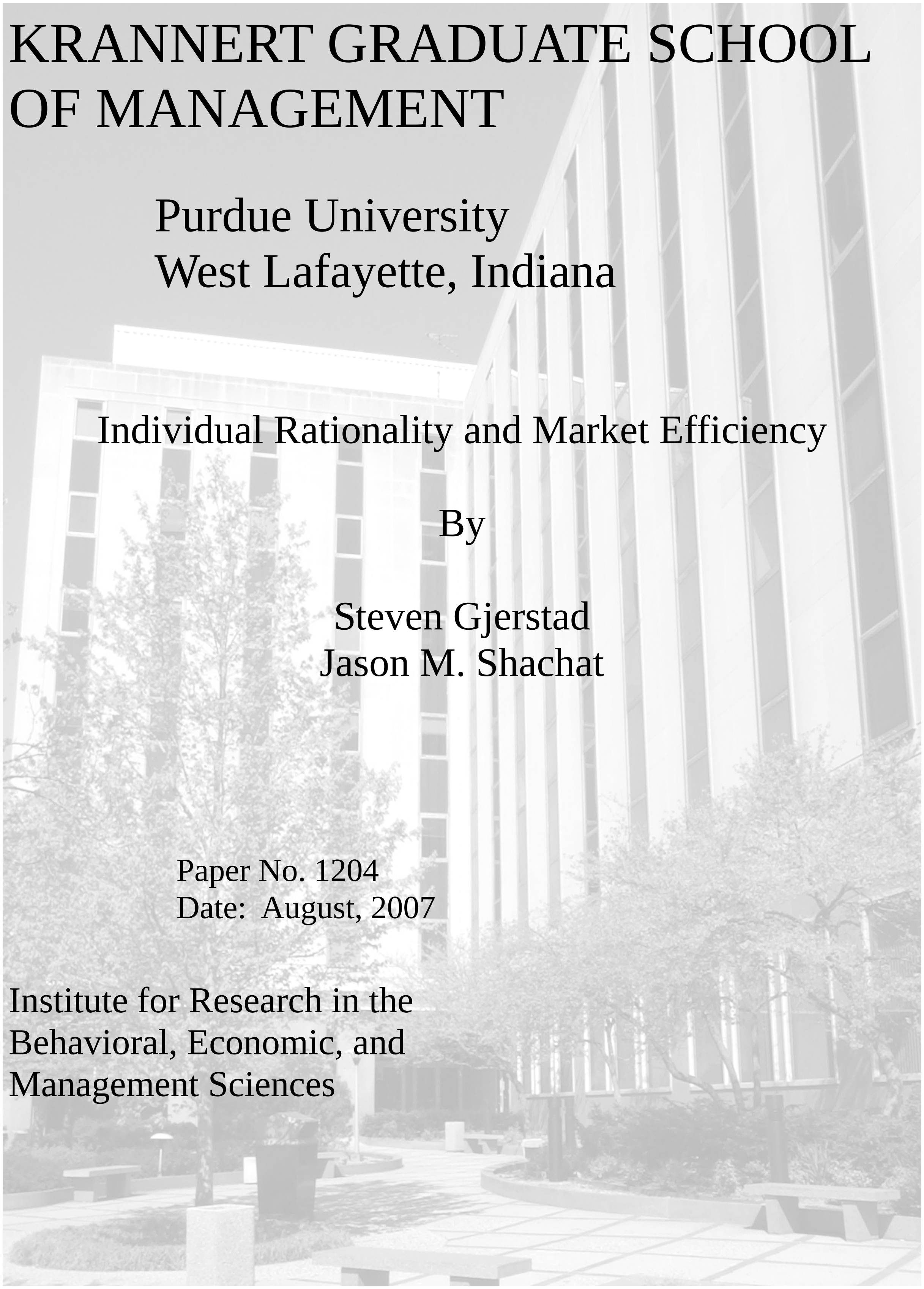

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Individual Rationality and Market Efficiency

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Individual Rationality and Market Efficiency

