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Why government bonds are sold by auction and corporate bonds by posted-price selling

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Abstract

When information is costly, a seller may wish to prevent prospective buyers from acquiring information, for the cost of information acquisition ultimately is borne by the seller. A seller can achieve the desired prevention through posted-price selling, by offering prospective buyers a discount. No such prevention is possible in the case of an auction. We establish the result that the seller prefers posted-price selling when the cost of information acquisition is high and auctions when it is low. We view corporate bonds as an instance of the former case, and government bonds as an instance of the latter.
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1. Introduction

In most industrialized countries, government bonds are sold by auction whereas corporate bonds are sold by posted-price selling (PPS). The latter form of sale, which is described by Grinblatt and Titman (1998, p. 58) for example, effectively has the investment bank bringing the issue to market set the price at which the securities are offered, albeit in consultation with the issuer and prospective buyers. This is in contrast to auctions, in which the sale price of the securities offered for sale is obtained from the bids made by the participants in the auction. In the

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Table 1
Issuing procedures for government bonds in OECD countries

Country	Auction	Posted-price selling
Australia	X	
Austria	X	X
Belgium	X	X
Canada	X	
Czech Republic	X	
Denmark	X	
Finland	X	X
France	X	[a]
Germany	X	
Greece	X	X
Hungary	X	
Iceland	X	
Ireland	X	
Italy	X	
Japan	X	X
Korea	X	
Luxembourg	X	X
Mexico	X	
Netherlands	X	
New Zealand	X	
Norway	X	
Poland	X	
Portugal	X	X
Slovak Republic	X	
Spain	X	X
Sweden	X	
Switzerland	X	
Turkey	X	
United Kingdom	X	[a]
United States	X	

Source: European Union; Organisation for Economic Co-Operation and Development; Web Sites of the Debt Management Offices of the Individual Countries.
[a] Posted-price selling is used, but rarely.

uniform-price auction used by the US Treasury, for example, the winning bidders pay the highest losing bid.[1]

Table 1 shows that auctions are used to sell local currency denominated government bonds in every single OECD country. In about one third of the countries, posted-price selling may also be used. In contrast, again in every single OECD country, the overwhelming majority of corporate bonds are sold by posted-price selling. Exceptions are few and very far between.

Our purpose in this paper is to provide an explanation for the afore-mentioned empirical regularity. We start with the observations that

(i) information about a security such as a bond is costly to acquire,
(ii) investors have an incentive to acquire information, and

[1] See Bikhchandani and Huang (1993) for an analysis of the Treasury securities markets.

(iii) the cost of the information acquired by investors is ultimately borne by the seller of the security.[2]

An investor who acquires information gains an informational advantage over both the seller and those investors who have not acquired information, and can expect to profit at their expense. Foreseeing the losses they will sustain to informed investors, uninformed investors shade their bids in case the security is auctioned, or require from the seller a discount to the expected value of the security in case the security is sold by PPS.[3] Uninformed investors may even withdraw from the sale.[4] This decreases the seller's expected proceeds from the sale.

Where information is costly, Matthews (1984, p. 197) notes that "both society and the seller will profit [...] if private information acquisition can be prohibited." However, he does not discuss how this can be achieved. We argue in this paper that the seller can prevent information acquisition by investors by refraining from using an auction, instead selling the security by posting a price that offers investors a discount to the security's expected value. Unlike that required to compensate uninformed investors for the losses they sustain to informed investors, the discount we consider is such that all investors choose to remain uninformed: they are indifferent between (i) incurring the cost of acquiring information and exploiting the informational advantage thereby obtained, and (ii) refraining from acquiring information, taking part in the sale, and obtaining the discount.

In contrast, information acquisition cannot be prevented in an auction. This is because the sale price is set not by the investment bank bringing the security to market, but by the bids submitted. Under such conditions, the expected payoff of an uninformed bidder is at most zero (Milgrom and Weber, 1982b), and only those investors who have acquired information will place bids. Under conditions of free entry into the auction, a bidder's expected payoff from placing a bid therefore equals the cost of acquiring information. As the seller's payoff equals the expected value of the security minus the bidders' expected payoffs, the seller's expected proceeds equal the expected value of the security minus the combined cost of information acquisition.[5]

Of course, the discount granted the buyer under PPS is costly to the seller but, under some conditions, it is less costly than the alternative of having the investor acquire information in an auction. We show underpricing in an auction to be higher than the discount offered under PPS when the cost of information acquisition is high, and lower when this cost is low.

Intuitively, a high discount must be offered under PPS in order to prevent investors from acquiring information when the cost of information acquisition is low. In the limit, when information is costless, only a price equal to the lower bound on the value of the security can deter investors from acquiring information under PPS. In contrast, costless information reduces the auction to one with no entry costs. Should a sufficiently large number of investors

[2] This result is due to French and McCormick (1984) and Matthews (1984). See also Harstad (1990) and Levin and Smith (1994).

[3] See Milgrom and Weber (1982a) for auctions and Rock (1986) for PPS.

[4] See Milgrom and Weber (1982b).

[5] Note that we do not consider full surplus extraction mechanisms (Crémer and McLean, 1985, 1988; McAfee et al., 1989). Should such a mechanism be used, no investor would acquire information. This is because the mechanism's surplus extraction property denies the investor the opportunity to recover the cost of any information he may acquire. The question of why full surplus extraction mechanisms are practically never observed, despite their obvious attractions to sellers, is one that lies beyond the scope of the present paper.

then enter the auction, the price converges to the expected value of the security (Wilson, 1977; Milgrom, 1981).

When the cost of information acquisition is relatively high, little or no discount to the expected value of the security must be offered investors under PPS in order to deter them from acquiring information. In contrast, the high cost of information acquisition—which is borne by the seller in expectation—decreases expected seller proceeds from the auction well below the expected value of the security.

How can the preceding reasoning explain the differing choice of selling mechanism for government and corporate bonds? The valuation of corporate bonds is more complex and costlier than that of government bonds, because corporate bonds are subject to default risk whereas government bonds are not. This suggests the use of PPS for the former and auctions for the latter.

Previous comparisons of auctions and PPS can be found in both economics and finance. The economics literature has considered both private values (Arnold and Lippman, 1995; Wang, 1993) and interdependent values (Bulow and Klemperer, 2002; Campbell and Levin, 2006; and Wang, 1998). However, because it has done so in settings with endowed information, this literature has not addressed the issue raised by Matthews (1984) that information production in auctions may be excessive.

The finance literature has compared common value auctions, PPS, and book-building in the context of initial public offerings (IPOs).[6] Book-building is a form of PPS preceded by preplay communication (Spatt and Srivastava, 1991). Where issuers have preferences for accurate valuation, underwriters can induce investors to acquire costly information through fixed price offerings or book-building (see Chemmanur and Liu, 2001 and Sherman, 2005, respectively).[7] This is achieved by having the issue price incorporate the information communicated by investors partially (book-building) or not at all (fixed price offering).[8]

We agree with the importance of accurate valuation, but note that accuracy need not require the *production* of new information. Consider for example the desire on the part of the underwriter to avoid excessive under- or over-pricing of the issue. This requires not so much inducing investors to produce new information as inducing them to *communicate* the information they already have as to their valuation of the issue. This implies that, in case there should be information that neither the underwriter nor investors have, there should be no need to incur the cost of producing such information, even for the purpose of accurately pricing the issue.

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6 In a setting with endowed information, Parlour and Rajan (2005) show that rationing may be desirable in IPOs. We argue in the conclusion that posted-price selling corresponds to extreme rationing among all bidders.

7 See also Sherman and Titman (2002).

8 Jagannathan and Sherman (2006) discuss a large number of reasons for choosing book-building over auctions. They summarize their argument as such (Jagannathan and Sherman, 2006, p. 24): "It is evident that auctions will be relatively successful when information gathering is not an issue, and when auctions for the same type of securities are held at regular intervals so that the pool of participants in the auction is stable. Auctions will be unreliable when a reward for information gathering and price discovery is important, when the number of bidders varies significantly over time in an unpredictable manner, or when a large number of bidders may try to free ride on the information gathering efforts of others." We discuss the applicability of the information gathering rationale to bond offerings in the two paragraphs that follow. The other rationales explain why shares are not auctioned directly to a large and changing number of small investors. They do not explain, we think, why shares are not auctioned to the investment banks that are members of the underwriting syndicate, or to the large institutional investors that are "regulars" in the process of building the book. An auction such as this would be conducted as regularly as book-building, to the small and stable number of underwriters or of regulars.

The preceding is not to say that new information is never to be produced. New information helps guide investment decisions. However, we believe information production to be of lesser importance in bond offerings than in share. Most firms that issue public bonds are publicly traded firms. They have public shares and ongoing information production. They therefore do not need new information to be produced during the bond issue.[9]

We proceed as follows. In Section 2, we consider the case of second-price auctions. In Section 3, we consider that of PPS. We compare auctions and PPS in Section 4. Section 5 illustrates our results by means of an example. We conclude in Section 6.

2. Second-price auctions

The first part of the present section is based on French and McCormick (1984). It is included in order to introduce the notation and for completeness.

Consider a seller who wishes to sell a single unit of a security that has unknown value V.[10] This value has cumulative distribution function $F_V(\cdot)$ and probability density function $f_V(\cdot)$ on the support $[V_l, V_h]$.

