma^b$. When such a function exists, the allocation game forms A and B will be called <u>isomorphic</u>.

4. ENVIRONMENTS

Let $X = [S,Q;v,U]$ denote a <u>symmetric environment</u>. S contains the private types that an agent can have. The agents' types $(s_1,\ldots,s_n)$ are simultaneously "drawn" from the symmetric distribution Q. The symbol v denotes the agents' valuation of the resource to be allocated, as a function of the actual types. It will always be the case that $v_i:S^n \longrightarrow (-\infty,+\infty)$, $i = 1,\ldots,n$, is a symmetric function. Lastly, U is a Von Neumann-Morgenstern utility function whose argument is final wealth.

A pair (A,X), where A is an allocation game form and X is an environment, will now denote an <u>allocation game</u>. In this context a <u>pure strategy</u> for agent i is a Q-measurable function $\sigma_i(X):S \longrightarrow \Sigma^a$. Given offering strategies $\sigma(X) \equiv (\sigma_1(X),\ldots,\sigma_n(X))$, an agent i with privately-known type s_i has a utility

$$V(A,X;\sigma(X),s_i) \equiv E\,[\pi_i{}^a(\sigma(X))\;U(v_i(\cdot)-\beta_i{}^a(\sigma(X))) + (1-\pi_i{}^a(\sigma(X)))\;U(-\alpha_i{}^a(\sigma(X)))\;|\;X,s_i]\;.$$

DEFINITION 4.1: The n-tuple $\sigma(X)$ of offering strategies constitute a <u>symmetric (Bayes-Nash) equilibrium</u> if, for any r in S, $V(A,X;\sigma(X),s_i) \geq V(A,X;(\sigma_{-i}(X),r),s_i)$ for every agent i whose private type is s_i.[4]

Given an equilibrium $\sigma^a(X)$ in the allocation game (A,X), the planner's expected payoff is equal to

$$P(A,X;\sigma^a(X)) \equiv E\,[\mathrm{sum}_1^n\ \pi_i{}^a(\sigma^a(X))\ \beta_i{}^a(\sigma^a(X)) + (1-\pi_i{}^a(\sigma^a(X)))\ \alpha_i{}^a(\sigma^a(X))\ |\ X\ ]$$

From now on, the planner's payoff will be considered the main criterion for allocating the resource.

5. UNAVOIDABILITY

DEFINITION 5.1: An allocation game form A is <u>unavoidable</u> within a range (or family) Z of environments if the following statement holds:

> If B is an allocation game form such that $P(B,X;\sigma^b(X)) \geq P(A,X;\sigma^a(X))$ for all environments X in Z, then B embeds A.

The next theorem says that two allocation game forms which are unavoidable within the same spectrum of environments, and which always bring the same expected income to the auctioneer, must be isomorphic. Hence, expected payoffs and unavoidability are exhaustive features of an allocation game form.

THEOREM 5.2: If two allocation game forms A, B are unavoidable within the same range Z of environments, and if $P(B,X;\sigma^b(X)) = P(A,X;\sigma^a(X))$ in all environments X of Z, then A and B are isomorphic.

PROOF: By assumption, we have an injective function $\Phi^a:\Sigma^a \longrightarrow \Sigma^b$ under which A is embedded in B, and an injective function $\Phi^b:\Sigma^b \longrightarrow \Sigma^a$ under which A embeds B. Applying the Schröder-Bernstein theorem (see Halmos [7]) one can construct a bijection between Σ^a and Σ^b under which A and B are isomorphic.

Q.E.D.

This theorem shows how the concept of unavoidability may refine and complete the actual classification of allocation game forms through mechanism design.

Also, one can infer at this point an interesting relationship between unavoidability and the revelation principle stated by, for instance, Myerson [16]. In the present notation this principle stipulates that, considering an arbitrary allocation game form $A = [(\Sigma^a)^n,(\pi_i^a;\beta_i^a,\alpha_i^a)_{i=1,\ldots,n}]$ and an environment $X = [S,Q;v,U]$, the allocation game (A,X) yields the planner the same expected income as the direct allocation game (D,X), where

$$\Sigma^d = S \quad ,$$

$$\pi_i^d(s_1,\ldots,s_n) = \pi_i^a(\sigma^a(X)(s_1,\ldots,s_n)),$$

$$\beta_i{}^d(s_1,\ldots,s_n) = \beta_i{}^a(\sigma^a(X)(s_1,\ldots,s_n)),$$
$$\alpha_i{}^d(s_1,\ldots,s_n) = \alpha_i{}^a(\sigma^a(X)(s_1,\ldots,s_n)),$$

for all i. The following proposition is a restatement of the revelation principle using unavoidability.

COROLLARY 5.3: Consider an allocation game (A,X) and a symmetric equilibrium $\sigma^a(X)$ in (A,X). Assume that $\sigma_i{}^a(X):S \rightarrow \Sigma^a$ is an injective function, for all i. If A is unavoidable within {X}, then (A,X) is a direct allocation game, or there exists a direct allocation game (D,X) where D is isomorphic to A.

PROOF: If (A,X) is already a direct allocation game, there is nothing to be proved. So let us assume that it is not.

Using the equilibrium $\sigma^a(X)$ construct a direct allocation game (D,X) as in the revelation principle stated above. Clearly then, A embeds D. But D must also embed A, since it gives the planner as much expected income as A in environment X and A is unavoidable within {X}. Therefore A and D are isomorphic by theorem 5.2.

Q.E.D.

Hence, in the presence of only one environment, one may focus on direct allocation games to find unavoidable mechanisms. This revelation principle does not hold, however, when one considers families of many environments. In this context direct revelation is subsumed by embeddedness.

6. UNAVOIDABLE AUCTION GAME FORMS

Let us now apply the above concept of unavoidability. Classes of environments must be identified within which the standard auction game forms defined in section 2 are unavoidable. Let us first make the following assumption.

