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Mechanism design with interdependent valuations: surplus extraction

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Abstract If valuations are interdependent and agents observe their own allocation payoffs, then two-stage revelation mechanisms expand the set of implementable decision functions. In a two-stage revelation mechanism agents report twice. In the first stage - before the allocation is decided - they report their private signals. In the second stage - after the allocation has been made, but before final transfers are decided - they report their payoffs from the allocation. Conditions are provided under which an uninformed seller can extract (or virtually extract) the full surplus from a sale to privately informed buyers, in spite of the buyers' signals being independent random variables.

Keywords: Auctions, Surplus Extraction, Interdependent Valuations, Mechanism Design.

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1 Introduction

Consider a seller of an object facing multiple, privately informed, bidders. Can the seller extract all the surplus from the transaction? Crémer and McLean [3], [4] (see also McAfee and Reny [8]) showed that full surplus extraction is generically possible when bidders' types are correlated random variables. Full surplus extraction is achieved by conditioning the payment of each bidder on the realization of the types of the other bidders. On the other hand, it is widely believed that if buyers' types are independent random variables, then full surplus extraction is not possible. This belief is indeed correct in the case in which a bidder's signal only affects his own payoff - the case of private values. A standard example of private values is when agents have private information about their own individual preferences.

In this paper I will show that, contrary to this widely held belief, full surplus extraction is possible when valuations are interdependent, even if types are independent random variables. Valuations are interdependent if the payoff of an agent depends not only on his own type, but also on the types (or informational signals) of the other agents. This is the case, for example, when buyers have private information about the quality of the good or service that the seller is trying to sell (e.g., in a mineral-rights auction, bidders have private estimates about the quantity of minerals in the tract).

The important insight of this paper is that interdependence of valuations is a form of correlation among bidders payoffs. This correlation can be exploited to achieve full surplus extraction by using a two-stage revelation mechanism, in which bidders first report their signals, and then the winning bidder reports his realized allocation payoff.

In the standard mechanism design model, agents only report their types to the designer; they do not report their (pre-monetary transfer) payoffs from the allocation, after an allocation has been made. Implicitly, standard mechanisms rule out the possibility of transfers after an agent has observed his own payoff from the allocation. Two-stage mechanisms, which have been introduced by Mezzetti [11] to study efficient decisions, allow transfers to be made after a final allocation has been determined.

More precisely, the designer (the seller in this paper) sets up two reporting stages. In the first stage, the seller asks about the agents' types. On the basis of these reports, a winner is selected and partial transfers are made. After the winner has observed his payoff from the allocation of the object, the seller asks him to report his realized payoff in a second reporting stage. Then, final payments from all bidders are collected that are contingent on reports in both stages.

While with private values an agent cannot obtain any new information from the observation of his allocation payoff, with interdependent valuations observing his realized payoff provides the agent with new information about the types, or informational signals, of the other agents. In other words, even though types are independent random variables, with interdependent valuations the realized payoff of an agent is correlated with the types of the other agents.

I study two versions of the model. In the first version, allocation payoffs are deterministic functions of the type profile. In this case, the allocation-payoff report of the winning bidder allows the seller to detect and punish first-stage lies by the losing bidders. In the second version, allocation payoffs are random functions of the type profile. In this version, the seller can use lotteries analogous to the ones used in Crémer and McLean [3], [4], but based on the payoff report of the winning buyer, to extract the full surplus from the agents. A difference with the mechanism introduced by Crémer and McLean is that, in order to fully exploit the correlation between allocation payoffs and agents' signals, the two main results of this paper (Theorems 2 and 3) require that the object be allocated randomly, and hence inefficiently, with positive probability. This inefficiency is associated with a loss of surplus to the seller, but this loss can be made arbitrarily small by making the probability of a random allocation arbitrarily small. The object must be allocated randomly so that, with positive probability, the designer will be able to use the second-stage allocation-payoff reports of all the other agents to cross-check the first-stage type report of any given agent i.

The paper is organized as follows. The next section introduces the model. Sections 3 and 4 contain the full surplus extraction results; Section 5 concludes.

2 The Model

An uninformed seller of a single item, agent 0, faces n prospective buyers. Each buyer has private information about his own type, or signal, $\theta_i \in \Theta_i$. Let $\Theta = \times_{i=1}^{n} \Theta_i$ be the set of signal profiles, $\theta = (\theta_1, \ldots, \theta_n)$ a generic element of Θ, and $\theta_{-i} \in \Theta_{-i} = \times_{j \neq i} \Theta_j$. Types are drawn independently across agents; that is, the θ_i's are independent random variables.

A decision $x = (x_0, x_1, ..., x_n)$ is a probability vector; x_i is the probability that agent i gets the object. Buyer i's utility function $U_i : X \times \Omega \times \mathbb{R}^{n+1} \to \mathbb{R}$ depends on the decision x, the state of the world $\omega \in \Omega$ and the transfer $t_i = (t_i^0, t_i^1, ..., t_i^n)$; t_i^j is buyer i's payment to the seller when the item is allocated to agent j. The state of the world is a random variable drawn from a probability measure that depends on the agent's types. For $i = 1, ..., n$,

$$U_i(x, \omega, t_i) = x_i v_i(\omega) - \sum_{j=0}^{n} x_j t_i^j, \tag{1}$$

where $v_i(\omega)$ is buyer i's allocation payoff when he gets the item and ω is the (realized) state of the world; $v_i(\cdot)$ is assumed to be a continuous and bounded function. The allocation payoff of a buyer that does not receive the object is normalized to zero (there are no allocational externalities). The seller's allocation payoff $v_0(\omega)$ is zero for all ω. Let $t = (t_1, ..., t_n)$. When the decision is x and the transfers are t, the seller's payoff is simply his revenue,

$$r = \sum_{j=0}^{n} \sum_{i=1}^{n} x_j t_i^j.$$

In many real world examples, agents observe their own realized allocation payoffs, and there are no obstacles to making final transfers that are contingent on such an observation. For example, after purchasing a good on ebay, or any other internet auction site, buyers observe the quality of the good. After the purchase, buyers can post feedback reviews of the seller. These reviews are accessible to future buyers and thus determine the seller's payoff through reputational effects.