There are $N > 1$ investors, indexed by $i = 1, \dots, N$. Investor i can, if he so desires, acquire information X_i at a cost c about the value of the security before entering his bid. We consider a pure common value model, $X_i = V + \varepsilon_i$, with the error term ε_i independent of V and i.i.d. across i.[11]

We let n^*, $0 \leqslant n^* \leqslant N$, denote the number of investors who choose to incur the cost of acquiring information. The number n^* is also the number of bidders in the auction, because any bidder who has not acquired information has an expected payoff that is at most equal to zero (Milgrom and Weber, 1982b). Once all n^* bids have been entered, the security is sold to the highest bidder, at a price equal to the second highest bid.[12]

By virtue of the symmetry across investors and bidders, we limit our analysis to bidder 1.[13] We drop the subscript 1 for ease of notation: $X \equiv X_1$. We let Y_{n^*-1} denote the highest order statistic of the signals $X_2, \dots, X_{n^*}$ received by the remaining $n^* - 1$ bidders.

Following Milgrom and Weber (1982b), we define $v_{n^*-1}(x, y) \equiv E[V \mid X = x, Y_{n^*-1} = y]$. Bidder 1 forms the expectation $v_{n^*-1}(x, y)$ of the value of the security on receiving the information $X = x$ and on presuming the highest order statistic amongst the remaining signals is

[9] We thank the referee for this insight.

[10] We consider the sale of a single unit for expositional convenience. Our results generalize to the case of K units, provided every buyer can purchase at most a single unit (Klemperer, 2004).

[11] Could the seller acquire information on behalf of investors? And would the seller communicate truthfully all the information thereby acquired? Recalling that a seller policy of committing to reveal truthfully any information he may have increases expected seller proceeds (Milgrom and Weber, 1982b), we can view the present setting as the one prevailing after the seller has acquired any information he has deemed desirable and communicated it to investors.

[12] The assumption of a second-price auction is without loss of generality for the general results of Sections 2, 3, and 4. It is made because (i) it corresponds to the uniform-price auctions used to sell government bonds and (ii) it permits the use of the closed-form solution for bidder profits computed by Kagel et al. (1995) in the example of Section 5.

[13] Milgrom (1981) shows the existence of a symmetric pure strategy equilibrium. Harstad (1991) shows that the symmetric equilibrium is the only locally nondegenerate risk neutral Nash equilibrium in increasing bid strategies if there are more than 3 bidders. (An equilibrium is locally nondegenerate when the probability of any given bidder winning the auction is positive for all bidders.) See also Kagel et al. (1995).

$Y_{n^*-1} = y$. We know from Milgrom and Weber (1982b) that bidder 1 bids[14]

$$v_{n^*-1}(x, x) = E\big[V \mid X = x, Y_{n^*-1} = x\big]. \tag{1}$$

Intuitively, bidder 1 adjusts his estimate of the value of the security for the fact that he wins the auction when he receives the highest signal amongst the n^* signals $X_1, \ldots, X_{n^*}$. His presumption that the second highest signal is equal to the highest signal—which he has received—ensures that he does not lose the auction to a bidder who has received a lower signal than he has. Bidder 1 is induced to bid truthfully because the second price auction implies that his bid affects his probability of winning the auction but not the price he pays upon winning.

Symmetry across bidders implies that the seller's expected proceeds equal

$$\Pi_{n^*} = E\big[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}\big], \tag{2}$$

and that a bidder's expected profit—gross of the cost of acquiring information—equals

$$\pi_{n^*} = \frac{1}{n^*}\big(E[V] - E\big[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}\big]\big). \tag{3}$$

Free entry in turn implies that n^* is such that $\pi_{n^*} = c$.[15] Combining, we can rewrite the seller's expected proceeds as $\Pi_{n^*} = E[V] - n^*c$. As noted in the introduction, the combined cost of information acquisition is borne by the seller and determines the extent of underpricing. This result was first derived by French and McCormick (1984).

It is interesting to contrast the present result—obtained under conditions of costly information acquisition—with that obtained in the more usual case of costless information acquisition. In the latter case, the expected selling price converges to the true value of the security as the number of bidders becomes large (Wilson, 1977; Milgrom, 1981). In contrast, expected seller proceeds decrease in the number of bidders in our case. This is because a larger number of bidders implies a higher combined cost of information acquisition.

We now wish to examine the comparative statics of Π_{n^*} with respect to the cost of acquiring information, c, the quality of the information that can be obtained about the value of the security, and the riskiness of the security. For that purpose, we must first determine the variation of a bidder's expected profit as a function of the number of bidders, $\partial\pi_{n^*}/\partial n^*$.

There is no general result concerning

$$\frac{\partial\pi_{n^*}}{\partial n^*} = -\frac{\pi_{n^*}}{n^*} - \frac{1}{n^*}\frac{\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]}{\partial n^*}. \tag{4}$$

To a large extent, this is because $\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^*$ cannot be signed. On the one hand, a larger number of bidders increases Y_{n^*-1}, the maximum of the signals received by the now larger number of bidders other than bidder 1. A higher signal Y_{n^*-1} implies a higher estimate of the value of the security, $v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1})$. On the other hand, a larger number of bidders decreases the estimate of the value of the security $v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1})$ for a given signal Y_{n^*-1}. This is because a larger number of bidders necessitates a greater downward adjustment for the winner's curse on the part of the winner of the auction.

Milgrom (1981) has shown that $\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^* > 0$ as n^* becomes large. This is not necessarily the case for small n^*. We consider both cases in our analysis.

14 Levin and Harstad (1986) show that this function is the unique symmetric Nash equilibrium.

15 We neglect the integer constraint on n^* in order to simplify the exposition.

We assume $\partial\pi_{n^*}/\partial n^* < 0$ for $n^* \geqslant 2$. We show at the end of Section 4 that our main result, that regarding the variation of expected proceeds in the cost of acquiring information, c, would in fact be strengthened were $\partial\pi_{n^*}/\partial n^* > 0$.

We represent a decrease in the quality of the information by a garbling Ξ of the information X_i, with $E[\Xi \mid V] = E[\Xi \mid \varepsilon_i] = 0$. The information available to a bidder who has incurred the cost c is now $X_i' \equiv X_i + \Xi$. The corresponding highest order statistic is $Y_{n^*-1}' = Y_{n^*-1} + \Xi$. We note that the garbling Ξ is identical across bidders. It can be viewed as some bidder-wide decrease in the informativeness of the signals that investors can acquire.

The nature of X' as a garbling of X and of Y_{n^*-1}' as a garbling of Y_{n^*-1} implies that

$$\begin{aligned} w_{n^*-1}(x, y, x', y') &\equiv E\big[V \mid X = x, Y_{n^*-1} = y, X' = x', Y_{n^*-1}' = y'\big] \\ &= E\big[V \mid X = x, Y_{n^*-1} = y\big] \\ &= v_{n^*-1}(x, y). \end{aligned} \tag{5}$$

We can now use the well known result that expected proceeds increase in the information available to bidders (Milgrom and Weber, 1982b) to write

$$\begin{aligned} &E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}] \\ &\quad = E\big[w_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}, Y_{n^*-1}', Y_{n^*-1}') \mid X > Y_{n^*-1}\big] \\ &\quad = E\big[w_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}, Y_{n^*-1}', Y_{n^*-1}') \mid X' > Y_{n^*-1}'\big] \\ &\quad \geqslant E\big[v_{n^*-1}(Y_{n^*-1}', Y_{n^*-1}') \mid X' > Y_{n^*-1}'\big]. \end{aligned} \tag{6}$$

The first equality is obtained by (5), the second by noting that

$$X' > Y_{n^*-1}' \quad \iff \quad X + \Xi > Y_{n^*-1} + \Xi \quad \iff \quad X > Y_{n^*-1}, \tag{7}$$

and the inequality by the result that expected proceeds increase in the information available to bidders. The lower expected seller proceeds for a given number of bidders n^* imply a higher profit per bidder, and induce a higher number of bidders $n^{*\prime}$ to enter the auction. We therefore have $n^{*\prime} > n^*$ and $\Pi_{n^{*\prime}} = E[V] - n^{*\prime}c < \Pi_{n^*}$. Thus, the lower the quality of the information that can be obtained about the value of the security, the larger the number of bidders participating in the auction and the lower the seller's expected proceeds.

We now consider the change in expected proceeds that results from a change in the riskiness of the security. We represent an increase in riskiness by a mean-preserving spread Ψ applied to the value V of the security, with $E[\Psi \mid V] = 0$. We define $V'' \equiv V + \Psi$ and have corresponding signal $X_i'' = V'' + \varepsilon_i = X_i + \Psi$ and highest order statistic $Y_{n^*-1}'' = Y_{n^*-1} + \Psi$.

