Online Appendix to "Optimal Transparency in Over-the-Counter Markets"

OA.1 Additional comments on related literature

In this appendix, we explain in more detail the relationship between our paper and the literature on search and bargaining under adverse selection, focusing especially on papers that studied the effects of information disclosure. (Some of the discussions relate to the results about the low-search-cost market that can be found in the earlier working paper Vairo and Dworczak, 2024.)

A classic question studied within the literature on search under adverse selection concerns the issue of information aggregation of prices when trading is decentralized (Wolinsky, 1990, Blouin and Serrano, 2001). In these papers, there are two sides of the market, each composed of a continuum of agents (e.g., buyers and sellers), who have private information about the common value of the good. Trade happens through repeated pairwise meetings, and the outcome of previous encounters is unobservable to other market participants. Their key finding is that, as the market becomes approximately frictionless, prices fail to fully reveal the true value of the good. Blouin and Serrano (2001) also take into account allocative efficiency, and find that the equilibrium outcome may only be inefficient when both sides of the market have private information. Unlike them, we also find inefficiency under one-sided private information when the search friction is negligible. Even though there are several other differences in the modeling assumptions used in those papers relative to this one, a key factor driving the discrepancy in the results comes from the trading procedure. In their setting, the two sides simultaneously announce their trading positions, which implies that inefficiency stems from adverse selection, and in particular from uninformed traders taking on a tough position because they fear trading at a loss. In our model, the informed party makes the first move, giving rise to an additional source of inefficiency due to signaling incentives.[1] An alternative approach, pursued by Inderst (2005), Guerrieri et al. (2010), and Lester

[1] Barsanetti and Camargo (2022) study a version of the model in Wolinsky (1990) where the informed seller proposes the price, and like us find that signaling through prices gives rise to inefficiency, even when the buyer does not have private information.

et al. (2019), augments the competitive screening environment from Rothschild and Stiglitz (1976) by introducing directed search and characterize the set of equilibrium contracts. Those papers also differ from ours in that it is the uninformed party (the competing principals) who proposes the terms of trade, and the informed party (the agents) who conduct the search.

Lauermann and Wolinsky (2016) study a model of one-sided sequential search under adverse selection in which, unlike in our setting, the informed party is the one who searches. Despite differences between the models, they identify a force similar to the one underlying some of our welfare results: Search trading regimes are at a disadvantage relative to auction-type ones due to a strong form of winner's curse, whereby the event of being contacted for a quote leads sellers to infer that the value of the asset is high and thus price more aggressively. In their setting, this inference by the seller arises due to exogenous private information possessed by the buyer, whereas in ours it is the result of the searching party gradually becoming more informed by observing the informed seller's price offers.

We also connect to the literature that studies the effects of transparency and information disclosure in dynamic adverse selection settings. Like us, a series of these papers study a long-run privately informed seller who trades with a sequence of uninformed short-lived buyers. In Hörner and Vieille (2009) and Fuchs et al. (2016), the seller possesses a single unit of an indivisible good, and inefficiency may arise in equilibrium due to the high quality seller delaying her sale in order to signal her type. Both papers find that public disclosure of previously rejected offers leads to lower equilibrium welfare. The reason is that, under public offers, the high quality seller may use rejecting a high price as an additional tool to signal her type. Kim (2017), who studies the effect of observability of the seller's time on the market, arrives at a similar conclusion.[2] Kaya and Roy (2022) study the role of the availability of past trading records in a setting with repeated sales, and find that welfare is non-monotone in record length. In Kaya and Kim (2018), the buyer observes a private signal about the seller's type. As a result of two-sided private information, transaction delay may now become a signal of the quality being low, due to pessimistic privately informed buyers refusing to trade. In the multi-unit environment studied by Fuchs et al. (2022), the seller may resort to both delay and a lower volume of trade in order to signal high quality, although they find that only the former is used in equilibrium. In their model, public disclosure of past transactions does not impact welfare in the continuous time limit, although it does have (ambiguous) welfare effects when trade happens in discrete time.

Our model differs from the models in these papers in several dimensions. First, in our setting, trade happens repeatedly over time and it is the informed party (the dealer) who

[2] Chaves (2020) shows that the effects of post-trade transparency can be very different in a setting in which there is bargaining between two long-lived agents and there is endogenous entry to the market.

proposes the terms of trade. That is, dealers signal quality through prices. As a result, inefficiency arises in our model through interior probabilities of trade which are necessary to deter low types from mimicking higher types who trade at higher prices (instead of through delay of a one-time transaction). Moreover, the aforementioned papers feature a single seller who, in every period, receives an offer from a new buyer, which the seller chooses whether or not to accept. Thus, the seller effectively conducts sequential search (with the discount factor representing the search friction). In our setting, there is more than one seller, and we study different trading regimes that differ both in the extent of public disclosures of information and in the amount of competition between sellers.

OA.2 Two-sided private information

In this appendix, we consider a perturbed version of our model in which dealers face a small degree of uncertainty about customers' private value for the asset. Formally, suppose that the period-t customer-buyer's payoff from trading the asset is $v_t+\Delta+\epsilon_t$, where ϵ_t is uniformly distributed on $[-\epsilon,\epsilon]$, independently across t and of v_t.[3] An analogous specification applies to the customer-seller case. The parameter $\epsilon > 0$ is a commonly known constant, which should be thought of as small. We assume that ϵ_t is privately observed by the period-t customer at the time of entering the market.

Introducing a small amount of customers' private information does not influence equilibrium trading behavior. In particular, in all of the regimes, dealers' quoting strategies as well as the probability that on-path quotes are accepted are virtually unaffected by this perturbation. The only adjustment that is required in the proofs is that the interior probabilities of trade that are required to satisfy dealers' incentive-compatibility constraints are now satisfied by slightly modifying dealers' quotes. This modification in the quotes is constructed to ensure that there is a cutoff type in $[-\epsilon,\,\epsilon]$ such that all customers above the cutoff agree to trade with probability one, and the ex-ante expected probability of trade is equal to the one in the baseline framework. Optimality of the quotes is supported by sufficiently pessimistic beliefs following off-path quotes (just like in the baseline framework)—when ϵ is sufficiently small, a change in beliefs about the asset's common value is large enough that the customer wants to reject the off-path quotes regardless of their private-value component. In this way, the extension allows us to purify the random acceptance decision by the customer that is a key force driving inefficiency in all the trading regimes that we study.

