Price Controls, Non-Price Quality Competition, and the Nonexistence of Competitive Equilibrium

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Abstract

We investigate how price ceilings and floors affect outcomes in continuous time, double auction markets with discrete goods and multiple qualities. When price controls exist, the existence of competitive equilibria is no longer guaranteed; hence, we investigate the nature of non-price competition and how markets might evolve in its presence. We develop a quality competition model based on matching theory. Equilibria of the quality competition model always exist in such price-constrained markets; moreover, they naturally correspond to competitive equilibria when competitive equilibria exist. Additionally, we characterize the set of equilibria of the quality competition model in the presence of price restrictions. In a series of experiments, we find that market outcomes closely conform to the predictions of the model. In particular, price controls induce non-price competition between agents both in theory and in the experimental environment; market behaviors result in allocations close to the predictions of the model.

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1 Introduction

We investigate how price ceilings and floors affect outcomes in continuous time, double auction markets in which both price and quality can vary. Price controls can prevent market prices from adjusting to equalize supply and demand. Nevertheless, they are a pervasive form of government regulation: rent control, the minimum wage, and price supports for agricultural commodities are all common instances. Changes in product quality have been suggested as a dynamic response to the inability of the market to equate supply and demand by price changes.\(^1\) Indeed, a number of works support the possibility that price controls induce quality competition in various regulated industries\(^2\), and other research investigates how job characteristics such as the amount of employer-supplied training are affected by the minimum wage.\(^3\) However, theoretical inquiry into this phenomenon has been frustrated by the fact that competitive equilibria may fail to exist when price controls are imposed, and thus equilibrium models have not been available to study this phenomenon.

Our study was initiated by a small set of exploratory experiments focused on the basic question of whether, in the presence of price controls, quality would adjust as a form of non-price competition; these exploratory experiments then led to the development of a theory and to more refined experiments.\(^4\) This question was addressed within a continuous trading environment in which potential trades were tendered through bids and asks; multiple different qualities were produced and consumed. The environment was studied with and without price controls.

\(^1\)Such an effect has been suggested by Feldstein (1973), Leffler (1982), and Hashimoto (1982), among others. See also the work of Carlton (1978), who shows that, when demand is uncertain and both supply and price must be chosen \textit{ex ante}, firms may “increase good quality” by increasing supply (so that demand is more likely to be met).


\(^3\)See Hashimoto (1982) and Neumark and Wascher (2001).

\(^4\)These exploratory experiments were first described in a working paper by Plott et al. (2007), as was a theory for the case of unit supply/demand in the context of an assignment model; here, we develop a matching-theoretic model to understand the phenomena observed in those exploratory experiments (as well as perform a second series of experiments focused on the precise predictions of that model).
The first, exploratory, set of experiments focused on the possibility of quality adjustments in response to a price floor. Examination of the data pointed to the possible existence of market principles that could explain the subtle patterns in the data and provide precise predictions that could be tested in a more simplified environment in which competitive equilibria do not exist. Our findings suggest that the appropriate model is related to models found in the matching theory literature. We adapt these models to our setting and thus make a number of predictions regarding equilibrium behavior; our adaptation also allows for easy computation of equilibria.

Evaluating the resulting model required the design of a second and more focused set of experiments that differed from the first series of exploratory experiments in terms of the parameters of the environment, number of discrete qualities available, and the shapes of the demand and supply curves. The behavior of market participants in this second series of experiments resulted in allocations and prices that were essentially indistinguishable from those suggested by the theory. The analysis and tests used in Series 2 were then applied to and supported by the data from the exploratory series.

To understand the effect of price controls, consider Figure 1, which illustrates the classical case of demand and supply. The Walrasian competitive equilibrium corresponds to the point \((p, q)\). If a price floor is imposed at \(\hat{p}\), no competitive equilibria exist. Experimental work has demonstrated that the prices will converge to \(\hat{p}\) and volume will be \(\hat{q}\) but suppliers will want to sell \(\tilde{q}\) which leads to an excess supply of \(\tilde{q} - \hat{q}\); this phenomenon was first studied by Isaac and Plott (1981). The suppliers could profitably trade a greater number of goods than \(\hat{q}\) at the price \(\hat{p}\) but buyers for that quantity do not exist.

In this work, we ask whether the competition generated by the excess supply would support the emergence of better qualities, if such additional, higher quality products were technically possible. Moreover, if such better quality products do emerge, what qualities would they be and what would be their prices and volumes?

The data from our first series of exploratory experiments led to the development of a
Figure 1: The effect of a price floor when only one quality is present.

theory to explain market outcomes in settings where price controls are present. Following
the intuition that led to the experiments, we call our model the *quality competition model*. In our model, the classical notion of competitive equilibrium is replaced by the notion of stability from cooperative game theory, which is closely related to the core of an appropriately defined dominance relation. In an economy without price controls (a special case of the model developed here), a correspondence exists between competitive equilibria and stable outcomes.\(^5\) However, even when competitive equilibria do not exist due to the presence of price controls, stable outcomes still exist in our setting.

A *stable* outcome is a set of transactions that is

1. *individually rational*, i.e., no agent wishes to unilaterally withdraw from a transaction to which he is currently committed, and

\(^5\)Building on the work of Shapley and Shubik (1971) and Kelso and Crawford (1982), Hatfield et al. (2013) showed a natural correspondence between competitive equilibria and stable outcomes in a setting with multiple goods and no price controls under conditions on preferences that guarantee the existence of competitive equilibria.
2. *unblocked*, i.e., there does not exist a new transaction between a buyer and a seller that both would choose to engage in given the opportunity (possibly no longer executing other transactions they are a party to).

The notion of stability does not require that all contracts specify the same price (or quality). Thus, traders, in their attempt to find contracting parties, are free to craft unique contracts if they so desire. This flexibility inherent in the model allows the existence of multiple qualities and multiple prices that differ across agents and serves as the foundation for non-price competition to emerge. In Figure 1, no buyer who is part of a contract at the price floor has an incentive to break that contract. Any sellers who are part of the excess supply would engage in a contract at the price floor if the opportunity presented itself. However, the price floor prevents sellers from offering better terms to a buyer and, thus, no seller is able to block the transaction of another seller. The allocation corresponding to the point $(\hat{p}, \hat{q})$ is stable so long as the suppliers in contracts have costs less than $\hat{p}$. Of course, as will be studied in the sections below, a supplier who is unable to trade at $\hat{p}$ and has the capacity to offer a higher quality at additional cost may have an incentive to do so. This may result in multiple qualities being exchanged in positive amounts in the market as part of a quality competition response to the price control.

The basic parametric structure of the markets we study is developed in Section 2. For completeness, both the exploratory experiments and the test experiments will be reviewed. The exploratory experiments are called Series 1 and the test experiments are called Series 2. The theory is applicable to a wide range of environments; however, testing is confined to the special cases made possible within constraints imposed by experimental methods and technology. As such, the experimental design imposes a number of simplifying conditions, such as an additively separable utility function over goods. The model, therefore, is developed in the special context of that setting. While the basic principles are very general, the precise predictions of the model suitable for study and testing obviously require an explicit parametric structure.
The model is developed in detail in Section 3. We show that in the experimental environment, stable outcomes of the quality competition model always exist even when price restrictions are present. In sum, stability is a natural generalization of competitive equilibrium; moreover, stable outcomes exist even when competitive equilibria do not exist due to price controls. Stability is related to, but not the same as, the core. In our setting, stability provides a sharper prediction, as the set of stable outcomes is a strict subset of the core.6

Moreover, the quality competition model generates specific, nontrivial, predictions regarding how price floors affect quality, quantity, and transaction prices. In particular, non-price competition and the possibility that multiple qualities transact can be seen as a response to price controls. When each buyer places the same value on marginal changes of quality, and similarly each seller has the same cost for marginal changes of quality, the model predicts that for price floors slightly above the competitive equilibrium price (for the efficient quality), agents either trade the efficient quality at the price floor, or trade a good of quality one increment higher at a price reflecting exactly the increase in a buyer’s utility (measured in dollars) from the quality difference. However, as the price floor is raised, eventually all trade will happen at the higher quality, and at a price strictly above the price floor. Analogous theoretical results are obtained for price ceilings.

This property leads to a striking phenomenon unanticipated by the classical model: Prices in a stable outcome can exist above (below) price floors (ceilings), thereby giving the appearance of ordinary market clearing and competitive equilibria, even though the price floor (ceiling) has substantially changed the market outcome; for example, the price floor may be high enough that supply exceeds demand for the efficient quality and, hence, only the inefficiently high quality good is traded at a price strictly higher than the price floor. Thus, in field environments, where parameters are unknown, price controls can have substantial effects on the types of goods offered and on economic efficiency while leaving no trace of

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6This difference becomes important when the agents supply/demand multiple units: see Section 3.1.2. In a subsequent paper, Hatfield et al. (2012) showed for the quality competition model that there exists a natural one-to-one correspondence between stable outcomes and core outcomes for the special case of unit demand and supply.
such an impact in terms of the market disruption or excess demand/supply that is ordinarily associated with price controls.

Markets with price controls are also considered by Dréze (1975). In that work, Dréze (1975) showed the existence of ℓ-equilibria for markets with price restrictions (and continuum goods) by showing that there exists a set of ad hoc allocation constraints on agents such that, when these constraints are imposed, there exist prices that support the allocation as a competitive equilibrium; the construction of these constraints requires a complete knowledge of all the parameters in the economy. Matching market stability, as developed in our quality competition model, does not require imposing these ad hoc constraints; instead, limitations and constraints on an agent’s ability to trade arise naturally from the willingness of other agents to agree to that trade. Moreover, our approach, in relying on the deferred acceptance operator of Hatfield and Kominers (2012), provides a simple and computationally easy method for calculating equilibrium outcomes. In subsequent work, Herings (2015) extended the concept of Dréze equilibrium to markets with non-divisible commodities and showed that the set of stable outcomes of our model is the same as the set of Dréze equilibria.

Section 4 contains the experimental design developed to illustrate the specific predictions of the quality competition model. Two different experimental configurations are used. The first series of experiments takes place in an environment with several different qualities, and was originally designed to simply look for non-price competition through quality adjustments. These experiments set the stage for the precise tests that follow and can be viewed as a check of robustness. In the second series of experiments, parameters were chosen to investigate the specific predictions made by the quality competition model. Section 4 also outlines the performance measures used to make the comparisons.

Section 5 contains the detailed predictions of the model generated by the parameter values used in the experiments. Section 6 contains the results: as is shown, the first experimental

\[ \text{7See also van der Laan (1980) and Herings and Konovalov (2009), among others.} \]
series demonstrates that the impact of the price constraints in the ten qualities system is essentially as predicted by the model. The second experimental series illustrates the support for the model in terms of the subtle configuration of prices and qualities predicted by the model. Section 7 concludes.

2 Experimental Environment

Experimental environments are simple special cases of the conditions under which a model is expected to apply. This simplicity is dictated by the capacity of subjects to manage incentives, the ability to calculate predicted outcomes for different models, and the technologies available. Markets were organized by computerized, continuous double auctions.

For ease of interpretation, variables indexed as different goods are interpreted as different qualities of the same commodity. Each quality is traded in a separate market, and so the terms “market,” “good,” and “quality” will be used interchangeably. The two sets of experiments studied differed in the number of markets, the exploratory experiments of Series 1 involving ten markets and the more focused experiments of Series 2 involved three markets. The functional forms used to induce preferences and costs were the same for both.

Each buyer’s valuation depended separately on the total number of units bought and the quality of each unit; similarly, each seller’s valuation (i.e., cost function) depended separately on the total number of units sold and the quality of each unit. This separation of quantity and quality in agents’ valuation functions ensured that the value/cost of an increase in quality was independent of the number (and quality) of units already bought/sold by that agent. Finally, each agent’s utility function was quasilinear in money.

For a buyer $b$ let the vector $(x^b_A, \ldots, x^b_J)$ be the consumption level of each of the 10 different qualities $A, \ldots, J$. The valuation function of each buyer is given by

$$u^b(x^b_1, \ldots, x^b_J) = f^b\left(\sum_{j \in \{A, \ldots, J\}} x^b_j\right) + \sum_{j \in \{A, \ldots, J\}} a^b_j x^b_j$$
where \( f^b \) is the utility from the number of goods consumed and \( a^b_j \) is the utility from the quality of good \( j \) for buyer \( b \). For a seller \( s \) let the vector \((x_1^s, \ldots, x_J^s)\) be the production level of each of the \( J \) different qualities. The valuation function of each seller is given by

\[
u^s(x_1^s, \ldots, x_J^s) = -c^s \left( \sum_{j \in \{A, \ldots, J\}} x_j^s \right) - \sum_{j \in \{A, \ldots, J\}} a_j^s x_j^s
\]

where \( c^s \) is the cost of the number of goods produced and \( a_j^s \) is the cost of producing a quality of good \( j \) for seller \( s \).

From the functional form of the valuation functions, it can be seen that with a proper choice of parameters the demand functions are downward-sloping (with respect to the quantity consumed) and the supply functions are upward-sloping (with respect to the quantity produced). In the experimental markets, the marginal benefit of an increase in quality is the same for all buyers and the marginal cost of an increase in quality is the same for all sellers. However, buyers’ and sellers’ preferences differed with respect to the amount of utility from a given quantity. The actual parameters used in experiments are contained in Section 4.