We first note that

$$\begin{aligned} v_{n^*-1}(x, y) &= E\big[V \mid X = x, Y_{n^*-1} = y\big] \\ &= E\big[V \mid X'' = x + \psi, Y_{n^*-1}'' = y + \psi, \Psi = \psi\big] \\ &= E\big[V'' - \Psi \mid X'' = x + \psi, Y_{n^*-1}'' = y + \psi, \Psi = \psi\big] \\ &= E\big[V'' \mid X'' = x + \psi, Y_{n^*-1}'' = y + \psi, \Psi = \psi\big] - \psi \\ &\equiv z_{n^*-1}(x + \psi, y + \psi, \psi) - \psi. \end{aligned} \tag{8}$$

We can now write

$$\begin{aligned}
&E\big[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}\big] \\
&\quad = E\big[z_{n^*-1}(Y_{n^*-1} + \Psi, Y_{n^*-1} + \Psi, \Psi) - \Psi \mid X > Y_{n^*-1}\big] \\
&\quad = E\big[z_{n^*-1}(Y_{n^*-1} + \Psi, Y_{n^*-1} + \Psi, \Psi) - \Psi \mid X + \Psi > Y_{n^*-1} + \Psi\big] \\
&\quad = E\big[z_{n^*-1}(Y''_{n^*-1}, Y''_{n^*-1}, \Psi) - \Psi \mid X'' > Y''_{n^*-1}\big] \\
&\quad = E\big[z_{n^*-1}(Y''_{n^*-1}, Y''_{n^*-1}, \Psi) \mid X'' > Y''_{n^*-1}\big] \\
&\qquad - E\big[\Psi \mid X'' > Y''_{n^*-1}\big] \\
&\quad = E\big[z_{n^*-1}(Y''_{n^*-1}, Y''_{n^*-1}, \Psi) \mid X'' > Y''_{n^*-1}\big] \\
&\qquad - E\big[E[\Psi|V] \mid X'' > Y''_{n^*-1}\big] \\
&\quad \geqslant E\big[v''_{n^*-1}(Y''_{n^*-1}, Y''_{n^*-1}) \mid X'' > Y''_{n^*-1}\big].
\end{aligned} \tag{9}$$

where $v''_{n^*-1}(x'', y'') \equiv E[V'' \mid X'' = x'', Y''_{n^*-1} = y'']$. Inequality (9) is established in a manner similar to that used to establish inequality (6), using the result that expected proceeds increase in the information available to bidders. As for the case of a decrease in the quality of the information, an increase in the riskiness of the security increases the number of bidders entering the auction from n^* to $n^{*\prime\prime}$ and decreases expected seller proceeds to $\Pi_{n^{*\prime\prime}} = E[V] - n^{*\prime\prime}c$.[16,17]

We now consider the change in expected seller proceeds that results from an increase in the cost of acquiring information, c. Clearly, an increase in c decreases the number of bidders. Whether the product n^*c increases or decreases in c depends on the elasticity of n^* with respect to c. Expected seller proceeds increase in c when the elasticity is greater than one and decrease when it is less than one.

A necessary and sufficient condition for the elasticity of n^* with respect to c to be less than one is $\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^* > 0$. To see this, note that

$$\begin{aligned}
-\frac{\partial n^*/\partial c}{n^*/c} &= -\frac{\partial n^*}{\partial c}\frac{c}{n^*} \\
&= \frac{1}{-\partial \pi_{n^*}/\partial n^*}\frac{c}{n^*} \\
&= \frac{c}{\pi_{n^*} + \partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^*}
\end{aligned} \tag{10}$$

where the second equality is true by applying the Implicit Function Theorem to the condition $\pi_{n^*} = c$ and the third follows from (4). Thus, expected seller proceeds decrease in c where $\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^* > 0$ and increase where the inequality is reversed.

Summarizing, we have:

Proposition 1. *A seller's expected proceeds from a second-price auction with costly information and endogenous entry increase in the quality of the information available to bidders and decrease in the riskiness of the security. The seller's expected proceeds decrease in the information*

[16] That expected proceeds increase in the information available to bidders is central to the derivation of inequalities (6) and (9) above. The intuition is that the higher the quality of the information available to bidders, the more similar bidders' assessment of the value of the security, the closer therefore the second highest bid to the highest bid and the higher expected proceeds. The two derivations differ in that the effect of information quality is direct in (6) whereas it is indirect in (9). In the latter case, the greater volatility makes the value of the security more difficult to estimate. This difference explains why the derivation of (9) is somewhat more involved than that of (6).

[17] See Keloharju et al. (2005) for empirical evidence on the relation between underpricing and volatility.

acquisition cost where the derivative $\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^*$ *is positive and increase where that derivative is negative.*

3. Posted-price selling

We now consider the case where the seller sells the security using PPS. We consider only posted-price schemes that deter investors from acquiring information. This is because posted-price schemes that fail to deter investors from acquiring information are likely to be dominated by auctions.[18]

How can the seller preclude the acquisition of information? The solution is to post a price $P < E[V]$ that is such as to leave each of the N investors indifferent between (i) incurring the cost of acquiring information and exploiting the informational advantage thereby obtained, and (ii) refraining from acquiring information, taking part in the sale, and obtaining the discount $E[V] - P$ if allocated the security. Formally, P is such that

$$\frac{E[\max[E[V|X_i] - P, 0]]}{N} - c = \frac{E[V] - P}{N}. \tag{11}$$

Rewriting,

$$\begin{aligned} c &= \frac{E[\max[E[V|X_i] - P, 0]]}{N} - \frac{E[E[V|X_i] - P]}{N} \\ &= \frac{1}{N} E\big[\max\big[P - E[V|X_i], 0\big]\big]. \end{aligned} \tag{12}$$

Equation (12) indicates that the price P must be such that the expected loss from buying an overvalued security is equal to the cost of acquiring information that would serve to guard against doing so. Note that the expected loss reflects the $1/N$ probability of being allocated the security when no other potential buyer acquires information.

We first note that (12) implies that $\partial P/\partial c > 0$. This is simply a consequence of the fact that a lower discount needs be offered investors to deter them from acquiring more costly information. In the case where information is costless, the acquisition of information can be prevented only

[18] That posted-price schemes that fail to deter investors from acquiring information are likely to be dominated by auctions is suggested by the results of Harstad (1990) and Bulow and Klemperer (1996). Harstad (1990) shows that entry costs are borne by the seller in expectation. (Although he considers only auctions, his results can easily be extended to PPS.) This implies that expected seller proceeds are higher with an auction when the auction induces less entry than does PPS, that is when $n^* \leqslant n^{PPS}$, where n^{PPS} denotes the number of investors who acquire information under PPS. When $n^* > n^{PPS}$, Bulow and Klemperer (1996) show that expected seller proceeds are higher with an ascending auction with n^* bidders than with PPS with $n^{PPS} < n^*$ bidders. This is because the greater competition that results from the presence of one or more additional bidders in the auction is more valuable to the seller than the increased bargaining power that comes from the posting of a price, which is equivalent to making a take-it-or-leave-it offer. We note that the results of Bulow and Klemperer (1996) are only suggestive in our case, because we consider a second-price rather than an ascending auction.

by setting a price $P = V_l$.[19] This is because information has value for all prices above V_l in such case.

We then consider the effect of a garbling of the information that investors can acquire. As in Section 2, we denote X_i' the garbled information. We know from Blackwell (1953) and Blackwell and Girshick (1954) that if X_i' is a garbling of X_i, then $E[V|X_i]$ is a mean-preserving spread of $E[V|X_i']$. This is because the higher the quality of the information, the more distinguishable the conditional expectation from the unconditional expectation, and therefore the more diffuse the distribution of the conditional expectation. As the RHS of (12) is convex in the conditional expectation and increasing in the price posted, we have $P \leqslant P'$, where P' denotes the price that deters investors from acquiring the garbled information X'. In words, a higher discount must be offered investors to deter them from acquiring higher quality information.

Finally, we consider the effect of a change in the riskiness of the security. As in Section 2, we represent an increase in riskiness by a mean-preserving spread Ψ applied to the value V of the security, with $E[\Psi|V] = 0$. We have $V'' = V + \Psi$ and corresponding signal $X_i'' = V'' + \varepsilon_i = X_i + \Psi$.

We first note that

$$E[V''|X_i] = E[V + \Psi|X_i] = E[V|X_i]. \tag{13}$$

We then note that $X_i'' = V'' + \varepsilon_i$ constitutes higher quality information about V'' than does $X_i = V'' - \Psi + \varepsilon_i$.[20] From Blackwell (1953) and Blackwell and Girshick (1954), this implies that $E[V''|X_i'']$ has a more diffuse distribution than does $E[V''|X_i]$.

We can now write

$$\begin{aligned} E\big[\max\big[P'' - E[V''|X_i''], 0\big]\big] &= Nc \\ &= E\big[\max\big[P - E[V|X_i], 0\big]\big] \\ &= E\big[\max\big[P - E[V''|X_i], 0\big]\big] \\ &\leqslant E\big[\max\big[P - E[V''|X_i''], 0\big]\big] \end{aligned} \tag{14}$$

where P'' denotes the price that deters investors from acquiring information when the security has value V''. Inequality (14) implies that $P'' \leqslant P$. In words, a higher discount must be offered investors to deter them from acquiring information about a more risky security.

Summarizing, we have:

Proposition 2. *Under posted-price selling with no information acquisition, the seller's expected proceeds increase in the information acquisition cost and decrease in the quality of the information available to bidders and the riskiness of the security.*

[19] To show this formally, let $\zeta \equiv E(V|X_i)$ and denote $H(\zeta)$ the prior distribution of ζ. Condition (12) becomes

$$c = \frac{1}{N}\int_{V_l}^{P} (P - \zeta)\,\mathrm{d}H(\zeta).$$

The seller must set $P = V_l$ for this condition to hold when $c = 0$.

[20] Note that what may loosely be referred to as the "signal-to-noise ratio" is larger for X_i'' than it is for X_i,

$$\frac{\mathrm{var}[V'']}{\mathrm{var}[\varepsilon_i]} > \frac{\mathrm{var}[V'']}{\mathrm{var}[\Psi] + \mathrm{var}[\varepsilon_i]}.$$

4. Auctions and posted-price selling compared

We are now in a position to compare auctions and PPS. We first consider the effect of the cost of acquiring information, c.

As noted in the introduction, auctions can be expected to dominate PPS for small c. In the limit, when c is zero, all investors enter the auction. The larger the number of investors N, the closer expected seller proceeds are to the expected value of the security $E[V]$ (Milgrom, 1981). In contrast, only a price P equal to the lowest value of the security V_l can deter investors from acquiring information when information is costless.

We now turn to the case of large c. In particular, we consider a cost c_h that is such that (11) holds even with $P = E[V]$. Formally,

$$c_h \equiv \frac{E[\max[E[V|X_i] - E[V], 0]]}{N}. \tag{15}$$

It is clear that no investor has any incentive to acquire information in such case, despite the fact that no discount is offered. This is because the cost of acquiring information is sufficiently high to deter the acquisition of information without the need for a discount. The seller's proceeds therefore equal $E[V]$.