For each regime r, let $\underline{\Lambda}_r^\epsilon$ and $\overline{\Lambda}_r^\epsilon$ be the level of welfare under, respectively, the least and most efficient equilibrium in regime r.

[3] The assumption of uniform distribution simplifies exposition but is not needed for our results.

Proposition OA.1. *For each $r \in \{\text{opaq}, \text{post}, \text{pre}, \text{full}\}$, $\underline{\Lambda}_r^{\epsilon} \to \underline{\Lambda}_r^{0}$ and $\overline{\Lambda}_r^{\epsilon} \to \overline{\Lambda}_r^{0}$ as $\epsilon \to 0$. Moreover, there exists $\epsilon^* > 0$ such that, when $\epsilon < \epsilon^*$, all welfare rankings coincide with those under $\epsilon = 0$.*

Proof. We focus on showing that the set of equilibrium outcomes is preserved under the limit as $\epsilon \to 0$ for the case of the opaque market. The arguments for the remaining regimes are analogous.

In the opaque market, we can write incentive-compatibility constraints as in the proof of Proposition 1. In particular, in any separating equilibrium, it has to be that the uninformed and high types trade with interior probability, in order to ensure that the low type does not benefit from deviating. Moreover, the low type must get her "complete-information" payoff, i.e., her equilibrium payoff must be

$$V_l^{\epsilon} \equiv \max_{b \in [-1+\Delta-\epsilon, -1+\Delta+\epsilon]} \frac{\epsilon - (b - (-1+\Delta))}{2\epsilon}(b+1).$$

When ϵ is small enough, this implies that $V_l^{\epsilon} = \Delta - \epsilon$ and the low type trades with probability one.

Next, we argue that the uninformed type must play a pure strategy when ϵ is sufficiently small. Let $b_u^{\epsilon} \in [\Delta - \epsilon, \Delta + \epsilon]$ be a quote in the support of the uninformed type's quoting strategy.[4] Any such quote leads to a payoff equal to

$$\frac{\epsilon - (b_u^{\epsilon} - \Delta)}{2\epsilon} b_u^{\epsilon},$$

which is strictly decreasing in b_u^{ϵ} when ϵ is sufficiently small. An analogous argument shows that the high type's quoting strategy must also be pure.

Let $\lambda_u^{\epsilon} = (\epsilon - (b_u^{\epsilon} - \Delta))/(2\epsilon)$ be the probability that b_u^{ϵ} is accepted. For ϵ sufficiently small, the incentive constraint preventing the low type from deviating to b_u^{ϵ} is

$$\Delta - \epsilon \geq \lambda_u^{\epsilon}(b_u^{\epsilon} + 1). \tag{OA.1}$$

As $\epsilon \to 0$, $b_u^{\epsilon} \to \Delta$ and the upper bound on λ_u^{ϵ} converges to $\Delta/(1+\Delta)$.

Analogously, letting $b_h^{\epsilon} \in [1 + \Delta - \epsilon, 1 + \Delta + \epsilon]$ be a quote of the high type and λ_h^{ϵ} be the associated probability of trade, the uninformed type's incentive constraint requires that

$$\lambda_u^{\epsilon} b_u^{\epsilon} \geq \lambda_h^{\epsilon} b_h^{\epsilon}, \tag{OA.2}$$

[4] Any quote below $\Delta - \epsilon$ would lead to trade with probability one, thus violating the low type's incentive compatibility; and any quote above $\Delta + \epsilon$ leads to trade with zero probability and is thus outcome equivalent to quoting $\Delta + \epsilon$.

which in the limit, gives an upper bound on λ_h^ϵ of $\lambda_u^\epsilon \Delta/(1+\Delta) \leq (\Delta/(1+\Delta))^2$.

By setting the customer's off-path beliefs to be maximally pessimistic subject to belief monotonicity (as in Appendix A.3), any pair of quotes $(b_u^\epsilon, b_h^\epsilon)$ with associated trade probabilities $(\lambda_u^\epsilon, \lambda_h^\epsilon)$ can be sustained in equilibrium. Thus, $\underline{\Lambda}_{\text{opaq}}^\epsilon \to \underline{\Lambda}_{\text{opaq}}^0$ and $\overline{\Lambda}_{\text{opaq}}^\epsilon \to \overline{\Lambda}_{\text{opaq}}^0$.

Analogous arguments establish the limiting welfare bounds for the remaining regimes.

Finally, we argue that the welfare rankings are preserved when ϵ is sufficiently small. Almost all of the inequalities in our welfare comparisons in the main text are strict and therefore, it follows from the first part of Proposition OA.1 that they are satisfied in a neighborhood of $\epsilon = 0$. The only exception pertains to the least efficient equilibrium in the pre-trade and fully transparent regimes, given that $\underline{\Lambda}_{\text{pre}}^0 = \underline{\Lambda}_{\text{full}}^0$. In that case, it is straightforward to extend the arguments in Appendix A.5 to show that $\underline{\Lambda}_{\text{pre}}^\epsilon = \underline{\Lambda}_{\text{full}}^\epsilon$ for ϵ sufficiently small, and therefore the welfare ranking between these two regimes is also unaffected by this perturbation. $\square$

OA.3 Equilibrium refinements

In this appendix, we formally define the belief-based refinements that were introduced in Section 2.3, we provide examples of equilibria that can arise without these refinements, and we discuss equilibria selected by the D1 criterion in the opaque regime.

OA.3.1 Definitions

For simplicity, we focus on describing how players update their beliefs after observing ask-quotes (i.e., when the customer is a buyer). Our refinements are defined symmetrically for the case in which dealers' quotes are bids to buy the asset.