Figure 2 illustrates the parametric configuration of the exploratory Series 1 experiments. Buyers and sellers could transact multiple units of any of ten qualities denoted \( A, B, \ldots, J \) where \( A \) is the lowest quality and \( J \) is the highest quality. Shown are the “isolated” demand and supply curves for the \( D \) and \( G \) qualities, i.e., the demand and supply curves illustrated as if only that quality existed. The isolated equilibrium price and quantity are shown for each of the ten qualities as a small disc labeled with the relevant quality. As quality increases, the benefit of an incremental increase in quality is reduced while the cost of an incremental increase in quality is increased; hence, there exists an efficient quality, quality \( D \), that maximizes consumer plus producer surplus.

The exploratory Series 1 was designed to study two issues. First, Series 1 was designed to check that our multi-market system converged to the competitive equilibrium, as had been shown previously in multi-market systems. The specific parametric environment studied
here with multiple qualities had not been examined before and, hence, a replication of known results was needed. In this environment, in any unconstrained competitive equilibrium, all trade takes place at a price in the interval $[4482, 4487]$ and at a quality of $D$. As summarized in Section 6.1, the goods traded and the associated prices did move in the direction of the general competitive equilibrium, and so the standard results for this environment were replicated.

Second, Series 1 was designed to examine the reaction of a multi-market system to the imposition of a price floor: in particular, a price floor placed above the competitive equilibrium price for the efficient quality. For selected sessions of Series 1 a price floor was imposed at 6000 (denoted in Figure 2 by a dashed horizontal line), a price that is above the isolated competitive equilibrium price of quality $G$ and below the isolated competitive equilibrium price of $H$ (and hence above the unconstrained competitive equilibrium price of quality $D$).
is excess supply relative to demand of quality $G$ goods, as exemplified in the figure. As will be documented in Section 6.1, non-price competition did emerge in the form of buyers and sellers transacting for higher quality goods—in particular, the theory developed in Section 3 suggests that agents will trade quality $G$ goods at a price of 6000, which is denoted with a circle in Figure 2.

![Diagram](image)

(a) Low price floor.  
(b) High price floor.

Figure 3: The effect of price floors on equilibrium quality and prices.

Study of the data from Series 1 led to the development of the quality competition model (developed in Section 3). Series 2 experiments were then designed to test the predictions of the model. The model produces very stark and unintuitive predictions for both price floors and price ceilings; there are two types of equilibria, and the essence of each type of equilibrium is illustrated in Figure 3(a) and Figure 3(b). However, the model applies with equal force to the ten quality levels of the exploratory Series 1 experiments; hence, the model is tested *ex post* on the data produced from that setting as well (in Section 6.1).

For price floors, the model predicts that equilibria will take one of two different forms, depending on the level of the price floor. In the first form, depicted in Figure 3(a), the price floor $p_f$ is just above the isolated competitive equilibrium price for some quality $\hat{q}$; the theory predicts that trade in two different qualities will emerge: trade in quality $\hat{q}$ goods will take place at the price floor $p_f$, while trade of goods with quality one increment higher, $\bar{q}$ will take place at a price $\tilde{p}$ reflecting the difference in a buyer’s valuation for the two goods. In the second form of equilibria, depicted in Figure 3(b), the price floor $p_f$ is significantly
above the isolated competitive equilibrium price for quality $\hat{q}$ goods (but below the isolated competitive equilibrium price for the next higher quality $\bar{q}$). In that case, all trade takes place at quality $\bar{q}$ at the isolated competitive equilibrium price for $\bar{q}$, denoted $\bar{p}$. Note that in this case, the price constraint is not binding in the usual sense, yet equilibrium behavior is influenced by the presence of the price constraint.

Similar logic holds for the case of price floors. Our experimental work considers both price floor and ceilings, as detailed in Section 4 below.

3 The Quality Competition Model

3.1 Framework

There is a finite set of buyers $B$ and a finite set of sellers $S$. Any given buyer and seller can make a trade $\omega$ that denotes a buyer $b(\omega) \in B$, a seller $s(\omega) \in S$, and a quality $q(\omega) \in Q$, where $Q$ is defined as a set of consecutive integers $\{q_{\text{min}}, \ldots, q_{\text{max}}\}$. If one seller sells multiple units of the same quality good to a buyer, this relationship will be represented by multiple trades. The finite set of trades is given by $\Omega$. For a given set of trades $\Psi \subseteq \Omega$, let $\Psi_b$ be the set of trades in $\Psi$ associated with buyer $b$, i.e., $\Psi_b \equiv \{\omega \in \Omega : b(\omega) = b\}$, and similarly let $\Psi_s \equiv \{\omega \in \Omega : s(\omega) = s\}$.\(^8\)

We can define transactions in terms of contracts. A contract $(\omega, p_\omega)$ is a trade along with an associated transfer price; the set of contracts is given by $X \equiv \Omega \times \mathbb{R}$. For a contract $x = (\omega, p_\omega)$, we let $b(x) \equiv b(\omega)$, $s(x) \equiv s(\omega)$, $q(x) \equiv q(\omega)$, and $p(x) \equiv p_\omega$. We also define $b(Y) \equiv \bigcup_{x \in Y} \{b(x)\}$ and $s(Y) \equiv \bigcup_{x \in Y} \{s(x)\}$; we let the set of all agents associated with some contract in $Y$ be denoted as $a(Y) \equiv b(Y) \cup s(Y)$. Finally, we let $Y_b$ be the set of contracts in $Y$ associated with buyer $b$, i.e., $Y_b \equiv \{x \in Y : b(x) = b\}$, and similarly let $Y_s \equiv \{x \in Y : s(x) = s\}$.

\(^8\)Note that the theory is developed in terms of trades as opposed to allocations in order to maintain consistency with the existing literature: see Hatfield et al. (2013).
We also define a price vector \( p \in \mathbb{R}^\Omega \) which states a price \( p_\omega \) for each \( \omega \in \Omega \). An arrangement \([\Psi; p]\) is a set of trades \( \Psi \subseteq \Omega \) and a price vector \( p \in \mathbb{R}^\Omega \).

A set of contracts \( Y \subseteq X \) is an outcome if it is feasible, i.e., no two contracts refer to the same trade: if \((\omega, p_\omega), (\omega, \tilde{p}_\omega) \in Y\), then \((\omega, p_\omega) = (\omega, \tilde{p}_\omega)\). Note that in contrast to arrangements, an outcome \( Y \) only describes prices for those trades that are part of contracts in \( Y \). Let

\[
\tau(Y) \equiv \{\omega \in \Omega : (\omega, p_\omega) \in Y \text{ for some } p_\omega \in \mathbb{R}\},
\]

the set of trades associated with contracts in \( Y \). For an arrangement \([\Psi; p]\), let

\[
\kappa([\Psi; p]) \equiv \{ (\omega, \tilde{p}_\omega) \in X : \omega \in \Omega \text{ and } \tilde{p}_\omega = p_\omega \},
\]

be the set of contracts that execute the trades in \( \Psi \) at prices \( p \) in the arrangement \([\Psi; p]\).

### 3.1.1 Preferences

Consistent with the development of matching theory, preferences will be described in terms of trades as opposed to the allocations introduced in the previous section. The exact experimental parameters will be described in Section 4.

The valuation function \( u^b \) of buyer \( b \in B \) for a set of trades \( \Psi \subseteq \Omega \) is given by

\[
u^b(\Psi) \equiv f^b(|\Psi_b|) + \sum_{\omega \in \Psi_b} v(q(\omega)) \]

where \( f^b(n) \) is the value \( b \) obtains from procuring \( n \) goods and \( v(q) \) is the additional utility \( b \) obtains from procuring a good of quality \( q \). Let \( f^b \) be strictly increasing and concave, and let \( v \) be strictly concave.

The valuation function of seller \( s \in S \) for a set of trades \( \Psi \subseteq \Omega \) is given by

\[
u^s(\Psi) \equiv -c^s(|\Psi_s|) - \sum_{\omega \in \Psi_s} e(q(\omega)) \]
where \( c^s \) is the cost \( s \) incurs from producing \( n \) goods and \( e(q) \) is the additional cost \( s \) incurs from producing a good of quality \( q \). Let \( c^s \) be strictly increasing and convex, and let \( e \) be strictly convex.\(^9\)

For ease of exposition, we assume that there is a unique quality \( \hat{q} \) that maximizes surplus, i.e.,

\[
\{ \hat{q} \} \equiv \arg\max_{q \in Q} \{ v(q) + e(q) \},
\]

and furthermore that \( \hat{q} \) is neither the highest nor lowest quality, i.e., \( q_{\text{min}} < \hat{q} < q_{\text{max}} \).

The utility functions of a buyer \( b \in B \) and a seller \( s \in S \) for an outcome \( Y \subseteq X \) are given by

\[
U^b(Y) \equiv u^b(\tau(Y)) - \sum_{y \in Y} p(y),
\]

\[
U^s(Y) \equiv u^s(\tau(Y)) + \sum_{y \in Y} p(y).
\]

For an arrangement \( [\Psi; p] \), we let \( U^i([\Psi; p]) \equiv U^i(\kappa([\Psi; p])) \) for all \( i \in B \cup S \).

Using these utility functions we define the demand correspondence for \( i \in B \cup S \) given a price vector \( p \in \mathbb{R}^\Omega \) as

\[
D^i(p) \equiv \arg\max_{\Psi \subseteq \Omega} U^i([\Psi; p]).
\]

Similarly, we define the choice correspondence from a finite set of contracts \( Y \subseteq X \) as

\[
C^i(Y) \equiv \arg\max_{Z \subseteq Y} U^i(Z)
\]

\(^9\)This characterization of buyers’ and sellers’ utility functions is equivalent to the cardinality condition of Bevia et al. (1999). These assumptions on preferences and agents are more restrictive assumptions than is necessary for some of our results; however, these assumptions closely parallel our experimental design. (In general, agents’ preferences must be substitutable in the sense of Hatfield and Milgrom (2005) (or, equivalently, grossly substitutable in the sense of Kelso and Crawford (1982)) to ensure existence of stable outcomes: see Hatfield and Kominers (2012) for a discussion of this point in a more general setting.) For a more general model (without price restrictions), see Hatfield et al. (2013, 2015).
3.1.2 Definition of Equilibrium

We now define two distinct notions of equilibrium, competitive equilibrium and stability.

**Definition.** A *competitive equilibrium* is an arrangement $[\Psi; p]$ such that

$$\Psi_i \in D^i(p)$$

for all $i \in B \cup S$.

This definition encodes both individual optimization (as each agent demands an optimal set of trades, given prices) and market clearing (as a buyer demands a trade with a seller at a given price if and only if the seller also demands that trade).

We now define stability:

**Definition.** An outcome $A \subseteq X$ is **stable** if it is

1. *Individually rational*: for all $i \in B \cup S$, $A_i \in C^i(A)$.

2. *Unblocked*: there does not exist a nonempty blocking set $Z \subseteq X$ such that

   (a) $Z \cap A = \emptyset$, and

   (b) for all $i \in a(Z)$, we have that $Z_i \subseteq Y^i$ for all $Y^i \in C^i(Z \cup A)$.

The first condition, individual rationality, states that no agent is strictly better off by choosing a strict subset of his contracts in $A$. The second condition states that there does not exist a set of contracts $Z$ such that each agent $i$ involved in $Z$ would strictly prefer to sign all of contracts associated with $i$ (and possibly drop some of his existing contracts in $A$) to just keeping his current contracts in $A$.

Note that a blocking set may be of any size and involve an arbitrary number of agents. However, in the context of our quality competition model, for any blocking set $Z$, the set $\{z\} \subseteq Z$ is also a blocking set for all $z \in Z$. In other words, for any blocking set, any singleton
subset of that blocking set is a blocking set in and of itself. Hence, while an outcome is stable only if there does not exist a blocking set, for any outcome that is not stable, the outcome is either not individually rational or there exists a blocking set containing one contract.

The notion of stability is also closely related to the core, defined below:

**Definition.** An outcome $A$ is in the core if it is core unblocked, i.e., there does not exist a set of contracts $Z$ such that, for all $i \in a(Z)$, $U^i(Z) > U^i(A)$.

An outcome is in the core if there does not exist a set of agents who, by dropping all of their current contracts and signing contracts only amongst themselves can make each of them strictly better off. The definition of the core differs from the definition of stability in two ways. First, a core block requires that all agents who are associated with the blocking set drop all of their contracts with agents not associated with the blocking set; this is a more stringent restriction than that imposed by stability, where agents associated with the blocking set may retain previously held contracts. Second, a core block does not require that $Z_i \in C^i(Z \cup A)$ for all $i \in a(Z)$; rather, it requires the less stringent condition that $U^i(Z) > U^i(A)$ for all $i \in a(Z)$.

However, when preferences are substitutable, as is the case here, the set of competitive equilibria, the set of stable outcomes, and the core are all closely related.