Would expected seller proceeds in an auction also equal $E[V]$? We show by contradiction that the answer is in the negative. Suppose the equilibrium is one in which no investor acquires information and all N investors bid $E[V]$ and have expected payoff zero. Consider investor i who contemplates deviating from that equilibrium. His expected payoff from acquiring information at a cost c_h—and bidding more than $E[V]$ if the information X_i he obtains is such that $E[V|X_i] > E[V]$—is[21]

$$E\big[\max\big[E[V|X_i] - E[V], 0\big]\big] - c_h = \frac{N-1}{N} E\big[\max\big[E[V|X_i] - E[V], 0\big]\big] > 0. \tag{16}$$

Investor i therefore has an incentive to acquire information. This induces some investors other than i to acquire information and other investors to withdraw from the auction. It reduces the auction to the one examined in Section 2, with expected seller proceeds $E[V] - n^* c_h < E[V]$.[22] We therefore conclude that PPS dominates auctions for relatively large c.[23]

Why is the cost c_h sufficient to deter information acquisition under PPS but not in an auction? Comparing (15) and (16), we note that what makes the former an equality and the latter an inequality is the factor $1/N$ in the former. This factor represents the probability of being allocated the security under PPS. Thus, an investor who acquires information that reveals the security to be underpriced ($E[V|X_i] > E[V]$) is constrained in his ability to profit from this information by the fact that he has only a $1/N$ probability of being allocated the security under PPS. No such constraint exists in an auction, for the investor can ensure that he receives the security with certainty by bidding more than $E[V]$. In words, the additional degree of freedom conferred investors in an auction—the choice of the bid—and the fact that the security is allocated to the highest bidder increase investors' ability to profit from the information they may acquire and therefore increases the cost necessary to deter them from acquiring information.

[21] Note that the price paid by bidder i in a second-price auction is $E[V]$, as this is the bid made by the other bidders under the equilibrium considered.

[22] If c_h is such that only a single investor enters the auction, expected seller proceeds equal $V_l < E[V]$.

[23] The qualifier 'relatively' is important. There are values of c that are so prohibitively large as to deter investors from acquiring information in the auction as well as under PPS. Seller proceeds are then $E[V]$ under either selling mechanism.

We can now establish our main result:

Proposition 3. *The seller prefers posted-price selling when the information acquisition cost is relatively high and auctions when it is low.*

Proof. The proof is immediate from the discussion above and the results in Propositions 1 and 2 regarding the relation between the information acquisition cost and expected proceeds from the auction and posted-price selling. Note that Proposition 3 holds regardless of the sign of $\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^*$. That sign affects not the existence of different subintervals within $[0, c_h]$ over which one or the other mechanism dominates, but the endpoints and possibly the number of these intervals. □

Proposition 3 helps us answer the question that motivates this paper, specifically why government bonds are sold by auction and corporate bonds by PPS. To the extent that corporate bonds present credit risk but government bonds do not, the cost of acquiring information should be relatively low for government bonds and relatively high for corporate bonds. In line with the analysis above, the former should be sold by auction and the latter by PPS. What is more, corporate bonds should be sold at a discount. Both predictions appear to be borne out by the evidence: primary debt issues are sold by PPS, and they are underpriced on average.[24]

The fact that many developing country government bonds are sold by PPS is in line with our analysis. Developing country government bonds can present substantial credit risk. They are therefore more in the nature of corporate bonds than of government bonds.

Of course, it is entirely possible that developing countries' use of PPS rather than auctions is motivated primarily by the fear of collusion among bidders in an auction.[25] It is interesting, then, to consider those EU countries that issue foreign currency denominated bonds.[26] Not one single country uses auction to sell foreign currency denominated bonds; all countries use posted-price selling. This is of course in stark contrast to these countries' dominant use of auctions for selling local currency denominated bonds. For some of these countries at least, it is difficult to ascribe such difference to the fear of collusion: demand should be larger, and the opportunity for collusion correspondingly smaller for the foreign currency denominated bonds of, say, Cyprus or Hungary than for these countries' local currency denominated bonds. Our contention is that foreign currency denominated bonds are sold by PPS rather than auction because the foreign investors that a foreign currency issue is designed to attract are likely to have higher information acquisition costs than the primarily local investors that take part in the local currency auction.[27]

We now consider the effect of the quality of information.[28] Propositions 1 and 2 show that an improvement in the quality of information leads to an increase in revenues with the auction,

[24] Smith (1999) reports the results of three studies, which find underpricing of primary debt issues to range from 5bp (Weinstein, 1978), through 50bp (Sorensen, 1982), to 160bp (Smith, 1986). See also Ederington (1974) and Wasserfallen and Wydler (1988).

[25] See Stiglitz (2003) for a brief discussion of Ethiopia and Umlauf (1993) for an analysis of Mexico.

[26] These countries are Austria, Cyprus, the Czech Republic, Denmark, Finland, Germany, Greece, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom.

[27] We acknowledge that our explanation is unlikely to account for, say, the United Kingdom's use of PPS for selling foreign currency bonds.

[28] The quality of information is of course not unrelated to its cost, as higher quality information can generally be obtained at higher cost. Nonetheless, they are not perfect substitutes.

but to larger underpricing under PPS. Therefore, an improvement in the quality of information should favor auctions over PPS. Supporting this view are developments related to the Internet. The Internet can be argued to have made possible a dramatic improvement in the quality of the information available to market participants. It is credited with having occasioned "an enormous change in the opportunities for the use of auctions" (Pinker et al., 2001, p. 3), as evidenced for example by the profusion of B2B exchanges that use auctions.

Finally, we consider the effect of the riskiness of the security. We know from Propositions 1 and 2 that an increase in riskiness decreases expected seller proceeds in both the auction and PPS. It is therefore not clear how riskiness affects the choice between auctions and PPS.

We have assumed throughout that $\partial\pi_{n^*}/\partial n^* < 0$. We now argue that our main result, that the seller prefers PPS when the cost of information acquisition is relatively high, would in fact be strengthened were $\partial\pi_{n^*}/\partial n^* > 0$. In such case, n^* would increase rather than decrease as c increases, thereby increasing total information acquisition costs n^*c and decreasing the attractiveness of the auction as compared to PPS.[29]

What of changes in the quality of the information and the riskiness of the security when $\partial\pi_{n^*}/\partial n^* > 0$? We know from Section 2 that a bidder's expected profit increases in response to a decrease in the quality of the information or an increase in the riskiness of the security. For the condition $\pi_{n^*} = c$ to remain true, fewer bidders must take part in the auction. This decreases total information acquisition costs and increases expected seller proceeds. Recalling from Section 3 that expected seller proceeds under PPS decrease in both the quality of the information and the riskiness of the security, we conclude that, in comparison with PPS, greater riskiness favors the auction whereas the effect of better information is unclear.

5. An example

In order to gain some insight into the properties of posted prices and auctions, let us consider an example. Suppose that the security has unconditional expected value $E[V] = \overline{V}$ and that its prior distribution is uniform on the interval $[V_l, V_h] = [\overline{V} - \sigma_V, \overline{V} + \sigma_V]$. Suppose further that each bidder observes a signal X that is uniformly distributed around the true value V,

$$X = V + \varepsilon, \quad \varepsilon \in [-\sigma_\varepsilon, \sigma_\varepsilon]. \tag{17}$$

We wish to determine how the choice between the auction and the posted-price scheme depends on the riskiness of the security, σ_V, the dispersion of the signal, σ_ε, and the information acquisition cost, c.[30]

5.1. The posted-price scheme

Consider first the posted-price scheme. To compute the seller's expected payoff, we need to compute $E[V|X]$ and the distribution of X. Assume $V_l + \sigma_\varepsilon < V_h - \sigma_\varepsilon$.[31] As shown in Appendix A, since X is the sum of two uniformly distributed random variables, it has a trapezoidal

[29] That $\partial n^*/\partial c > 0$ when $\partial\pi_{n^*}/\partial n^* > 0$ is immediate from the condition $\pi_{n^*} = c$.

[30] Note that the standard deviation of V is $\sigma_V/\sqrt{3}$ and that of ε is $\sigma_\varepsilon/\sqrt{3}$.

