Supplement to "Inefficient rushes in auctions"

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Ángel Hernando-Veciana
Departamento de Economia, Universidad Carlos III

Fabio Michelucci
CERGE-EI

A. Auxiliary results

A necessary condition for the incumbent's incentive compatibility

Lemma 4. *A direct mechanism* (p, x) *is incentive compatible for the incumbent only if* $Q_1(s_1, p)$ *in (12) is increasing in* s_1.

Proof. Let $X_1(s_1, x) \equiv \int_{[0,1]^n} x_1(s_1, s_{-1})\, dF_{-1}(s_{-1})$. An incumbent with type s_1 has incentives to report her true type s_1 rather than $\tilde{s}_1$ only if

$$\begin{aligned} U^*(s_1) \equiv \hat{v}(s_1)Q_1(s_1, p) + X_1(s_1, x) &\geq \hat{v}(s_1)Q_1(\tilde{s}_1, p) + X_1(\tilde{s}_1, x) \\ &= \big(\hat{v}(s_1) - \hat{v}(\tilde{s}_1)\big)Q_1(\tilde{s}_1, p) + \hat{v}(\tilde{s}_1)Q_1(\tilde{s}_1, p) + X_1(\tilde{s}_1, x) \\ &= \big(\hat{v}(s_1) - \hat{v}(\tilde{s}_1)\big)Q_1(\tilde{s}_1, p) + U^*(\tilde{s}_1). \end{aligned}$$

Thus, we can deduce from the top and bottom lines above and the inequality resulting from interchanging the roles of s_1 and $\tilde{s}_1$ that

$$\big(\hat{v}(s_1) - \hat{v}(\tilde{s}_1)\big)Q_1(\tilde{s}_1, p) \leq U^*(s_1) - U^*(\tilde{s}_1) \leq \big(\hat{v}(s_1) - \hat{v}(\tilde{s}_1)\big)Q_1(s_1, p),$$

which implies that $Q_1(s_1, p)$ must be increasing in s_1. □

The conditions of Proposition 2 in the setting of Section 4

We shall show here that the conditions Proposition 2 are met in our application in Section 4 for any function π if Δ, the difference in setup costs of the entrants and the incumbent, is neither so low that the first best always allocates to one of the entrants nor so high that the second best always allocates to the incumbent.

Since $\check{s} \in [0, \rho(0)]$ (see Figure 1), the conditions of Proposition 2 are met if $\check{s} \in (0, \rho(0))$. This happens when $\rho(0) > 0$ and $\phi(1) = 1$, which require that $\pi(0, \overline{C} - \delta) - \pi(0, \overline{C}) < \Delta$ and $\Delta < \int_0^1 (\pi(s_1, \overline{C} - \delta - 1) - \pi(s_1, \overline{C}))\, dF_1(s_1)$ by (3) and (4), respectively.

Ángel Hernando-Veciana: angel.hernando@uc3m.es
Fabio Michelucci: fabio.michelucci@cerge-ei.cz

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These values of Δ exist for any function π, since the submodularity of π implies that $\pi(0,\overline{C}-\delta)-\pi(0,\overline{C}) \le \pi(s_1,\overline{C}-\delta)-\pi(s_1,\overline{C})$ and the monotonicity of π implies that $\pi(s_1,\overline{C}-\delta) < \pi(s_1,\overline{C}-\delta-1)$.

Existence of an increasing solution to (5)

Let $\Gamma(\epsilon) \equiv \{(s,s_1) : s_1 \in [0,1], s \in [0,\rho(s_1)-\epsilon]\}$. That (5) has a unique solution in any point in the interior of $\Gamma(\epsilon)$ for $\epsilon > 0$ follows from applying standard results[26] to the following transformation of (5):

$$\gamma'(s_i) = \frac{f(s_i)\displaystyle\int_{\gamma(s_i)}^{1}\big(v(s_i,s_1)-\hat{v}(s_1)\big)\,dF_1(s_1)}{f_1\big(\gamma(s_i)\big)\dfrac{F\big(\rho\big(\gamma(s_i)\big)\big)-F(s_i)}{2}\big(\hat{v}\big(\gamma(s_i)\big)-v\big(s_i,\gamma(s_i)\big)\big)}.$$

It also shows why the solution is strictly increasing. That the numerator is positive follows from (V); see footnote 14. That the denominator is positive is a consequence of the fact that the solution lies in $\Gamma(0)$, and $\hat{v}(s_1)-v(s_i,s_1) > 0$ in the interior since $\hat{v}(s_1)-v(s_i,s_1)=0$ in the upper right frontier of $\Gamma(0)$ where $s_i=\rho(s_1)$; see Figure 2.