In this paper, I will assume that if the item is allocated to buyer $i = 1, ..., n$, then for any realization of the state of the world ω, buyer i observes his realized allocation payoff $v_i(\omega)$ before final transfers are made.

Partial transfers can be made before the winning buyer observes his allocation payoff. In particular, in the mechanism I will propose the payment of the winning buyer does not depend on the reported allocation payoff, and thus can be made before this is observed. Losing buyers, on the other hand, may have to make (or receive) payments that depend on the allocation report of the winner.

Under private values, there is no loss of generality in assuming that the seller only uses standard revelation mechanisms in which buyers are only asked to report their signals (types). With interdependent valuations and observable allocation payoffs, allowing the seller to collect messages in two reporting stages enlarges the set of implementable decision functions. This is because the second-stage payoff reports can be used to cross check the first-stage type reports. Thus, for example, while there are no efficient standard mechanisms when valuations are interdependent and signals are multidimensional, independent, random variables (e.g., see Jehiel and Moldovanu [6]), Mezzetti [11] shows that efficient two-stage mechanisms always exist.[1] In a two-stage revelation mechanism, messages about the buyers' signals are collected in the first stage and are used to determine the allocation of the item. After the agents have observed their allocation payoffs they report them in the second stage; messages from

[1] More precisely, Jehiel and Moldovanu [6] show that if one restricts attention to one-stage mechanisms, then incentive compatibility is inconsistent with making efficient decisions, even if one does not impose any budget balancing or individual rationality constraint. Mezzetti [11] shows that with two-stage mechanisms incentive compatibility, efficiency and budget balancing can always be achieved.

both stages are used to determine the total monetary transfers from the buyers to the seller. Thus, a *two-stage mechanism* $m = \langle x, t \rangle$ consists of an allocation function $x : \Theta \to X$, and $n(n+1)$ transfer functions $t_i^j : \Theta \times \mathcal{V}^j \to \mathbb{R}$, where $j = 0, 1, ..., n$, $i = 1, ..., n$, and $\mathcal{V}^j \subset \mathbb{R}$ is the set of j's feasible allocation payoffs when the item is allocated to him (in this paper, the only agent who obtains new information from observing his own allocation payoff is the buyer who gets the item).[2]

In the next section, I will assume that signals are continuous variables and that the state of the world coincides with the signal profile, $\Omega = \Theta$. This version of the model, in which allocation payoffs are deterministic functions of the type profile, called Model D, permits a more transparent presentation of the effects at work with interdependent valuations. When the player receiving the object observes his own allocation payoff, he may discover without doubt that some other player misreported his type in the first reporting stage. On the basis of the allocation payoff reported by the winner in the second reporting stage, the seller can then discover and severely punish first-stage lies of the losing buyers.

Section 4 studies a second version, Model R, in which the state space does not coincide with the space of signal profiles, and allocation payoffs are random functions of the type profile.[3] In this version, by observing his own allocation payoff the winner does not detect for sure that other players lied. Full surplus extraction is still possible, however, because the interdependence of valuations implies that the (random) allocation payoff of the winner is correlated with the types of all players. The seller can then use lotteries like in Crémer and McLean [3], [4] to induce buyers to truthfully report their types. Loosely speaking, the winner's allocation payoff provides an informative signal about the types of the other buyers that allows the seller to severely punish first-stage lies about types. Both models have been used in

[2] Mezzetti [10] discusses the revelation principle and shows that studying two stage revelation mechanisms is without loss of generality (see also Myerson [13]).

[3] To keep the analysis comparable with Crémer and McLean [4], in this version of the model the signal and state spaces are finite.

the literature, (e.g., see Crémer and McLean [3], [4] and Gresik [5] for Model D, and McLean and Postlewaite [9] for Model R).

3 Surplus Extraction in the Deterministic Model

In this section, I will study the case in which the set of states of the world coincides with the set of type profiles.

Definition 1 *In* Model D*: (i) The sets* Θ_i *are closed and bounded subset of* $\mathbb{R}$*; (ii)* $F_i(\theta_i)$ *and* $F_{-i}(\theta_{-i}) = \prod_{j \neq i} F_j(\theta_j)$ *are the cumulative probability distributions of* $\theta_i \in \Theta_i$ *and* $\theta_{-i} \in \Theta_{-i}$*, respectively; (iii) The set of states of the world is* $\Omega = \Theta$*.*

In Crémer and McLean [3], [4], full surplus extraction occurs at the interim level. Each agent type participates in a lottery which leaves him with zero expected surplus. In this section, I will derive conditions under which it is possible for the seller to extract all the surplus ex-post (i.e., for all type realizations), in spite of signals being statistically independent. It is useful to begin with a simple example that illustrates the main idea.

Example 1. Consider the following special case of the auction model in Myerson [12]. There is a single item for sale and two bidders (potential buyers). Bidder i observes a private signal θ_i; the other player regards θ_i as a random variable with uniform distribution over the interval $[1, 2]$. Buyer i's valuation for the object (the allocation payoff from receiving the object) is

$$v_i(\theta) = \theta_i + \alpha\theta_j \qquad i \neq j,\, i, j = 1, 2,$$

where $\alpha \in (0, 1)$ is a known parameter. Following Myerson [12], one can show that all common auctions (e.g., a first-price, a second-price (Vickrey), or an ascending auction) with no reserve price are optimal. Let $\theta^{(1)} = \max\{\theta_1, \theta_2\}$ and $\theta^{(2)} = \min\{\theta_1, \theta_2\}$. In a Vickrey or in an ascending auction, bidder i wins the object if $\theta_i = \theta^{(1)}$, and pays a price $p = (1+\alpha)\theta^{(2)}$. Thus, by using a standard optimal auction the seller does not extract the full surplus $\theta^{(1)} + \alpha\theta^{(2)}$.[4]