[31] See Appendix B for the solution to the case $V_l + \sigma_\varepsilon > V_h - \sigma_\varepsilon$.

distribution with density function

$$f_X(x) = \begin{cases} \frac{x+\sigma_\varepsilon - V_l}{4\sigma_V\sigma_\varepsilon}, & V_l - \sigma_\varepsilon \leqslant x \leqslant V_l + \sigma_\varepsilon, \\ \frac{1}{2\sigma_V}, & V_l + \sigma_\varepsilon \leqslant x \leqslant V_h - \sigma_\varepsilon, \\ \frac{V_h+\sigma_\varepsilon - x}{4\sigma_V\sigma_\varepsilon}, & V_h - \sigma_\varepsilon \leqslant x \leqslant V_h + \sigma_\varepsilon. \end{cases} \tag{18}$$

Futhermore, conditional on observing the signal X, the expected value of the security is given by

$$E[V|X] = \begin{cases} \frac{V_l+X+\sigma_\varepsilon}{2}, & V_l - \sigma_\varepsilon \leqslant X \leqslant V_l + \sigma_\varepsilon, \\ X, & V_l + \sigma_\varepsilon \leqslant X \leqslant V_h - \sigma_\varepsilon, \\ \frac{V_h+X-\sigma_\varepsilon}{2}, & V_h - \sigma_\varepsilon \leqslant X \leqslant V_h + \sigma_\varepsilon. \end{cases} \tag{19}$$

To determine the magnitude of the discount required to deter information acquisition by buyers, we need to compute $E[\max[P - E(V|X), 0]]$. For $P \leqslant V_l + \sigma_\varepsilon$, we have

$$\begin{aligned} E\big[\max\big[P - E[V|X], 0\big]\big] &= \int_{V_l-\sigma_\varepsilon}^{2P-V_l-\sigma_\varepsilon} \left(P - \frac{X+\sigma_\varepsilon+V_l}{2}\right)\frac{X+\sigma_\varepsilon-V_l}{4\sigma_V\sigma_\varepsilon}\,\mathrm{d}X \\ &= \frac{(P-V_l)^3}{6\sigma_V\sigma_\varepsilon} \end{aligned} \tag{20}$$

and for $V_l + \sigma_\varepsilon \leqslant P \leqslant \overline{V}$,

$$\begin{aligned} E\big[\max\big[P - E[V|X], 0\big]\big] &= \int_{V_l-\sigma_\varepsilon}^{V_l+\sigma_\varepsilon} \left(P - \frac{X+\sigma_\varepsilon+V_l}{2}\right)\frac{X+\sigma_\varepsilon-V_l}{4\sigma_V\sigma_\varepsilon}\,\mathrm{d}X \\ &\quad + \int_{V_l+\sigma_\varepsilon}^{P} \frac{P-X}{2\sigma_V}\,\mathrm{d}X = \frac{3(P-V_l)^2-\sigma_\varepsilon^2}{12\sigma_V}. \end{aligned} \tag{21}$$

Solving the no information acquisition condition $E[\max[P - E[V|X], 0]] = Nc$ for P then yields

$$P = \begin{cases} V_l + \sqrt[3]{6Nc\sigma_V\sigma_\varepsilon}, & P \leqslant V_l + \sigma_\varepsilon, \\ V_l + \sqrt{4Nc\sigma_V + \sigma_\varepsilon^2/3}, & V_l + \sigma_\varepsilon \leqslant P \leqslant \overline{V}. \end{cases} \tag{22}$$

Note that when $c \leqslant \tilde{c} \equiv \sigma_\varepsilon^2/(6N\sigma_V)$, $P \leqslant V_l + \sigma_\varepsilon$ and the first expression for P applies, whereas when $c \geqslant \tilde{c}$, the second does. Summarizing, the posted-price schedule is given by

$$P = \begin{cases} V_l + \sqrt[3]{6Nc\sigma_V\sigma_\varepsilon}, & c \leqslant \frac{\sigma_\varepsilon^2}{6N\sigma_V}, \\ V_l + \sqrt{4Nc\sigma_V + \sigma_\varepsilon^2/3}, & c \geqslant \frac{\sigma_\varepsilon^2}{6N\sigma_V}. \end{cases} \tag{23}$$

Let us consider its properties. Note first that $P = V_l$ for $c = 0$, confirming the result from Section 3 that, unless the posted price is set at the lower bound of the value distribution, buyers always choose to become informed if doing so is costless. Second, observe that $\partial P/\partial c > 0$ for all c: a higher information acquisition cost makes a smaller discount necessary to deter information acquisition. Third, $\partial P/\partial \sigma_\varepsilon > 0$: when the signal becomes less precise, a lower discount is required to prevent information acquisition. Finally, note that $\partial P/\partial \sigma_V < 0$: a higher discount must be given to buyers in order to deter them from acquiring information about a more risky security.[32] All these effects confirm the results of the general model of Section 3.

The information acquisition cost c_h such that information acquisition can be prevented without giving buyers a discount can be obtained as the solution to

$$P = \overline{V} - \sigma_V + \sqrt{4Nc_h\sigma_V + \frac{\sigma_\varepsilon^2}{3}} = \overline{V} \tag{24}$$

and is therefore given by

$$c_h = \frac{\sigma_V}{4N} - \frac{\sigma_\varepsilon^2}{12N\sigma_V}. \tag{25}$$

Note that c_h increases both when the security becomes more risky (σ_V rises) and when the precision of the signal increases (σ_ε falls).

Figure 1 pictures the posted price (upper panel) and the corresponding discount $\overline{V} - P$ (lower panel) as a function of the information acquisition cost c for $N = 10$ potential buyers, $\overline{V} = 1/2$, $\sigma_V = 1/2$ (implying $V_l = 0$ and $V_h = 1$) and two degrees of signal precision: $\sigma_\varepsilon = 0.1$ (solid line) and $\sigma_\varepsilon = 0.2$ (dashed line). Note first that for all values of the information acquisition cost, P is higher for $\sigma_\varepsilon = 0.2$ than for $\sigma_\varepsilon = 0.1$. Also, observe that in both cases, underpricing diminishes rapidly as the information acquisition cost c increases. For a value of c exceeding c_h (about 0.012 in both cases although, consistent with the general analysis, c_h is lower when the signal dispersion is higher), no discount is required to deter information acquisition and the item can be sold at its unconditional expected value $\overline{V} = 1/2$ using the posted-price scheme.

5.2. *The auction*

Kagel et al. (1995) show that in the setting considered here, the expected gross profit per bidder when $n \geqslant 2$ bidders participate in the auction is given by

$$\pi_n = 2\sigma_\varepsilon \frac{n-1}{n^2(n+1)}. \tag{26}$$

[32] Consider first the case $P = \overline{V} - \sigma_V + \sqrt[3]{6Nc\sigma_V\sigma_\varepsilon}$. We have

$$\frac{\partial P}{\partial \sigma_V} = -1 + \frac{1}{3\sigma_V}\sqrt[3]{6Nc\sigma_V\sigma_\varepsilon} = -1 + \frac{P - \overline{V} + \sigma_V}{3\sigma_V} = \frac{P - (\overline{V} + 2\sigma_V)}{3\sigma_V} < 0.$$

Similarly, for the case $P = \overline{V} - \sigma_V + \sqrt{4Nc\sigma_V + \sigma_\varepsilon^2/3}$, we have

$$\frac{\partial P}{\partial \sigma_V} = -1 + \frac{2Nc}{\sqrt{4Nc\sigma_V + \sigma_\varepsilon^2/3}}.$$

This expression is negative if and only if $4N^2c^2 < 4Nc\sigma_V + \sigma_\varepsilon^2/3$. This condition can be rewritten as $4Nc(Nc - \sigma_V) < \sigma_\varepsilon^2/3$. Now, using the fact that $Nc = (3(P - V_l)^2 - \sigma_\varepsilon^2)/(12\sigma_V)$ and $P - V_l < \sigma_V$, we have

$$Nc - \sigma_V = \frac{3(P - V_l)^2 - \sigma_\varepsilon^2 - 12\sigma_V^2}{12\sigma_V} < -\frac{9\sigma_V + \sigma_\varepsilon^2}{12\sigma_V} < 0.$$

Hence, the condition $4Nc(Nc - \sigma_V) < \sigma_\varepsilon^2/3$ always holds and the result $\partial P/\partial\sigma_V < 0$ follows.

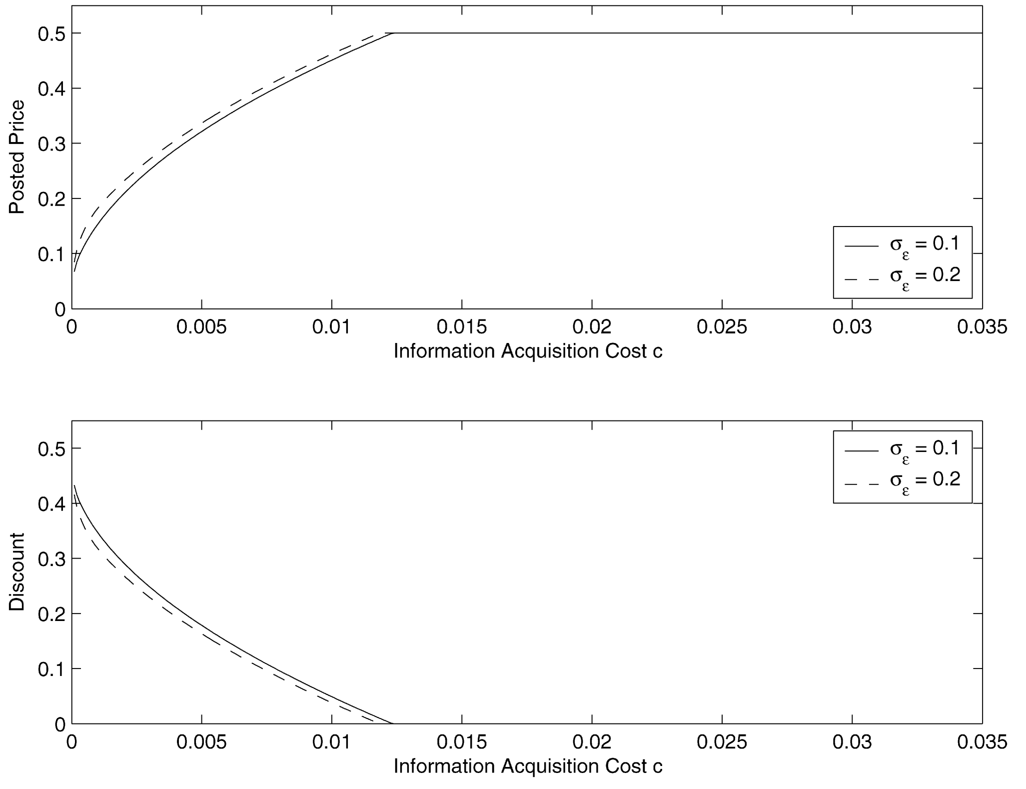

Fig. 1. Posted price and discount as a function of the information acquisition cost c.