ASSUMPTION 6.1: In any allocation game (A,X),

(i) The set Σ^a contains a (non-participation, status quo) offering policy that gives utility 0 at any instance of the allocation functions.

(ii) The allocation functions $\pi_i{}^a$, $\beta_i{}^a$, $\alpha_i{}^a$ are Q-measurable.

(iii) The utility function is normalized so that $U(0) = 0$.

(iv) A symmetric equilibrium exists and is played.

The second-price sealed-bid auction game form

Along with the second-price sealed-bid auction game form of definition 2.2, consider an environment $X^{sp} = [S^{sp},Q^{sp};v^{sp},U^{sp}]$ where

(i) The set of private types $S^{sp} = \Sigma^{sp} = [c,d]$.

(ii) Q^{sp} is strictly increasing and atomless.

(iii) The valuation function v^{sp} is defined as $v_i{}^{sp}(s_1,\ldots,s_n) = \min\,(s_i,\max_{j\neq i}\, s_j)$, for $i = 1,\ldots,n$. That is, bidder i's *ex post* valuation is the minimum of his private type and the best type his competitors have.

(iv) The utility function U^{sp} is increasing and strictly concave.

Clearly, an auctioneer operating SP in this environment extracts all the buyer's surplus, since the two highest valuations are always equal.

Take now an allocation game form B that does at least as well as SP in environment X^{sp}. An agent's expected gain in (B, X^{sp}) must be non-positive. But a rational agent's expected surplus must also be non-negative, for he can always choose a harmless offer. Therefore, an agent's average income at equilibrium is 0. If agents are strictly risk averse, their surplus at equilibrium will indeed be 0 almost surely. A proof that B embeds SP is now at hand, using the symmetric equilibrium strategy in (B, X^{sp}) as the desired injective function.

THEOREM 6.2: <u>Given assumption 6.1, the second-price sealed-bid auction game form, where</u> $\pi_1^{sp} + \ldots + \pi_n^{sp} = 1$ <u>and</u> $\sigma_* = 0$, <u>is unavoidable within a range Z of environments that contains</u> X^{sp}.

A formal proof of this theorem is presented in Appendix A. We must admit that this result deserves a criticism that is often addressed to mechanism design: the environmnent X^{sp} is indeed a very special one. Combined with proposition 3.2, however, the last theorem implies an interesting statement.

COROLLARY 6.3: <u>In environment X^{sp}, the first-price sealed-bid auction game form yields a lower expected price than the second-price sealed-bid auction game form</u>.

PROOF: Suppose the auctioneer gets at least as much expected income in (FP,X^{sp}) as in (SP,X^{sp}). By theorem 6.2, FP must embed SP. This contradicts proposition 3.2. <u>Q.E.D</u>.

This corollary elucidates the common belief that the first-price sealed-bid auction game form will be preferred to the second-price sealed-bid auction game form by a risk neutral auctioneer facing risk averse bidders. Riley and Samuelson [18] proved this to be true when the bidders' private valuations are independently identically distributed. The corollary says, however, that this is wrong in an environment like X^{sp}, where bidders are strictly risk averse but there is a strong common value element in the valuation function.

<u>The first-price sealed-bid auction game form</u>

Imagine now an environment where agents have independent private valuations and are "infinitely risk averse", i.e., indifferent between being given a lottery ticket or getting the worst outcome of this lottery with certainty. Then, in a first-price sealed-bid auction, someone bidding his own valuation will bid optimally. This auction will thus extract all the buyer's surplus.[5]

Let now the planner operate another allocation game form in the previous environment. Clearly, an agent who does not get the resource must always pay 0 and a winning agent's payment must not exceed his personal valuation, by individual rationality. If this game form is to give as much expected income to the planner as the first-price sealed-bid auction game form, it must then make the agent with the highest valuation pay his own valuation and all other agents pay nothing. Hence, observing that the symmetric equilibrium strategy in this auction is an injective function, we conclude that the current allocation game form embeds the first-price sealed-bid auction game form. Let us make this assertion a formal one.

Consider a sequence of environments X_m^{fp} such that:

(i) Each of these environments have the same set of types $S = \Sigma^{fp} = [c,d]$.

(ii) Types in each X_m^{fp} are independently identically distributed according to the same distribution Q. This distribution is atomless and increasing on $[c,d]$. It has a density $q(s)$ such that $q(s)/Q(s) > L$ for all s in $[c,d]$, where L is a positive real number smaller than $1/(n-1)$.[6]

(iii) Valuation functions in each X_m^{fp} are ith-component projections, i.e., $v_i(s_1,...,s_n) = s_i$ for any agent i.

(iv) In each X_m^{fp} the utility function U_m is strictly increasing, twice differentiable, and concave. Moreover, the first-order derivative of $U_m(\cdot)$ at 0, denoted $U_m'(0)$, is greater than L for all m.

(v) The corresponding sequence of coefficients of absolute risk aversion is pointwise increasing. Also, for all $K > L$ there exist a positive $m(K)$ and a $\delta(K) \geq (4/KL(n-1))^{1/4}$ such that, for all $\delta \leq \delta(K)$ and $m \geq m(K)$, $-U_m''(w)/U_m'(w) \geq K$ when w belongs to $(-\delta,\delta)$.

The last feature means that, in the neighborhood of the status quo, agents can be extremely risk averse, approaching the level where their utility function would be kinked at 0. The purpose of the lower bound on $\delta(K)$ is to obtain the following lemma.

LEMMA 6.4: Let $b_m(\cdot)$ be the symmetric increasing equilibrium bidding strategy in the auction (FP, X_m^{fp}). Then $b_m(s)$ converges to s, for all s in [c,d].

PROOF: Clearly, $b_m(c) = c$ for every m.

Take an arbitrary but fixed s in (c,d]. By Riley and Samuelson [18]'s proposition 4, the sequence $b_m(s)$ is increasing. Suppose there is an $\varepsilon > 0$ $(\varepsilon < 1)$ such that $b_m(s) < s-\varepsilon$ for all m. We shall then get a contradiction.