I now show that the seller could exploit the interdependence of valuations and design a two-stage mechanism that extracts the full surplus. Consider the following "*shoot-the-liar*" mechanism. Bidders are first asked to report their signals (in the first reporting stage). The bidder who reports the highest signal wins the object, and then is asked to report the value obtained from the object (in the second reporting stage). The payment, or transfer, to the seller from bidder i, $i \neq j$, as a function of the reports, is as follows:

$$\begin{aligned} t_i^i(\theta_1^r, \theta_2^r, v_i^r) &= \theta_i^r + \alpha\theta_j^r \\ t_i^j(\theta_1^r, \theta_2^r, v_j^r) &= \begin{cases} 0 & \text{if } v_j^r = \theta_j^r + \alpha\theta_i^r \\ P & \text{if } v_j^r \neq \theta_j^r + \alpha\theta_i^r, \end{cases} \end{aligned}$$

where $P > 1$ is a constant. To see that the incentive compatibility constraints for the bidders are satisfied (i.e., that bidder i wants to report truthfully), note first that t_i^i does not depend on i's reported allocation payoff v_i^r. Hence, truthful reporting of his realized allocation payoff is optimal for the winning bidder, in the second reporting stage. Suppose that bidder j truthfully reports his signal in the first reporting stage, and if he wins he then truthfully reports his realized valuation in the second reporting stage. The expected payoff to player i from reporting $\theta_i^r \neq \theta_i$, while his signal is θ_i, then is

$$U_i(\theta_i^r; \theta_i) = \int_1^{\theta_i^r} (\theta_i - \theta_i^r)\, d\theta_j - \int_{\theta_i^r}^2 P d\theta_j = (\theta_i^r - 1)(\theta_i - \theta_i^r) - P(2 - \theta_i^r),$$

while i's expected payoff from truthfully reporting $\theta_i^r = \theta_i$ is zero. Clearly, for $P > 1$, U_i is maximized by reporting truthfully in the first stage, $\theta_i^r = \theta_i$. In this two-stage

[4] That Myerson's optimal auction has no reserve price is due to the type support being $[1, 2]$. The conclusion that Myerson's optimal auction does not extract the full surplus is general.

revelation mechanism, each bidder obtains a zero payoff and the seller extracts the full surplus for all type realizations.[5]

As this example makes clear, the seller is able to extract the full surplus if, intuitively, potentially profitable lies in the first reporting stage can be detected with positive probability, when buyers truthfully report their allocation payoffs in the second stage. In the next subsection, I will formalize this intuition by providing a condition under which full surplus extraction is possible. Subsection 3.2 contains the main result of this section; I will show that even when full surplus extraction is not possible, virtual full surplus extraction can be obtained.

3.1 Full Surplus Extraction

Let $s(\theta) = \max_{j=0,\ldots,n} v_j(\theta)$ be the full surplus associated with type profile θ, and let $x^*(\theta_i, \theta_{-i})$ be an efficient allocation rule:

$$x_i^*(\theta_i, \theta_{-i}) > 0 \quad \text{if and only if} \quad i \in \arg\max_{j=0,\ldots,n} v_j(\theta_i, \theta_{-i}).$$

An efficient allocation rule guarantees that the sum of all players' payoffs coincides with the full surplus for all type profiles θ. (The efficient allocation is that the seller keeps the item if v_i is negative for all buyers i.). Let

$$r(\theta; m) = \sum_{j=0}^{n} \sum_{i=1}^{n} x_j(\theta) t_i^j(\theta, v_j(\theta))$$

be the seller's revenue for the type profile θ, when the mechanism used is $m = \langle x, t \rangle$.

[5] The "shoot-the-liar" mechanism contains a discrete penalty jump for being discovered lying. Full surplus extraction can also be achieved with smooth transfers; e.g., by setting

$$\begin{aligned} t_i^i(\theta_1^r, \theta_2^r, v_1^r, v_2^r) &= \theta_i^r + \alpha\theta_j^r \\ t_i^j(\theta_1^r, \theta_2^r, v_1^r, v_2^r) &= \frac{1}{\alpha^2}\gamma\left(v_j^r - \theta_j^r - \alpha\theta_i^r\right)^2 + \frac{1}{\alpha}\left(\frac{\theta_i^r - 1}{2 - \theta_i^r}\right)\left(v_j^r - \theta_j^r - \alpha\theta_i^r\right), \end{aligned}$$

where $\gamma > 0$ is a constant.

Definition 2 *In the two-stage mechanism $m = \langle x, t \rangle$, the seller extracts the full surplus for all type realizations, if there is a perfect Bayesian equilibrium of m in which the seller's revenue $r(\theta; m)$ equals the full surplus $s(\theta)$ for all type profiles θ.*

To extract the full surplus for all type realizations, the seller must use an efficient allocation rule. Furthermore, on the equilibrium path the seller should not charge the losing bidders (i.e., their transfers should be zero) and must charge the winning bidder i an amount equal to i's valuation for the object, $v_i(\theta_i, \theta_{-i})$. With such equilibrium transfers and without out of equilibrium penalties, a type θ_i that reports θ_i' would obtain an expected payoff equal to

$$\int_{\Theta_{-i}} x_i^*(\theta_i', \theta_{-i}) \left[v_i(\theta_i, \theta_{-i}) - v_i(\theta_i', \theta_{-i}) \right] dF_{-i}(\theta_{-i}) = V_i(\theta_i; \theta_i') - V_i(\theta_i'; \theta_i'),$$

where

$$V_i(\theta_i; \theta_i') = \int_{\Theta_{-i}} x_i^*(\theta_i', \theta_{-i}) v_i(\theta_i, \theta_{-i}) dF_{-i}(\theta_{-i})$$

is the expected allocation payoff of buyer i of type θ_i when he reports θ_i', all other players report truthfully, and the seller uses an efficient allocation rule.

We now introduce an assumption that, as Theorem 1 shows, is necessary and sufficient for the seller to be able to extract the full surplus for all type realizations.