Hence, letting $x \equiv 2\sigma_\varepsilon/c$, the number of bidders that choose to enter the auction is given by the lesser of the total number of potential buyers N and the integer part of the solution to $x(n-1) = n^2(n+1)$. Using the trigonometric resolution (Spiegel, 1974), this solution is

$$n^* = \frac{2}{3}\sqrt{3x+1}\cos\left(\frac{1}{3}\arccos\left(-\frac{18x+1}{\sqrt{(3x+1)^3}}\right)\right) - \frac{1}{3}. \tag{27}$$

The solution exists if and only if $(18x+1)/\sqrt{(3x+1)^3} < 1$, i.e., $x \geqslant \underline{x} \equiv (11+\sqrt{125})/2$, implying $c < \bar{c} \equiv 4\sigma_\varepsilon/(11+\sqrt{125})$. One can show that $\lim_{x\to\underline{x}} n^* = (1+\sqrt{5})/2$, $\partial n^*/\partial x > 0$, and $\lim_{x\to\infty} n^* = \infty$.[33] Thus, n^* increases without bound as the dispersion of the signal σ_ε increases, and decreases towards $(1+\sqrt{5})/2$ as the information acquisition cost c rises.

[33] We have

$$\frac{\partial n^*}{\partial x} = \frac{1}{\sqrt{3x+1}}\left(\cos\left(\frac{1}{3}\arccos\left(-\frac{18x+1}{\sqrt{(3x+1)^3}}\right)\right) + \frac{2x-1}{\sqrt{3x(x^2-11x-1)}}\sin\left(\frac{1}{3}\arccos\left(-\frac{18x+1}{\sqrt{(3x+1)^3}}\right)\right)\right)$$

which is positive since $\pi/2 < \arccos(-(18x+1)/\sqrt{(3x+1)^3}) < \pi$.

When $n^* > N$, all N potential buyers acquire information, enter the auction and make a positive expected net profit of

$$\pi_N - c = 2\sigma_\varepsilon \frac{N-1}{N^2(N+1)} - c. \tag{28}$$

When $n^* \leqslant N$, only some bidders enter the auction and—ignoring the integer constraint—make an expected profit of 0.

As a result, underpricing in the auction is given by

$$\begin{aligned} N\pi_N &= 2\sigma_\varepsilon \frac{N-1}{N(N+1)}, && n^* \geqslant N, \\ n^*\pi_{n^*} &= n^* c = \left(\frac{2}{3}\sqrt{3x+1}\cos\left(\frac{1}{3}\arccos\left(-\frac{18x+1}{\sqrt{(3x+1)^3}}\right)\right) - \frac{1}{3}\right)c, && n^* < N. \end{aligned} \tag{29}$$

Observe that underpricing increases with signal dispersion σ_ε

$$\begin{aligned} &\frac{\partial(N\pi_N)}{\partial\sigma_\varepsilon} = 2\frac{N-1}{N(N+1)} > 0, \\ &\frac{\partial(n^*c)}{\partial\sigma_\varepsilon} = \frac{\partial n^*}{\partial x}\frac{\mathrm{d}x}{\mathrm{d}\sigma_\varepsilon}c = 2\frac{\partial n^*}{\partial x} > 0. \end{aligned} \tag{30}$$

Thus, the noisier the signal, the lower the seller's proceeds from the auction, in stark contrast to the posted-price scheme, where a noisier signal raises the seller's revenue.

Note also that for the range of the information acquisition cost c over which all N bidders enter the auction, underpricing is independent of c and given by $N\pi_N = 2\sigma_\varepsilon(N-1)/(N(N+1))$. On the other hand, over the range of c such that $n^* < N$, underpricing is nonmonotonic in c. It is increasing for small c, but decreasing for large c. This is because

$$\frac{\partial(n^*c)}{\partial c} = n^*\left(1 + \frac{c}{n^*}\frac{\partial n^*}{\partial c}\right) = n^* \frac{\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^*}{\pi_{n^*} + \partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^*} \tag{31}$$

and $\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^*$ is negative for small n^* and positive for large n^*. Indeed, using (4), we have

$$\frac{\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]}{\partial n^*} = -\frac{\partial(n^*\pi_{n^*})}{\partial n^*} = 2\sigma_\varepsilon \frac{n^{*2} - 2n^* - 1}{n^{*2}(n^*+1)^2}, \tag{32}$$

which is negative for $n^* < 1 + \sqrt{2}$ and positive for $n^* > 1 + \sqrt{2}$.

These effects are illustrated in Fig. 2, which is based on the same parameter values as Fig. 1. The upper panel depicts the number of bidders, the lower panel the expected revenue from the auction. When the signal is relatively precise ($\sigma_\varepsilon = 0.1$, solid line), all $N = 10$ potential buyers acquire information and participate in the auction when c is less than 0.002. Over this range, underpricing is given by $2\sigma_\varepsilon(N-1)/(N(N+1)) = 0.0164$. When c rises above 0.002, the number of bidders falls. Up to a value of c of 0.014, the total information acquisition cost rises, and auction proceeds fall. As c increases beyond 0.014, however, underpricing decreases slightly, reflecting the fact that $\partial E[v_{n^*-1}(Y_{n^*-1}, Y_{n^*-1}) \mid X > Y_{n^*-1}]/\partial n^*$ is negative for small n^*. When signal dispersion is high ($\sigma_\varepsilon = 0.2$, dashed line), underpricing is larger than in the case $\sigma_\varepsilon = 0.1$, but exhibits the same pattern: it is constant at $2\sigma_\varepsilon(N-1)/(N+1) = 0.0327$ for low c, increases up to $c = 0.028$, and decreases slightly thereafter.

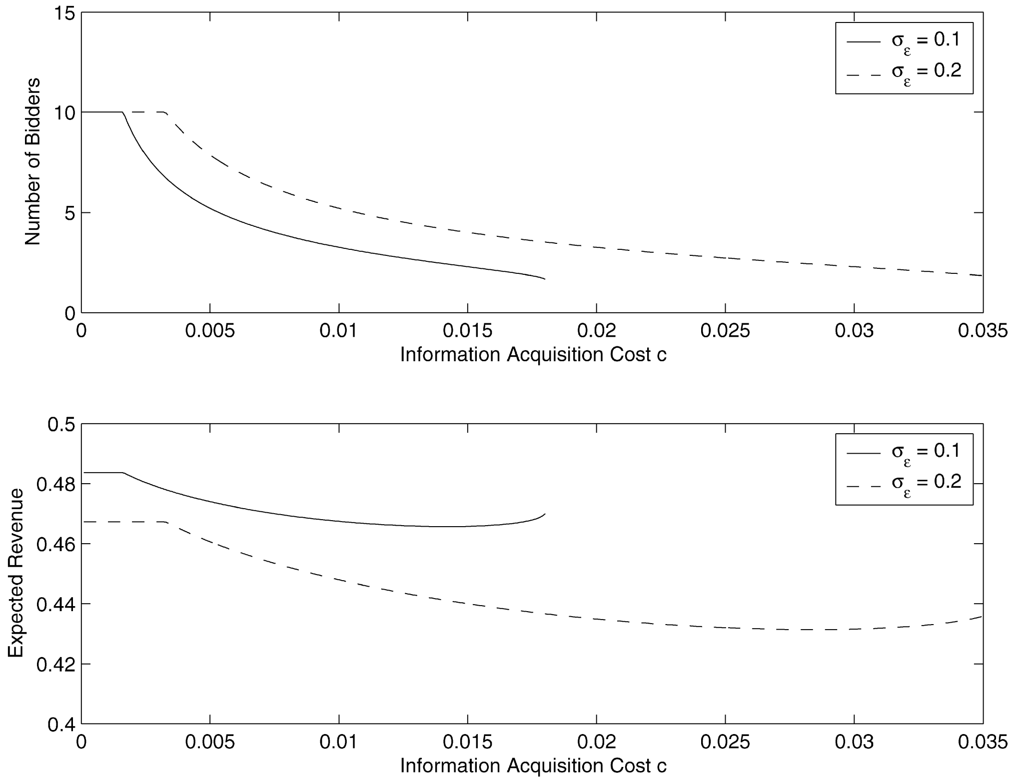

Fig. 2. Number of bidders and expected revenue from the auction as a function of the information acquisition cost c.

These results suggest that the seller may want to charge an entry fee in order to reduce the number of bidders participating in the auction and therefore aggregate underpricing. This is particularly true when c is low and bidders' expected profit—net of the information acquisition cost—is positive. Paralleling the arguments in French and McCormick (1984), the best the seller can do is to constrain the number of entrants to two bidders. He can do this by setting an entry fee k, to be paid before information is acquired,[34] such that

$$\pi_n = 2\sigma_\varepsilon \frac{n-1}{n^2(n+1)} = c + k \tag{33}$$

is satisfied for $n = 2$. Solving, the optimal entry fee is given by

$$k = \frac{\sigma_\varepsilon}{6} - c. \tag{34}$$

Note that the optimal entry fee is increasing in signal dispersion, reflecting the fact that bidders' expected gross profit and therefore their incentive to enter the auction is increasing in signal dispersion.

Although the entry fee allows the seller to constrain the number of bidders participating in the auction, it does not deter them from acquiring information. Interestingly, since the optimal entry

[34] If the entry fee were paid at the time the bid were submitted, expected proceeds likely would be lower because bidders with low value estimates may decide not to bid. See French and McCormick (1984) and Milgrom and Weber (1982b).

fee eliminates the impact of signal dispersion on bidders' incentives to enter the auction, the seller's expected revenue with entry fees becomes independent of signal dispersion and equals $\overline{V} - 2c$.