Let $v_{i,t} \in [-1,1]$ denote the estimate of the expected value of the asset of dealer $i \in \{A, B\}$ at the start of period t. For any $n \in \mathbb{N}$ and $X \subset \mathbb{R}^n$, we use $\Delta(X)$ to denote the set of finite-support probability distributions over X. We index players by $j \in \{c, d\}$ to represent, respectively, the customer and the dealer. Let $\mu^j(b_i|h_t^j) \in \Delta([-1,1]^2)$ be player j's belief about $(v_{i,t}, v_{-i,t})$ after observing that dealer i quotes b_i, conditional on her history h_t^j. Let $\mu_i^j(b_i|h_t^j) \in \Delta[-1,1]$ and $\mu_{-i}^j(b_i|h_t^j) \in \Delta[-1,1]$ be her belief about dealer i and $-i$'s type, and let $v^j(b_i|h_t^j) \in [-1,1]$ be the associated posterior mean of the asset's value v_t. Let $\mu^j((b_i, b_{-i})|h_t^j) \in \Delta([-1,1]^2)$, $\mu_i^j((b_i, b_{-i})|h_t^j) \in \Delta[-1,1]$, $\mu_{-i}^j((b_i, b_{-i})|h_t^j) \in \Delta[-1,1]$, and $v^j((b_i, b_{-i})|h_t^j) \in [-1,1]$ be defined analogously for the case in which player j simultaneously observes a pair of quotes (b_i, b_{-i}). The first set of objects is relevant for the dealers and for the customers only in the pre-trade opaque regimes, and the second set is relevant for the customers only in the pre-trade transparent regimes. Let $\mu^j(h_t^j) \in \Delta([-1,1]^2)$, $\mu_i^j(h_t^j) \in \Delta[-1,1]$, $\mu_{-i}^j(h_t^j) \in \Delta[-1,1]$, and $v^j(h_t^j) \in [-1,1]$ be players' beliefs conditional on h_t^j prior to observing b_i or (b_i, b_{-i}). Let $\mathcal{H}_t^j$ denote the set of possible period-t histories for player j (which will depend on the trading protocol). For any $\mu \in \Delta([-1,1]^2)$, let $\operatorname{supp}(\mu)$ be the support of μ. For any $h_t \in \mathcal{H}_t^d$ at which the dealer must provide a quote, let $\sigma(b|h_t)$ be the probability density function of dealers' equilibrium quoting strategy (which we take to mean the probability *mass* function in case of discrete distributions) evaluated at $b \in \mathbb{R}$ (which is well defined in all equilibria of the trading regimes that we study).

Our belief-based equilibrium refinements used throughout Section 3 can be formally defined as follows.

(A1) *Never dissuaded once convinced:* for any $b \in \mathbb{R} \cup \mathbb{R}^2$, $t \in \mathbb{N}$, and $h_t^c \in \mathcal{H}_t^c$,

$$\operatorname{supp}(\mu^c(h_t^c)) \supset \operatorname{supp}(\mu^c(b|h_t^c)).$$

(A2) *Monotonicity and individual rationality:* for any $b, b' \in \mathbb{R} \cup \mathbb{R}^2$ (where $b = (b_i, b_{-i})$ and $b' = (b_i', b_{-i}')$ in case $b, b' \in \mathbb{R}^2$, and $b = b_i$ and $b' = b_i'$ in case $b, b' \in \mathbb{R}$), $t \in \mathbb{N}$, and $h_t^c \in \mathcal{H}_t^c$,[5]

$$b' \geq b \implies v^c(b'|h_t^c) \geq v^c(b|h_t^c).$$

Moreover, let

$$S(b, h_t^c) \equiv \big\{(v_i, v_{-i}) \in \operatorname{supp}\mu^c(h_t^c) : v_k \leq b_k \text{ for every dealer } k \text{ who trades with positive probability if the customer accepts}\big\}.$$

If $S(b, h_t^c) \neq \emptyset$, then

$$\operatorname{supp}\big(\mu^c(b \,|\, h_t^c)\big) \subset S(b, h_t^c).$$

(A3) *Unprejudiced beliefs:* For any $b = (b_i, b_{-i}) \in \mathbb{R}^2$, $t \in \mathbb{N}$, and $h_t^c \in \mathcal{H}_t^c$, let

$$V(b, h_t^c) \equiv \big\{(v_i, v_{-i}) : \exists k \in \{i, -i\} \text{ such that } \mathbb{E}\big[\sigma(b_k \,|\, h_t^d) \,\big|\, v^d(h_t^d) = v_k,\, h_t^c\big] > 0\big\},$$

where the expectation is taken over h_t^d according to the customer's belief given h_t^c. If $S(b, h_t^c) \cap V(b, h_t^c) \neq \emptyset$, then

$$\operatorname{supp}\big(\mu^c(b \,|\, h_t^c)\big) \subset V(b, h_t^c).$$

[5] If $b = (b_i, b_{-i}), b' = (b_i', b_{-i}') \in \mathbb{R}^2$, we say that $b' \geq b$ if $b_i' \geq b_i$ and $b_{-i}' \geq b_{-i}$.

OA.3.2 Counterintuitive equilibria without refinements

We now discuss new equilibria that would arise if we were to dispense with some of the refinements we imposed on off-path beliefs.

We start by considering the never-dissuaded-once-convinced refinement. As we argued in the paper, this refinement ensures that, in the regimes with post-trade transparency, the continuation outcome after a trade that fully reveals the state is the efficient one. We show that, without the refinement, it is possible to construct an equilibrium in the post-trade transparent market where the continuation outcome after a fully revealing quote is fully inefficient.

Claim OA.1. *Without the never-dissuaded-once-convinced refinement (A1), the post-trade transparent market admits an equilibrium in which trade happens with zero probability following a quote that (publicly) reveals the value of the asset to be high.*[6]

Proof. Consider the following equilibrium construction. Dealers' quoting strategies at $Z_t = 0$ are the same as in the proof of Proposition 2. At $Z_t = 1$, following a fully revealing trade at a price equal to $1+\Delta$, we set dealers' strategies to be such that both the uninformed and the high type provide quotes strictly above $1+\Delta$ and the customer always rejects.[7] To ensure that this is a continuation equilibrium, we set the customer's off-path beliefs at this node of the game to assign probability one to type -1 after any off-path quote weakly below $1+\Delta$. These off-path beliefs are obviously not consistent with our refinement, since they entail the customer revising her belief after learning that the state is high. In all other on-path $Z_t = 1$ histories, we set the continuation equilibrium to be the same as in Proposition 2. It is now straightforward to check that the chosen $Z_t = 0$ strategies and continuation equilibria form an equilibrium of the overall game. $\square$

Second, we discuss the role of the refinement (A3) in pre-trade transparent regimes.