By definition of the environments one can find m and δ such that $-U_m''(w)/U_m'(w) \geq 8/L\varepsilon^2(n-1)$ for all w in $(-\delta,\delta)$.

By the Mean Value Theorem one can also find t in [c,d], where $\varepsilon/2 < t - b_m(t) < \delta$ and $b_m'(t) < 1$.

By definition, $b_m(t) = \arg\max_b U_m(t-b)\, Q^{n-1}(b_m^{-1}(b))$. The first-order necessary condition leads to the following differential equation

$$(1) \qquad b_m'(t) = (n-1)\,\frac{q(t)}{Q(t)}\,\frac{U_m(t-b_m(t))}{U_m'(t-b_m(t))} \quad .$$

Using Taylor's theorem we have

$$0 = U_m(0) = U_m(t-b_m(t)) - (t-b_m(t))U_m'(t-b_m(t)) + (t-b_m(t))^2\, U_m''(\theta)/2$$

where θ belongs to $(0,t-b_m(t))$. Divide both sides of the equation by $U_m'(t-b_m(t))$ to get

$$\frac{U_m(t-b_m(t))}{U_m'(t-b_m(t))} = (t-b_m(t)) - (t-b_m(t))^2\,\frac{U_m''(\theta)}{2\,U_m'(t-b_m(t))} \quad ,$$

$$\geq\ -\,\frac{U_m''(\theta)}{U_m'(\theta)}\,\varepsilon^2/8 \quad ,$$

$$\geq\ 1/L(n-1) \quad .$$

Hence, by equation 1, $b_m'(t) \geq 1$, which is the seeked contradiction. <u>Q.E.D</u>.

Since we consider infinite risk aversion as a limiting case of extreme risk aversion, our formal statement will now be that the first-price sealed-bid auction game form is <u>asymptotically unavoidable</u> when agents are extremely risk averse.

THEOREM 6.5: <u>The first-price sealed-bid auction game form, where</u> $\pi_1^{fp} + \ldots + \pi_n^{fp} = 1$, <u>is (asymptotically) unavoidable within a range of environments that contains the sequence of environments</u> X_m^{fp}.

This theorem is proven at Appendix B.

The open ascending-bid auction game form

In the previous two theorems unavoidability was established using a symmetric equilibrium strategy as the desired injective function between policy spaces. This approach worked out due to an obvious one-to-one application between the space of types (an interval of real numbers) and the policy space (the same interval of real numbers) of the considered sealed-bid auction game form.

The set of bidding policies we are now focusing on is much richer than an interval of real numbers. In order to construct the function Φ as we did before, we have to find a family Z^{ob} of environments such that the increasing symmetric equilibrium strategy $\sigma^{ob}:Z^{ob}xS \longrightarrow \Sigma^{ob}$ is a bijective function. The environments in Z^{ob} will be analogous to X^{sp}, since (A) embeds (SP).

Take an open ascending-bid auction game form (OB) fulfilling the description of definition 2.3. In this game form the bidding policies $\tau_1(\cdot),\ldots,\tau_n(\cdot)$ have a given domain $[c,d]$. Let Ω^{ob} be the smallest set of functions $g:\{1,\ldots,n\}$ x $[c,d]^n \longrightarrow [0,+\infty)$ that can generate the current set of bidding policies Σ^{ob} through the consistency assumption. The desired family Z^{ob} of environments can then be depicted as follows:

(i) All environments have the same set of types $S = [c,d]$.

(ii) Each environment is indexed by a function g in Ω^{ob} and a vector of types $s = (s_1,\ldots,s_n)$ belonging to $[c,d]^n$.

(iii) Each environment, denoted $X_{s,g}$, has a specific distribution function Q_s on $[c,d]^n$. This distribution is atomless and strictly increasing.

(iv) The agents' valuation function in environment $X_{s,g}$ is precisely the function $g(\cdot)$.

(v) In every $X_{s,g}$, the utility function is the same. It is increasing and strictly concave.

THEOREM 6.6: Provided $\pi_1^{ob} + \ldots + \pi_n^{ob} = 1$, the open ascending-bid auction game form (OB) is unavoidable within any range of environments that contains the family Z^{ob}.

PROOF: Consider an allocation game form A such that $P(B,X;\sigma^a(X)) \geq P(OB,X;\sigma^{ob}(X))$, for all environments X in Z^{ob}.

Let us build a bijection between Z^{ob} and Σ^{ob}. Note that the symmetric increasing equilibrium strategy $\sigma^{ob}(X;s_i)$ is equal to $\tau_i(p)$ where, provided $c \leq s_n < \ldots < s_1$,

$\tau_i(p) = g_1(s_i,\ldots,s_i)$ when $p \leq g_1(s_n,\ldots,s_n)$,

$\tau_i(p) = g_1(s_i,\ldots,s_i,s_n)$ if $g_1(s_n,\ldots,s_n) < p \leq g_1(s_{n-1},\ldots,s_{n-1},s_n)$

......

$\tau_i(p) = g_1(s_i,s_i,s_3,s_4,\ldots,s_n)$ when $g(s_3,s_3,s_3,s_4,\ldots,s_4) < p$,

the function $g(\cdot)$ being the valuation function in environment X (see Milgrom and Weber [14]) This equilibrium strategy then determines a function $\sigma^{ob}:Z^{ob}x[c,d] \longrightarrow \Sigma^{ob}$ that is well defined and bijective.

Now, one can construct an injective function $\Phi(X):[c,d] \longrightarrow \Sigma^a$ by theorem 6.2. The extension $\Phi:Z^{ob}x[c,d] \longrightarrow \Sigma^a$ is then an injective function. Hence, A embeds OB through the application $\Phi\ (\sigma^{ob})^{-1}$. Q.E.D.