5.3. The posted-price scheme and the auction compared

Figure 3 compares the revenue from the posted-price scheme and the auction for the situation considered above when there are no entry fees. The upper panel considers the case of low signal dispersion ($\sigma_\varepsilon = 0.1$), the lower panel that of high signal dispersion ($\sigma_\varepsilon = 0.2$). Note that in both cases, the auction is preferred when the information acquisition cost is low, and the posted-price scheme when it is high. In the case where signal dispersion is relatively low (upper panel), bidders' expected profits and the number of bidders that enter the auction are not very large, and the auction is preferred to the posted-price scheme for values of c between 0 and 0.011. In contrast, when signal dispersion is relatively high (lower panel), bidders' expected profits and the number of bidders entering the auction—and therefore underpricing in the auction—are larger, and the posted-price scheme is preferred for values of the information acquisition cost c above 0.009.

Figure 4 performs the same comparison when the seller uses entry fees to reduce the number of participating bidders. Recall that in this case, the auction's expected revenue is $E[V] - 2c$

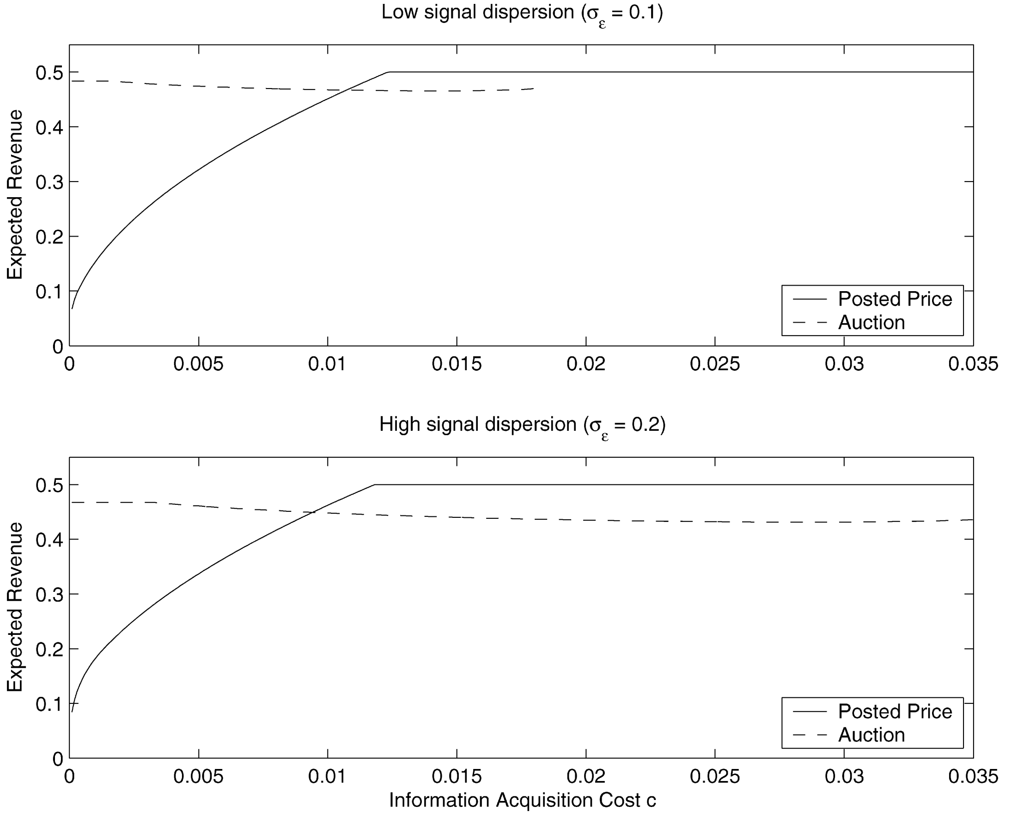

Fig. 3. Expected revenue from the auction and the posted-price scheme as a function of the information acquisition cost c.

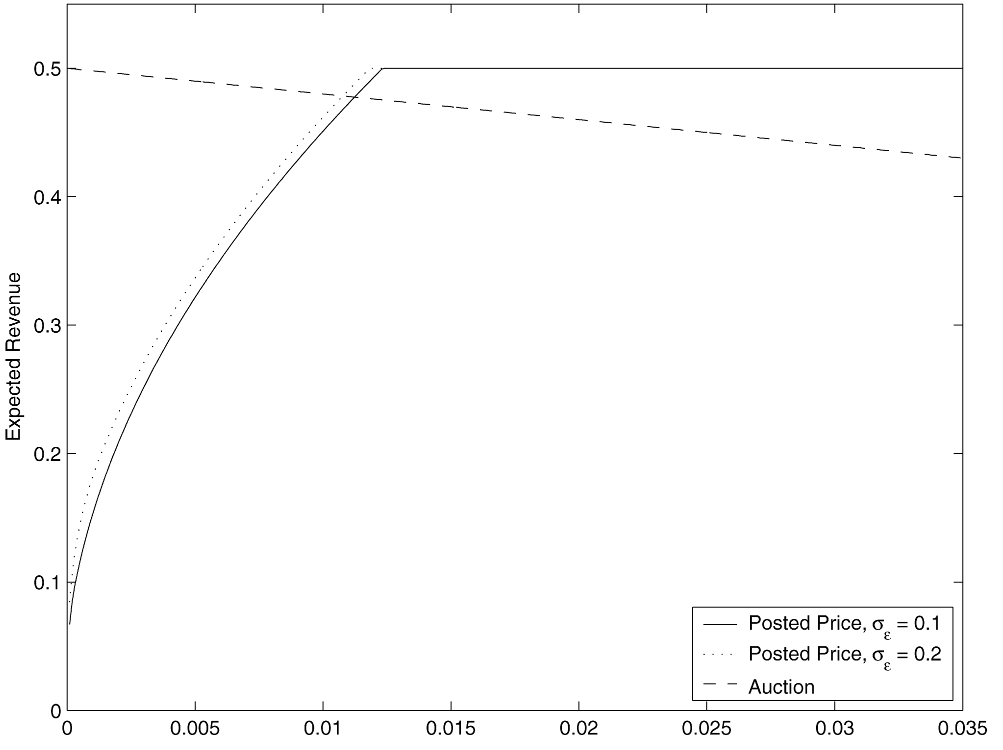

Fig. 4. Expected revenue from the auction and the posted-price scheme as a function of the information acquisition cost c when entry fees are used.

and does not depend on the signal's dispersion. The seller's revenue from the auction again exceeds that from the posted price when the information acquisition cost is low. For values of c exceeding about 0.011, however, the posted price is preferred. Furthermore, consistent with our earlier analysis, the range of values of c over which the posted price is preferred to the auction is larger, the greater the dispersion of the signal. Thus, just as in the case without fees, a lower signal quality favors the posted price over the auction, and a higher riskiness of the security has the opposite effect.

6. Conclusion

We believe a general lesson can be drawn from our analysis. It is that (i) the strength with which the price and allocation prescribed by a selling scheme react to investors' bids and (ii) investors' incentives to acquire information are positively related. The allocation reacts very weakly and the price not at all to investors' bids under PPS, but much more strongly in an auction.[35] This makes investors' incentives to acquire information much greater in auctions than under PPS, to the point that only those investors who have acquired information will enter a bid in an auction. In contrast, the price posted by the seller under PPS can be set in such way as to deny investors any incentive to acquire information.

[35] Under PPS, the allocation depends only on investors' decision whether to place a bid, but not on the amount bid.

That too strong a reaction of prices and allocations to bids may decrease seller proceeds has been noted by Biais and Faugeron-Crouzet (2002) in their extensive comparison of IPO selling mechanisms. Biais and Faugeron-Crouzet consider a setting with endowed information, and show that book-building or the French Mise en Vente procedure dominates auctions precisely because "prices should not adjust to demand too strongly." Biais and Faugeron-Crouzet view the strong adjustment of price to demand as spurring tacit collusion among bidders in an auction. In contrast, we view such adjustment as inducing bidders to acquire costly information, whose cost ultimately is borne by the seller.

Our comparison of auctions and PPS can be viewed as extending Persico's (1992) comparison of first- and second-price auctions. As discussed by Chari and Weber (1992) and shown formally by Persico (2000), the incentives to acquire information are lower in second-price auctions than in their first-price counterparts. In a first-price auction, it is valuable to bid close to one's opponents to minimize the price paid upon winning. Information helps in making such bids. No such concern arises in a second-price auction, because the price paid by the winner does not depend on the bid he has entered. Our analysis demonstrates that PPS gives investors even lower incentives to acquire information than do second-price auctions. Indeed, PPS can be used fully to deter them from acquiring information.

Our analysis is also related to the work of Parlour and Rajan (2005). They analyze an auction with a rationing scheme in which the winning bidder is chosen randomly among the K highest bidders and the price paid by the winning bidder is set at the $(K + 1)$th highest bid. In a setting with endowed information, they show that rationing with $K = N - 1$ is optimal when bidders have low quality information. This effect arises because rationing mitigates the winner's curse. Their result recalls our result that PPS dominates auctions when the information investors may acquire is of low quality, because PPS can be viewed as rationing among all N bidders. In such case, the sale price must of course be set by the seller, for buyers would otherwise bid only the lowest value for the item being sold.

Throughout, we have assumed that the decision to acquire information was an "all-or-nothing" decision: information either was acquired in its entirety, or it was not acquired at all. This is not likely to be the case in practice. Instead, some information may be acquired at such a low cost that the seller will not wish to preclude its acquisition. Other information may be sufficiently costly to acquire that the seller will be able to preclude its acquisition at the cost of a relatively small discount.