Claim OA.2. *Suppose that customers' beliefs are no longer required to satisfy the unprejudiced beliefs refinement (A3). We can then construct an equilibrium of the pre-trade transparent market where the uninformed and the high type (at all histories in which the customer is a buyer, except at $Z_t = 1$ after the uninformed type learns that the value of the asset is low) provide quotes strictly above $1+\Delta$, which the customer always rejects.*

Proof. Fix the high type's and the uninformed type's quotes in both Z_t states to be $b_u > 1+\Delta$ and $b_h > 1+\Delta$, respectively, with $b_u < b_h$. Let $v(b_A, b_B)$ be the customer's posterior estimate

[6] It is possible to have a similar construction of a fully inefficient continuation equilibrium in the fully transparent market, which we omit for brevity.

[7] The dealer cannot have the low type on equilibrium path in this continuation game.

of the asset's value following a pair of quotes (b_A, b_B). We set these beliefs to satisfy

$$v(b_h, \tilde{b}) = \begin{cases} 1, & \text{if } \tilde{b} \geq b_u, \\ -1, & \text{if } \tilde{b} < b_u, \end{cases} \quad \text{and} \quad v(b_u, \tilde{b}) = \begin{cases} 1, & \text{if } \tilde{b} \geq b_h, \\ 0, & \text{if } \tilde{b} \in [b_u, b_h), \\ -1, & \text{if } \tilde{b} < b_u. \end{cases}$$

These beliefs are monotone and consistent with Bayes' rule on-path. They do not satisfy our refinement on beliefs, since the refinement would require, for example, that $v(b_h, \tilde{b}) = 1$ for all off-path $\tilde{b}$.

Let us verify that this profile of strategies and beliefs can be sustained as an equilibrium. If either one of the two dealers has a low type, the continuation equilibrium at $Z_t = 1$ is the Bertrand outcome described in Proposition 3. Otherwise, at $Z_t = 1$, the uninformed and the high type provide quotes $b_u, b_h > 1 + \Delta$ and never trade. They cannot profitably deviate, since the customer's off-path beliefs dictate that they can only trade by quoting a price less than $-1 + \Delta$ which yields a loss for these two types of dealers. The same argument implies that the uninformed and high types cannot profitably deviate at $Z_t = 0$. For the low type, we set her $Z_t = 0$ strategy to be the same as in Proposition 3. If she quotes a price higher than $-1 + \Delta$, she trades with zero probability at $Z_t = 0$, and her optimal continuation payoff is $(1-q)\Delta/2$. Therefore, the condition preventing a deviation to a quote outside of the support of her equilibrium strategy is $(1 - q)\Delta \geq \delta\gamma(1 - q)\Delta$, which is always satisfied. □

The equilibrium from Claim OA.2 is highly inefficient. In particular, it features zero trade in both Z_t states conditional on the asset value being high and the customer being a buyer. Moreover, this equilibrium cannot be sustained in the fully transparent market, since any off-path beliefs consistent with refinement (A2) would imply that there must be trade with probability one when $Z_t = 1$, the customer is a buyer, and dealers' types are (u, h). Therefore, this example suggests that, if we dispense with refinement (A3), then the least efficient equilibrium in the pre-trade transparent regime might be strictly worse than that in the fully transparent market.

Finally, we argue that, in the absence of refinement (A3), it is possible to strictly improve the most efficient equilibrium of the pre-trade transparent regime. This improvement obtains from having dealers coordinate on a "collusive" continuation equilibrium when $Z_t = 1$ where they quote the monopoly price and the customer always accepts. By increasing the low-type dealer's continuation payoff, this construction relaxes her incentive-compatibility constraint, thereby making it possible to sustain a higher probability of trade when $Z_t = 0$ and both dealers are uninformed.

Claim OA.3. *Suppose that customers' beliefs are no longer required to satisfy the unprejudiced beliefs refinement (A3). We can then construct an equilibrium where trading strategies are the same as in Proposition 3, with one difference: If at least one dealer provides a quote revealing that the state is low at $Z_t = 0$ and the customer is a seller at $Z_{t+1} = 1$, then dealers quote $-1 - \Delta$ at $Z_{t+1} = 1$ and the customer agrees to trade with probability one. If the pre-trade transparent regime does not admit a fully efficient equilibrium ($\overline{\Lambda}_{\text{pre}} < 1$), then in this equilibrium welfare is strictly higher than $\overline{\Lambda}_{\text{pre}}$.*

Proof. Let players' strategies be as described in the claim. In order to sustain the collusive continuation equilibrium at $Z_{t+1} = 1$, we can set the customer's off-path beliefs so that she believes that the value of the asset is high whenever she observes quotes $(-1 - \Delta, \tilde{b})$ with $\tilde{b} > -1 - \Delta$. This makes deviations unprofitable for dealers at this stage of the game. Moreover, the customer is indifferent between accepting and rejecting after observing a pair of quotes $(-1-\Delta, -1-\Delta)$, and hence accepting is optimal for her. The incentive-compatibility constraint preventing the low type from deviating to Δ in period t with $Z_t = 0$ yields

$$(1-q)\Delta + \frac{\delta\gamma}{4}\Delta \geq \frac{(1-q)\lambda_u}{2}(1+\Delta) + \frac{\delta\gamma(1-q)}{4}\kappa,$$

where, as before, $\lambda_u \in [0, 1]$ denotes the probability that the customer accepts after observing a pair of quotes (Δ, Δ). It can be verified, by analogous steps as in the proof of Proposition 3, that the remaining incentive-compatibility constraints are satisfied. Hence, in this equilibrium, it is possible to sustain

$$\lambda_u = \frac{(1-q)(2\Delta - \delta\gamma\kappa/2) + \delta\gamma\Delta/2}{(1-q)(1+\Delta)},$$

which is strictly higher than its counterpart in the most efficient equilibrium of the pre-trade transparent regime. Thus, expected welfare is also strictly higher in the equilibrium described in the claim. □

One can similarly construct other equilibria featuring collusive behavior when $Z_t = 1$, which will in general lead to ambiguous welfare effects depending on whether collusion is used to punish or reward deviations. As in the previous case, refinement (A3) rules out the equilibrium from Claim OA.3 in the fully transparent regime.