Assumption 1 *For all $i = 1, ..., n$, and all $\theta_i, \theta_i' \in \Theta_i$, if $V_i(\theta_i; \theta_i') > V_i(\theta_i'; \theta_i')$, then there exist a positive-measure set $\Theta_{-i}^+ \subset \Theta_{-i}$ and a $j \neq i$ such that (i) $v_j(\theta_i, \theta_{-i}) \neq v_j(\theta_i', \theta_{-i})$ for all $\theta_{-i} \in \Theta_{-i}^+$, and (ii) $\int_{\Theta_{-i}^+} x_j^*(\theta_i', \theta_{-i}) dF_{-i}(\theta_{-i}) > 0$.*

Assumption 1 requires that, if the lie θ_i' is profitable for type θ_i under the efficient decision rule (i.e., if $V_i(\theta_i; \theta_i') - V_i(\theta_i'; \theta_i') > 0$), then with positive probability the item will go to another agent j (condition (ii)), whose observed allocation payoff will be inconsistent with the reported type of agent i (condition (i)). Under this assumption, by cross-checking i's type report with the other agents' allocation reports, the seller is able to detect with positive probability all profitable lies by all agents. Note that, given that the number of agents is finite, if a profitable lie θ_i' for type θ_i can be detected with positive probability, then there must be a j that detects it with positive probability. However, the agent detecting the lies of agent i needs not be always the same j; Assumption 1 allows j to differ for different values of θ_i, θ_i', and θ_{-i}.

Condition (i) in Assumption 1 is satisfied if the valuation function of player j is a strictly monotone function of the type of player i, a common assumption in auction theory. Condition (ii) rules out that a type θ_i can make a report θ_i' that underestimates his expected payoff from owning the object and guarantees that he will always win it.

To extract the full surplus for all type realizations, the seller should use the following *shoot-the-liar* mechanism. First, based on the first-stage signal reports, the item is allocated efficiently (i.e., given to the buyer with the highest valuation). Second, the seller collects a transfer from the buyer i that obtains the item; this transfer, which can be made before the winner observes his allocation payoff, is equal to the full value of the item to i, $v_i(\theta^r)$. Third, the winning buyer reports his realized allocation payoff in the second reporting stage. If this report is inconsistent with the type reports made by the other buyers in the first stage, then all other buyers are imposed severe (but bounded) fines.[6] On the equilibrium path no buyer will lie, and thus only the winning bidder will need to make a payment to the seller.

Theorem 1 *In Model D, there is a two-stage mechanism in which the seller extracts the full surplus from the agents for all type realizations, if and only if Assumption 1*

[6] A drawback of this shoot-the-liar mechanism is that in the second stage the winning buyer is indifferent between reporting his true allocation payoff and reporting any other payoff. As a result, there might be additional equilibria that do not yield full surplus extraction. It is an open question under which conditions more complex mechanisms that do not have this feature can be constructed. See Brusco [2] for a study of unique implementation of the full surplus extraction outcome in the model of Crémer and McLean [4].

In a related paper, Bennouri and Falconieri [1] study a common-value auction with uninformed bidders and bidders that receive independent signals before the auction. They show that, when both informed and uninformed bidders are risk-neutral, the seller can extract the full surplus. This can be done by always assigning all the objects to the uninformed bidders. As in the shoot-the liar mechanism, the informed bidders are indifferent between telling the truth and misreporting.

holds.

Proof. (If) Consider a two-stage revelation mechanism that uses an efficient decision rule. Let the transfer function be:

$$\begin{aligned} t_i^i(\theta^r, v_i^r) &= v_i(\theta^r) \\ t_i^j(\theta^r, v_j^r) &= \begin{cases} 0 & \text{if} \quad v_j^r = v_j(\theta^r) \\ P & \text{if} \quad v_j^r \neq v_j(\theta^r). \end{cases} \end{aligned}$$

Suppose that all the agents $j \neq i$ always truthfully report their signals in the first stage and their allocation payoffs, if they get the item, in the second reporting stage. Since agent i's transfer does not depend on his reported allocation payoff, he has no incentive to deviate from truthfully reporting it in the second stage. If agent i of type θ_i truthfully reports his signal in the first stage, then he gets zero total utility. If he reports a type θ_i', then he obtains

$$\begin{aligned} &\int_{\Theta_{-i}} x_i^*(\theta_i', \theta_{-i}) \left[v_i(\theta_i, \theta_{-i}) - v_i(\theta_i', \theta_{-i}) \right] dF_{-i}(\theta_{-i}) - P \sum_{j \neq i} \int_{\Theta_{-i}^j} x_j^*(\theta_i', \theta_{-i}) dF_{-i}(\theta_{-i}) \\ &\qquad = V_i(\theta_i; \theta_i') - V_i(\theta_i'; \theta_i') - P \sum_{j \neq i} \int_{\Theta_{-i}^j} x_j^*(\theta_i', \theta_{-i}) dF_{-i}(\theta_{-i}), \end{aligned}$$

where Θ_{-i}^j is the subset for which $v_j(\theta_i, \theta_{-i}) \neq v_j(\theta_i', \theta_{-i})$ for player $j \neq i$. If $V_i(\theta_i; \theta_i') - V_i(\theta_i'; \theta_i') \leq 0$, then misreporting is not profitable. If $V_i(\theta_i; \theta_i') - V_i(\theta_i'; \theta_i') > 0$, then, by Assumption 1, for all θ_i there is a $j \neq i$ such that $\int_{\Theta_{-i}^j} x_j^*(\theta_i', \theta_{-i}) dF_{-i}(\theta_{-i}) > 0$. To deter any first-stage type misreport, it is then sufficient to set

$$P \geq \sup_{i, \theta_i, \theta_i'} \left\{ \frac{V_i(\theta_i; \theta_i') - V_i(\theta_i'; \theta_i')}{\int_{\Theta_{-i}^j} x_j^*(\theta_i', \theta_{-i}) dF_{-i}(\theta_{-i})} \right\}.$$

(Only if) Suppose Assumption 1 is violated. Then, there exists a buyer i and signals θ_i and θ_i' such that: (i) $V_i(\theta_i; \theta_i') > V_i(\theta_i'; \theta_i')$, (ii) for all buyers $j \neq i$ and all subsets $\Theta_{-i}^+ \subset \Theta_{-i}$, either $v_j(\theta_i, \theta_{-i}) = v_j(\theta_i', \theta_{-i})$, or $\int_{\Theta_{-i}^+} x_j^*(\theta_i', \theta_{-i}) dF_{-i}(\theta_{-i}) = 0$.