Does the presence of these two sorts of information invalidate our analysis? We believe the answer is in the negative. We conjecture that the need for PPS intended to preclude the acquisition of the second sort of information will remain, but that PPS will be combined with screening or preplay communication intended to induce investors to reveal truthfully the first sort of information.

PPS preceded by preplay communication is of course book-building (Spatt and Srivastava, 1991). Thus, some form of book-building should be observed in bond offerings. There appears to be evidence to that effect (Rayport, 1993). A recognition that information is not of an "all-or-nothing" nature therefore suggests that the difference between the mechanisms used in selling corporate bonds (PPS preceded by preplay communication, i.e., book-building) and government bonds (auctions) is not so much one of kind as of degree: less information is produced in the former case and more in the latter. We believe the further investigation of this distinction is an interesting topic for further research.

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Appendix A. Proof of Eqs. (18) and (19)

Proof of Eq. (18). Recall that the density of x is given by the convolution

$$f_X(x) = \int_{-\infty}^{\infty} f_V(x-\varepsilon) f_\varepsilon(\varepsilon)\,\mathrm{d}\varepsilon. \tag{35}$$

Note that $f_\varepsilon(\varepsilon) = 1/(2\sigma_\varepsilon)$ on $[-\sigma_\varepsilon, \sigma_\varepsilon]$ and 0 elsewhere. Hence,

$$f_X(x) = \int_{-\sigma_\varepsilon}^{\sigma_\varepsilon} f_V(x-\varepsilon)\frac{1}{2\sigma_\varepsilon}\,\mathrm{d}\varepsilon. \tag{36}$$

Now, $f_V(x-\varepsilon) = 1/(2\sigma_V)$ if $V_l \leqslant x-\varepsilon \leqslant V_h$ and 0 elsewhere. This condition, which can be written as $x - V_h \leqslant \varepsilon \leqslant x - V_l$, constrains the range of ε over which f_V is nonzero. Three cases can be distinguished. If $x - V_l \leqslant \sigma_\varepsilon$ (i.e., for $x \in [V_l - \sigma_\varepsilon, V_l + \sigma_\varepsilon]$), one has

$$f_X(x) = \int_{-\sigma_\varepsilon}^{x-V_l} \frac{1}{2\sigma_V}\frac{1}{2\sigma_\varepsilon}\,\mathrm{d}\varepsilon = \frac{x+\sigma_\varepsilon - V_l}{4\sigma_V\sigma_\varepsilon}. \tag{37}$$

If $x - V_h \geqslant -\sigma_\varepsilon$ (i.e., for $x \in [V_h - \sigma_\varepsilon, V_h + \sigma_\varepsilon]$), one has

$$f_X(x) = \int_{x-V_h}^{\sigma_\varepsilon} \frac{1}{2\sigma_V}\frac{1}{2\sigma_\varepsilon}\,\mathrm{d}\varepsilon = \frac{V_h+\sigma_\varepsilon - x}{4\sigma_V\sigma_\varepsilon}. \tag{38}$$

Finally, if $x - V_l \geqslant \sigma_\varepsilon$ and $-\sigma_\varepsilon \leqslant x - V_h$ (i.e., for $x \in [V_l + \sigma_\varepsilon, V_h - \sigma_\varepsilon]$), one has

$$f_X(x) = \int_{-\sigma_\varepsilon}^{\sigma_\varepsilon} \frac{1}{2\sigma_V}\frac{1}{2\sigma_\varepsilon}\,\mathrm{d}\varepsilon = \frac{1}{2\sigma_V}. \tag{39}$$

Proof of Eq. (19). Note that using Bayes' rule,

$$E[V|X] = \frac{\int_{-\infty}^{\infty} V f_X(X|V) f_V(V)\,\mathrm{d}V}{\int_{-\infty}^{\infty} f_X(X|V) f_V(V)\,\mathrm{d}V}. \tag{40}$$

Using the fact that $f_X(x|V) = 1/(2\sigma_\varepsilon)$ on $[V - \sigma_\varepsilon, V + \sigma_\varepsilon]$ and $f_V(V) = 1/(2\sigma_V)$ on $[V_l, V_h]$ and 0 elsewhere, one can again distinguish three cases. If $V_l + \sigma_\varepsilon \leqslant X \leqslant V_h - \sigma_\varepsilon$, one has

$$E[V|X] = \frac{\int_{X-\sigma_\varepsilon}^{X+\sigma_\varepsilon} V \frac{1}{2\sigma_\varepsilon}\frac{1}{2\sigma_V}\,\mathrm{d}V}{\int_{X-\sigma_\varepsilon}^{X+\sigma_\varepsilon} \frac{1}{2\sigma_\varepsilon}\frac{1}{2\sigma_V}\,\mathrm{d}V} = \frac{\frac{V^2}{2}|_{X-\sigma_\varepsilon}^{X+\sigma_\varepsilon}}{V|_{X-\sigma_\varepsilon}^{X+\sigma_\varepsilon}} = X. \tag{41}$$

If $X < V_l + \sigma_\varepsilon$, one has

$$E[V|X] = \frac{\int_{V_l}^{X+\sigma_\varepsilon} V \frac{1}{2\sigma_\varepsilon}\frac{1}{2\sigma_V}\,\mathrm{d}V}{\int_{V_l}^{X+\sigma_\varepsilon} \frac{1}{2\sigma_\varepsilon}\frac{1}{2\sigma_V}\,\mathrm{d}V} = \frac{\frac{V^2}{2}|_{V_l}^{X+\sigma_\varepsilon}}{V_{V_l}^{X+\sigma_\varepsilon}} = \frac{X+\sigma_\varepsilon+V_l}{2}. \tag{42}$$

Finally, if $X > V_h - \sigma_\varepsilon$, one has

$$E[V|X] = \frac{\int_{X-\sigma_\varepsilon}^{V_h} V \frac{1}{2\sigma_\varepsilon}\frac{1}{2\sigma_V}\,\mathrm{d}V}{\int_{X-\sigma_\varepsilon}^{V_h} \frac{1}{2\sigma_\varepsilon}\frac{1}{2\sigma_V}\,\mathrm{d}V} = \frac{\frac{V^2}{2}|_{X-\sigma_\varepsilon}^{V_h}}{V|_{X-\sigma_\varepsilon}^{V_h}} = \frac{V_h+X-\sigma_\varepsilon}{2}. \tag{43}$$

Appendix B. The posted-price scheme for $V_l + \sigma_\varepsilon > V_h - \sigma_\varepsilon$

When $V_l + \sigma_\varepsilon > V_h - \sigma_\varepsilon$, $X = V + \varepsilon$ has a trapezoidal distribution with density function

$$f_X(x) = \begin{cases} \frac{x+\sigma_\varepsilon-V_l}{4\sigma_V\sigma_\varepsilon}, & V_l - \sigma_\varepsilon \leqslant x \leqslant V_h - \sigma_\varepsilon, \\ \frac{1}{2\sigma_\varepsilon}, & V_h - \sigma_\varepsilon \leqslant x \leqslant V_l + \sigma_\varepsilon, \\ \frac{V_h+\sigma_\varepsilon-x}{4\sigma_V\sigma_\varepsilon}, & V_l + \sigma_\varepsilon \leqslant x \leqslant V_h + \sigma_\varepsilon. \end{cases} \tag{44}$$

Conditional on observing the signal X, the expected value of the security is given by

$$E[V|X] = \begin{cases} \frac{V_l+X+\sigma_\varepsilon}{2}, & V_l - \sigma_\varepsilon \leqslant X \leqslant V_h - \sigma_\varepsilon, \\ \overline{V}, & V_h - \sigma_\varepsilon \leqslant X \leqslant V_l + \sigma_\varepsilon, \\ \frac{V_h+X-\sigma_\varepsilon}{2}, & V_l + \sigma_\varepsilon \leqslant X \leqslant V_h + \sigma_\varepsilon. \end{cases} \tag{45}$$

To determine the magnitude of the discount required to deter information acquisition by buyers, we need to solve $E[\max[P - E[V|X], 0]] = Nc$. For all $P < \overline{V}$, we have

$$\begin{aligned} E\big[\max\big[P - E[V|X], 0\big]\big] &= \int\limits_{V_l-\sigma_\varepsilon}^{2P-V_l-\sigma_\varepsilon} \left(P - \frac{X+\sigma_\varepsilon+V_l}{2}\right)\frac{X+\sigma_\varepsilon-V_l}{4\sigma_V\sigma_\varepsilon}\,\mathrm{d}X \\ &= \frac{(P-V_l)^3}{6\sigma_V\sigma_\varepsilon}. \end{aligned} \tag{46}$$

Hence, the posted-price schedule is given by

$$P = \overline{V} - \sigma_V + \sqrt[3]{6Nc\sigma_V\sigma_\varepsilon}. \tag{47}$$

Its properties are the same as in the case $V_l + \sigma_\varepsilon < V_h - \sigma_\varepsilon$ analyzed in the text: (1) for $c = 0$, one has $P = V_l$, (2) $\partial P/\partial c > 0$, (3) $\partial P/\partial\sigma_\varepsilon > 0$, and (4) $\partial P/\partial\sigma_V < 0$.

The information acquisition cost c_h such that information acquisition can be prevented without giving buyers a discount can be obtained as the solution to

$$P = \overline{V} - \sigma_V + \sqrt[3]{6Nc\sigma_V\sigma_\varepsilon} = \overline{V} \tag{48}$$

and is therefore given by

$$c_h = \frac{\sigma_V^2}{6N\sigma_\varepsilon}. \tag{49}$$

As in the case $V_l + \sigma_\varepsilon < V_h - \sigma_\varepsilon$, c_h increases both when the security becomes more risky (σ_V rises) and when the precision of the signal increases (σ_ε falls).

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