This theorem completes our investigation of the unavoidability of the standard auction game forms. Note that, in proving unavoidability we used the symmetric equilibrium strategies to construct the injective function Φ between policy spaces. Hence, an alternative allocation game form would embed a standard auction game form via relevant chosen policies.

The intuitions underlying theorems 6.2, 6.5 and 6.6 were straightforward but the formal proofs were tedious. We shall now have a glance at a mathematical technology that may sharpen the concept of unavoidability and ease its application.

7. A NATURAL MATHEMATICAL TOOL - CATEGORY THEORY

> MONSIEUR JOURDAIN: "Par ma foi! il y a plus de quarante ans que je dis de la prose sans que j'en susse rien,..."
>
> (Molière, Le bourgeois gentilhomme)

In a pathbreaking paper Sonnenshein [19] used category theory - a new branch of algebra - to derive an axiomatic characterization of the price mechanism. We will now suggest that category theory is relevant for classifying auction allocation game forms in general. This theory actually enters the scene in a natural fashion, for there is an immediate translation of the notions of embedding and unavoidability in its language.[7]

A category can be defined essentially by specifying three things: a class of objects, the morphims or applications between the objects, and a rule to compose morphisms. For instance, let us define the category K of allocation mechanisms as follows:

(i) An object of this category is an allocation game form $A = [(\Sigma^a)^n, (\pi_i^a; \beta_i^a, \alpha_i^a)_{i=1,\ldots,n}]$.

(ii) The set of morphisms from an object A to an object B, denoted $Mor_K(A,B)$, is the set of injective applications $\Phi: \Sigma^a \longrightarrow \Sigma^b$ such that

$$\pi_i^a(\sigma_1,\ldots,\sigma_n) = \pi_i^b(\Phi(\sigma_1),\ldots,\Phi(\sigma_n)) \quad ,$$

$$\beta_i^a(\sigma_1,\ldots,\sigma_n)\, I_{\{\pi_i^a(\sigma_1,\ldots,\sigma_n)>0\}} = \beta_i^b(\Phi(\sigma_1),\ldots,\Phi(\sigma_n))\, I_{\{\pi_i^b(\Phi(\sigma_1),\ldots,\Phi(\sigma_n))>0\}} \quad ,$$

$$\alpha_i^a(\sigma_1,\ldots,\sigma_n)\, I_{\{\pi_i^a(\sigma_1,\ldots,\sigma_n)<1\}} = \alpha_i^b(\Phi(\sigma_1),\ldots,\Phi(\sigma_n))\, I_{\{\pi_i^b(\Phi(\sigma_1),\ldots,\Phi(\sigma_n))<1\}} \quad .$$

That is, $Mor_K(A,B)$ is the set of functions under which B embeds A.

(iii) The composition of morphisms is the usual composition of functions.

An object A of the category K is called an initial object (or universally repelling) if, for every object B of K, the set $Mor_K(A,B)$ is a singleton. Also, K′ is a subcategory of K if

(i) Every object of K′ belongs to K.

(ii) For all objects A, B of K′, $Mor_{K'}(A,B)$ is a subset of $Mor_K(A,B)$.

(iii) The composite of two morphisms in K′ is the same as their composite in K.

(iv) For any object A in K′, the identity morphism id_A belongs to $Mor_{K'}(A,A)$.

Here is now an equivalent definition of unavoidability.

DEFINITION 7.1: An allocation game form A is unavoidable with respect to a family Z of environments if A is universally repelling in a subcategory K_Z of K, that contains every allocation game forms for which $P(B,X;\sigma^b(X)) \geq P(A,X;\sigma^a(X)$ at all environments X in Z.

Hence, in the language of category theory, unavoidable allocation mechanisms are universal elements of subcategories.[8] This may be a welcome fact for establishing in general that some allocation mechanisms are unavoidable, since the construction of universals is a central topic of category theory, and powerful techniques have already been designed for this purpose.

8. CONCLUSION

This article proposed new concepts to explain the prevalence of some allocation mechanisms like auctions. First, an allocation game form B was said to embed another game form A if there was an injective application from the policy space of A to the policy space of B such that, whatever the agents in A did, the corresponding offering policies in B yielded the same outcome.

Then, an allocation game form A was called unavoidable within a range of environments if it was embedded in any other game form that performed as well as or better (in the sense of, for instance, providing at least as much expected income to the planner) in all those environments. The second-price sealed-bid auction game form was showed to be unavoidable within a range of environments where there is a strong common value element in the agents' valuation function and agents are strictly risk averse. The first-price sealed-bid auction game form appeared to be unavoidable within environments where agents have independently identically distributed valuations and are extremely risk averse. Finally, the open ascending-bid auction game form was also unavoidable, over the class of environments where agents are strictly risk averse and have a non-decreasing valuation function, with at most n-2 jumps, that does not depend on its highest argument.

One next step from the present paper would be to join the current research on the informational requirements of resource allocation mechanisms. The main question there, stated by, for instance, Hurwicz [9], Mount and Reiter [15], Reichelstein and Reiter [17], is whether a policy space is big enough to implement a given performance level. Being unavoidable could perhaps constitute an intuitive and practical definition of "big enough".

Several frequently encountered pricing schemes, manufacturing systems, and reporting (accounting) rules should also be found to be unavoidable. For it seems plausible that many institutions are basically used, not because they maximize an objective in a hypothetically-fixed environment, but because no sensible performance can be achieved in a range of circumstances without them.

APPENDIX A

Proof of theorem 6.2

Consider an allocation game form B such that $P(B,X^{sp};\sigma^{b}(X^{sp})) \geq P(SP,X^{sp};\sigma^{sp}(X^{sp}))$. From now on let us write $\sigma(s_i)$ and $\sigma^{sp}(s_i)$ for $\sigma_i{}^{b}(X^{sp})(s_i)$ and $\sigma_i{}^{sp}(X^{sp})(s_i)$ respectively.