**Theorem 1.** For any competitive equilibrium $[\Psi; p]$, $\kappa([\Psi; p])$ is a stable outcome; furthermore, any stable outcome is in the core. Conversely, for any core outcome $A$, there exists a stable outcome $\hat{A}$ such that $\tau(A) = \tau(\hat{A})$.

This theorem shows that when competitive equilibria exist, they induce stable outcomes. In fact, when no price restrictions are present, a converse result holds as well: all stable outcomes induce competitive equilibria.\(^{10}\) However, when price restrictions are present,

\(^{10}\)Formally, when we say that a stable outcome induces a competitive equilibrium, we mean that for a stable outcome $A$, there exists a price vector $\tilde{p} \in \mathbb{R}^\Omega$ such that $[\tau(A); \tilde{p}]$ is a competitive equilibrium where, for all $(\omega, p_\omega) \in A$, we have that $\tilde{p}_\omega = p_\omega$. See Hatfield et al. (2013) for a proof and discussion of this result.
competitive equilibria may not exist, and so stable outcomes do not, in general, induce competitive equilibria.

While the core is a natural solution concept in this setting, it does not make specific predictions about prices, as if a buyer and seller may engage in multiple trades with each other, those trades can be at prices that are not supportable in a stable outcome or competitive equilibrium. Furthermore, the set of realizable utility outcomes is strictly larger for the set of core outcomes than for the set of stable outcomes. For instance, suppose there is only one buyer $b$, one seller $s$, a set of trades $\Omega = \{\psi, \omega\}$, and let

$$u^b(\Psi) = 4|\Psi|$$
$$u^s(\Psi) = -3 \max\{0, |\Psi| - 1\};$$

the buyer has constant marginal utility from each item, while the seller only incurs a cost if he sells both items. Then $\{(\psi, 2), (\omega, 2)\}$ is a core outcome, but it is not stable (and does not induce a competitive equilibrium). In particular, the seller will obtain a utility of at least 3 in any stable outcome, but only receives a utility of only 1 in this core outcome.\footnote{Note that the set of core outcomes does not coincide with the set of stable outcomes only in settings where both buyers and sellers may demand multiple contracts. This phenomenon is present only when there are a finite number of buyers and sellers or indivisible goods; for economies with a continuum of agents and divisible goods, the set of competitive equilibria allocations again coincides with the core; see Kaneko and Wooders (1986), Hammond et al. (1989), and Kaneko and Wooders (1996).}

### 3.2 Characterization of Equilibrium

Before we fully characterize the set of stable outcomes, it will be helpful to consider the case where there are no price restrictions and the set of trades is restricted to one quality. Let $\Omega(q) \equiv \{\omega \in \Omega : q(\omega) = q\}$ and let $X(q) \equiv \Omega(q) \times \mathbb{R}$.

**Theorem 2.** Suppose there are no price restrictions, and the set of contracts is given by $X(q)$. Then a stable outcome exists, and for any stable outcome $A$:
1. The number of contracts $|A|$ is an element of

$$\arg\max_{n \in \mathbb{Z}_{\geq 0}} \left\{ \sum_{b \in B} [f(n_b) + v(\bar{q})] - \sum_{s \in S} [c(n_s) + e(\bar{q})] \right\}$$

where

$$\sum_{b \in B} n_b = \sum_{s \in S} n_s = n.$$

2. For all $(\omega, p_\omega) \in A$, $p_\omega \in [p^{\min}(\bar{q}), p^{\max}(\bar{q})]$, where

$$p^{\min}(\bar{q}) \equiv \max_{b \in B, s \in S} \left\{ f^b(|A_b| + 1) - f^b(|A_b|) + v(\bar{q}), c^s(|A_s|) - c^s(|A_s| - 1) + e(\bar{q}) \right\}$$

$$p^{\max}(\bar{q}) \equiv \min_{b \in B, s \in S} \left\{ f^b(|A_b|) - f^b(|A_b| - 1) + v(\bar{q}), c^s(|A_s| + 1) - c^s(|A_s|) + e(\bar{q}) \right\}$$

The theorem makes two specific predictions about behavior when only one quality is available. First, the theorem predicts that a surplus-maximizing number of trades will take place. Second, the theorem predicts that all trades will take place at a price in the interval $[p^{\min}(\bar{q}), p^{\max}(\bar{q})]$. The lower bound of this interval is the minimal price such that both no buyer wishes to buy one more unit, and every seller wishes to sell his prescribed number of units. Conversely, the upper bound of this interval is the maximal price such that both every buyer wishes to buy his prescribed number of units, and no seller wishes to sell one more unit.

### 3.2.1 Without Price Restrictions

When no price restrictions are present the set of stable outcomes is as in Theorem 2 where the one quality present is the efficient quality $\hat{q}$.

**Theorem 3.** Suppose there are no price restrictions. A stable outcome exists, and for any stable outcome $A$, $A$ is efficient and:

1. For all $\psi \in \tau(A)$, $q(\psi) = \hat{q}$. 
2. The number of contracts $|A|$ is an element of

$$\arg \max_{n \in \mathbb{Z}_{\geq 0}} \left\{ \sum_{b \in B} [f(n_b) + v(\hat{q})] - \sum_{s \in S} [c(n_s) + e(\hat{q})] \right\}$$

where

$$\sum_{b \in B} n_b = \sum_{s \in S} n_s = n.$$

3. For all $(\omega, p_\omega) \in A$, $p_\omega \in [p_{\text{min}}(\hat{q}), p_{\text{max}}(\hat{q})]$

The theorem makes three specific predictions. First, the theorem predicts that all trade will take place at the efficient quality $\hat{q}$, i.e., the volume of trade in any quality other than $\hat{q}$ will be 0. Second, the theorem predicts that a surplus-maximizing number of trades will take place, given that quality. Finally, the theorem predicts that all trades will take place at prices in the interval $[p_{\text{min}}(\hat{q}), p_{\text{max}}(\hat{q})]$: The lower bound is high enough such that no buyer wishes to buy an additional item, and every seller receives nonnegative surplus from each item he sells, and, conversely, the higher bound is low enough such that every buyer receives nonnegative surplus from each item he buys, and no seller wishes to sell an additional item.

3.2.2 With Price Restrictions

We now consider the case where there is a price floor $p_f$. In characterizing the set of stable outcomes, there are essentially three cases to consider, as exemplified in Figure 4. The first case is when the price floor does not bind, i.e., $p_f < p_{\text{min}}(\hat{q})$. In this case, the price floor has no effect on the market.

In the second case, the price floor is above $p_{\text{max}}(q)$ for some $q \geq \hat{q}$, and below $p_{\text{min}}(q+1) - [v(q+1) - v(q)]$; this is the case where the price floor lies above the lower set of dashed lines but below the dotted lines in Figure 4. In this case, there may be trade at both the quality $q$ and $q+1$ in the same stable outcome; that is, a given stable outcome $A$ may have one contract of the form $(b, s, q, p_f)$ and another contract of the form $(\bar{b}, \bar{s}, q+1, p_f + [v(q+1) - v(q)])$. The price of the higher quality good must be greater than the price of the lower quality good.
Figure 4: Illustration of the experimental market with two vertically differentiated qualities. The lighter crossing lines represent the demand and supply curves for the efficient low quality \( \hat{q} \); the darker crossing lines represent the demand and supply curves for the inefficiently high quality \( \hat{q} + 1 \). The dashed lines denote \( p_{\min}(q) \) and \( p_{\max}(q) \) for each quality \( q \in \{ \hat{q}, \hat{q} + 1 \} \). The dotted black lines represent \( p_{\min}(\hat{q} + 1) - [v(\hat{q} + 1) - v(\hat{q})] \) and \( p_{\max}(\hat{q} + 1) - [v(\hat{q} + 1) - v(\hat{q})] \). When the price floor is below the lower set of dashed lines, Case 1 of Theorem 4 applies. When the price floor is above the lower set of dashed lines but below the dotted lines, Case 2 of Theorem 4 applies. When the price floor is above the dotted lines but below the higher set of dashed lines, Case 3 of Theorem 4 applies.

by exactly the difference in the buyers’ valuations of the qualities; otherwise, a buyer who is worse off given the current prices and the quality he is trading at will offer a slightly higher price to a seller currently trading at the other quality. Furthermore, the lower price must be at the price floor, as otherwise sellers of the (inefficiently) high quality good would offer a buyer of the lower quality good the same good at a slightly lower price and gain the efficiency surplus. However, when the prices differ by this exact amount, and the lower quality good trades at the price floor, both qualities can trade in positive quantities as part of a stable outcome. In this stable outcome, none of the sellers who are not currently trading can make a positive profit by offering the higher quality good at a lower price, and these sellers also can not offer the lower quality good at a lower price, as it is trading at the price floor.
In the third case, the price floor is such that \( p_f + [v(q + 1) - v(q)] > p^{\text{max}}(q + 1) \) holds; this is the case where the price floor lies above the dotted lines in Figure 4 (but below the higher set of dashed lines). In this case, it will no longer be possible to sell the quality \( q \) good, since there will be sellers without a current trading partner willing to trade the quality \( q + 1 \) good at a price that makes it attractive to current buyers of the quality \( q \) good. In that case, trade will be limited to only quality \( q + 1 \) goods, so long as the price floor remains below \( p^{\text{min}}(q + 1) \); hence, the stable outcome will be as if trade at only quality \( q + 1 \) was available. Note that, in this case, the price floor \( p_f \) affects the outcome even though no trade occurs at \( p_f \). In particular, while no trade happens at the price floor in any stable outcome, the allocation induced by any stable outcome does not correspond to a competitive equilibrium allocation, as, in a competitive equilibrium, every seller must not desire to sell additional goods—but a seller would be happy to sell a lower quality good at the price floor if that seller could find a willing buyer.

We formalize this discussion below.

**Theorem 4.** Consider a price floor \( p_f \leq p^{\text{min}}(q^{\text{max}}) \). A stable outcome exists. There are three cases:

1. \( p_f < p^{\text{min}}(\hat{q}) \): Then any stable outcome is as in Theorem 3.

2. \( p^{\text{max}}(q) < p_f < p^{\text{min}}(q + 1) - [v(q + 1) - v(q)] \) for some \( q \geq \hat{q} \): Then in any stable outcome \( A \),

   \((a)\) For any contract \( x \in A \), we have that either

   i. \( q(x) = q \) and \( p(x) = p_f \), or

   ii. \( q(x) = q + 1 \), and \( p(x) = p_f + [v(q + 1) - v(q)] \).

   \((b)\) The number of contracts \( |A| \) is an element of

   \[
   \arg \max_{n \in \mathbb{Z}_{\geq 0}} \left\{ \sum_{b \in B} \left[ f^b(n_b) + v(q) - p_f \right] \right\}
   \]
where

\[ \sum_{b \in B} n_b = n. \]

3. \( p_{\text{max}}(q + 1) - [v(q + 1) - v(q)] < p_f < p_{\text{min}}(q + 1) \) for some \( q \geq \hat{q} \): Then any stable outcome is as in Theorem 2 with quality \( q + 1 \).

Imposing a price floor induces three separate forms of inefficiency. First, some agents may contract at an inefficient quality. Second, some agents may not contract at all, even though there exist surplus-increasing trades; for a contract to increase the welfare of both parties, it must have a price below the price floor. Finally, the wrong agents may contract—that is, in case 2 of Theorem 4, there may be sellers who would like to contract with a buyer at the price floor, and in fact have a lower marginal cost of production than a current seller; however, they can not undercut that current seller due to the price floor.

A natural question is whether Theorem 4 is robust to allowing quality to vary continuously. If quality is a continuous variable, and the value for quality and cost of quality is such that \( v(q) - c(q) \) is strictly quasiconcave in quality, then only one quality will be traded in any stable outcome: if the price floor \( p_f < p_{\text{min}}(\hat{q}) \), then only the efficient quality will be traded (corresponding to case 1 of Theorem 4), and if \( p_f > p_{\text{max}}(\hat{q}) \), then all trades will take place at the same inefficiently high quality \( q \), where \( q \) is such that \( p_f \in [p_{\text{min}}(q), p_{\text{max}}(q)] \) (corresponding to case 2 of Theorem 4, but with trade only at \( p_f \)). However, if \( v(q) - c(q) \) is not strictly quasiconcave, then it is possible to have price floors such that multiple qualities trade in a given stable outcome (corresponding to case 2 of Theorem 4) and price floors such that all trade in any stable outcome occurs at a price strictly higher than \( p_f \) (corresponding to case 3 of Theorem 4). Note that, as in the case with discrete qualities, it may be the case that all trade occurs at a price strictly higher than the price floor, and yet the stable outcome does not correspond to a competitive equilibrium.

We now consider the case where there is a price ceiling, which is analogous to the case of a price floor, except that the roles of buyers and sellers are reversed.
Theorem 5. Consider a price ceiling $p_c \geq p_{\text{max}}(q_{\text{min}})$. A stable outcome exists. There are three cases:

1. $p_c > p_{\text{max}}(\hat{q})$: Then any stable outcome is as in Theorem 3.