Auxiliary results for Definition 4

That $\sigma(s_i) \le \hat{v}(0)$ in (7) is a direct consequence of $\phi(0)=0$ which implies that $v(s_i,0)-\hat{v}(0) \le 0$, see Definition 2.

To see that there is a unique solution $\sigma(s_i) \in [\hat{v}(0),\hat{v}(\phi(s_i))]$ to (8), note that its left hand side is positive at $\sigma(s_i)=\hat{v}(0)$ by Definition 2 since $\phi(s_i)>0$, strictly decreasing in $\sigma(s_i)$, and negative at $\sigma(s_i)=\hat{v}(\phi(s_i))$ if $\phi(s_i)<1$, because Definition 2 implies that $v(s_i,s_1)-\hat{v}(\phi(s_i))=0$, and if $\phi(s_i)=1$ because of the condition $\int_0^1(v(s_i,s_1)-\hat{v}(1))\,dF_1(s_1) \le 0$.

That $\sigma(s_i) \ge \hat{v}(1)$ in (9) is direct from $\int_0^1(v(s_i,s_1)-\hat{v}(1))\,dF_1(s_1) > 0$.

Auxiliary result to Section 7

Lemma 5. *The equilibrium of Proposition 7 implements, in the survival auction, the allocation associated to* $\{\phi_i\}$.

Proof. The allocation associated to $\{\phi_j\}$ assigns the good to the incumbent with the highest type, say incumbent j, if $\phi_j(s_i;s_{-j}) \le s_j$ and otherwise to the entrant with the highest type, where s_j is incumbent j's type, s_i is the highest type of the entrants, and s_{-j} is the vector of the other incumbents' types.

We first consider the case $\phi_j(s_i;s_{-j}) \le s_j$. This condition implies that

$$v\big(s_i,\phi_j(s_i;s_{-j}),s_{-j}\big) \le \hat{v}(s_j). \tag{38}$$

[26] For instance, Theorem 2.3, page 10, in Coddington and Levinson (1984).

This is a consequence of $\hat{v}$ being increasing and the implication of Definition 5 that $v(s_i, \phi_j(s_i; s_{-j}), s_{-j}) \le \hat{v}(\phi_j(s_i; s_{-j}))$. The inequality in (38) implies that the incumbent with the highest type is not outbid by the entrants in either Case A, C, or D. Besides, the incumbent with highest type is not eliminated in Case B as he bids higher than the other incumbents. Thus, the incumbent with the highest type wins as desired.

Suppose now that $\phi_j(s_i; s_{-j}) > s_j$. The entrant with the highest type is not eliminated in Cases A and E because the entrants' bid function is strictly increasing in these cases. Besides, no entrant is eliminated in Case B. Finally, the entrant with the highest type is not eliminated in Cases C and D because $\phi_j(s_i; s_{-j}) > s_j$ means that she outbids the incumbent. Thus the entrant with the highest type wins as desired. □

B. Probability of rushes arbitrarily close to 1

Proposition 8. *Suppose that $\hat{v}(s_1) = s_1 + 1$ and $v(s_i, s_1) = s_i + s_1 + \frac{\alpha}{\delta - s_1}$, where $\alpha > 0$ and $\delta \equiv \frac{1}{1-e^{-\frac{1}{\alpha^2}}}$, and that F and F_1 are uniform. In equilibrium, the probability that a rush occurs tends to 1 as α goes to zero. In the limit, the good is allocated between the two entrants with equal probability and independently of their types.*

Proof. To prove the proposition we show that both $\rho(s_1)$ and $\gamma(s_i)$ tend to 1 as α goes to zero for $s_1 \in [0, 1)$ and $s_i \in (0, 1)$, respectively. The former is straightforward since, by definition,

$$\rho(s_1) = 1 - \frac{\alpha}{\dfrac{1}{1 - e^{-\frac{1}{\alpha^2}}} - s_1},$$

and $\lim_{\alpha \to 0} \frac{\alpha}{\frac{1}{1-e^{-\frac{1}{\alpha^2}}} - s_1} = 0$ for any $s_1 \in [0, 1)$.