Note that $\sigma^{sp}(s_i) = s_i$ (Milgrom and Weber [14]). Therefore the last inequality can be written

$$n!\ E\ [\mathrm{sum}_1^n\ \pi_i{}^{b}(\sigma^{b}(X^{sp}))\ \beta_i{}^{b}(\sigma^{b}(X^{sp})) + (1-\pi_i{}^{b}(\sigma^{b}(X^{sp})))\ \alpha_i{}^{b}(\sigma^{b}(X^{sp}))\ |\ X^{sp}\ ]$$

$$\geq\ n!\ E\ [v_1{}^{sp}(\cdot)\ I_{\{s_1 > \ldots > s_n\}}\ |\ X^{sp}\ ] \qquad (A.1)$$

by symmetry. We shall now take $\sigma^{b}(X^{sp})$ as the desired injective function from $[c,d]$ to Σ^{b}.

LEMMA A.1: A bidder's expected gain in (B,X^{sp}) is 0.

PROOF: By assumption 6.1 (individual rationality),

$$U^{sp}(0) \leq E\,[\pi_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))\; U^{sp}(v_i^{\,sp}-\beta_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))$$
$$+ (1-\pi_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n)))U^{sp}(-\alpha_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n)))|X^{sp},s_i],$$
$$\leq U^{sp}(E\,[\pi_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))(v_i^{\,sp}-\beta_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))$$
$$+ (1-\pi_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n)))(-\alpha_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n)))\;|\;X^{sp},s_i]),$$

using Jensen's inequality. Thus

$$E\,[\pi_i^{\,b}\;\beta_i^{\,b} + (1-\pi_i^{\,b})\;\alpha_i^{\,b}\;|\;X^{sp}] \;\leq\; E\,[v_i^{\,sp}\;\pi_i^{\,b}\;|\;X^{sp}\;] \qquad (A.2)$$

for any bidder i.

Suppose that inequality (A.2) is strict from some individual i. We then have

$$\mathrm{sum}_1^n\;\; E\,[\pi_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))\beta_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n)$$
$$+ (1-\pi_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n)))\alpha_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))\;|\;X^{sp}]$$
$$< \;E\,[\mathrm{sum}_1^n\;\pi_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))v_i^{\,sp}\;|\;X^{sp}\;]\;,$$
$$= \;n!\;E\,[\mathrm{sum}_1^n\;\pi_i^{\,b}\;v_i^{\,sp}\;I_{\{s_1\;>\;\ldots\;>\;s_n\}}\;|\;X^{sp}\;]\;,$$
$$\leq \;n!\;E\,[v_1^{\,sp}\;I_{\{s_1\;>\;\ldots\;>\;s_n\}}\;|\;X^{sp}\;]\;.$$

This contradicts inequality (A.1). One must then admit that (A.2) holds as an equality for all i. <u>Q.E.D.</u>

LEMMA A.2: $\pi_i^{\,b}\;(v_i^{\,sp}-\beta_i^{\,b}) + (1-\pi_i^{\,b})(-\alpha_i^{\,b}) = 0$ <u>for all i, almost surely</u>.

PROOF: If not, then

$$U^{sp}(0) = U^{sp}(E\,[\pi_i^{\,b}(v_i^{\,sp}-\beta_i^{\,b}) + (1-\pi_i^{\,b})(-\alpha_i^{\,b})\;|\;X^{sp}])\ \text{by lemma A.1,}$$
$$> E\,[\pi_i^{\,b}\;U^{sp}(v_i^{\,sp}-\beta_i^{\,b}) + (1-\pi_i^{\,b})U^{sp}(-\alpha_i^{\,b})\;|\;X^{sp}]\quad \text{by}$$

Jensen's inequality and the strict concavity of $U^{sp}(\cdot)$. This contradicts individual rationality. <u>Q.E.D.</u>

LEMMA A.3: $\alpha_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))I_{\{\pi_i^b(\sigma(s_1),\ldots,\sigma(s_n))<1\}} = 0,$

<u>and</u> $\beta_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))\ I_{\{\pi_i^b(\sigma(s_1),\ldots,\sigma(s_n))>0\}}$

$$= v_i^{\,sp}(s_1,\ldots,s_n)\ I_{\{\pi_i^b(\sigma(s_1),\ldots,\sigma(s_n))>0\}}.$$

<u>for all i, almost surely</u>.

PROOF: Following lemma A.2 we have $I_{\{\alpha_i^b=0;\ \pi_i^b\ <\ 1\}} =$

$I_{\{\alpha_i^b=0;\ 0\ <\ \pi_i^b\ <\ 1\}} = I_{\{v_i^{sp}-\beta_i^b=0;\ 0\ <\ \pi_i^b\ <\ 1\}} = I_{\{v_i^{sp}-\beta_i^b=0;\ 0\ <\ \pi_i^b\}}$

for all i, almost surely. If one of these indicator functions has a positive expectation, then

$U(0) = U(E\ [\pi_i^{\,b}(v_i^{\,sp}-\beta_i^{\,b}) + (1-\pi_i^{\,b})(-\alpha_i^{\,b})\ |\ X^{sp}])$,

$\quad > E\ [\pi_i^{\,b}\ U^{sp}(v_i^{\,sp}-\beta_i^{\,b}) + (1-\pi_i^{\,b})U^{sp}(-\alpha_i^{\,b})\ |\ X^{sp}]$ by

Jensen's inequality and the strict concavity of $U^{sp}(\cdot)$. This contradicts individual rationality. <u>Q.E.D.</u>

LEMMA A.4: $\pi_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n)) = \pi_i^{\,sp}(s_1,\ldots,s_n)$ <u>for all i, almost surely</u>.

PROOF: It is enough to show that $\pi_1^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))$ agrees with $\pi_1^{\,sp}(s_1,\ldots,s_n)$ on the set where $s_1 > \ldots > s_n$.