OA.3.3 D1 equilibrium in the static opaque market

In this section, we apply the divinity criterion (D1) by Banks and Sobel (1987) to the opaque market. Intuitively, the divinity criterion states that an off-path belief should only place probability weight on types of competitors for which the deviation could lead to a strict improvement over their equilibrium payoff. We show that this refinement uniquely selects the most efficient separating equilibrium.

The customer's strategy can be described by $a \in \{0,1\}$, which specifies whether or not she agrees to trade. Given a quote $b \in \mathbb{R}$, an acceptance decision by the customer, and the dealer's type $\theta \in \{-1,0,1\}$, the dealer's and the customer's payoffs can be written as $u_D(a,b,\theta) = a(b-\theta)$ and $u_C(a,b,\theta) = a(\theta + \Delta - b)$, respectively. Let $\pi : \mathbb{R} \to \Delta\{-1,0,1\}$ be the customer's posterior belief about θ after observing the dealer's quote, and let $\mathrm{MBR}(\pi, b) \subset [0,1]$ be the set of acceptance probabilities that are a best reply for the customer, given the quote b and her belief π. Let

$$D(\theta, b) \equiv \bigcup_{\pi \in \Delta\{-1,0,1\}} \{\beta \in \mathrm{MBR}(\pi, b) : u_D^*(\theta) < u_D(\beta, b, \theta)\},$$

where $u_D^*(\theta)$ is the equilibrium payoff of dealer type θ. Let $\bar{D}(\theta, b)$ be the closure of $D(\theta, b)$. The D1 criterion requires that the customer's beliefs, following an off-path quote b, assign zero probability to type θ whenever there exists θ' such that $\bar{D}(\theta, b) \subsetneq D(\theta', b)$.

Proposition OA.2. *In the opaque market, the unique D1 Perfect Bayesian equilibrium coincides with the best equilibrium under the solution concept defined in Section 2.*

Proof. Step 1: Ruling out semi-pooling equilibria. Suppose by contradiction that there are types $\theta < \theta'$ and a price b^* that belongs to the support of the equilibrium strategy of both types θ and θ'. Equilibrium payoffs for these two types are $u_D^*(\theta) = a(b^*)(b^* - \theta)$ and $u_D^*(\theta') = a(b^*)(b^* - \theta')$, where $a(b^*)$ is the equilibrium acceptance probability of the customer following b^*. Consider first the case in which $a(b^*) > 0$. By customer's optimality, this requires that $b^* < \theta' + \Delta$. Now, consider a quote $\tilde{b} = \theta' + \Delta - \epsilon$, where $\epsilon > 0$ is arbitrarily small. We argue that such a quote must be off-path. First, $\tilde{b}$ cannot be offered only by types weakly larger than θ' because, if it were, it would be accepted by the customer with probability one and type θ would benefit from deviating to it. Therefore, some type $\hat{\theta} < \theta'$ must be making this offer in equilibrium. But since no type $\theta'' > \theta'$ would be willing to offer $\theta' + \Delta - \epsilon < \theta''$, such a quote gets rejected with probability one by the customer. This is a contradiction, since type $\hat{\theta}$ can ensure a strictly positive payoff by offering b^* instead.

Since $\tilde{b}$ is an off-path quote, we apply the D1 criterion and show that beliefs following $\tilde{b}$ assign probability one to types θ' and higher. To see this, applying the above definitions,

$$\bar{D}(\theta, \tilde{b}) = \left[\frac{a(b^*)(b^* - \theta)}{\tilde{b} - \theta}, 1\right], \quad D(\theta', \tilde{b}) = \left(\frac{a(b^*)(b^* - \theta')}{\tilde{b} - \theta'}, 1\right].$$

When ϵ is sufficiently small, the fact that $a(b^*) > 0$ and $\theta' > \theta$ implies that

$$\frac{a(b^*)(b^* - \theta)}{\tilde{b} - \theta} > \frac{a(b^*)(b^* - \theta')}{\tilde{b} - \theta'},$$

and therefore $\bar{D}(\theta, \tilde{b}) \subsetneq D(\theta', \tilde{b})$. This implies that type θ does not belong to the support of $\pi(\tilde{b})$. Now, consider any other $\hat{\theta} < \theta$ (in our setting we three types, this implies $\hat{\theta} = -1$, $\theta = 0$ and $\theta' = 1$). By incentive compatibility, it must be that $u_D^*(\hat{\theta}) \geq a(b^*)(b^* - \hat{\theta})$, and thus $\bar{D}(\hat{\theta}, \tilde{b}) \subset \left[\frac{a(b^*)(b^* - \hat{\theta})}{\tilde{b} - \hat{\theta}}, 1\right]$. An analogous argument then shows that $\bar{D}(\hat{\theta}, \tilde{b}) \subsetneq D(\theta', \tilde{b})$, thus excluding type $\hat{\theta}$ from the support of $\pi(\tilde{b})$ as well. But then, if the customer's off-path beliefs following $\theta' + \Delta - \epsilon$ are fully supported on types θ' and higher, she will strictly want to accept such a quote. This is a contradiction, since then types θ and θ' would benefit from deviating to $\tilde{b}$.

It remains to consider the case with $a(b^*) = 0$. In this case, types θ and θ' get zero equilibrium payoffs. This implies that $\theta = 0$ and $\theta' = 1$, since type -1 can always ensure a payoff of Δ by quoting a price close to $-1 + \Delta$. Consider a quote $\tilde{b} = \Delta - \epsilon$, when $\epsilon > 0$ is small enough. By the same arguments as in the previous case, such a quote must be off-path. We now argue that D1 requires the belief $\pi(\tilde{b})$ to assign zero probability to type -1. To see this, note that $u_D^*(-1) \geq \Delta$, and therefore $\bar{D}(-1, \tilde{b}) \subset \left[\frac{\Delta}{1+\tilde{b}}, 1\right]$. On the other hand, since $a(b^*) = 0$, we have $D(0, \tilde{b}) = (0, 1]$. Thus, $\bar{D}(-1, \tilde{b}) \subsetneq D(0, \tilde{b})$. Hence, the customer's belief following $\tilde{b}$ assigns zero probability to type -1. This yields a contradiction, since then the customer would accept this quote with probability one, giving rise to a profitable deviation for type 0 whose equilibrium payoff is 0.