We argue by contradiction that $\gamma(s_i)$ tends to 1 for $s_i \in (0, 1)$. Suppose an $s_i \in (0, 1)$ for which $\gamma(s_i)$ remains below and away from 1 as α tends to zero. Definition 3 implies that γ satisfies

$$\gamma'(s_i) = \frac{f(s_i) \displaystyle\int_{\gamma(s_i)}^{1} \big(v(s_i, s_1) - \hat{v}(s_1)\big)\, dF_1(s_1)}{f_1\big(\gamma(s_i)\big) \dfrac{F\big(\rho\big(\gamma(s_i)\big)\big) - F(s_i)}{2} \Big(\hat{v}\big(\gamma(s_i)\big) - v\big(s_i, \gamma(s_i)\big)\Big)}$$

and, hence, under the particular assumptions of the proposition,

$$\gamma(s_i) = \int_0^{s_i} \frac{\displaystyle\int_{\gamma(\tilde{s}_i)}^{1} \left(\tilde{s}_i + \frac{\alpha}{\dfrac{1}{1 - e^{-\frac{1}{\alpha^2}}} - s_1} - 1 \right) ds_1}{\dfrac{\rho\big(\gamma(\tilde{s}_i)\big) - \tilde{s}_i}{2} \left(1 - \tilde{s}_i - \dfrac{\alpha}{\dfrac{1}{1 - e^{-\frac{1}{\alpha^2}}} - \gamma(\tilde{s}_i)} \right)} \, d\tilde{s}_i. \tag{39}$$

Since for any $s_1 < 1$, $\rho(s_1)$ tends to 1 as α tends to zero and $\lim_{\alpha\to 0} \frac{\alpha}{\frac{1}{1-e^{-\frac{1}{\alpha^2}}}-\gamma(\tilde{s}_i)} = 0$, the denominator in (39) tends to $\frac{(1-\tilde{s}_i)^2}{2} > 0$, since $\tilde{s}_i < s_i < 1$. Moreover, the integral in the numerator is equal to[27]

$$(\tilde{s}_i - 1)\big(1-\gamma(\tilde{s}_i)\big) + \frac{1}{\alpha} + \alpha \ln\big(1-\gamma(\tilde{s}_i)\big(1-e^{-\frac{1}{\alpha^2}}\big)\big),$$

which diverges to infinity as α tends to zero. This contradicts that $\gamma(s_i)$ is below and away from 1. □

C. An economic application: Privatizations with an insider

In this appendix, we provide another economic application of our results. In this application there is large uncertainty about a common component of the bidder's values relative to idiosyncratic differences and the common component is the incumbent's private information.[28]

An asset is privatized. This asset may generate two cash flows $\underline{V}$ and $\overline{V}$, $\underline{V} < \overline{V}$, with probability ξ and $1-\xi$, respectively. The asset generates the cash flow only after incurring in some operating cost that differs across bidders. We assume that each bidder knows privately its operating cost. We assume that bidder i's operating cost follows an independent distribution G_i with support $[\underline{c}, \overline{c}]$. We also assume that bidder 1, the *incumbent*, knows privately whether the asset's cash flow is equal to $\underline{V}$ or $\overline{V}$. Besides, we assume that $\overline{V} - \underline{V} \geq \overline{c} - \underline{c}$ and $\underline{V} > \overline{c}$, i.e., the operating cost differences are small compared to the cash flow uncertainty, and the asset always has positive net value.