2. $p_{\text{min}}(q) > p_c > p_{\text{max}}(q - 1) + [e(q) - e(q - 1)]$ for some $q \leq \hat{q}$: Then in any stable outcome $A$,

   (a) For any contract $x \in A$, either
   
   i. $q(x) = q$ and $p(x) = p_c$, or
   
   ii. $q(x) = q - 1$ and $p(x) = p_c - [e(q) - e(q - 1)]$.

   (b) The number of contracts $|A|$ is an element of

   $$\arg \max_{n \in \mathbb{Z}_{\geq 0}} \left\{ \sum_{s \in S} [p_c - c(n_b) - e(q)] \right\}$$

   where

   $$\sum_{s \in S} n_s = n.$$ 

3. $p_{\text{min}}(q - 1) + [e(q) - e(q - 1)] > p_c > p_{\text{max}}(q - 1)$ for some $q \leq \hat{q}$: Then any stable outcome is as in Theorem 2 with quality $q - 1$.

4 Experimental Series and Markets

The general structure of the experiments is contained in Table 2. A total of nine experiments were conducted. Each experiment consisted of 7-8 buyers and 7-8 sellers. Subjects were undergraduate students at the California Institute of Technology who had previous experience in participating in computerized double auction markets.\footnote{Subject experience included participation in other market experiments in which the same software was used. While such experience was gained in markets that differed substantially from the markets studied here, subjects were thus less likely to misunderstand instructions or make operational mistakes, both of which are typical sources of variance in market experiments. Subjects were not told the number of other participants,}
Caltech Laboratory for Experimental Economics and Political Science and each experiment lasted about three hours. A subject was randomly assigned to be either a seller or a buyer upon arrival. Subjects were then given instructional sheets, record sheets, and payoff tables that described his or her own redemption values or costs.

All markets were conducted through Caltech’s electronic market system, Marketscape. This program supports multiple markets through a double auction system with an open book, and meets standard conditions for market experiments. Goods of varying quality may be traded, and the order book for each good is visible to all of the participants. The best buy offers and the best sell offers in all markets are public on a single screen as are the prices of the last contracts accepted in each of the markets. The system operates in a sequence of periods. Each period is of fixed length and a countdown clock shows the number of seconds left in a period. Buyers are free to submit orders to buy at a price and quantity, which are entered into the book, where they remain until traded or cancelled. Similarly, sellers submit sell orders of a price and quantity, which are entered into the sell order book. A buyer sees a list of the sell orders listed from the lowest price to the highest for each quality market on his/her screen, and a seller sees a corresponding list of the buy offers listed from the highest price to the lowest for each quality market on his/her screen. These books are updated in real time as new orders are submitted. A trade takes place when a buyer or seller submits an order that “crosses” an offer of a counterparty.

When a period closes, a buyer’s earnings for that period are the total value of all goods purchased minus the sum of the purchase prices. A seller’s earnings are the sum of the prices for items he sold minus the costs of production.

Each period is independent: purchases and sales in a prior period have no effect on another period’s payoffs. The subject has the opportunity to record and study profits for the period and the profitability of previous periods. The number of periods is unknown to the nature of other subjects’ incentives, or the length of experiment. Motivated by the absence of such public information in markets found in the field, experimental markets do not provide such information to subjects except as might be required by the experimental questions posed.
There were four types of buyers and four types of sellers in each session. The redemption values and costs differed across different types. The information of each individual was limited to information about his or her own payoff. They were not aware of the existence of different types or the costs, payoffs, or conversion rates of others. The instruction sheet can be found in Appendix B. The type of currency used in the experiments was francs. The conversion rate differed across subjects, depending on their types. Before each experiment started, a trial period was conducted to familiarize subjects with the procedure. Each individual maintained his or her own record of activities and earnings but the records were also maintained in the computer and were available to individual subjects at the end of each period. During a period the computer maintained a real time record of purchases and earnings together with a time series of prices in each market.

4.1 Experimental Markets

As was outlined in Section 2, there were two series of experimental markets. Series 1 is based on ten different qualities of the good, called $A, B, \ldots, J$. $A$ is the the lowest quality (i.e., the quality with the lowest value to the buyer and the lowest cost to produce for the seller), and $J$ is the highest quality. We conducted five sessions in Series 1.

We did not impose any price controls for the first two sessions (1.1 and 1.2). In the last three sessions (1.3–5), we imposed a price floor of 6000, which is above $p^\text{max}(G)$. In sessions 1.4 and 1.5, we removed the price floor in later periods to see if the market would adjust to the competitive equilibrium.

In Series 2, there are three qualities, $A$, $B$, and $C$, in the experimental market. We conducted four sessions for Series 2, as the symmetry of the problem allows for pooling of data across experiments. In sessions 2.1 and 2.2, we imposed price floors of 1312 and 1470, respectively. These sessions correspond to the second and third cases of Theorem 4, respectively. In sessions 2.3 and 2.4, we imposed price ceilings of 1088 and 930, which
correspond to the second and third cases of Theorem 5, respectively. In session 2.2, we removed the price floor in the last 3 periods to see if the market adjusted to the competitive equilibrium.

4.2 Preferences and Incentive Procedures

4.2.1 Series 1 (Ten Qualities)

Buyers (sellers) were given tables stating their valuations (costs) of obtaining (producing) a good depending on the good’s quality and how many goods had already been bought (sold) by that agent. Table 3 shows the values given to a Type 1 buyer. For a buyer \( b \) of type \( k \), where \( k \in \{1, 2, 3, 4\} \), the valuation function of \( b \) is given by

\[
u^b(|\Psi|) = (6438 - 150k) - 300|\Psi_b|\|\Psi_b| + \sum_{\omega \in \Psi_b} v(q(\omega)),\]

where the utility \( v(q) \) obtained from a quality \( q \) good is given by

\[
\begin{align*}
v(A) &= 0, & v(B) &= 692, & v(C) &= 1250, \\
v(D) &= 1686, & v(E) &= 2012, & v(F) &= 2240, \\
v(G) &= 2382, & v(H) &= 2450, & v(I) &= 2456, \\
v(J) &= 2412.
\end{align*}
\]

Table 3 also shows the costs given to a Type 1 seller. For a seller \( s \) of type \( k \), where \( k \in \{1, 2, 3, 4\} \), the valuation function of \( s \) is given by

\[
u^s(|\Psi|) = -((3398 + 5k) + 10|\Psi_s|\|\Psi_s| - \sum_{\omega \in \Psi_s} e(q(\omega)),\]

\]
where the cost \( e(q) \) from producing a quality \( q \) good is given by

\[
\begin{align*}
    e(A) &= 0 & e(B) &= 277 & e(C) &= 600 \\
    e(D) &= 964 & e(E) &= 1368 & e(F) &= 1807 \\
    e(G) &= 2280 & e(H) &= 2782 & e(I) &= 3312 \\
    e(J) &= 3865.
\end{align*}
\]

Notice the marginal utility from an additional unit depends only on the number of units the buyer (seller) has already consumed (produced), not on the characteristics or combination of units the buyer (seller) has already consumed (produced). This ensures that the marginal valuation of an additional unit is independent of the composition of the commodities the subject has already purchased or sold.

### 4.2.2 Series 2 (Three Qualities)

In Series 2, there were three qualities of goods, \( A, B, \) and \( C \). Similar to Series 1, subjects were given tables stating their valuations and costs. Table 4 shows the values given to a Type 1 buyer. For a buyer \( b \) of type \( k \), where \( k \in \{1, 2, 3, 4\} \), the valuation function of \( b \) is given by

\[
u^b(\Psi) = ((1690 - 45k) - 90|\Psi_b|)|\Psi_b| + \sum_{\omega \in \Psi_b} v(q(\omega)),
\]

where the utility \( v(q) \) obtained from a quality \( q \) good is given by

\[
\begin{align*}
    v(A) &= 0 & v(B) &= 600 & v(C) &= 800.
\end{align*}
\]

Note that, as in Series 1, the marginal utility of an additional good only depends on that good's quality and on the number of goods the agent has already bought, not the quality of the goods the agent has already bought.

Table 4 also shows the costs given to a Type 1 seller in Series 2. For a seller \( s \) of type \( k \),
where $k \in \{1, 2, 3, 4\}$, the valuation function of $s$ is given by

$$u^*(|\Psi|) = -((-90 + 45k) + 90|\Psi_s|)|\Psi_s| - \sum_{\omega \in \Psi_s} e(q(\omega)),$$

where the cost $e(q)$ from producing a quality $q$ good is given by

$$e(A) = 0 \quad e(B) = 200 \quad e(C) = 800.$$  

Note that, as in Series 1, the marginal disutility of an additional good only depends on that good’s quality and on the number of goods the agent has already sold, not the quality of the goods the agent has already sold.

5 Model Predictions

5.1 Series 1 (Ten Qualities)

Experiments based on Series 1 parameters had ten qualities, as described in the introduction and depicted in Figure 2. The quality $D$ is the most efficient. With no price controls, in any stable outcome (or competitive equilibrium) with 8 sellers and 8 buyers, 44 units of quality $D$ are traded at a price in the interval $[4482, 4487]$. When there are 8 sellers and 8 buyers, total surplus from trade is 73458 in any stable outcome.

For sessions 1.3–5 a price floor of 6000 was imposed. The price interval for quality $G$ is $[p^\text{min}(G), p^\text{max}(G)] = [5778, 5783]$; the price interval for quality $H$ is $[p^\text{min}(H), p^\text{max}(H)] = [6265, 6270]$. The marginal value to the buyer of an increase in quality from $G$ to $H$ is 68. Hence the set of stable outcomes is characterized by case 2 of Theorem 4. The theorem predicts that 32 units of either quality $G$ or $H$ will be traded, with the price of $G$ being 6000.
and the price of $H$ being 6068. However, the minimum cost to produce good $H$ is 6195, which is greater than 6068, and so it is expected that all trade will be of quality $G$ goods at the price floor of 6000; this outcome is represented by the intersection of the price floor and the demand curve for quality $G$ goods. When there are 8 sellers and 8 buyers, total surplus from trade is 48464 in any stable outcome.

5.2 Series 2 (Three Qualities)

Experiments based on Series 2 parameters had three qualities. The “middle” quality $B$ is the most efficient. With no price controls, in any stable outcome (or competitive equilibrium) with 8 sellers and 8 buyers, 44 units of quality $B$ are traded at a price in the interval $[1190, 1210]$. Total market surplus is 42460 in any stable outcome.

![Figure 5](image_url)

(a) $p_f = 1312$.  
(b) $p_f = 1470$.

Figure 5: In each subfigure, the lower pair of crossing lines denote the supply and demand for the efficient quality $B$, while the upper pair of crossing lines denote the supply and demand for the inefficiently high quality $C$; the dashed lines at 1190 and 1210 denote $p_{\text{min}}(B)$ and $p_{\text{max}}(B)$, while the dashed lines at 1590 and 1610 denote $p_{\text{min}}(C)$ and $p_{\text{max}}(C)$. In Figure 5(a), the black line at 1312 denotes the price floor at which quality $B$ goods trade, while the dotted line at 1512 denotes the price at which quality $C$ goods trade. In Figure 5(b), the black line at 1470 denotes the price floor; in this case, only quality $C$ goods trade, and do so at a price in the interval $[1590, 1610]$.

In session 2.1, a price floor $p_f = 1312$ was introduced, as depicted in Figure 5(a); this

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15 When there are 8 sellers and 7 buyers, as in experiment 1.3, 28 units of $G$ should be traded in any stable outcome. When there are 7 sellers and 7 buyers, as in experiment 1.5, 28 units of $G$ should be traded in any stable outcome.

16 When there are 8 sellers and 7 buyers, as in experiment 1.3, total surplus is 43446 in any stable outcome. When there are 7 sellers and 7 buyers, as in experiment 1.5, total surplus is 43336 in any stable outcome.
price floor is above the equilibrium price interval for the efficient quality $B$. The stable outcome induced by this price floor is described in case 2 of Theorem 4, since

$$1312 = p_f < p_{\min}(C) - [v(C) - v(B)] = 1390.$$ 

Hence, from Theorem 4, we have that in any stable outcome the quality $B$ will trade at the price floor of 1312, while quality $C$ will trade at 1512, i.e., the price floor plus the value to the buyer of an increase in quality from $B$ to $C$. The total quantity traded will be 38 units when there are 8 sellers and 8 buyers present. Total market surplus is in the interval $[28200, 41800]$ in any stable outcome.

In session 2.2, a price floor $p_f = 1470$ was introduced, as depicted in Figure 5(b). The stable outcome induced by this price floor is described in case 3 of Theorem 4, since

$$1470 = p_f > p_{\max}(C) - [v(C) - v(B)] = 1410.$$ 

Hence, from Theorem 4, we have that in any stable outcome the quality $B$ will not be traded, while quality $C$ will trade in the interval $[1590, 1610]$. The total quantity traded will be 34 units, and total market surplus is 26860 in any stable outcome; this outcome is depicted as the crossing of the supply and demand curves for quality $C$ in Figure 5(b).