Step 2: Applying D1 to the set of separating equilibria. In any separating equilibrium, $u_D^*(-1) = \Delta$, $u_D^*(0) = \lambda_0 \Delta$ and $u_D^*(1) = \lambda_1 \Delta$, where λ_0 and λ_1 are the respective probabilities that the customer agrees to trade at a price equal to Δ and $1 + \Delta$, respectively. Consider a quote $\tilde{b} = \Delta - \epsilon$ where $\epsilon > 0$ is arbitrarily small. Applying the above definitions, we have

$$\bar{D}(-1, \tilde{b}) = \left[\frac{\Delta}{\tilde{b} + 1}, 1\right], \quad D(0, \tilde{b}) = \left(\frac{\lambda_0 \Delta}{\tilde{b}}, 1\right].$$

In order to sustain a fully separating equilibrium, it cannot be that the customer's beliefs after observing $\tilde{b} = \Delta - \epsilon$, for ϵ small enough, rule out the low type. Otherwise, the low and the uninformed types could trade with probability one by quoting $\tilde{b}$. For this to be consistent with D1, $\bar{D}(-1,\tilde{b}) \subsetneq D(0,\tilde{b})$ could not hold, which is the case if and only if

$$\frac{\Delta}{\tilde{b}+1} \leq \frac{\lambda_0 \Delta}{\tilde{b}}.$$

Taking ϵ to 0 yields $\lambda_0 \geq \Delta/(1+\Delta)$.

An analogous argument shows that $\lambda_1 \geq \lambda_0\Delta/(1+\Delta)$ in any D1 equilibrium. Since we showed in the proof of Proposition 1 that any separating equilibrium must satisfy $\lambda_0 \leq \Delta/(1+\Delta)$ and $\lambda_1 \leq \lambda_0\Delta/(1+\Delta)$, it follows that the D1 refinement uniquely selects the most efficient separating equilibrium. One can also check that these equilibrium strategies, together with appropriate off-path beliefs, indeed form a D1 equilibrium. □

OA.4 Unique implementation of the optimal mechanism

In this appendix, we propose an indirect mechanism that uniquely implements the optimal direct mechanism from Theorem 4.

Consider the following trading mechanism, which we refer to as a *coarse second-price auction with modified payments and rationing*, run by a trading platform. In every period t in which the customer is a buyer:[8]

- Dealers submit a quote in $B \equiv \{-1, \underline{b}, 0, 1\}$, where $\underline{b} \in (-1, -1+\min\{\Delta, 1/2\})$.
- The period-t buyer observes dealers' quotes and decides whether or not to trade.
- Let b_i denote the ith lowest quote. If the buyer accepts, the platform randomizes the decision of whether or not there is trade as follows: (i) if $b_1 = b_2 = 0$, there is trade with probability $2\min\{\Delta, 1/2\}$; (ii) otherwise, there is trade with probability one.
- Conditional on trade, the dealer who submitted the lowest quote sells the asset. Ties are broken as follows: in period one, if dealers' period-zero quotes differed, the dealer whose period-zero quote was lower (higher) sells; all other ties are broken uniformly at random.
- Payments are as follows: (i) if $b_1 = -1$ and $b_2 \in \{\underline{b}, 0\}$, trade happens at a price of $-1 + \min\{\Delta, 1/2\}$; (ii) otherwise, trade happens at a price equal to b_2.
- There are no payments made to the platform, so the mechanism balances the budget.
- At the end of each period, dealers observe each other's quotes. There is no post-trade transparency.

[8] If the customer is a seller, the auction is defined symmetrically.

Throughout this section, we use the same equilibrium notion and refinements as in Section 3. The individual-rationality requirement in refinement (A2), however, must be adapted to the pricing rule of the present mechanism. Dealers no longer trade at their own quotes, but at prices prescribed by the platform that are weakly more favorable to them. It would therefore be too restrictive to require that a dealer not incur a loss at her own quote. Instead, individual rationality should be evaluated at the transaction price prescribed by the platform. This motivates the following modification of refinement (A2) from Appendix OA.3:

(A2′) *Monotonicity and individual rationality:* The monotonicity condition is as in (A2). For any time t, history $h_t^c \in \mathcal{H}_t^c$, and pair of quotes $b \in \mathbb{R}^2$, let $T(b)$ denote the set of dealers who trade with positive probability if the customer accepts. For any $k \in T(b)$, let $p_k(b)$ denote the transaction price prescribed by the protocol for dealer k conditional on the customer accepting and dealer k trading. Let

$$S(b, h_t^c) \equiv \big\{(v_i, v_{-i}) \in \operatorname{supp} \mu^c(h_t^c) : v_k \leq p_k(b) \text{ for all } k \in T(b)\big\}.$$

If $S(b, h_t^c) \neq \emptyset$, then $\operatorname{supp}(\mu^c(b \mid h_t^c)) \subset S(b, h_t^c)$.

With this change to the refinement (A2), (A3) applies verbatim, with $S(b, h_t^c)$ as defined in (A2′) above.

Proposition OA.3. *In any equilibrium of the coarse second-price auction with modified payments and rationing, expected welfare coincides with that in the optimal mechanism. Moreover, an ex-post equilibrium exists, so optimal welfare is implementable in the ex-post sense.*

Proof. Step 1: Uniqueness of the equilibrium total probability of trade. We first show that, in any equilibrium, the ex-post *total* probability of trade of the optimal mechanism in Theorem 4 is implemented. In some cases, the identity of the dealer who trades in equilibrium is not uniquely pinned down, and hence individual probabilities of trade need not coincide with what is prescribed by the function $x(\theta_i, \theta_{-i})$. However, the equilibrium outcome will always lead to the same total probability of trade $x(\theta_A, \theta_B) + x(\theta_B, \theta_A)$.

In order to show uniqueness of the equilibrium probability of trade, it is enough to show that: *(i)* a pair of quotes $(0, 0)$ is observed in equilibrium with probability one if both dealers are uninformed, and it is observed with probability zero otherwise; and *(ii)* in any equilibrium and for any pair of quotes on the equilibrium path, the customer must agree to trade with probability one. Indeed, once we ensure that the customer always accepts and that the event $b_1 = b_2 = 0$ is equivalent to the event $\theta_A = \theta_B = 0$, then, by construction of the platform trading rules, the total allocation from the optimal mechanism is implemented.