This problem can be formulated as a particular case of our model, adopting the convention that $s_1 \geq 1/2$ denotes that the asset's value is equal to $\overline{V}$ and $s_1 \leq 1/2$ that it is equal to $\underline{V}$, that the operating cost of bidder 1 is $\overline{c} - 2s_1(\overline{c} - \underline{c})$ if $s_1 < 1/2$ and $\overline{c} - (2s_1 - 1)(\overline{c} - \underline{c})$ if $s_1 \geq 1/2$, and the operating cost of i, $i \neq 1$, is $\overline{c} - s_i(\overline{c} - \underline{c})$. Thus,

[27] Note that

$$\begin{aligned}\int_{\gamma(\tilde{s}_i)}^{1} \frac{\alpha}{\frac{1}{1-e^{-\frac{1}{\alpha^2}}} - s_1}\, d\tilde{s}_i &= -\alpha\left[\ln\left(\frac{1}{1-e^{-\frac{1}{\alpha^2}}} - s_1\right)\right]_{s_1=\gamma(\tilde{s}_i)}^{s_1=1} \\ &= -\alpha\left(\ln\left(\frac{1}{1-e^{-\frac{1}{\alpha^2}}} - 1\right) - \ln\left(\frac{1}{1-e^{-\frac{1}{\alpha^2}}} - \gamma(\tilde{s}_i)\right)\right) \\ &= -\alpha \ln\left(\frac{e^{-\frac{1}{\alpha^2}}}{1-\gamma(\tilde{s}_i)\big(1-e^{-\frac{1}{\alpha^2}}\big)}\right) \\ &= \frac{1}{\alpha} + \alpha\ln\big(1-\gamma(\tilde{s}_i)\big(1-e^{-\frac{1}{\alpha^2}}\big)\big).\end{aligned}$$

[28] A similar role can be played by differences in individual synergies, which may be a more relevant example in the case of takeovers.

the corresponding value functions are[29]

$$\hat{v}(s_1) = \begin{cases} \underline{V} - \big(\overline{c} - 2s_1(\overline{c} - \underline{c})\big) & \text{if } s_1 \Big[0, \dfrac{1}{2}\Big), \\ \overline{V} - \big(\overline{c} - (2s_1 - 1)(\overline{c} - \underline{c})\big) & \text{if } s_1 \in \Big[\dfrac{1}{2}, 1\Big], \end{cases}$$

$$v(s_i, s_1) = \begin{cases} \underline{V} - \big(\overline{c} - s_i(\overline{c} - \underline{c})\big) & \text{if } s_1 \Big[0, \dfrac{1}{2}\Big), \\ \overline{V} - \big(\overline{c} - s_i(\overline{c} - \underline{c})\big) & \text{if } s_1 \in \Big[\dfrac{1}{2}, 1\Big] \end{cases}$$

and the distributions are

$$F_1(s_1) = \begin{cases} \xi\big(1 - G_1\big(\overline{c} - 2s_1(\overline{c} - \underline{c})\big)\big) & \text{if } s_1 < \dfrac{1}{2}, \\ \xi + (1-\xi)\big(1 - G\big(\overline{c} - (2s_1)(\overline{c} - \underline{c})\big)\big) & \text{if } s_1 \geq \dfrac{1}{2}, \end{cases}$$

$$F_i(s_i) = \big(1 - G_i\big(\overline{c} - s_i(\overline{c} - \underline{c})\big)\big), \quad i \neq 1.$$

It is thus direct from Definition 1 that the first best is characterized by

$$\rho(s_1) = \begin{cases} 2s_1 & \text{if } s_1 < \dfrac{1}{2}, \\ 2s_1 - 1 & \text{if } s_1 \geq \dfrac{1}{2}, \end{cases}$$

and thus not implementable by Lemma 1. Besides, the maximand of (2) becomes

$$\int_0^{\min\{q,1/2\}} (s_i - 2s_1)(\overline{c} - \underline{c})\, dF_1(s_1) + \int_{1/2}^{\max\{q,1/2\}} (s_i - 2s_1 + 1)(\overline{c} - \underline{c}\, dF_1(s_1).$$

This expression is increasing in q for $q \in [0, s_i/2] \cup [1/2, 1/2 + s_i/2]$ and decreasing in q for $q \in [s_i/2, 1/2] \cup [1/2 + s_i/2, 1]$. Thus, $s_i/2$ and $s_i/2 + 1/2$ are two local maxima and

$$\phi(s_i) = \begin{cases} s_i/2 & \text{if } s_i \leq \hat{s}, \\ s_i/2 + 1/2 & \text{if } s_i > \hat{s}, \end{cases}$$

where $\hat{s} \in (0, 1)$ solves

$$\int_{\hat{s}/2}^{1/2} (\hat{s} - 2s_1)\, dF_1(s_1) + \int_{1/2}^{1/2+\hat{s}/2} (\hat{s} - 2s_1 + 1)\, dF_1(s_1) = 0.$$

Consequently, for any $s_i > \hat{s}$ and $s_1 \in (s_i/2, 1/2)$ it is satisfied that $s_i < \rho(s_1)$ and $s_1 < \phi(s_i)$, as required by Proposition 2.