Analogous arguments apply to the case of price ceilings. In session 2.3, a price ceiling $p_c = 1088$ was imposed, as depicted in Figure 6(a); this price floor is below the equilibrium price interval for the efficient quality $B$. The stable outcome induced by this price floor is described in case 2 of Theorem 5, since

$$1088 = p_c > p_{\max}(A) + [e(B) - e(A)] = 1010.$$ 

Hence, from Theorem 5, we have that in any stable outcome the quality $B$ will trade at the price ceiling of 1088, while quality $A$ will trade at 888, the price ceiling minus the extra cost
Figure 6: In each subfigure, the upper pair of crossing lines denote the supply and demand for the efficient quality $B$, while the lower pair of crossing lines denote the supply and demand for the inefficiently low quality $A$; the dashed lines at 1190 and 1210 denote $p_{\text{min}}(B)$ and $p_{\text{max}}(B)$, while the dashed lines at 790 and 810 denote $p_{\text{min}}(A)$ and $p_{\text{max}}(A)$. In Figure 6(a), the black line at 1088 denotes the price ceiling at which quality $B$ goods trade, while the dotted line at 888 denotes the price at which quality $A$ goods trade. In Figure 6(b), the black line at 930 denotes the price floor; in this case, only quality $A$ goods trade, and do so at a price in the interval $[790, 810]$. 

to the seller of an increase in quality from $A$ to $B$. The total quantity traded will be 38 units, and the total market surplus is in the interval $[28200, 41800]$ in any stable outcome.

In session 2.4, a price ceiling of $p_c = 930$ was introduced, as depicted in Figure 6(b). The stable outcome induced by this price ceiling is described in case 3 of Theorem 5, since

$$930 = p_c < p_{\text{min}}(A) + [e(B) - e(A)] = 990.$$ 

Hence, from Theorem 5, in any stable outcome, the quality $B$ will not be traded, while quality $A$ will trade in the interval $[790, 810]$. The total quantity traded will be 34 units, and the total market surplus is 24860 in any stable outcome with 8 sellers and 8 buyers; this outcome is depicted as the crossing of the supply and demand curves for quality $C$ in Figure 5(b). Note that in session 2.4 there were only 7 buyers and 7 sellers. The theoretical predictions of the trading price remain the same but the stable outcome now entails only 30 units of quality $A$ being traded. The total market surplus is 24060 in any stable outcome with 7 sellers and 7 buyers.
A summary of all predictions is given in Table 1 below.

Table 1: Theoretical predictions (8 sellers and 8 buyers)

<table>
<thead>
<tr>
<th>Series 1</th>
<th>Quality</th>
<th>Quantity</th>
<th>Price</th>
<th>Total surplus</th>
</tr>
</thead>
<tbody>
<tr>
<td>No price control</td>
<td>D</td>
<td>44</td>
<td>[4482, 4487]</td>
<td>73458</td>
</tr>
<tr>
<td>Price floor 6000</td>
<td>G</td>
<td>32</td>
<td>6000</td>
<td>48464</td>
</tr>
<tr>
<td>Series 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No price control</td>
<td>B</td>
<td>44</td>
<td>[1190, 1210]</td>
<td>42460</td>
</tr>
<tr>
<td>Price floor 1312</td>
<td>B and C</td>
<td>38</td>
<td>1312(B), 1512(C)</td>
<td>[28200, 41800]</td>
</tr>
<tr>
<td>Price floor 1470</td>
<td>C</td>
<td>34</td>
<td>[1590, 1610]</td>
<td>26860</td>
</tr>
<tr>
<td>Price ceiling 1088</td>
<td>A and B</td>
<td>38</td>
<td>888(A), 1088(B)</td>
<td>[28200, 41800]</td>
</tr>
<tr>
<td>Price ceiling 930</td>
<td>A</td>
<td>34</td>
<td>[790, 810]</td>
<td>26860</td>
</tr>
</tbody>
</table>

6 Results

The discussion of our results is heavily influenced by the exploratory nature of the experiments. The exploratory Series 1 experiments were motivated by empirical questions regarding non-price competition and quality adjustments. Hence, Series 1 experiments were designed to incorporate a broad environment consisting of several qualities; they were designed without the insight of a theory that might make specific predictions regarding prices, qualities and volumes. By contrast, Series 2 experiments were designed to test the predictions of the specific theory that revealed itself after the small number of experiments conducted in Series 1.

Thus, Series 1 could properly be discussed as a robustness check of the results from Series 2 and discussed following a discussion of the results of Series 2. However, we discuss Series 1 first because the development of the theory was motivated by the results of Series
1, even though the data from Series 1 are sparse and become convincing only when viewed in the light of the Series 2 data.

6.1 Series 1 (Ten Qualities)

The experiments in Series 1 are exploratory due to the fact that no precise theory was available to guide experimental design. Our objective was to impose a price floor in an environment with multiple qualities and then observe whether changes in the qualities transacted might emerge due to non-price competition. The exploratory series consists of ten qualities. The series has experiments operating with no price floor, experiments operating with a price floor and experiments operating a few periods with a price floor and then operating with the price floor removed. Thus Series 1 can be viewed as having (sixteen) periods in which no price floors existed and (seventeen) periods in which price floors are imposed. Table 2 contains the sequence of experiments.

The periods in which ten markets operate with no price floors are summarized in Result 1 and the periods for which the ten markets operate with price floors are summarized in Result 2. While Series 1 is exploratory, having subsequently developed and tested the theory as outlined in Section 3 the data from Series 1 can be studied through the lens that the theory provides. Thus, while Series 1 is exploratory it serves as additional support for the results reported as Series 2.

Our first result shows that in the sessions with ten qualities and no price restrictions, the price and quantity traded of each quality of good essentially converged to the predictions of the model. The experiments with no price floors summarized by Result 1 illustrate the well-known fact that in the absence of price floors the theoretical competitive model is an appropriate model of market behavior.\(^\text{17}\) Result 2 is focused on the periods in which price floors were implemented. These periods demonstrate an impact of price floors qualitatively consistent with the intuition derived from classical reasoning and quantitatively consistent

with the quality competition model developed in Section 3.

**Result 1.** In the absence of any price restrictions for the Series 1 market, (i) market efficiency, (ii) market volume, (iii) the pattern of qualities traded, and (iv) the price of the efficient quality are near or approach the competitive equilibrium/stable outcome values.

**Support.** The data from Series 1 consists of twenty periods (seven periods from 1.1, three periods from 1.2, four periods from 1.4, and two from 1.5) and 596 transactions.

(i) The competitive equilibrium predicts that the market efficiency will be 100%. Table 5 shows that average efficiency across periods with no price floor is 90.4% (with a standard deviation of 5.8%) and that efficiency increases monotonically across periods.

(ii) Volumes are also shown in Table 5. The competitive equilibrium predicts that quality $D$ will emerge with an equilibrium quantity of 44 units; moreover, given the structure of demands, so long as no buyer or seller makes a loss, the sum of the volumes of all qualities can be no greater than 44 units. As shown in the table the average number of units traded by period is very close to the theoretical prediction.

(iii) Table 6 summarizes the proportion of trade by quality during the second half of periods 5–7 in session 1.1. The average difference between the actual volume and predicted volume is .3 and 62.1% of the units traded are for the predicted quality $D$. Qualities $C$ and $E$ each traded 12% of the time and are the qualities most efficient besides $D$. All other qualities are traded less.

(iv) Prices for quality $D$ goods are also very close to the prices predicted by the model. The average traded price for quality $D$ goods is 4503.7 during the second half of periods 5–7 in session 1.1, while the range of competitive equilibrium prices is [4482, 4487]; the difference between the average traded price and the theoretical prediction is 0.3%.

Given the experimental design, it is possible to pool across periods and experimental sessions in order to increase the statistical power. Statistical testing of static equilibriums...
Equilibrium models may be enhanced by the use of the time series of price discovery process. Following the methodology in the work of Noussair, Plott, and Riezman (1995, 1997) and Myagkov and Plott (1997), we estimate the Ashenfelter/El-Gamal model of market convergence for our data.\textsuperscript{18} This model assumes that the average price for each experiment may start from a different origin but all markets will experience adjustment, as described by a common functional form, and converge to a common asymptotic value. The parameter of interest for the Series 1 experiments when no price control is imposed is the equilibrium price of quality $D$. Hence, we estimate the functional form

$$p_i^*(D) - \frac{p_{\text{min}}(D) + p_{\text{max}}(D)}{2} = \beta_1 d_1 \frac{1}{T} + \beta_2 d_2 \frac{1}{T} + \beta_4 d_4 \frac{1}{T} + \gamma \left(1 - \frac{1}{T}\right) + u_i$$

where $i$ indicates the particular experiment, and $t$ represents time as measured by the number of market periods in the experiment. We let $p_i^*(D)$ denote the mean traded price in period $t$ for quality $D$; recall that the theoretical prediction is that the price lies in the interval $[p_{\text{min}}(D), p_{\text{max}}(D)]$. We let $d_i$ be a dummy variable that takes a value of 1 for the experiment $i$, and 0 otherwise.\textsuperscript{19} The parameter $\beta_i$ represents the origin of a possible convergence process for session $i$. The parameter $\gamma$ represents the asymptotic difference between the common asymptotic value and the theoretical prediction; hence, $\gamma$ will be close to 0 if the difference between the traded prices and the theoretical prediction approaches 0 toward the end of each experiment. The random error term $u_i$ is distributed normally with mean zero.

Table 7 contains the estimation results. The estimated coefficient of $\gamma$ is not significantly different from 0, indicating that the traded prices of quality $D$ are not significantly different from the midpoint of the theoretical prediction near the end of the experiment.

\textsuperscript{18} The statistical model used here was developed by Noussair et al. (1995) and was suggested by Mahmoud El-Gamal, motivated by the work of Ashenfelter et al. (1992).

\textsuperscript{19} We do not use the data from Session 1.5 because there are only two periods in which a price control was not imposed. For session 1.4, we use data only from periods 4 to 7, i.e., those periods in which a price control was not imposed.
Our Result 2 examines the periods of Series 1 in which a price floor of 6000 was imposed. The experimental design was focused only on the possibility that price floors could induce non-price competition in the form of increased product quality; however, the subsequently developed theory of Section 3 allows us to make precise predictions regarding outcomes. Hence, the data are analyzed in terms of stable outcomes, which differ substantially when price floors do not exist. Result 2 supports the existence of quality competition created by price floors; additionally, it adds data supporting the conclusions of Series 2, which is focused directly on tests of the model.

**Result 2.** When a price floor of 6000 was imposed for the Series 1 market, (i) market efficiency, (ii) market volume, (iii) the pattern of qualities traded, and (iv) the price of the efficient quality all converge to near the price-constrained quality competition model stable outcomes.

**Support.** Table 5 contains the results of the experimental sessions. All predictions are closer to the predicted stable outcomes with price controls than to the equilibrium without price controls:

(i) The efficiency of any stable outcome under conditions the price floor is 66%, while the average efficiency of price controlled periods pooled across all experiments is 62% (with a standard deviation of 3%).

(ii) Volumes predicted for any stable outcome under the price control are respectively 28, 32, and 28 for experiments 1.3, 1.4, and 1.5, respectively. The actual volumes for those experiments are on average 27.8, 32.3, and 31.5 respectively. The volumes are substantially removed from those predicted with no price controls and are near the volumes predicted by the quality competition model under price controls.

(iii) Quality $G$ is predicted as the only quality to trade in any stable outcome under price controls and it constitutes 83.6% of all trades. No quality $D$ goods are traded when
the price floor is present, while when no price control is imposed quality $D$ is the most frequently traded quality.

(iv) Finally, all trades took place at the price floor of 6000 when the price floor was imposed. This removes any need for statistical analysis, as this was the predicted price.

The results of Series 1 provide evidence that price floors have an influence in the form of stimulating transactions at qualities above the efficient quality. The magnitudes of other variables tend to be near those predicted by the non-price quality competition model. However, the model also produces very subtle predictions under appropriate parameters. The next section reports experiments that were designed to test these more refined predictions.

6.2 Series 2 (Three Qualities)

In Series 2, four experimental sessions were conducted, as described in Section 4. In each session, the data for multiple variables converge tightly to the the patterns suggested by the stable outcome; the characteristics of the stable outcome for each session were described in Section 5. The results of each session are discussed independently in order to illustrate the pattern of observed behaviors in relation to the variables addressed by the model. However, the symmetry of the experimental design allows the data to be pooled for increased statistical power. As the data converged so tightly and so quickly for variables predicted by the model there seemed to be little to learn from additional sessions with the same parameters. Tables 8 to 11 provide the time series of average prices and volumes by period for each session and can be used as a reference to the structure of the results.

Results 3 and 4 address the case of the price floors imposed during sessions 2.1 and 2.2. The price floor is 1312 in session 2.1, and hence the theory predicts that two qualities may trade in positive amounts. The price floor is raised to 1470 in session 2.2, and hence the theory predicts that only the highest quality will trade in positive amounts. For both cases the results are close to all predictions of the model. The price floor was removed in Session
Figure 7: Experimental data for session 2.1 when a price floor of 1312, denoted by a gray line, was imposed. The diamonds denote trades of the high quality good (quality \( C \)), the circles trades of the medium quality good (quality \( B \)), and the crosses trades of the low quality good (quality \( A \)). The black line at 1512 denotes the predicted price of trades with high quality goods. The experiment took place over 9 periods, delineated by the vertical dashed gray lines.