1.a) Continuation equilibrium in period one. Let b_θ be a quote in the support of the bidding strategy of type θ in period zero, and let us derive equilibrium continuation strategies in period one. Since dealers observe each other's quotes in period zero, both dealers will share a common belief about the asset's value in period one, which we denote by $\hat{v} \in \{-1, 0, 1\}$.

If $\hat{v} = 1$, there are multiple equilibrium strategies in period one; e.g., both dealers may quote 1, or one dealer may quote 1 while the other quotes a lower value and, upon winning, sells at a price of 1. Nevertheless, all possible equilibria must lead to trade with probability one at a price of 1. This is because the customer in period one will learn that the state is high by observing dealers' quotes and will strictly prefer to trade at any price below $1 + \Delta$. Clearly, trade cannot happen at a price lower than 1 in equilibrium, so it must be that at least one of the dealers quotes 1.

If $\hat{v} = 0$, both dealers are uninformed. Since equilibrium is separating and we already argued that at least one dealer quotes 1 when $\hat{v} = 1$, it cannot be that dealers quote 1 at this node of the game. Since quotes below 0 lead to strictly negative payoffs, it must be that they both quote 0.

Finally, consider the case $\hat{v} = -1$. The only quotes that can be played after this history while still preserving separating strategies for dealers are in $\{-1, \underline{b}\}$. If both dealers were initially informed, symmetry requires that they both provide the same quote. If they both bid $\underline{b}$, then the customer would agree to trade with probability one, and dealers could profitably undercut each other by deviating to -1. Hence, it must be that they both quote -1. If one dealer was initially informed and the other one was uninformed, there are two kinds of continuation equilibria that are consistent with our equilibrium refinements (although only one of them will survive in the end): *(i)* both dealers quote -1 (in which case, by the tie-breaking rule, the initially informed dealer sells, at a price of -1), and *(ii)* the type -1 dealer quotes -1 and the type 0 dealer quotes $\underline{b}$. Note that the uninformed dealer gets a zero payoff in all cases, whereas the informed dealer gets at most $\min\{\Delta, 1/2\}$ if the type-(ii) equilibrium is played, and gets 0 otherwise.

1.b) Equilibrium strategies in period zero. First, it must be that type 1 quotes 1 with probability one. If type 1 placed positive probability on some quote $b < 1$, then, since strategies are symmetric, both dealers would quote b with positive probability when both have type 1; the customer, inferring from the (separating) quotes that $v = 1$, would accept at the price $b < 1$, so the winning dealer would sell the asset strictly below its value. Quoting 1 instead yields a zero payoff in period zero, and type 1's continuation payoff is zero in every continuation equilibrium identified above, so this deviation is strictly profitable. Next, we look at the uninformed and the low types. For strategies to be separating, it must be that their quoting strategies are supported on some subset of $\{-1, \underline{b}, 0\}$. Also, note that the continuation equilibrium is unique and yields a zero payoff in all cases, except when quotes reveal that one dealer has a low type and the other one is uninformed, in which case there are two candidate equilibria described previously. For $j = 1, 2$, let $\rho_j \in [0, 1]$ be the probability that players coordinate on the jth-type equilibrium following this history. Note that our restriction to stationary strategies requires that (ρ_1, ρ_2) do not depend on the actual quotes that are given in period t as long as they induce the same hierarchy of beliefs over the dealers' types. For $\theta \in \{-1, 0\}$, let $\underline{b}_\theta$ and $\bar{b}_\theta$ be the minimum and the maximum quote in the support of type θ's strategy, respectively, and let $F_\theta(b)$ be the corresponding cdf, and $p_\theta(b)$ the probability mass function (which exists because the auction has a finite bid space).

First, we show that $\underline{b}_0 > -1$. This is because, if $\underline{b}_0 = -1$, the uninformed dealer's belief conditional on winning the auction is strictly higher than -1 (by symmetry), and hence this quote would lead to a negative profit. Second, we show that it must be that $\bar{b}_{-1} < \underline{b}_0$. Suppose otherwise. The previous step implies that $\underline{b}_0 = \underline{b}$, which implies that the low-type dealer does not trade in period t when she quotes 0 (this is because the customer will always refuse to trade whenever the winning bid is $\bar{b}_{-1}$), and hence her overall payoff from this quote is equal to her continuation payoff, which is $\delta\gamma(1-q)\rho_2\lambda_1 \min\{\Delta, 1/2\}/2$, where λ_1 is the probability that the buyer agrees to trade when $Z_t = 1$ and she observes a pair of quotes equal to $(-1, \underline{b})$ (which need not be equal to 1 given that the buyer is indifferent when $\Delta \leq 1/2$). By deviating to $\underline{b}$ she gets to trade with strictly positive probability at a price higher than -1 in the current period in the event that the competitor is uninformed. Moreover, if the future customer is a buyer and if she quotes 0 in the following period after learning that the competitor is uninformed, she can ensure a continuation payoff of $1/2$. Overall, this deviation yields a strictly higher payoff in the current period and a weakly higher continuation payoff, a contradiction.

Next, we show that $\underline{b}_0 = 0$. Suppose that $\underline{b}_0 = \underline{b}$. By the previous step, this quote leads to strictly negative payoffs, and is thus suboptimal for the uninformed dealer. Thus, $\underline{b}_0 = \bar{b}_0 = 0$, which implies that randomization by the platform happens in equilibrium if and only if both dealers are uninformed.

Finally, we show that $\underline{b}_{-1} = \bar{b}_{-1} = -1$ by ruling out $\bar{b}_{-1} = \underline{b}$. Suppose first that $\Delta > 1/2$. Since the price $-1 + \min\{\Delta, 1/2\} = -1/2$ prescribed after the pairs $(-1, \underline{b})$ and $(-1, 0)$ lies strictly below $-1 + \Delta$, the buyer (whose posterior mean is -1 at both pairs) accepts with probability one. The low type's payoff from quoting -1 is therefore

$$\big[qp_{-1}(\underline{b}) + (1-q)\big]\tfrac{1}{2} + \tfrac{\delta\gamma}{2}(1-q)\rho_2\lambda_1\tfrac{1}{2},$$

while quoting $\underline{b}$ yields

$$\tfrac{q}{2}\,p_{-1}(\underline{b})(\underline{b}+1) + \tfrac{\delta\gamma}{2}(1-q)\rho_2\lambda_1\tfrac{1}{2},$$

and since $\underline{b}+1 < 1/2$, the former is strictly larger, a contradiction.