In any mechanism that extracts the full surplus for all type realizations, the winning buyer must be charged his valuation for the object, as computed from the type reports. Then, type θ_i profits from reporting that his type is θ_i': the lie is discovered with probability zero and θ_i's expected utility is $V_i(\theta_i;\theta_i') - V_i(\theta_i';\theta_i') > 0$. The fact that $V_i(\theta_i;\theta_i') - V_i(\theta_i';\theta_i') > 0$ implies that $x_i^*(\theta_i', \theta_{-i}) > 0$ for a subset of Θ_{-i} having positive probability measure. Hence, the seller cannot extract the full surplus for all type realizations. ■

3.2 Virtual Full Surplus Extraction

While there are important examples where it is satisfied, Assumption 1 is restrictive. Even if valuations are fully interdependent (i.e., if they depend on the types of all agents) it can be violated, as shown by the following modification of Example 1.

Example 2. As in Example 1, there is a single item for sale and two buyers with valuations $v_i(\theta) = \theta_i + \alpha\theta_j$, $\alpha \in (0, 1)$, but now buyer 1's type has support $[1, 3]$, while 2's type has support $[1, 2]$. For all types of buyer 1 in the set $(2, 3]$, buyer 1 can report $\theta_1^r = 2$, making sure that $x_2^*(2, \theta_2) = 0$ with probability one: this lie will never be detected in a mechanism that uses an efficient allocation rule. Assumption 1 is violated and full surplus extraction is impossible.

What prevents full surplus extraction in Example 2 is that a buyer can pay less than the full surplus while being sure that he will get the object. In both examples, if buyer j is given the item, then any lie by i will be discovered. The seller could then induce truthtelling by assigning the item to each buyer with positive probability, irrespective of the type reports. Knowing that with positive probability any lie will be discovered and severely punished, buyers will report their true types. Since the allocation will be inefficient with positive probability, the seller will not be able to extract the full surplus. However, the seller could extract the full surplus when the allocation decision is efficient and, by making the probability of a random allocation arbitrarily small, he could obtain a revenue arbitrarily close to the full surplus.

Definition 3 *In the two-stage mechanism $m = \langle x, t \rangle$, the seller extracts within ε of the full surplus for all type realizations, if there is a perfect Bayesian equilibrium of m in which the seller's revenue $r(\theta; m)$ is greater than $s(\theta) - \varepsilon$ for all type profiles θ. The seller can* virtually extract the full surplus for all type realizations*, if for all $\varepsilon > 0$ there is a mechansim $m(\varepsilon)$ under which the seller extracts within ε of the full surplus for all type realizations.*

We now introduce an assumption, which is satisfied by Example 2, under which the seller will be able to virtually extract the full surplus for all type realizations.

Assumption 2 *For all $i = 1, ..., n$, and all $\theta_i, \theta_i' \in \Theta_i$, if $V_i(\theta_i; \theta_i') > V_i(\theta_i'; \theta_i')$, then there exists a positive-measure set $\Theta_{-i}^+ \subset \Theta_{-i}$ and a $j \neq i$, such that, $v_j(\theta_i, \theta_{-i}) \neq v_j(\theta_i', \theta_{-i})$ for all $\theta_{-i} \in \Theta_{-i}^+$.*

Assumption 2 guarantees that, for every possible lie by agent i that is profitable under the efficient decision rule, there is a positive probability that another agent j would be able to detect the lie, if he were allocated the object. As in Assumption 1, the agent detecting the lie need not always be the same, but may differ for different values of θ_i, θ_i', and θ_{-i}. Contrary to Assumption 1, which imposes condition (ii), Assumption 2 does not require that it is efficient to allocate the object to the agent that is able to detect the lie. Thus, Assumption 2 is strictly weaker than Assumption 1. If, as is often assumed, $v_j(\theta_i, \theta_{-i})$ is a strictly monotone function of θ_i, then Assumption 2 holds, while Assumption 1 need not hold (it does not hold in Example 2). Furthermore, by the transversality theorem, given $\theta_i, \theta_i' \in \Theta_i$, $\theta_i \neq \theta_i'$, for generic, smooth, payoff functions, the equalities $v_j(\theta_i, \theta_{-i}) = v_j(\theta_i', \theta_{-i})$ for all $j \neq i$ only hold for a zero-measure set of values of θ_{-i}; that is, Assumption 2 holds for generic, smooth, valuation functions $v_j : \Theta \to \mathbb{R}$.

The following theorem, the main result of this section, shows that if Assumption 2 is satisfied, then the seller can virtually extract the full surplus for all type realizations, by using a modified shoot-the-liar mechanism in which (i) the efficient allocation is implemented with a probability close to, but bounded away from, one, and (ii) each player receives the object with small, but positive, probability.[7]

Theorem 2 *In Model D, if Assumption 2 holds, then the seller can virtually extract the full surplus for all type realizations.*

Proof. In the first stage, besides collecting signal reports from the bidders, the designer observes the realization of a random variable Y that takes values $y = 0$ with probability $1-\delta$, and $y = 1$ with probability δ (the probability δ is chosen by the designer). The allocation rule and transfer functions will also depend on the realization of the random variable Y. Let the allocation rule be

$$\begin{aligned} x_i(\theta_i^r, \theta_{-i}^r, y &= 0) = x_i^*(\theta_i^r, \theta_{-i}^r) \\ x_i(\theta_i^r, \theta_{-i}^r, y &= 1) = \frac{1}{n}, \end{aligned}$$

and the transfer functions be:

$$\begin{aligned} t_i^i(\theta^r, v_i^r, y &= 0) = v_i(\theta^r) \\ t_i^i(\theta^r, v_i^r, y &= 1) = 0 \\ t_i^j(\theta^r, v_j^r, y) &= \begin{cases} 0 & \text{if} \quad v_j^r = v_j(\theta^r) \\ P & \text{if} \quad v_j^r \neq v_j(\theta^r). \end{cases} \end{aligned}$$

Agents have no incentives to deviate in the second stage. If all the other agents always truthfully report their signals in the first stage and their allocation payoffs in the second stage, then agent i of type θ_i gets a total utility of $\frac{\delta}{n}\int_{\Theta_{-i}} v_i(\theta_i, \theta_{-i})dF_{-i}(\theta_{-i})$ by truthfully reporting his signal in the first stage. If he reports a type $\theta_i' \neq \theta_i$, then