2.2 due to the fact that the data were so close to the predictions and thus an opportunity to test the consequences of floor removal presented itself.

**Result 3.** When a price floor of 1312 was imposed for the Series 2 market, (i) the goods traded, (ii) the prices of those goods, (iii) the volume of trade, and (iv) the market efficiency all converge to the stable outcome values.

**Support.** Figure 7 shows traded prices in session 2.1 and Table 8 contains the related average period prices, variances, and market volumes for each quality.

(i) The theory predicts that only goods of quality \( B \) and \( C \) will be traded and, as predicted, there is very little trade in quality \( A \).

(ii) Quality \( B \) goods move quickly to trade at the price floor of 1312; the variance falls to
zero and remains there. Quality $C$ also trades as predicted—the average price in the last period is 1496, which is very near to the predicted price of 1512, and the price variance falls from period 6 onwards to near zero.

(iii) Total market volume over the last half of the session is very close to the predicted quantity (40.4 as compared to 38, or 6.3% higher).

(iv) Finally, Table 8 shows the market efficiency in each period, and in each period the market efficiency is within the theoretically predicted interval of $[0.664, 0.984]$. □

Result 4. When a price floor of 1470 was imposed for the Series 2 market, (i) the goods traded, (ii) the prices of those goods, (iii) the volume of trade, and (iv) the market efficiency all converge to the stable outcome values. When the price floor is removed the markets move quickly to the stable outcome in the absence of price controls, which corresponds to a competitive equilibrium.

Support. Figure 8 shows prices for each transaction in session 2.2 and Table 9 contains the related average period prices, variances, and market volumes for each quality.

(i) The theory predicts that goods of quality $A$ will not trade, and indeed there is only one transaction at that quality when the price floor is imposed. The theory also predicts that goods of the efficient quality $B$ will not trade, and on average there were two trades per period of quality $B$ goods.

(ii) The theory predicts that a positive number of quality $C$ goods will trade at a price in the interval $[1590, 1610]$: this interval is very near the average price of 1589.8 in the last period before the price floor was removed.

(iii) Market volume for quality $C$ is 32 units for the last period, which compares well to the theoretical volume of 34; total volume of quality $B$ and quality $C$ is 34 units for the last period.
Figure 8: Experimental data for session 2.2 when a price floor of 1470, denoted by the thick gray line, was imposed. The diamonds denote trades of the high quality good (quality C), the circles trades of the medium quality good (quality B), and the crosses trades of the low quality good (quality A). The black lines at 1590 and 1610 denote the range of predicted prices of trades with high quality goods. The experiment took place over 7 periods, delineated by the vertical dashed gray lines. The price floor was removed after Period 4; the gray lines at 1190 and 1210 denote the range of predicted prices of trades with medium quality goods.

(iv) Finally, Table 9 also shows the market efficiency for each period: average market efficiency for the periods when the price floor was imposed is 78.3%, which is only slightly higher than the predicted efficiency of 69.3%.

Figure 8 also shows how quickly the market adjusts to the competitive equilibrium, which can be seen as a test of how quickly market outcomes move from one stable outcome to another in response to change in the environment. As soon as the price floor is removed, trade shifts from quality C goods to quality B goods; moreover, the price of quality B goods adjusts from 1470 to 1193 in the last period, which is within the competitive equilibrium interval of [1190, 1210]. Furthermore, market volume increases to 44 in the last two periods, as suggested by the theory. Finally, efficiency rose to nearly 100%, as predicted. □
Figure 9: Experimental data for session 2.3 when a price ceiling of 1088, denoted by a gray line, was imposed. The diamonds denote trades of the high quality good (quality C), the circles trades of the medium quality good (quality B), and the crosses trades of the low quality good (quality A). The black line at 888 denotes the predicted prices of trades of quality A goods.

Results 5 and 6 address the case of the price ceilings imposed during sessions 2.3 and 2.4. The price ceiling is 1088 in session 2.3, and hence the theory predicts that two qualities may trade in positive amounts. The price ceiling is lowered to 930 in session 2.4, and hence the theory predicts that only the lowest quality will trade in positive amounts. For both cases the results are close to all of the predictions of the model.

**Result 5.** When a price ceiling of 1088 was imposed for the Series 2 market, (i) the goods traded, (ii) the prices of those goods, (iii) the volume of trade, and (iv) the market efficiency all converge to the stable outcome values.

**Support.** Figure 9 shows the price for each transaction in session 2.3 and Table 10 contains the related average prices, price variance, market volumes, and market efficiency for each period.
(i) The theory predicts that only goods of quality $A$ and $B$ will be traded and, as predicted, there is very little trade in quality $C$.

(ii) Quality $B$ moves quickly to trade at 1088, the price predicted by the quality competition model; the price variance falls to zero and remains there. Quality $A$ also trades as predicted—the average price in the last period is 879.5, which is very near the predicted price of 888, and the variance has a tendency to fall over time, actually equaling zero in the next to the last period.

(iii) Total market volume over the last few periods of the session is very close to the predicted quantity (40.4 as compared to 38, or 6.3% higher).

(iv) Finally, Table 10 shows the market efficiency in each period, and in each period the market efficiency is within the theoretically predicted interval of $[0.664, 0.984]$. □

**Result 6.** When a price ceiling of 930 was imposed for the Series 2 market, (i) the goods traded, (ii) the prices of those goods, (iii) the volume of trade, and (iv) the market efficiency all converge to the stable outcome values.

**Support.** Figure 10 shows the price for each transaction in session 2.4 and Table 11 contains the related average prices, price variance, market volumes, and market efficiency for each period.

(i) The theory predicts that quality $C$ will not trade, and indeed there are no transactions of quality $C$ goods. The theory also predicts that goods of the efficient quality $B$ will not trade, and there are only two instances of quality $B$ trading after the first two periods.

(ii) The theory predicts that quality $A$ goods will trade with a price in the interval $[790, 810]$; the average price of quality $A$ falls within this interval for the last two periods; moreover, the price variance for quality $A$ is quite small in the last two periods.
Figure 10: Experimental data for session 2.4 when a price ceiling of 930, denoted by a gray line, was imposed. The circles denote trades of the medium quality good (quality B), and the crosses trades of the low quality good (quality A). The black lines at 790 and 810 denote the range of predicted prices of trades of low quality goods.

(iii) Market volume for quality A is 32 units for the last period, which compares well to the theoretical volume of 34.

(iv) Finally, Table 11 shows the market efficiency for each period: average market efficiency for the periods when the price floor was imposed is 67.4%, which is only slightly lower than the predicted efficiency of 69.3%.

The summary of the patterns of activity across experiments is best captured by pooling the observations and performing a general test comparing the experimental outcomes to the theoretical predictions. To remove ambiguity about the support for the theory given that the number of experimental sessions is not large, we considered using a Bayesian model based on a large number of variables each with a well-specified prediction but decided a pooling analysis is more transparent. For this purpose we estimate the Ashenfelter/El-Gamal model of market convergence for pooled Series 2 experiments. Our analysis reflects the symmetry of
the experimental design and predictions, i.e., that the theoretical predictions of the impact of floors and ceilings are near mirror images.

We first consider price controls that result in outcomes described in the second part of Theorems 4 and 5. These are the sessions in which the floor (ceiling) was relatively low (high) and in which two qualities may trade in positive amounts in a stable outcome. In such a stable outcome, the price of the lower (higher) quality is at the floor (ceiling) and the other is above (below) the floor (ceiling). Hence, we estimate the difference between the traded price and the theoretical prediction for session 2.1 (in which a price floor was imposed) and session 2.3 (in which a price ceiling was imposed) of quality C (i.e., high quality) and quality A (i.e., low quality) goods, respectively, denoting this $\bar{Y}_i^t$. We estimate

$$\bar{Y}_i^t = \beta_1 d_1 \frac{1}{t} + \beta_3 d_3 \frac{1}{t} + \gamma \left(1 - \frac{1}{t}\right) + u_i^t$$

where we let $i$ denote the particular experiment, and $t$ denote time as measured by the number of market periods in the experiment. We use the difference between mean traded prices and theoretical predictions as a dependent variable (as opposed to the mean traded prices).

**Result 7.** The pooled data from sessions 2.1 and 2.3 support the theoretical predictions of the model.

**Support.** The estimated coefficient of $\gamma$ is not significantly different from 0, indicating that the traded prices for the high (low) quality are not significantly from the theoretical predictions different near the end of the experimental sessions in this regime. Table 7 contains the estimation results.

We next consider price controls that result in outcomes described in the third parts of Theorems 4 and 5. In the case of such a price floor (ceiling), all trade happens at a price strictly above (below) the price floor. Hence, we estimate the difference between the traded price and the theoretical prediction for session 2.2 (in which a price floor was imposed) and 2.4
(in which a price ceiling was imposed) of quality $C$ and quality $A$ goods, respectively. In both cases, the theory predicts that only a single quality is traded and no trades occur at the price floor (ceiling). In session 2.2, the price floor was removed after period 4 and so we only use data until period 4. We estimate

$$\tilde{p}^C_i(q) - \frac{p^\text{min}(q) + p^\text{max}(q)}{2} = \beta_2 d_2 \frac{1}{t} + \beta_4 d_4 \frac{1}{t} + \gamma \left(1 - \frac{1}{t}\right) + u^i_t$$

where $q = C$ when a price floor is imposed, and $q = A$ when a price ceiling is imposed.

**Result 8.** The pooled data from sessions 2.2 and 2.4 support the theoretical high (low) quality price predictions of the model, and only the predicted quality is traded in positive amounts. Hence, the pooled data from sessions 2.1 and 2.3 support the theoretical predictions of the model.

**Support.** Table 7 contains the estimation results. Note that the model predicts that $\gamma$ will fall within the interval $[-10, 10]$, as $p^\text{max}(q) - p^\text{min}(q) = 20$ for this experiment for all $q \in Q$; the estimated coefficient of $\gamma$ is $-8.3$, indicating that trade near the end of the experimental sessions is occurring at prices within the theoretically predicted interval.

7 Conclusion

We have focused on a market in which multiple qualities of a commodity may be bought and sold. In this environment, when no price controls are imposed, competitive equilibria exist, and naturally correspond to matching-theoretic stable outcomes. However, in the presence of price controls, competitive equilibria need not exist, but the equilibria of the quality competition model, based on matching-theoretic stable outcomes, do exist. Thus, the notion of a stable outcome of the quality competition model is a natural generalization of competitive equilibrium for such environments. Furthermore, the predictions of the quality competition model capture the behavior of laboratory experimental markets along multiple dimensions:
price, quality, market volume, and market efficiency. This experimental agreement between pure theory and experiment is particularly surprising given the imperfect information available to experimental subjects: While the subjects had experience in experimental markets (which is known to reduce price variance), they were informed only of their own valuations and not those of other participants.

The work presented here suggests that matching theory can provide a theoretical basis for the intuition that price controls induce non-price competition. Economic intuition suggests that attempts to avoid price controls will lead markets to respond to price floors by quality enhancements and to respond to price ceilings with lowered quality. The theoretical predictions of Theorems 4 and 5 show that observed quality responds in ways suggested by economic intuition to price controls. In particular, the predicted non-price competition is very visible in the experimental data with pronounced effects on both the quality of the goods bought and sold and market efficiency. However, the nature of the market response implies that the effects of price controls need not be visible in empirical studies as the equilibrium price need not equal the price control even when the price control is binding. That is, a price floor can have a major impact on allocation (and indeed in our experiments the efficiency losses are in the range of 30%) while the market prices in a stable outcome are well above the price floor. Hence, without information about the underlying parameters a price control can appear to have no effect at all while still substantially affecting market outcomes. This presents a significant challenge to future empirical work in the field in this area.

This work also suggests that matching theory and other cooperative game-theoretic approaches may be useful in other contexts in which competitive equilibria fail to exist. For instance, when production quotas are imposed (such as due to trade restrictions), competitive equilibria may fail to exist, but such economies may be able to be modeled within the framework of matching theory, as suggested by Ostrovsky (2008).\(^{20}\) Similarly, in settings with fixed costs, competitive equilibria often fail to exist due to the non-convexities inherent

\(^{20}\)Indeed, the work of Ostrovsky (2008) suggests that such constraints may be incorporated even when the quota-restricted good is an input to a downstream production process.
in those settings (see, e.g., Eswaran, Lewis, and Heaps (1983)), and it may be that stable outcomes exist in some such markets. Finally, the model described here may also be used to understand markets with imperfect competition—see the recent work by Azevedo (2014) and Azevedo and Leshno (2016). We conjecture that stability may provide a robust solution concept for predicting behavior in these settings as well.
References


A Proofs

A.1 Proof of Theorem 1

See Theorems 6 and 10 in Hatfield et al. (2013).

A.2 Proof of Theorem 2

Existence follows from Theorem 2 in Hatfield et al. (2013). The quantity predicted is the efficient quantity, and that is part of any stable outcome: see Theorems 3 and 7 in Hatfield et al. (2013).