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Abstract

The demonstration by Smith [1962] that prices and allocations quickly converge to the competitive equilibrium in the continuous double auction (CDA) was one of the first – and remains one of the most important – results in experimental economics. His initial experiment, subsequent market experiments, and models of price adjustment and exchange have added considerably to our knowledge of how markets reach equilibrium, and how they respond to disruptions. Perhaps the best known model of exchange in CDA market experiments is the random behavior in the "zero-intelligence" (ZI) model by Gode and Sunder [1993]. They conclude that even without trader rationality the CDA generates efficient allocations and "convergence of transaction prices to the proximity of the theoretical equilibrium price," provided only that agents meet their budget constraints. We demonstrate that – by any reasonable measure – prices don't converge in their simulations. Their budget constraint requires that a buyer's currency never exceeds her value for the commodity, which is an unnatural restriction. Their conclusion that market efficiency results from the structure of the CDA independent of traders' profit seeking behavior rests on their claim that the constraints that they impose are a part of the market institution, but this is not so. We show that they in effect impose *individual rationality*, which is an aspect of agents' behavior. Researchers on learning in markets have been misled by their interpretation of the ZI simulations, with deleterious effects on the debate on market adjustment processes.

Keywords: Bounded rationality; double auction; exchange economy; experimental economics; market experiment; "zero intelligence" model

JEL Classification Numbers: C70, C92, D44, D51

1 Introduction

Hayek [1945] asked how interactions among many buyers and sellers in a market coordinate dispersed information to reach an efficient allocation at stable prices. Chamberlin [1948] found that when buyers and sellers randomly encounter one another, negotiate prices, and possibly trade, prices are volatile and extracted surplus is only a fraction of available surplus. Smith [1962] had a key insight into the convergence process. He replaced Chamberlin's decentralized information with the centralized information of the continuous double auction (CDA), and found that trade prices quickly approached the competitive equilibrium price, and extracted surplus approximated the competitive equilibrium surplus. His experiment provided a framework for analysis of Hayek's question. In Smith's CDA experiment, the experimenter induces costs and values that are private information in naturally occurring markets. Induced costs and values combined with public data on bids, asks, and trade prices are crucial for development of models of behavior in the CDA.

Several such models have been developed. These include the strategic model in Wilson [1986], three models that depart from full rationality – Friedman [1991], Easley and Ledyard [1993], and Gjerstad and Dickhaut [1998] – and the model of random behavior by Gode and Sunder [1993].[1] Gode and Sunder reach the most striking conclusions. They assert (p. 135) that in the CDA the "convergence of price to equilibrium and the extraction of almost all the total surplus seem to be consequences of the double-auction rules." The purpose of this paper is to assess these two claims: neither claim withstands scrutiny. Consequently their position that trader rationality is largely unnecessary in models of market dynamics lacks foundation.

Our paper is organized as follows. In Section 2, we summarize the model by Gode and Sunder, indicate its influence among researchers on learning in markets, and evaluate their two main claims. Prices from their simulations belie their claim that prices converge. Their claim that allocations are efficient in the absence of trader rationality or profit seeking behavior relies on their peculiar "budget constraint," whereby no trader can come to the market with currency that exceeds her value for the commodity. In Section 3 we demonstrate that markets with induced costs and values are equivalent to exchange economies, and we use our exchange economy representation to demonstrate that the constraints imposed by Gode and Sunder are in fact individual rationality constraints. In Section 4 we consider examples that suggest the fundamental economic significance of the market adjustment problem, and indicate several challenges that serious models of adjustment should confront.