[7] It is simple to show that even when Assumption 2 fails, by using two-stage mechanisms the seller can typically strictly increase his expected revenue over the revenue he would obtain in a standard revelation mechanism.

he gets

$$\frac{\delta}{n}\int_{\Theta_{-i}} v_i(\theta_i,\theta_{-i})dF_{-i}(\theta_{-i})+(1-\delta)\int_{\Theta_{-i}} x_i^*(\theta_i',\theta_{-i})\left[v_i(\theta_i,\theta_{-i})-v_i(\theta_i',\theta_{-i})\right]dF_{-i}(\theta_{-i})$$
$$-P\sum_{j\neq i}\int_{\Theta_{-i}^j}\left(\frac{\delta}{n}+(1-\delta)x_j^*(\theta_i',\theta_{-i})\right)dF_{-i}(\theta_{-i})$$

$$=\frac{\delta}{n}\int_{\Theta_{-i}} v_i(\theta_i,\theta_{-i})dF_{-i}(\theta_{-i})+(1-\delta)\left[V_i(\theta_i;\theta_i')-V_i(\theta_i',\theta_i')\right]$$
$$-P\sum_{j\neq i}\int_{\Theta_{-i}^j}\left(\frac{\delta}{n}+(1-\delta)x_j^*(\theta_i',\theta_{-i})\right)dF_{-i}(\theta_{-i})$$

where Θ_{-i}^j is the subset for which $v_j(\theta_i,\theta_{-i})\neq v_j(\theta_i',\theta_{-i})$ for player $j\neq i$. If $V_i(\theta_i;\theta_i')-V_i(\theta_i',\theta_i')>0$, by Assumption 2, Θ_{-i}^j has probability measure greater than zero for at least a $j\neq i$. To deter first-stage type misreporting, it is then sufficient to set

$$P\geq\frac{n(1-\delta)}{\delta}\sup_{i,\theta_i,\theta_i'}\left\{\frac{V_i(\theta_i;\theta_i')-V_i(\theta_i',\theta_i')}{\sum_{j\neq,i}\int_{\Theta_{-i}^j}dF_{-i}(\theta_{-i})}\right\}.$$

This shows that truthful reporting is an equilibrium of the proposed mechanism. The object is allocated efficiently with probability $(1-\delta)$, and randomly with probability $\frac{\delta}{n}$ to each buyer; the seller only charges the winning buyer when the decision is efficient. This implies that the seller's revenue is

$$\begin{aligned} r(\theta;m) &= (1-\delta)\max_i v_i(\theta) \\ &= s(\theta)-\delta s(\theta). \end{aligned}$$

For any given ε, by setting

$$\delta<\frac{\varepsilon}{\sup_\theta\{s(\theta)\}},$$

it is $r(\theta;m)>s(\theta)-\varepsilon$. ■

In the mechanism used in the proof of Theorem 2, the only payment to the seller is from the bidder receiving the object, when the decision implemented is efficient. In such a case the winner pays an amount equal to his valuation. With probability δ the object is assigned randomly and the seller does not collect any payments.

Assumption 2 and Theorem 2 could be extended to the case in which θ_i is multi-dimensional without any modification.

4 Surplus Extraction in the Random Model

In the model of this section, observing his own allocation payoff $v_i(\omega)$ provides agent i with a signal that is imperfectly correlated with the types θ_{-i} of the other agents. This implies that, even if the winning buyer truthfully reports his allocation payoff, the seller cannot be certain that a player lied in the type reporting stage. I will show below, however, that, by using lotteries as in Crémer and McLean [4], the seller can virtually extract the full surplus for all type realizations.

A small difference with the deterministic case is that for any given type profile θ, the losers' payments (which were zero in the deterministic case) will vary with the actual realization of the state of the world ω (but will average out to zero over all states of the world, conditional on the type profile θ). To facilitate comparison with Crémer and McLean [4], in this version of the model I will assume that the type and state spaces are finite.

Definition 4 *In* Model R*: (1) The sets Θ_i and Ω are finite; (2) $f_i(\theta_i) > 0$ and $f_{-i}(\theta_{-i}) = \prod_{j \neq i} f_j(\theta_j) > 0$ are the probabilities of $\theta_i \in \Theta_i$ and $\theta_{-i} \in \Theta_{-i}$; (3) $g(\omega|\theta)$ is the probability of ω conditional on θ, and $g(\omega|\theta_i) = \sum_{\theta_{-i} \in \Theta_{-i}} g(\omega|\theta_i, \theta_{-i}) f_{-i}(\theta_{-i})$ is the probability of ω conditional on θ_i.*

More notation is needed. Let $v_i(\theta) = \sum_{\omega \in \Omega} v_i(\omega) g(\omega|\theta)$ be the expected payoff of player i conditional on the type profile being θ. Let $\Omega(v_i)$ be the set of states of the world ω for which $v_i(\omega) = v_i$, and let $\mathcal{V}^i = \{v_i \in \mathbb{R} : \exists \omega \in \Omega \text{ s.t. } v_i(\omega) = v_i\}$ be the set of feasible allocation payoffs for agent i. Since the type sets Θ_i and the set of states of the world Ω are finite, $\mathcal{V}^i$ is also finite; let k_i be its cardinality. We can identify $\mathcal{V}^i$ with the vector $(v_i^1, ..., v_i^{k_i})$.

Let $\pi(v_j|\theta_i, \theta_{-i}) = \sum_{\omega \in \Omega(v_j)} g(\omega|\theta_i, \theta_{-i})$ be the probability that $v_j(\omega) = v_j$, conditional on θ_{-i} and θ_i; let $\pi_j(\theta_i, \theta_{-i}) = \left(\pi(v_j^1|\theta_i, \theta_{-i}), ..., \pi(v_j^{k_j}|\theta_i, \theta_{-i})\right)$ be the vector of probabilities of j's allocation payoffs, conditional on θ_i and θ_{-i}. Note that $\pi_j(\theta_i, \theta_{-i})$ has dimension k_j.