Suppose that $E\ [\pi_i^{\,b}(\sigma(s_1),\ldots,\sigma(s_n))\ I_{\{s_1\ >\ \ldots\ >\ s_n\}}\ |\ X^{sp}]$ is positive at some i > 2. Then

$$\text{sum}_1^n \ E\ [\pi_i{}^b(\sigma(s_1),\ldots,\sigma(s_n))\beta_i{}^b(\sigma(s_1),\ldots,\sigma(s_n)$$
$$+\ (1-\pi_i{}^b(\sigma(s_1),\ldots,\sigma(s_n)))\alpha_i{}^b(\sigma(s_1),\ldots,\sigma(s_n))\ \mid\ X^{sp}]$$
$$=\ E\ [\text{sum}_1^n\ \ \pi_i{}^b(\sigma(s_1),\ldots,\sigma(s_n))v_i{}^{sp}(s_1,\ldots,s_n)\ \mid\ X^{sp}]\ ,$$
$$=\ n!\ \ E\ [\text{sum}_1^n\ \ \pi_i{}^b\ v_i{}^{sp}\ I_{\{s_1\ >\ \ldots\ >\ s_n\}}\ \mid\ X^{sp}]\ \ ,$$
$$<\ n!\ \ E\ [v_1{}^{sp}\ I_{\{s_1\ >\ \ldots\ >\ s_n\}}\ \mid\ X^{sp}]\ .$$

This contradicts inequality (A.1).

A similar argument leads one to admit that

$$E\ [\pi_1{}^b(\sigma(s_1),\ldots,\sigma(s_n))\ +\ \pi_2{}^b(\sigma(s_1),\ldots,\sigma(s_n))\ I_{\{s_1\ >\ \ldots\ >\ s_n\}}\ \mid\ X^{sp}]$$
$$=\ 1\ .$$

Now presume the event $\{\pi_2{}^b(\sigma(s_1),\ldots,\sigma(s_n)) > 0;\ s_1 >\ldots> s_n\}$ has a positive probability. Then agent 2's payment depends upon his revealed information, because $\beta_2{}^b(\sigma(s_1),\ldots,\sigma(s_n)) = v_2{}^{sp}(s_1,\ldots,s_n) = s_2$ when $s_1 > \ldots > s_n$. Hence, agent 2 has an incentive to shade his private type s_2, so $\sigma(s_2) = s_2$ is not an equilibrium strategy. This contradiction forces one to admit finally that $\pi_1{}^b(\sigma(s_1),\ldots,\sigma(s_n)) = 1$ when $s_1 > \ldots >s_n$.

Q.E.D.

LEMMA A.5: The function $\sigma:[c,d] \longrightarrow \Sigma^b$ is injective.

PROOF: Suppose not. Take $t < t'$ in $[c,d]$ such that $\sigma(t) = \sigma(t')$. Then, when agent i has private type t, his utility is

$$E\ [\pi_1{}^b(\sigma(t),\ldots,\sigma(s_n))\ U^{sp}(v_1{}^{sp}(t,\ldots,s_n)-\beta_1{}^b(\sigma(t),\ldots,\sigma(s_n))$$
$$+\ (1-\pi_1{}^b(\sigma(t),\ldots,\sigma(s_n)))U^{sp}(-\alpha_1{}^b(\sigma(t),\ldots,\sigma(s_n)))|X^{sp},t]$$
$$=\ E\ [\pi_1{}^b(\sigma(t'),\ldots,\sigma(s_n))\ U^{sp}(v_1{}^{sp}(t,\ldots,s_n)-\beta_1{}^b(\sigma(t'),\ldots,\sigma(s_n))$$

$$+ (1-\pi_1^{\,b}(\sigma(t'),\ldots,\sigma(s_n)))U^{sp}(-\alpha_1^{\,b}(\sigma(t'),\ldots,\sigma(s_n)))|X^{sp},t],$$

$$= E\,[\pi_1^{\,b}(\sigma(t'),\ldots)\; U^{sp}(v_1^{\,sp}(t,\ldots,s_n)-v_1^{\,sp}(t',\ldots,s_n)) \mid X^{sp},t]\,,$$

$<$ 0, by the above lemmas. This is a contradiction. <u>Q.E.D.</u>

APPENDIX B

Proof of theorem 6.5

In order to prove the theorem we need a precise definition of asymptotic robustness. This definition will be based on a notion of quasi-injective and asymptotic embedding.

DEFINITION B.1: Let Σ^a be a set of real numbers. A sequence of functions $\Phi_m:\Sigma^a \longrightarrow \Sigma^b$ is <u>quasi-injective</u> if, for any two sequences $\{\sigma_m^{\,1}\}$, $\{\sigma_m^{\,2}\}$ in Σ^a, there exists an integer N such that $\Phi_m(\sigma_m^{\,1}) = \Phi_m(\sigma_m^{\,2})$ for all $m \geq N$ implies that $|\sigma_m^{\,1} - \sigma_m^{\,2}|$ converges to 0.

DEFINITION B.2: A game form $B = [(\Sigma^b)^n,(\pi_i^{\,b};\beta_i^{\,b},\alpha_i^{\,b})_{i=1,\ldots,n}]$ <u>embeds</u> an auction game form A <u>asymptotically</u>, with Σ^a a set of real numbers, if there exists a quasi-injective sequence of functions Φ_m from Σ^a to Σ^b such that, for all $(\sigma_1,\ldots,\sigma_n)$ in $(\Sigma^a)^n$, the sequences $\pi_i^{\,b}(\Phi_m(\sigma_1),\ldots,\Phi_m(\sigma_n))$,

$\beta_i^{\,b}(\Phi_m(\sigma_1),\ldots,\Phi_m(\sigma_n))\; I_{\{\pi_i^b(\Phi_m(\sigma_1),\ldots,\Phi_m(\sigma_n))>0\}}$,

$\alpha_i{}^b(\Phi_m(\sigma_1),\ldots,\Phi_m(\sigma_n))\ I_{\{\pi_i^b(\Phi_m(\sigma_1),\ldots,\Phi_m(\sigma_n))<1\}}$, converge in in some probability measure to $\pi_i{}^a(\sigma_1,\ldots,\sigma_n)$, $\beta_i{}^a(\sigma_1,\ldots,\sigma_n)\ I_{\{\pi_i^a(\sigma_1,\ldots,\sigma_n)>0\}}$, $\alpha_i{}^a(\sigma_1,\ldots,\sigma_n)\ I_{\{\pi_i^a(\sigma_1,\ldots,\sigma_n)<1\}}$ respectively.