2 Gode and Sunder's zero-intelligence model

Gode and Sunder populate a market with simple bidding agents – which they call zero-intelligence (ZI) traders – in order to assess the forces that generate efficient outcomes in CDA markets. In a CDA market, a seller may submit an ask at any time during a trading period. Similarly, at any time a buyer may submit a bid. An ask placed at or below the current high bid results in a trade at the bid price; a bid that meets or exceeds the current low ask results in a trade at the ask price. In the simulations that Gode and Sunder conduct, their ZI-constrained (ZI-C) traders

[1] Cason and Friedman [1996] compare predictions of the first two and the last of these five models to outcomes from market experiments with human subjects. Gjerstad [2007] briefly summarizes all five models.

have restricted bids or offers: a ZI-C buyer bids between zero and her budget; a ZI-C seller submits ask prices between his cost and some upper bound. They call this budget constraint "the market discipline" (p. 123) because the market prevents agents from violating their budget constraints. They compare outcomes of markets populated with these ZI-C traders to markets populated with ZI unconstrained (ZI-U) traders that are not subject to these constraints. In the first paragraph of their conclusions (p. 134), they summarize the conclusions that they draw from this comparison.

> "The primary cause of the high allocative efficiency of double auctions is the market discipline imposed on traders; learning, intelligence, or profit motivation is not necessary. The same market discipline also plays an important role in the convergence of transaction prices to equilibrium levels."

These claims in their conclusions reiterate their earlier claims about price convergence[2] and the source of market efficiency.[3] Our objective is to demonstrate that these two claims are erroneous. Nevertheless, their argument has misled many researchers and has been widely accepted.[4,5]

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[2] "Convergence of transaction prices to the proximity of the theoretical equilibrium price in ZI-C markets is a consequence of the market discipline." (p. 131)

[3] "Efficiency of the double auction derives largely from its structure, independent of traders' motivation, intelligence, or learning." (p. 119); "Adam Smith's invisible hand may be more powerful than some have thought; it can generate aggregate rationality not only from individual rationality but also from individual irrationality." (p. 119); "A double auction ... can sustain high levels of allocative efficiency even if agents do not ... seek profits." (p. 120); "[A ZI trader] has no intelligence [and it] does not seek ... profits." (p. 121) "Our point is that imposing market discipline on random, unintelligent behavior is sufficient to raise the efficiency from the baseline level to almost 100 percent in a double auction. The effect of human motivations ... has a second-order magnitude at best." (p. 134)

[4] As of July 2007, there have been 102 citations of the paper in the Social Sciences Citation Index; fifty-four of these are since 2003. The average number of citations is 48.8 for the fifty-three papers published in the JPE in 1993; only six have more than 102 citations.

[5] "The rules for competition, if well designed, can ensure that a market produces an allocation that is close to efficient even with traders who are *incapable of calculating what is in their interest*, according to experiments by Gode and Sunder (1993). The wisdom of the market compensates for the market participants' lack of rationality." (McAfee and McMillan [1996], emphasis added.) "Gode and Sunder (1993) give examples of double auction markets in which "zero-intelligence" traders (computers which bid randomly *subject only to budget constraints*) may achieve near perfect market efficiency." (Conlisk [1996], emphasis added.) "Gode and Sunder ... find that market efficiency levels close to 100% are attained even when their traders have "zero intelligence" in the sense that they submit random bids and asks that are *subject only to a budget constraint*." (Tesfatsion [2002], emphasis added.) "[T]he continuous flow of offers, coupled with traders' *budget constraints*, generates a mechanical but powerful push in the direction of efficient outcomes." (Samuelson [2005], emphasis added.) "Gode and Sunder (1993) ... suggest that efficiency of the double-auction institution *derives largely from its structure* rather than from individual learning." (List [2005], emphasis added.) "[I]t has been repeatedly observed that, in laboratory experiments, double-auction institutions consistently produce allocations and *prices close to the predictions of price-taking models*. These predictions are even sustained when subjects are random decision-makers as in Gode and Sunder (1993)." (Bosch-Domènech and Silvestre [1997], emphasis added.) "Gode and Sunder (1993) supported market "rationality" even when composed of "irrational" economic units. ... Efficiency derived mainly from the structure of the market itself rather than from the advantages typically ascribed to human economic agents (i.e., motivation, intelligence, and learning ability). (Evans [1997].) "Contrary to one of the shibboleths of neoclassical economics on the necessity for explicit optimization by agents at a micro level for allocative efficiency in markets, they [Gode and Sunder] found that it is the *operation of the rules of double auction* that is instrumental for over 90% of allocative efficiency even with so-called zero intelligence traders." (Markose, Arifovic, and Sunder [2007], emphasis added.)