4.1 Virtual Full Surplus Extraction

Like in Model D, let $s(\theta) = \max_{j=0,...,n} v_j(\theta)$ be the full surplus associated with the type profile θ, and let $x^*(\theta_i, \theta_{-i})$ be an efficient allocation rule. The seller's revenue for the type profile θ in mechanism $m = \langle x, t \rangle$ is

$$r(\theta; m) = \sum_{j=0}^{n} \sum_{i=1}^{n} \sum_{\omega \in \Omega} x_j(\theta) t_i^j(\theta, v_j(\omega)) g(\omega|\theta).$$

As in the previous section, the definiton of virtual full surplus extraction for all type realizations is given in Definition 3.

The following assumption is the appropriate adaptation of Assumption 2 to Model R. It is close in spirit to the condition in Theorem 2 of Crémer and McLean [4]. As we shall see, it ensures that the seller can virtually extract the full surplus for all type realizations.

Assumption 3 *For all i and all θ_{-i}, there exists a buyer $j(\theta_{-i}) \neq i$ such that $\pi_{j(\theta_{-i})}(\theta_i, \theta_{-i}) \neq \sum_{\theta_i' \neq \theta_i} \rho_i(\theta_i') \pi_{j(\theta_{-i})}(\theta_i', \theta_{-i})$ for all $\theta_i \in \Theta_i$, and all $\rho_i(\theta_i') \geq 0$.*

Assumption 3 is a joint restriction on the conditional distribution $g(\omega|\theta)$ and the payoff functions of the agents. It says that, for all i and θ_{-i}, there is a bidder $j \neq i$ such that j's payoff-probability vector conditional on θ_{-i} and θ_i is not a positive linear combination of all the other payoff-probability vectors of bidder j, conditional on θ_{-i} and $\theta_i' \neq \theta_i$. I will say that $j(\theta_{-i})$ is the bidder cross-checking i at θ_{-i}. The bidder cross-checking i needs not always to be the same; $j(\theta_{-i})$ may differ for different values of θ_{-i}.

Since the probability vector $\pi_j(\theta_i, \theta_{-i})$ has dimension k_j, Assumption 3 holds generically only if, for each player i, the set of possible payoffs $\mathcal{V}^j$ of another player $j \neq i$ has at least as many elements as the set of types of player i. If for a player i the sets of possible payoffs of all other players j contains less elements than Θ_i (i.e., if k_j is less than the cardinality of Θ_i), then Assumption 3 cannot hold generically, because it is always possible to write one of the k_j dimensional allocation-probability vectors $\pi_j(\theta_i, \theta_{-i})$ as a linear combination, and in a positive-measure number of cases as a positive linear combination, of the other vectors $\pi_j(\theta_i', \theta_{-i})$, with $\theta_i' \neq \theta_i$. Intuitively, the set of states of the world must be sufficiently rich relative to the set of agent types for Assumption 3 to hold generically.

In the mechanism proposed by Crémer and McLean [3], [4], the seller fully extracts the surplus by using an efficient auction (e.g., a first price, or a Vickrey auction), augmented with a lottery (side-bet) for each type of each agent. The lottery stipulates that an agent must make additional payments to the seller that depend on the types reported by the other agents.

A similar approach can be followed when valuations are interdependent and decision payoffs are observable, even if the types θ_i are independent. Given the agents' reported type profile, the designer assigns the object according to the efficient allocation rule with probability $1 - \delta$, with $\delta \in (0, 1)$. With probability δ, the object is randomly assigned, with each buyer obtaining the item with probability δ/n. The agent who receives the object is asked to pay his expected allocation payoff given the reported types. When agent i does not get the object, he only pays if the winning buyer is $j(\theta_{-i})$, the agent cross-checking i at θ_{-i}. In such a case, i must pay (or be paid) an amount that depends on the reported allocation payoff of the winning buyer.

If Assumption 3 holds, these payments can be structured so that their expected value is zero if agent i truthfully reports his type and it is arbitrarily high if he lies.

The important difference with Crémer and McLean is that this mechanism exploits the correlation between the types of the agents and the random allocation payoff of the winning agent, rather then the correlation among the types of all agents. Another difference is that, in order to fully exploit this correlation, with positive probability the object is assigned randomly. This introduces an inefficiency, and hence a loss of surplus to the seller, but this loss can be made arbitrarily small by lowering δ and raising the stakes in the lotteries offered to the losing buyers.[8]

The object must be allocated randomly for the same reason as for the virtual full surplus extraction result in Theorem 2. In Crémer and McLean, the type reports of all the other agents provide the designer with signals that are correlated with agent i's payoff. In this paper, the designer only obtains a signal that is correlated with agent i's payoff if some agent different from i gets the object and reports his allocation payoff. Assigning the object randomly with positive probability guarantees that the designer will be able to exploit as much as possible the correlation between types and allocation payoffs.

If, after the allocation decision, the designer had access to a public signal correlated with the true value of the object for the winning bidder, then the designer could use lotteries for everybody (rather than just one of the losing bidders) to induce truthtelling. Under appropriate conditions on the informativeness of the public signal, the designer could extract the full surplus and would not need to resort to an inefficient allocation with positive probability. It is, however, much more natural to assume, as I have done throughout this paper, that the winner's allocation payoff remains private.

Theorem 3 *In Model R, if Assumption 3 holds, then the seller can virtually extract the full surplus for all type realizations.*

[8] As in Crémer and McLean [3], [4] these lotteries may involve large prizes and penalties; see Kosmopoulou and Williams [7] for a criticism of this feature of the mechanism.