DEFINITION B.3: An allocation game form A, with Σ^a a set of real numbers, is <u>asymptotically unavoidable</u> within a range Z of environments if the following statement holds:

> If B is an allocation game form such that $P(B,X;\sigma^b(X)) \geq P(A,X;\sigma^a(X))$ for all environments X in Z, then B embeds A asymptotically.

Consider now an allocation game form B such that $P(B,X_m;\sigma_m) \geq P(FP,X_m;b_m)$ for all m. (From now on we shall drop the superscript fp on X_m, and we shall denote $\sigma_m(s_i)$ the symmetric equilibrium strategy in (B,X_m) of an agent i with private information s_i.) Using the Monotone Convergence Theorem and lemma 6.4 we have

$$n!\ \liminf_m\ E\ [\mathrm{sum}_1^n\ [\pi_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))\ \beta_i{}^b(\sigma_m(s_1),\ldots) + (1-\pi_i{}^b(\sigma_m(s_1),\ldots))\ \alpha_i{}^b(\sigma_m(s_1,\ldots))]\ I_{\{s_1 > \ldots > s_n\}}\ |\ X_m]$$

$$\geq\ n!\ \ E\ [s_1\ I_{\{s_1 > \ldots > s_n\}}\ |\ X_m]\ , \qquad \text{(B.1)}$$

by symmetry. We will take the sequence of strategies $\sigma_m(\cdot)$ as the desired quasi-injective sequence of functions.

LEMMA B.4: <u>For all i,</u>

$$\lim_m E\,[\alpha_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))I_{\{\pi_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n)) < 1\}} \mid X_m] = 0.$$

PROOF: Define the point-to-set mappings

$$\Omega_m{}^1(\varepsilon) = \{(s_1,\ldots,s_n) \text{ in } [c,d]^n \mid |\alpha_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))| > \varepsilon\}\ ,$$
$$\Omega_m{}^2(\varepsilon) = \{(s_1,\ldots,s_n) \text{ in } [c,d]^n \mid \pi_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n)) < 1-\varepsilon\}\ ,$$

where ε is an arbitrary positive real number. Suppose that $\limsup_m E\,[\Omega_m{}^1(\varepsilon^*) \cap \Omega_m{}^2(\varepsilon^*) \mid X_m] > 0$ for some $\varepsilon^* > 0$. Then $\limsup_m E\,[\Omega_m{}^1(\varepsilon) \cap \Omega_m{}^2(\varepsilon) \mid X_m] > 0$ for all $0 < \varepsilon < \varepsilon^*$. Now, by definition of the environments X_m,

$$\begin{aligned}&\liminf_m E\,[\pi_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))\ U_m(s_i-\beta_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))) + \\ &\quad (1-\pi_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n)))\ U_m(-\alpha_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))) \mid X_m] \\ &\quad \le \liminf_m ((1-\varepsilon)U_m(d) + \varepsilon U_m(-\varepsilon))\ E\,[\Omega_m{}^1(\varepsilon) \cap \Omega_m{}^2(\varepsilon) \mid X_m]\ , \\ &\quad < 0\ ,\end{aligned}$$

for any ε between 0 and ε^*. This contradicts assumption 6.1 (individual rationality). So $\lim_m E\,[\Omega_m{}^1(\varepsilon) \cap \Omega_m{}^2(\varepsilon) \mid X_m] = 0$, for all $\varepsilon > 0$.

Let $\Omega_m = \cup_{\varepsilon\downarrow 0}\ (\Omega_m{}^1(\varepsilon) \cap \Omega_m{}^2(\varepsilon))$. This set is $\{(s_1,\ldots,s_n) \mid \alpha_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))I_{\{\pi_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n)) < 1\}} = 0\}$.

Now $\lim_m E\,[\Omega_m \mid X_m] = \lim_m \lim_{\varepsilon\downarrow 0} E\,[\Omega_m{}^1(\varepsilon) \cap \Omega_m{}^2(\varepsilon) \mid X_m]$, by the Monotone Convergence Theorem; so $\lim_m E\,[\Omega_m \mid X_m] = \lim_m \lim_{\varepsilon\downarrow 0} E\,[\Omega_m{}^1(\varepsilon) \cap \Omega_m{}^2(\varepsilon) \mid X_m] = 0$, by the Iterated Limit Theorem (Bartle [1], p. 133). <u>Q.E.D.</u>

LEMMA B.5: $\operatorname{plim} \pi_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n)) = \pi_i{}^{fp}(s_1,\ldots,s_n)$.

PROOF: The argument used in the proof of the last lemma can be applied again to demonstrate that

$$[\beta_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))-s_i]\ I_{\{\pi_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n)) > 0\}}$$

converges in probability to a non-positive number.