Gode and Sunder characterize our position as a disagreement about the specification of zero on the intelligence scale, and argue that the specific reference point doesn't matter. This misses our point. Gode and Sunder claim that when the market institution enforces the traders' budget constraints (or imposes "the market discipline"), that leads to price convergence and market efficiency. We dispute this conclusion. We show that their constraint cannot be meaningfully interpreted as a budget constraint. Rather, the constraint they impose can only be interpreted as a restriction on traders' behavior. Since their ZI-C simulations reach efficient outcomes and their ZI-U simulations do not, it follows that some restriction on trader behavior is crucial for market efficiency. Moreover, price convergence requires some form of learning or adaptation.

2.1 Price convergence

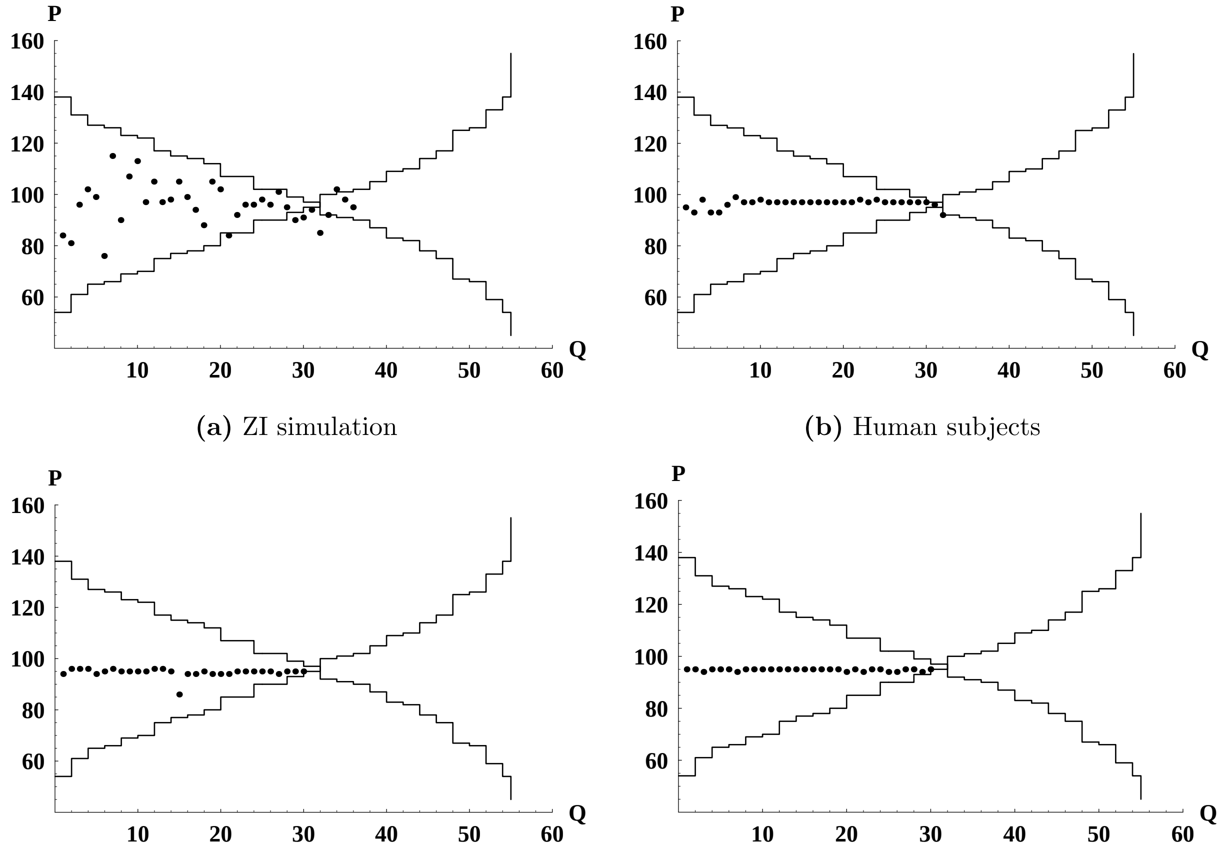
Numerous CDA experiments beginning with Smith [1962] demonstrate that trades by human subjects quickly and reliably converge to the equilibrium price. Gode and Sunder claim that they obtain "convergence of transaction prices to equilibrium levels" in their markets with budget constrained traders. Figures 1 (a) and (b) compare a representative outcome from a simulation of the ZI model to a representative outcome from an experiment with human subjects. Comparison of these two price paths demonstrates that their claim is incorrect.[6] Further comparison with a model that includes simple learning demonstrates that something more than individual rationality – but far less than full strategic rationality – approximates the competitive equilibrium outcome.