Suppose instead that $\Delta \leq 1/2$, and note that the assumption $q < 2\Delta^2/(1+\Delta^2)$ then implies $q < 2/5$. If $p_{-1}(\underline{b}) > 0$, the low type's equilibrium payoff equals her payoff from quoting $\underline{b}$, which is at most

$$\tfrac{q}{2}\,p_{-1}(\underline{b})(\underline{b}+1) + \tfrac{\delta\gamma}{2}(1-q)\rho_2\lambda_1\Delta \;\leq\; \tfrac{q}{2}\Delta + \tfrac{\delta\gamma}{2}(1-q)\Delta \;<\; (1-q)\Delta + \tfrac{\delta\gamma}{2}(1-q)\Delta,$$

using $\underline{b}+1 < \Delta$ and $q/2 < 1-q$. But the right-hand side is the payoff from deviating to a quote of 0 in both periods, a contradiction. Thus $\underline{b}_{-1} = \bar{b}_{-1} = -1$.

Observe that, under the above quoting strategies for the dealers, the buyer will agree to trade with probability one, except in the event that $\Delta \leq 1/2$ and the platform prescribes trading at a price of $-1+\Delta$ (which only happens when one dealer has type -1 and the other one has type 0) in which case the buyer is indifferent. In particular, this says that when $\Delta > 1/2$ the efficient outcome is uniquely implemented.

For the case $\Delta \leq 1/2$, we can use the type -1 dealer's incentive-compatibility constraint to show that the buyer must in fact agree to trade with probability one when she is indifferent and that the continuation equilibrium when dealers' types are $(-1,0)$ must be of type *(ii)*. To show this, we write the condition ensuring that the type -1 dealer does not want to deviate and quote 0 in both periods when $\Delta \leq 1/2$, which is

$$(1-q)\lambda_0\Delta + \frac{\delta\gamma}{2}(1-q)\rho_2\lambda_1\Delta \geq (1-q)\Delta + \frac{\delta\gamma}{2}(1-q)\Delta,$$

where λ_0 is the probability that the customer accepts when she observes the pair of quotes $(-1,0)$. The above can be satisfied if and only if $\lambda_0 = \lambda_1 = \rho_2 = 1$. Once we establish that the customer will accept to trade after any on-path pair of quotes, that randomization by the platform occurs in equilibrium if and only if both dealers are uninformed, and that the continuation equilibrium after a pair of quotes $(-1,0)$ must be the one where the low-type dealer trades for sure, it follows immediately that the total trade probability resulting in any equilibrium is that from the optimal mechanism.

Step 2: Construction of an ex-post equilibrium. Consider the following quoting strategies. In period zero, a dealer of type θ quotes θ. In period one, if dealer i was initially uninformed and her competitor quoted -1 in period zero, dealer i quotes $\underline{b}$; in all other cases, dealer i quotes her current estimate of the asset value (in particular, an initially uninformed dealer whose competitor quoted 1 quotes 1). The customer agrees to trade with probability one after every on-path pair of quotes. The customer's off-path beliefs are specified as follows: After any off-path pair of quotes, she assigns probability one to the profile minimizing the implied posterior mean of the asset value within the set permitted by the applicable refinements, and she trades only if doing so at the prescribed price is weakly profitable given her posterior.

We now check that the ex-post incentive constraints are satisfied.

First, consider a dealer of type 1. Quoting 1 yields her a weakly positive payoff at every history, whereas any lower quote either loses the auction, is rejected by the customer (whose posterior mean at the corresponding off-path pair is at most 0), or results in a sale at a price weakly below 1; hence there is no profitable deviation.

Second, consider the uninformed dealer. In period one, if she learned that the competitor has the high type, she quotes 1, ties, and wins by the tie-breaking rule (her period-zero quote was $0 < 1$), trading at a price of 1 for a zero profit; every alternative quote leads to rejection (the customer's posterior mean at $(0, 1)$, $(\underline{b}, 1)$, and $(-1, 1)$ is at most 0, while the prescribed price is 1), and thus also to a zero payoff. If she learned that the competitor has the low or uninformed type, there is also no deviation that leads to trading at a profit. In period zero, if the competitor has type 1, any quote yields at most a zero payoff. If the competitor is uninformed, quoting 0 yields zero in both periods. Deviating to 1 yields zero in period zero (the competitor wins at a price of 1) and zero in period one: The manipulated competitor quotes 1, the tie is resolved in the competitor's favor (her period-zero quote was lower), and every undercut is rejected by the customer, whose posterior mean at the resulting off-path pairs is at most 0 while the prescribed price is 1. Deviating to $\underline{b}$ or -1 is unprofitable even though it confers tie-breaking priority: The customer rejects the off-path pair $(\underline{b}, 0)$ in period zero, and every subsequent trade occurs at a price of $\underline{b}$ or $-1 + \min\{\Delta, 1/2\}$, strictly below the dealer's estimate of 0. Finally, if the competitor has the low type, all quotes yield zero.

Third, consider dealer i with type -1. If the competitor is uninformed, she trades with probability one at $-1 + \min\{\Delta, 1/2\}$ in period zero and, if the customer is a buyer, in period one, for a total payoff of $(1 + \delta\gamma/2) \min\{\Delta, 1/2\}$. If she deviates to 0, she trades with probability $\min\{\Delta, 1/2\}$ at a price of 0 in period zero; in period one the competitor quotes 0, and her best continuation is to quote 0 (trading with probability $\min\{\Delta, 1/2\}$ at a price of 0) or -1 (trading with probability one at $-1 + \min\{\Delta, 1/2\}$): her undercut $(\underline{b}, 0)$ is rejected, since the customer's posterior mean there is -1 while the prescribed price is 0. The deviation therefore yields exactly $(1+\delta\gamma/2) \min\{\Delta, 1/2\}$, her equilibrium payoff. Deviations to $\underline{b}$ and 1 yield strictly less, by the same belief specifications. Finally, if the competitor has the low type, all quotes yield zero.

Under all pairs of equilibrium quotes the customer is willing to trade, confirming her on-path optimality; hence the outcome implemented is that of Theorem 4. □

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