[29]Note that these value functions deviate from our assumptions in that they are not continuous in s_1 when $\overline{V} - \underline{V} > \overline{c} - \underline{c}$. This does not upset our results because they do not hinge on continuity.

D. Nonstandard tie-breaking rules

In this section, we show that one can modify the tie-breaking rule of the open ascending auction to ensure that the good is allocated to the entrant with the largest value in case of a tie. This proposal is less appealing than the two-round auction we describe in Section 6 or our survival auction in Section 7 because it requires bidders who lose to pay. For simplicity, we shall assume, as in Section 5.2, assumptions (I)–(V).

Suppose an open ascending auction with the following modified tie-breaking rule. Each bidder who ties submits a (nonnegative) sealed bid in an auxiliary auction. The bidder who submits the lowest bid in the auxiliary auction gets the good and pays the price at which the tie occurred. The other bidders do not get the good but have to pay the lowest bid in the auxiliary auction. In case of a tie in the auxiliary auction, the object is allocated according to the uniformly random tie-breaking rule among those who tie in the auxiliary auction. Note that this auxiliary auction can be interpreted as a multi-unit Vickrey auction in which the number of prizes is equal to the number of bidders who tied in the original auction minus 1. In this interpretation, the prize lets the bidder avoid that the tie of the original auction is resolved by allocating the object to her.

We shall propose a strategy profile for our open ascending auction with the tie-breaking rule above, and argue that it is an equilibrium that implements the second best. We start with the general observation that $(p-V)^+$ is the optimal bid in the auxiliary auction for a bidder who knows that his value is equal to V and who has tied at a price p in the open ascending auction. To see why, note that when the bidder bids less than all the others in the auxiliary auction, she gets payoff $V-p$, and when she loses, she gets payoff $-\tilde{b}$, for $\tilde{b}$ the minimum of the bids in the auxiliary auction. Thus, in the case $p \geq V$, bidding $(p-V)^+$ guarantees that the bidder outbids the other bidders if and only if it is more profitable than otherwise. In the case $p < V$, the bidder strictly prefers to outbid the others for any $\tilde{b} \geq 0$. The chances of doing so are maximized by bidding zero, which is our proposed bid $(p-V)^+$ in this case.

The previous paragraph characterizes the incumbent's optimal bidding in the auxiliary auction. Under this continuation play by the incumbent, the same arguments as in Section 5.1 imply that it is weakly dominant for the incumbent to bid his value in the open ascending auction, i.e., Lemma 3(i) also holds here. Hence, the entrants can infer the incumbent's type when he quits and the argument in the previous paragraph characterizes the entrants' optimal bidding in the auxiliary auction. Once we assume this bidding of the entrants in the auxiliary auction, it is easy to see that we can argue as in Section 5.1 that the properties of Lemma 3(ii) and (iii) also hold here. Consequently, it only remains to propose the entrants' bidding in information sets in which no bidder has quit yet. We propose a bid function constructed as in Section 5.1. In particular, our proposed bid function is equal to $\hat{v}(\gamma_e(s_i))$, where $\gamma_e(s_i)$ is defined by a version of Definition 3 in which (5) is replaced by

$$\begin{aligned}\beta \int_{\gamma_e(s_i)}^{1} \big(v(s_i, s_1) - \hat{v}(s_1)\big) \frac{dF_1(s_1)}{1 - F_1\big(\gamma_e(s_i)\big)} \\ + (1-\beta) \frac{1}{1 - F(s_i)} \int_{s_i}^{\rho(\gamma_e(s_i))} \big(v\big(\tilde{s}, \gamma_e(s_i)\big) - \hat{v}\big(\gamma_e(s_i)\big)\big)\, dF(\tilde{s}) = 0.\end{aligned} \tag{40}$$