If $\limsup_m E\,[\pi_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))I_{\{s_1 > \ldots > s_n\}} \mid X_m] > 0$ for some $i \geq 2$, then

$$0 \geq E\,[\mathrm{sum}_1^n\,[\pi_i{}^b(\sigma_m(s_1),\ldots)(\beta_i{}^b(\sigma_m(s_1),\ldots)-s_i]I_{\{s_1 > \ldots > s_n\}}|X_m],$$

$$= E\,[\mathrm{sum}_1^n\,[\pi_i{}^b(\beta_i{}^b)\ I_{\{s_1 > \ldots > s_n\}} \mid X_m]$$

$$- E\,[\pi_1{}^b\ s_1\ I_{\{s_1 > \ldots > s_n\}}|X_m]$$

$$- E\,[\mathrm{sum}_2^n\ \pi_i{}^b\ s_i\ I_{\{s_1 > \ldots > s_n\}}|X_m],$$

$$> E\,[\mathrm{sum}_1^n\,[\pi_i{}^b(\sigma_m(s_1),\ldots)(\beta_i{}^b(\sigma_m(s_1),\ldots)-s_1]I_{\{s_1 > \ldots > s_n\}}|X_m],$$

for infinitely many m's. This contradicts inequality (B.1). So

$$\lim_m E\,[\pi_i{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))I_{\{s_1 > \ldots > s_n\}} \mid X_m] = 0$$

for $i = 2,\ldots,n$.

If $\liminf_m E\,[\pi_1{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))I_{\{s_1 > \ldots > s_n\}} \mid X_m] < 1-\varepsilon$ for some positive ε, then

$$\liminf_m E\,[\pi_1{}^b(\sigma_m(s_1),\ldots)(\beta_1{}^b(\sigma_m(s_1),\ldots)\ I_{\{s_1 > \ldots > s_n\}} \mid X_m],$$

$$\leq \liminf_m E\,[s_1\ I_{\{H_1^b > 1-\varepsilon;\, s_1 > \ldots > s_n\}} + \pi_1{}^b s_1\ I_{\{H_1^b < 1-\varepsilon;\, s_1 > \ldots > s_n\}}|X_m],$$

$$< E\,[s_1\ I_{\{s_1 > \ldots > s_n\}} \mid X_m]\ .$$

This also contradicts inequality (B.1). Hence, one must agree that $\lim_m E\,[\pi_1{}^b(\sigma_m(s_1),\ldots,\sigma_m(s_n))I_{\{s_1 > \ldots > s_n\}} \mid X_m] = 1$.

Q.E.D.

LEMMA B.6: For all i,

$$\lim_m E\left[(\beta_i^b(\sigma_m(s_1),\ldots)-s_i) I\{\pi_i^b(\sigma_m(s_1),\ldots,\sigma_m(s_n)) > 0\} \mid X_m\right] = 0.$$

PROOF: It was established in the proof of lemma B.5 that

$$E\left[s_1\, I_{\{s_1 > \ldots > s_n\}} | X_m\right] \geq \liminf_m E\left[\beta_1^b\, I_{\{s_1 > \ldots > s_n\}} | X_m\right].$$

Inequality (B.1) in turn implies that

$$E\left[s_1\, I_{\{s_1 > \ldots > s_n\}} | X_m\right] \geq \liminf_m E\left[\beta_1^b\, I_{\{s_1 > \ldots > s_n\}} | X_m\right].$$

Q.E.D.

LEMMA B.7: The sequence of functions $\sigma_m:[c,d] \longrightarrow \Sigma^b$ is quasi-injective.

PROOF: Take two sequences $\{t_m^1\}$ and $\{t_m^2\}$ in $[c,d]$ such that $\sigma_m(t_m^1) = \sigma_m(t_m^2)$ but, say, $t_m^1 < t_m^2 - \varepsilon$ infinitely often.

Let agent 1's private valuation in environment X_m be s_m^1. By the previous lemmas,

$$\begin{aligned}
&\liminf_m E\left[\pi_1^b(\sigma_m(t_m^1),\ldots)\, U_m(t_m^1-\beta_1^b(\sigma_m(t_m^1),\ldots)) + \right.\\
&\qquad \left.(1-\pi_1^b(\sigma_m(t_m^1),\ldots))\, U_m(-\alpha_1^b(\sigma_m(t_m^1),\ldots)) \mid X_m, t_m^1\right]\\
&= \liminf_m E\left[\pi_1^b(\sigma_m(t_m^2),\ldots)\, U_m(t_m^1-\beta_1^b(\sigma_m(t_m^2),\ldots)) \mid X_m, t_m^1\right]\\
&< 0.
\end{aligned}$$

This again contradicts individual rationality. Q.E.D.

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FOOTNOTES

1 Another important type of auction is the Dutch auction. In this auction the auctioneer starts with a very high price and decreases it until a bidder stops her and claims the object for that price. Such a procedure is used, for instance, in Holland for selling tulips or in Canada for selling tobacco (Cassady [3]). The Dutch auction is strategically equivalent to the first-price sealed-bid auction (Milgrom and Weber [12]). This is the reason why we do not explicitly consider it in this paper.

2 The formal result is actually established for two-person trading situations, but the authors conjecture that it should hold as well in the n-person case. This is because the robustness criterion they propose is, as they say, very strong: a trading institution is called robust if it allows equilibria in dominant strategy and is ex post individually rational.

3 In section 4 environments will be adjoined to auction game forms. A probability measure will then be induced on the policy sets by a distribution of types and a symmetric equilibrium strategy.

4 Such an equilibrium concept is usually adopted for symmetric allocation games like the ones here.

5 This assertion would be wrong without assuming private valuations. If the infinitely risk averse bidders had an unknown common valuation $v(s_1,...,s_n)$, they would rather submit bids equal to the lowest possible value of $v(\cdot)$, i.e., bidder i would

propose

$$\inf \{v(s_1,\ldots,s_n) \mid Q_{s_i}(s_1,\ldots,s_n) > 0\} \ .$$

6 Note that the uniform distribution on [c,d], for example, fulfills these requirements.

7 A recent book by Blyth [2] constitutes a lucid introduction to category theory. One can also consult Maclane [10] to get a more exhaustive view of the theory from one of its founders.

8 The term "universal" was recently used in mechanism design by Forges [5]. Her notion is not categorical, however, but rather similar to Hagerty and Rogerson [6]'s robustness. "A mechanism, she says, is "universal" if it does not depend on the parameters of the game, like the prior assessments of the players."

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