For the final part of the proof, we need to show that all contracts \((\omega, p_\omega) \in A\) transact at a price \(p_\omega \in [p^{\min}(\bar{q}), p^{\max}(\bar{q})]\). There are two cases to consider:

1. Suppose that there exists an \(\omega \in A\) such that \(p_\omega < p^{\min}(\bar{q})\). There are two cases to consider:
   
   (a) Suppose that \(p_\omega < f^b(|A_b| + 1) - f^b(|A_b|) + v(b)\) for some buyer \(b\). Then there exists a blocking set of the form \(\{(\psi, p_\psi)\}\) where \(b(\psi) = b\) and \(s(\psi) = s(\omega)\) along with a price
   
   \[
   p_\psi = \frac{(f^b(|A_b| + 1) - f^b(|A_b|) + v(\bar{q})) + p_\omega}{2},
   \]

   as both seller and buyer will choose this contract.

   (b) Suppose that \(p_\omega < c^s(|A_s|) - c^s(|A_s| - 1) + e(\bar{q})\) for some seller \(s = s(\omega)\). Then \(A\) is not individually rational for \(S\), as \(A_s \setminus \{(\omega, p_\omega)\}\) makes \(s\) strictly better off.

2. The case when there exists a contract \(\omega \in A\) such that \(p_\omega > p^{\max}(\bar{q})\) is analogous.

A.3 Proof of Theorem 3

From Theorems 2, 3, and 6 of Hatfield et al. (2013) a stable outcome exists and is efficient. Hence it must only include contracts with quality \(\hat{q}\). The bounds on the prices then follow
from the same arguments as in the proof of Theorem 2.

A.4 Proof of Theorem 4

We first prove that a stable outcome exists. We let

\[ \bar{p}^B \equiv \max_{b \in B} f^b(1) - f^b(0) + v(q_{\text{max}}) + 1; \]

note that no contract \((\omega, p_{\omega})\) with a price \(p_{\omega} > \bar{p}^B\) can be individually rational for any buyer, and so without loss of generality we may consider the contractual set \(\hat{X}[p_f] \equiv \{x \in X : p(x) \in [p_f, \bar{p}^B]\}\).

\[
P^B(Z) \equiv \left\{ (\omega, p_{\omega}) \in X[p_f, \bar{p}^B] : p_{\omega} = \inf_{(\omega, p_{\omega}) \in Z} p_{\omega} \right\}
\]

\[
P^S(Z) \equiv \left\{ (\omega, p_{\omega}) \in X[p_f, \bar{p}^B] : p_{\omega} = \sup_{(\omega, p_{\omega}) \in Z} p_{\omega} \right\}
\]

We consider a model with augmented preferences, where each agent \(i\) is endowed with a strict ordering \(\omega^1 \succ_i \ldots \succ_i \omega^{K_i}\) over trades involving \(i\). This induces a strict ordering \(\succ_i\) over sets such that

\[
\hat{Z} \succ_i Z \Leftrightarrow |\hat{Z}| < |Z| \text{ or } \max_{\succ_i} \tau(Z) \sqcup \tau(\hat{Z}) \in \tau(\hat{Z})
\]

We define an augmented choice function on \(\hat{X}[p_f]\)

\[
\hat{C}^b(Y) \equiv \max_{\succ_b} \{Z \in C^b(P^B(Y))\}
\]

for each \(b \in B\) and

\[
\hat{C}^s(Y) \equiv \max_{\succ_s} \{Z \in C^s(P^S(Y))\}
\]
for each $s \in S$, where $\max_s$ denotes the maximal set according to the order $\triangleright$. Note that this is a choice function, not a choice correspondence. Existence of a stable outcome $A$ for these augmented preferences then follows as the existence proof in Hatfield and Kominers (2016)—note that the assumption of a finite contractual set is not required for the proof of existence in that work. Finally, since $\hat{C}^i(Y) \subseteq C^i(Y)$ for all $i \in B \cup S$ and all $Y \subseteq X$, $A$ is a stable outcome for the original preferences.

We now characterize the set of stable outcomes, given the price restriction for each case. There are three cases to consider:

1. $p_f < p^{\text{max}}(\hat{q})$: Then the outcome described in Theorem 3 is still feasible, and hence is stable as it is still individually rational and unblocked. (Note that all blocking sets would also be blocking sets for the model with no price restrictions.)

2. $p^{\text{max}}(q) < p_f < p^{\text{min}}(q + 1) - [v(q + 1) - v(q)]$: We proceed in several steps:

   (a) We first show that $p_\psi = p_\omega + [v(q(\psi)) - v(q(\omega))]$ for all $(\psi, p_\psi), (\omega, p_\omega) \in A$ where $q(\psi) \geq q(\omega)$. There are two cases.

   i. If $p_\psi < p_\omega + [v(q(\psi)) - v(q(\omega))]$, we have that $Z = \{(\chi, p_\chi)\}$ is a blocking set, where $b(\chi) = b(\omega), s(\chi) = s(\psi), q(\chi) = q(\psi)$ and

   $$p_\chi = \frac{p_\psi + [p_\omega + [v(q(\psi)) - v(q(\omega))]]}{2}.$$  

   This contract is chosen from $A \cup \{(\chi, p_\chi)\}$ by $b(\chi)$, as it is strictly better for $b(\chi)$ than $(\omega, p_\omega)$; it is also chosen from $A \cup \{(\chi, p_\chi)\}$ by $s(\chi)$, as it is strictly better for $s(\chi)$ than $(\psi, p_\psi)$.\footnote{Note that $(\chi, p_\chi)$ must be individually rational, as $(\psi, p_\psi)$ and $(\omega, p_\omega)$ were individually rational for $b(\chi)$ and $s(\chi)$, respectively.}

   ii. If $p_\psi > p_\omega + [v(q(\psi)) - v(q(\omega))]$, we have that $Z = \{(\chi, p_\chi)\}$ is a blocking set,
where $b(\chi) = b(\psi)$, $s(\chi) = s(\omega)$, $q(\chi) = q(\omega)$ and

$$p_\chi = \frac{p_\omega + [p_\psi - [v(q(\psi)) - v(q(\omega))]]}{2}.$$

This contract is chosen from $A \cup \{(\chi, p_\chi)\}$ by $b(\chi)$, as it is strictly better for $b(\chi)$ than $(\psi, p_\psi)$; it is also chosen from $A \cup \{(\chi, p_\chi)\}$ by $s(\chi)$, as it is strictly better for $s(\chi)$ than $(\omega, p_\omega)$.\footnote{Note that $(\chi, p_\chi)$ must be individually rational, as $(\omega, p_\omega)$ and $(\psi, p_\psi)$ were individually rational for $b(\chi)$ and $s(\chi)$, respectively.}

(b) We now show that there are at most two consecutive qualities. Suppose not. Then there exist $(\psi, p_\psi), (\omega, p_\omega) \in A$ where $q(\psi) > q(\omega) + 1$. Consider the contract $\chi$ where $b(\chi) = b(\psi)$, $s(\chi) = s(\psi)$, $q(\chi) = q(\psi) - 1$, and

$$p_\chi = p_\psi - [v(q(\psi)) - v(q(\psi) - 1)] - \epsilon$$

for some small $\epsilon > 0$. Note that from part 2a, $p_\psi = p_\omega + [v(q(\psi)) - v(q(\omega))]$, which implies that $p_\chi > p_\omega \geq p_f$ for $\epsilon > 0$ small enough, and hence $(\chi, p_\chi)$ is a valid contract. $\{(\chi, p_\chi)\}$ is a blocking set, as both $b(\chi)$ and $s(\chi)$ are strictly better off dropping $(\psi, p_\psi)$ and choosing $(\chi, p_\chi)$.\footnote{Note that $(\chi, p_\chi)$ must be individually rational, as $(\psi, p_\psi)$ and $(\omega, p_\omega)$ were individually rational for $b(\chi)$ and $s(\chi)$, respectively.}

(c) We now show that if two consecutive qualities are traded in a stable outcome $A$, then one of them is traded at the price floor $p_f$. Suppose not. Let $(\psi, p_\psi), (\omega, p_\omega) \in A$ where $q(\psi) = q(\omega) + 1$. Consider a contract $(\chi, p_\chi)$ such that $b(\chi) = b(\omega)$, $s(\chi) = s(\psi)$, $q(\chi) = q(\omega)$, and $p_\chi = p_\omega - \epsilon$ for some small $\epsilon > 0$. $\{(\chi, p_\chi)\}$ is a blocking set for $\epsilon > 0$ small enough, as both $b(\chi)$ and $s(\chi)$ are strictly better off dropping $(\omega, p_\omega)$ and $(\psi, p_\psi)$ and choosing $(\chi, p_\chi)$—note that the seller is better off as he gains almost all the surplus from switching to a more efficient quality.\footnote{Note that $(\chi, p_\chi)$ must be individually rational, as $(\psi, p_\psi)$ and $(\omega, p_\omega)$ were individually rational for $b(\chi)$ and $s(\chi)$, respectively.}

(d) We now show that the two traded qualities are $q$ and $q + 1$. It will be helpful to
define the following notation:

\[ M(q) \equiv \arg \max_{n \in \mathbb{Z}_{\geq 0}} \left\{ \sum_{b \in B} \left[ f^b(n_b) + v(q) - p_f \right] \right\} \]

where

\[ \sum_{b \in B} n_b = n \]

To see that the two traded qualities are \( q \) and \( q + 1 \), suppose not; let the two traded qualities be \( q' \) and \( q' + 1 \). There are two cases to consider:

i. Suppose that \( q' > q \); hence, \( p_f < p_{\min}(q') \). There are two subcases to consider:

- Suppose that

\[ p_{\min}(q') = \max_{b \in B} \left\{ f^b(|\hat{A}_b| + 1) - f^b(|\hat{A}_b|) + v(q') \right\} \]

for some \( \hat{A} \) that is stable for the contract set \( X(q') \). Then at the price \( p_f \) the buyers strictly demand at least \( m + 1 \) goods of quality \( q' \), where \( m = \max M(q') \); however, there are at most \( m \) sellers willing to trade a quality \( q' \) at a price \( p_f \). Hence, either \( A \) is not individually rational or there exists a blocking set \( \{(\chi, p_\chi)\} \) where \( q(\chi) = q' \) and \( p_\chi = p_f + \epsilon \) for \( \epsilon > 0 \) small enough with a buyer whose demand is not satisfied and a current seller.

- Suppose that

\[ p_{\min}(q') = \max_{s \in S} \left\{ c^s(|\hat{A}_s|) - c^s(|\hat{A}_s| - 1) + e(q') \right\} \]

for some \( \hat{A} \) that is stable for the contract set \( X(q') \). Then at the price \( p_f \) the buyers strictly demand at least \( m \) goods of quality \( q' \), where \( m = \min M(q') \); while there are at most \( m - 1 \) sellers willing to trade a quality
\( q' \) at a price \( p_f \). Hence either \( A \) is not individually rational or there exists a blocking set \( \{(\chi, p_{\chi})\} \) where \( q(\chi) = q' \) and \( p_{\chi} = p_f + \epsilon \) for \( \epsilon > 0 \) small enough with a buyer whose demand is not satisfied and a current seller.

ii. Suppose that \( q' < q \); hence, \( p_f > p^\text{max}(q' + 1) \). There are two subcases to consider:

- Suppose that

\[
p^\text{max}(q' + 1) = \min_{b \in \mathcal{B}} \left\{ f^b(|\hat{A}_b|) - f^b(|\hat{A}_b| - 1) + v(q' + 1) \right\}.
\]

for some \( \hat{A} \) that is stable for the contract set \( X(q' + 1) \). Then at the price \( p_f \) the buyers demand at most \( m - 1 \) goods of quality \( q' + 1 \) or less, where \( m = \min \mathcal{M}(q' + 1) \); however, there are at least \( m \) sellers willing to trade a quality \( q' + 1 \) or less at a price \( p_f \). Hence either \( A \) is not individually rational or there exists a blocking set \( \{(\chi, p_{\chi})\} \) where \( q(\chi) = q' + 1 \) and \( p_{\chi} = p_f + [v(q' + 1) - v(q')] - \epsilon \) for \( \epsilon > 0 \) small enough with a seller who is not satisfied and a current buyer.

- Suppose that

\[
p^\text{max}(q' + 1) = \min_{s \in \mathcal{S}} \left\{ c^s(|\hat{A}_s|) - c^s(|\hat{A}_s| - 1) + e(q' + 1) \right\}.
\]

for some \( \hat{A} \) that is stable for the contract set \( X(q' + 1) \). Then at the price \( p_f \) the buyers demand at most \( m \) goods of quality \( q' + 1 \) or less, where \( m = \max \mathcal{M}(q' + 1) \); however, there are at least \( m + 1 \) sellers willing to trade a quality \( q' + 1 \) or less at a price \( p_f \). Hence either \( A \) is not individually rational or there exists a blocking set \( \{(\chi, p_{\chi})\} \) where \( q(\chi) = q' + 1 \) and \( p_{\chi} = p_f + [v(q' + 1) - v(q')] - \epsilon \) for \( \epsilon > 0 \) small enough with a seller who is not satisfied and a current buyer.
The above results imply that if both $q$ and $q + 1$ quality goods are traded, they must be traded at prices $p_f$ and $p_f + [v(q + 1) - v(q)]$. If only quality $q$ is traded, it must be traded at $p_f$, as if any other contract of the form $(\omega, p_\omega)$ exists, there will exist a blocking set of the form $\{(\psi, \frac{p_\omega + p_f}{2})\}$, as we know at a price $p_f > p_{\text{max}}(q)$ more sellers will demand to sell a good of quality $q$ then there are buyers willing to buy such a good. If only quality $q + 1$ is traded, then it must trade at $p_f + [v(q + 1) - v(q)]$, as if there exists a contract for a quality $q + 1$ good of the form $(\omega, p_\omega)$ where $p_\omega < p_f + [v(q + 1) - v(q)]$, then there is a blocking set of the form $\{(\psi, p_\omega - [v(q + 1) - v(q)])\}$ where $b(\psi) = b(\omega), s(\psi) = s(\omega), q(\psi) = q(\omega) + 1$. If $p_\omega < p_f + [v(q + 1) - v(q)]$, there will exist a blocking set of the form $\{(\psi, p_\omega - [v(q + 1) - v(q)])\}$, as we know at a price $p_\omega < p_{\text{min}}(q + 1)$ more buyers will demand to buy a good of quality $q + 1$ then there are sellers willing to sell such a good.