This equation guarantees, as (5) for the standard tie-breaking rule, that an entrant with type $s_i \in (0, \overline{s})$ does not have incentives to change her bid marginally when all the others bidders play our proposed equilibrium. To see why, note that a marginal deviation (upward) only matters if it allows the bidder to outbid the lowest of the other bidders' bids (and thus, avoid being the first bidder quitting), i.e., in the marginal event of tying with the lowest bid of the other bidders. The probability that the lowest bid of the other bidders is the other entrant's bid conditional on this marginal event is equal to β. In this case, Lemma 3(iii) and $\phi(s_i) = 1$ imply that our entrant competes in the last round against the incumbent until the incumbent quits. This gives our entrant expected positive profits equal to the expression that it is multiplied by β in (40). The probability that the lowest bid of the other bidders is the incumbent's bid conditional on the former marginal event is equal to $1 - \beta$. In this case, our entrant quits immediately because the incumbent's type is equal to $\gamma_e(s_i)$, and it is a consequence of Lemma 3(ii) and $s_i < \rho(\gamma_e(s_i))$. That $s_i < \rho(\gamma_e(s_i))$ is a consequence of $s_i < \overline{s}$, $\overline{s} = \rho(\gamma_e(\overline{s}))$, ρ strictly decreasing, and γ_e strictly increasing. Our entrant loses and makes a zero payoff unless the other entrant also quits immediately after the incumbent. This occurs when the other entrant's type, say $\tilde{s}$, lies in $(s_i, \rho(\gamma_e(s_i)))$, i.e., with conditional probability $\frac{F(\rho(\gamma_e(s_i)))-F(s_i)}{1-F(s_i)}$. In this case, our entrant competes in the auxiliary auction with the other entrant. Since the other entrant has a higher type, i.e., $\tilde{s} > s_i$, the auxiliary auction under our proposed strategies results in our bidder not obtaining the object but having to pay the other entrant's bid in the auxiliary auction. This is equal to $\hat{v}(\gamma_e(s_i)) - v(\tilde{s}, \gamma_e(s_i))$ since the incumbent has quit at price $\hat{v}(\gamma_e(s_i))$ and the other entrant infers that her value is equal to $v(\tilde{s}, \gamma_e(s_i))$.

The proof that entrants do not have incentives to deviate from our proposed bid function in the information sets in which no bidder has quit yet is a straightforward adaptation of the proof of Proposition 3 that we do not include.

When bidders use the proposed strategies, there are two possibilities along the equilibrium path. The first one is that one of the entrants—the one with the lowest signal—quits before the incumbent. In this case, the entrant with the largest signal outbids the incumbent as a consequence of Lemma 3(i) and (iii), and $\phi(s_i) = 1$ for any $s_i \in [0, 1]$. Thus, the allocation is second best in this case. The other case is when the incumbent quits first. Then Lemma 3(ii) implies that the entrant with the largest type wins, as required by the second best, if the entrants do not tie. If they do tie, Lemma 3(ii) implies that both entrants' values are less than the current price. Thus, our tie-breaking rule and the bidding we propose for the auxiliary auction imply that the good also gets allocated to the entrant with the largest type, as required by the second best.

The following proposition summarizes our discussion in this section and no further proof is required.

Proposition 9. *Under assumptions (I)–(V), the following profile of strategies is an equilibrium of the open ascending auction with the modified tie-breaking rule:*

- *The incumbent quits at price $\hat{v}(s_1)$ when his type is s_1.*
- *An entrant with type s_i quits at the following prices:*

- $\hat{v}(\gamma_e(s_i))$ *in information sets in which no bidder has quit yet, where* γ_e *is defined in (40).*
- $\max\{v(s_i, s_1), \hat{v}(s_1)\}$ *in information sets in which the incumbent quits at a price* $\hat{v}(s_1)$.
- $\hat{v}(\phi(s_i)) = \hat{v}(1)$ *in information sets in which the incumbent is the only other active bidder.*

- *In the tie-breaking auction, the incumbent bids zero and an entrant with type* s_i *bids* $\max\{0, \hat{v}(s_1) - v(s_i, s_1)\}$ *when the incumbent quits at price* $\hat{v}(s_1)$.

This equilibrium implements the second best.

Reference

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