Proof. By Assumption 3 and Farkas' Lemma, for any given i, θ_i and θ_{-i}, there exists a $j(\theta_{-i})$ and a $k_{j(\theta_{-i})}$ dimensional vector

$$h_{j(\theta_{-i})}(\theta_i, \theta_{-i}) = \left(h_{j(\theta_{-i})}(v^1_{j(\theta_{-i})}|\theta_i, \theta_{-i}), ..., h_{j(\theta_{-i})}(v^{k_{j(\theta_{-i})}}_{j(\theta_{-i})}|\theta_i, \theta_{-i})\right)$$

such that the following scalar-product relations hold: (i) $h_{j(\theta_{-i})}(\theta_i, \theta_{-i})\pi_{j(\theta_{-i})}(\theta_i, \theta_{-i}) > 0$, and (ii) $h_{j(\theta_{-i})}(\theta_i, \theta_{-i})\pi_{j(\theta_{-i})}(\theta'_i, \theta_{-i}) \leq 0$ for all $\theta'_i \neq \theta_i$. Consider the two-stage revelation mechanism with allocation rule

$$x_i(\theta^r_i, \theta^r_{-i}) = \frac{\delta}{n} + (1-\delta)x^*_i(\theta^r_i, \theta^r_{-i}),$$

where $\delta \in (0, 1)$ and $x^*(\cdot)$ is an efficient allocation rule. Let the transfer functions be:

$$\begin{aligned}
t^i_i(\theta^r, v^r_i) &= v_i(\theta^r) \\
t^j_i(\theta^r, v^r_j) &= 0 \quad \text{if} \quad j \neq j(\theta^r_{-i}) \\
t^j_i(\theta^r, v^r_j) &= \mu \left[h_j(\theta^r_i, \theta^r_{-i})\pi_j(\theta^r_i, \theta^r_{-i}) - h_j(v^r_j|\theta^r_i, \theta^r_{-i})\right] \quad \text{if} \quad j = j(\theta^r_{-i}),
\end{aligned}$$

where $\mu > 0$, and $j(\theta_{-i})$ is the buyer cross-checking i at θ^r_{-i}, as defined in Assumption 3. First, note that the winning buyer has no incentive to deviate from telling the truth in the second stage, because his transfer $t^i_i(\cdot)$ does not depend on the second-stage payoff report. Then, suppose all types of bidders $j \neq i$ truthfully report their signals in the first stage and their allocation payoffs in the second stage. Agent i of type θ_i gets zero expected utility by reporting truthfully. To see this, note that, for a given θ_{-i}: (i) i's payoff is zero when he or a player $j \neq j(\theta_{-i})$ is allocated the object, and (ii) by Assumption 3 and the definition of $h_{j(\theta_{-i})}(\theta)$, when $j(\theta_{-i})$ obtains the object, the expected value of $t^{j(\theta_{-i})}_i$ is:

$$\mu \sum_{m=1}^{k_{j(\theta_{-i})}} \left[h_{j(\theta_{-i})}(\theta_i, \theta_{-i})\pi_{j(\theta_{-i})}(\theta_i, \theta_{-i}) - h_{j(\theta_{-i})}(v^m_{j(\theta_{-i})}|\theta_i, \theta_{-i})\right] \pi_{j(\theta_{-i})}(v^m_{j(\theta_{-i})}|\theta_i, \theta_{-i}) = 0.$$

On the other hand, if type θ_i of player i lies and reports θ_i', he will obtain a negative expected payoff provided that μ is sufficiently large. To see this, note that, for a given θ_{-i}: (i) i gets a zero payoff when a player $j \neq j(\theta_{-i})$ is allocated the object; (ii) i' s payoff is $v_i(\theta_i, \theta_{-i}) - v_i(\theta_i', \theta_{-i})$ when he obtains the object, and (iii) by Assumption 3 and the definition of $h_{j(\theta_{-i})}(\theta)$, when $j(\theta_{-i})$ obtaines the object, the expected value of the transfer from buyer i to the seller, $t_i^{j(\theta_{-i})}$, is:

$$
\begin{aligned}
& \mu \sum_{m=1}^{k_{j(\theta_{-i})}} \left[h_{j(\theta_{-i})}(\theta_i', \theta_{-i}) \pi_{j(\theta_{-i})}(\theta_i', \theta_{-i}) - h_{j(\theta_{-i})}(v_{j(\theta_{-i})}^m | \theta_i', \theta_{-i}) \right] \pi_{j(\theta_{-i})}(v_{j(\theta_{-i})}^m | \theta_i, \theta_{-i}) \\
= \;& \mu \left[h_{j(\theta_{-i})}(\theta_i', \theta_{-i}) \pi_{j(\theta_{-i})}(\theta_i', \theta_{-i}) - h_{j(\theta_{-i})}(\theta_i', \theta_{-i}) \pi_{j(\theta_{-i})}(\theta_i, \theta_{-i}) \right] > 0.
\end{aligned}
$$

Since $v_i(\theta_i, \theta_{-i}) - v_i(\theta_i', \theta_{-i})$ is bounded and $j(\theta_{-i})$ is allocated the object with a probability of at least δ/n, by choosing μ sufficiently large the seller can make sure that a player that misreports obtains a negative expected utility. This shows that truthful reporting is an equilibrium of the mechanism. Since the object is allocated efficiently with probability $(1 - \delta)$ and randomly with probability $\frac{\delta}{n}$ to each buyer, and the seller always charges the winning buyer his valuation, the seller's revenue is

$$
\begin{aligned}
r(\theta; m) &= (1 - \delta) s(\theta) + \frac{\delta}{n} \sum_{i=1}^{n} v_i(\theta) \\
&= s(\theta) - \delta \left[s(\theta) - \sum_{i=1}^{n} \frac{v_i(\theta)}{n} \right].
\end{aligned}
$$

For any given ε, by setting

$$
\delta < \frac{\varepsilon}{\sup_\theta \left\{ s(\theta) - \sum_{i=1}^{n} \frac{v_i(\theta)}{n} \right\}},
$$

it is $r(\theta; m) > s(\theta) - \varepsilon$. ■

5 Conclusions

Some authors have criticized the full surplus extraction results of Crémer and McLean [3], [4] as being counterintuitive (e.g., see McAfee and Reny [8] and Neeman [14]). It is not the goal of this paper to contribute to the debate about the plausibility of these results. This paper simply makes the theoretical point that, by using two-stage mechanisms, the setting in which agents' types are independent random variables and valuations are interdependent is very similar to the setting in which agents' types are correlated random variables. This makes intuitive sense. After all, interdependency of valuations is a form of correlation of the agents' preferences. This point has been missed in the previous literature, because attention has been restricted to mechanisms in which all transfers must be made before agents observe their own allocation payoffs.

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