Finally, we prove that the number of trades is as given in the theorem. Suppose not. It is clear that if $m, m' \in M(q)$ and $m < \hat{m} < m'$, then $\hat{m} \in M(q)$. Hence, there are two cases to consider:

i. Suppose $|A| < m$ for all $m \in M(q)$. Then there exists a buyer $b$ such that $f^b(|A_b|) + v(q) - p_f > 0$. Furthermore, there exists a seller $s$ such that $p_f - [c^*(|A_s|) + e(q)] > 0$ as we know from the definition of $p_{\text{max}}(q)$ that the number of items of quality $q$ sellers are willing to sell at $p_f$ is strictly greater than the number of items buyers are willing to buy. Hence, a set $\{(\chi, p_\chi)\}$ such that $b(\chi) = b, s(\chi) = s, q(\chi) = q,$ and $p_\chi = p_f$ constitutes a blocking set.

ii. Suppose $|A| > m$ for all $m \in M(q)$. Then there exists a buyer $b$ such that $f^b(|A_b|) + v(q) - p_f < 0$. Then the outcome is not individually rational for $b$. (Recall that the buyers are indifferent between the two qualities, given their prices, in the stable outcome $A$.)
3. \( p_{\text{max}}(q+1) - [v(q+1) - v(q)] < p_f < p_{\text{min}}(q+1) \): First, note that steps (a)-(d) of Case 2 still hold. We now show that no contract with a quality \( q \) good transacts as part of a stable outcome. Suppose both qualities do trade in equilibrium. There are two cases

(a) Suppose

\[
p_{\text{max}}(q+1) = \min_{b \in B} \left\{ f^b(|\hat{A}_b|) - f^b(|\hat{A}_b| - 1) + v(q+1) \right\}.
\]

Then since \( p_{\text{max}}(q+1) < p_f + [v(q+1) - v(q)] \), and all buyers receive the same utility, there must be less than \( m \) buyers, where \( m = \min \mathcal{M}(q+1) \). However, sellers wish to sell at least \( m \) goods of quality \( q + 1 \) at that price. Hence there is a blocking contract where a seller who is not currently signing a contract offers a slightly lower price (and quality \( q + 1 \)) to a buyer currently buying.

(b) Suppose

\[
p_{\text{max}}(q+1) = \min_{s \in S} \left\{ c^s(|\hat{A}_s|) - c^s(|\hat{A}_s| - 1) + e(q+1) \right\}.
\]

Then since \( p_{\text{max}}(q+1) < p_f + [v(q+1) - v(q)] \), and all buyers receive the same utility, there are at most \( m \) buyers, where \( m = \max \mathcal{M}(q+1) \). However, sellers wish to sell at least \( m + 1 \) goods of quality \( q + 1 \) at that price. Hence there is a blocking contract where a seller who is not currently signing a contract offers a slightly lower price (and quality \( q + 1 \)) to a buyer currently buying.

The rest of the proof then follows as in the proof of Theorem 2.

A.5 Proof of Theorem 5

The proof is analogous to the proof of Theorem 4.
B Instructions

Introduction Welcome to the Laboratory for Experimental Economics and Political Science. This is an experiment in the economics of market decision making. The instructions are simple and if you follow them carefully and make good decisions you might earn money which will be paid to you in cash. We are going to conduct a market in which you will be a participant in a sequence of market days or trading periods. Attached to the instructions you will find a table labeled PAYOFF TABLE that describes the value to you of any decisions you might make. You are not to reveal this information to anyone. It is your own private information. The type of currency used in this market is francs. All trading and earnings will be in terms of francs. At the end of the experiment, your francs will be converted to dollars, and paid to you in cash. Your conversion rate is found on your table of values/costs. It may vary between people. Do not reveal this to anyone. The commodity being bought and sold comes in 10 different qualities, ranging from A to J. You will be designated as either a buyer or seller. If you are buyer your PAYOFF TABLE will be titled BUYER RECORD SHEET. If you are a seller, your PAYOFF TABLE will be labeled SELLER RECORD SHEET.

Specific Instructions to Buyers During each market period you are free to purchase from any seller or sellers as many units as you want. Each unit is one of ten different qualities, ranging from A to J. For the first unit that you buy during a trading period, you will receive the amount listed in the row marked “1st Unit Value” and the column corresponding to the quality of the item on your TABLE OF VALUES. If you purchase a second unit during that same period, you repeat the procedure, this time referring to the row marked “2nd Unit Value”, and so on. Notice that your units increase regardless of the quality of the previous units purchased. That is, for the first unit you follow the first row, regardless of quality and for the second unit you follow the second row, regardless of the quality of the first unit. Similarly for the third unit you follow the third row regardless of the quality of the previous two unit. Your payoffs are computed as follows: you will receive the difference between the
value on your table and what you paid for the purchase.

\[ \text{Earnings} = \text{Table Value} - \text{Purchase Price}. \]

If the value of the item is greater than the purchase price you make money. If the value of the item is less than the purchase price, you lose money. Your total payoffs will be accumulated over several trading periods and the total amount will be paid to you after the experiment.

**Specific Instructions to Sellers** During each market period you are free to sell to any buyer or buyers as many units as you might want. Each unit is one of seven different qualities, ranging from A to G. The cost of the first unit that you sell during a trading period is listed in the row marked “1st Unit Cost” and the column corresponding to the quality of the item on your TABLE OF COSTS. If you sell a second unit during that same period, you repeat the procedure, this time referring to the row marked “2nd Unit Cost”, and so on. Your payoffs are computed as follows: you will receive the difference between the sale price of the unit and its cost on your table.

\[ \text{Earnings} = \text{Sale Price} - \text{Cost of Unit} \]

If the sale price of the item is greater than the cost you make money. If the sale price is less than the cost, you lose money. Your total payoffs will be accumulated over several trading periods and the total amount will be paid to you after the experiment.

**Market Organization** The exercise is organized as follows. The market will be conducted in a series of trading periods. Each period lasts for at most 15 minutes. Any buyer is free at any time during the period to make a verbal bid to buy a unit of a certain quality at a specified price. Likewise, any seller is free to make a verbal offer, or “ask”, for one unit of a
specified quality for a specified price. This is done by stating the quality, your ID number, and your bid or ask is (example: “quality F, Buyer 2 bids 40” or “quality D, Seller 5 asks 200”). Bids and asks are recorded on the blackboard by the market manager. Once a new bid or ask is announced, any new bid for that quality must be higher than the previous bid and any new ask for that quality must be lower than the previous ask. A unit is traded when a buyer accepts an existing ask (i.e. calling out “Buyer 2 accepts for quality A”) or when a seller accepts an existing bid (i.e. calling out “Seller 6 accepts quality G”). When this happens, the buyer and the seller record the quality, price, and value or cost in the appropriate column of their Record sheet. Each column represents a trading period. Buyers and sellers can cancel their own asks or bids by calling out “Seller 7 cancels in quality B” or “Buyer 3 cancels in quality C”. Except for the bids, asks, and cancellations, you are not allowed to speak. There are likely to be many bids and asks that are not accepted, but you are free to keep trying. You are free to make as much profit as you can.
# C Tables

Table 2: Experiments and conditions

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Table 3: Type 1 buyer’s valuation and Type 1 seller’s cost in Series 1

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Type 1 buyer’s valuation for the $n^{th}$ good at quality $q$  
Type 1 seller’s cost for the $n^{th}$ good at quality $q$
Table 4: Type 1 buyer’s valuation and Type 1 seller’s cost in Series 2

<table>
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<td>1995</td>
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<td>735</td>
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<table>
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<td>1145</td>
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<td>1685</td>
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Table 5: Efficiency and number of units traded by period for Series 1

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<td>No</td>
<td>No</td>
<td>With</td>
<td>With</td>
<td>With</td>
</tr>
<tr>
<td>price</td>
<td>floor</td>
<td>price</td>
<td>floor</td>
<td>price</td>
<td>price</td>
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<td>0.815</td>
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<td>0.651</td>
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<td>0.952</td>
<td>0.532</td>
<td>0.641</td>
<td>0.628</td>
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<td>0.952</td>
<td>0.532</td>
<td>0.641</td>
<td>0.628</td>
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<tr>
<td>Period 5</td>
<td>0.913</td>
<td>0.952</td>
<td>0.532</td>
<td>0.641</td>
<td>0.628</td>
</tr>
<tr>
<td>Period 6</td>
<td>0.913</td>
<td>0.952</td>
<td>0.532</td>
<td>0.641</td>
<td>0.628</td>
</tr>
<tr>
<td>Period 7</td>
<td>0.913</td>
<td>0.952</td>
<td>0.532</td>
<td>0.641</td>
<td>0.628</td>
</tr>
<tr>
<td>Period 8</td>
<td>0.913</td>
<td>0.952</td>
<td>0.532</td>
<td>0.641</td>
<td>0.628</td>
</tr>
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<td>Mean efficiency</td>
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<td>0.881</td>
<td>0.604</td>
<td>0.650</td>
<td>0.923</td>
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<td>1.000</td>
<td>0.661</td>
<td>0.660</td>
<td>1.000</td>
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<tr>
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<td>1.000</td>
<td>1.000</td>
<td>0.661</td>
<td>0.660</td>
<td>1.000</td>
</tr>
<tr>
<td>Average number of units traded per period</td>
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<td>44.3</td>
<td>27.8</td>
<td>32.3</td>
<td>31.5</td>
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<tr>
<td>Number of trades in a stable outcome</td>
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<td>39</td>
<td>28</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td>(Theoretical prediction)¹</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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| ¹ The number of trades and efficiency in stable outcomes differ across sessions because the number of sellers and buyers differ across sessions.

Table 6: Proportion of trade by quality during the second half periods in Series 1 (percent)

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<thead>
<tr>
<th>Experimental Treatments</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
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<tr>
<td>No price floor (Periods 5-7, Experiment 1.1)</td>
<td>7.6</td>
<td>4.6</td>
<td>12.1</td>
<td>62.1</td>
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<td>0.0</td>
<td>0.0</td>
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<tr>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.5</td>
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Table 7: Coefficient estimates

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<th>$\beta_2$</th>
<th>$\beta_3$</th>
<th>$\beta_4$</th>
<th>$\gamma$</th>
<th>$n$</th>
<th>$R^2$</th>
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</thead>
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<td></td>
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<tr>
<td></td>
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<td>(96.2)</td>
<td>(43.0)</td>
<td>(20.8)</td>
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</tr>
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<td>19</td>
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</tr>
<tr>
<td></td>
<td>(15.7)</td>
<td>(16.3)</td>
<td>(3.5)</td>
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<tr>
<td>Series 2</td>
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<td>17</td>
<td>0.671</td>
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<td>(4.1)</td>
<td>(3.2)</td>
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1Standard errors are in parentheses.

Table 8: Results when a price floor of 1312 was imposed.

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<th>Quality B</th>
<th>Quality C</th>
<th>Efficiency</th>
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<td>32</td>
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<td>–</td>
<td></td>
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</tr>
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<td>–</td>
<td>0</td>
<td>1312.0</td>
<td>24</td>
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<tr>
<td></td>
<td>–</td>
<td></td>
<td>(0.0)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>–</td>
<td>0</td>
<td>1312.0</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td></td>
<td>(0.0)</td>
<td></td>
</tr>
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<td></td>
<td>(0.0)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>–</td>
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<td>1312.0</td>
<td>22</td>
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<td>–</td>
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<tr>
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<td>–</td>
<td>0</td>
<td>1312</td>
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Table 9: Results when a price floor of 1470 was imposed.

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<th>Efficiency</th>
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<td>[1190, 1210]</td>
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Table 10: Results when a price ceiling of 1088 was imposed.

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<td>889.0</td>
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<td>0</td>
<td>.910</td>
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<td>(0.0)</td>
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<td>1088</td>
<td>–</td>
<td>–</td>
<td>–</td>
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</table>
Table 11: Results when a price ceiling of 930 was imposed.

<table>
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<tr>
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<th>Quality C</th>
<th>Efficiency</th>
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<td>0</td>
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<td>(8.7)</td>
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<td></td>
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