Although ZI-C simulations fail to converge, the simple heuristic belief learning (HBL) model from Gjerstad [2007] (based on the model in Gjerstad and Dickhaut [1998]) leads to price convergence in a standard market experiment with induced values and costs. Figure 1 (c) demonstrates that price standard deviations with this model are similar to markets with human subjects.[7] Price standard deviations from the ZI model exceed those from human subject experiments and from the HBL model by a factor of about five. Figure 1 (d) reinforces the point that the HBL model captures price convergence. This figure depicts the outcome from a market with HBL model sellers and human buyers. Among five fifteen period sessions with HBL model agents on one side of the market and human subjects on the other side of the market, in this trading period the price standard deviation was lowest. The median of the price standard deviation is nearly 20 times as large in ZI simulations as it is in this period with sharp price convergence.

Prices in the Gode and Sunder model fluctuate in a range that is bounded above by the highest unit value of the buyers and below by the lowest unit cost of the sellers. These ranges tend to narrow as trade proceeds within a period, but in each new period values and costs are renewed. Their definition of price convergence appears particularly contrived when it is interpreted in a practical context. Suppose that grain distributors and food producers arrive at the Minneapolis Grain Exchange to trade Hard Red Spring Wheat, with quotes in single contracts for 5000 bushels. Would we say that the market price had converged if at 9:35 a.m. – just after the market opens – the

[6] In these two graphs, the standard deviations of trade prices in the selected periods are closest to the median of this statistic from simulations of 150 periods with the ZI-C model (median standard deviation 8.53) and for periods 6 – 15 from each of five sessions with human subjects (median standard deviation 1.70).

[7] Figure 1 (c) shows the price sequence from the HBL model simulation that is closest to the median standard deviation from all 15 periods in ten simulations (median standard deviation 1.74).



(a) ZI simulation

(b) Human subjects

(c) Heuristic belief model

(d) Human buyers vs. HBL model sellers

Figure 1: Supply, demand, and trade prices from models and experiments.

first buyer paid \$624, at 9:45 a.m. the next buyer paid \$371, later the third paid \$736, and so on all day, until the last buyer paid \$514 at 1:13 p.m., where \$514 is close to the price at the intersection of supply and demand? In the Gode and Sunder story not only does this happen on the first day, something similar happens day after day. The benchmark for price convergence should be more substantial than either (1) trade of the last unit in the period near the competitive equilibrium price or (2) convergence in mean. In CDA experiments price convergence is much more robust.

2.2 The "budget constraint" fallacy

The interpretation of the budget constraint in Gode and Sunder is inconsistent with both economic theory and common sense. Their budget constrained buyer always arrives at a market with an amount of money exactly equal to her value for the commodity she intends to purchase. This constraint cannot be interpreted as a budget constraint or as a form of market discipline. Surely, if a buyer arrives at the market with currency M, there is an economic rationale for the market organizers to restrict her bids b to the interval $[0, M]$, otherwise she won't be able to make payment if she bids more than M and ends up trading at a price greater than M. The inequality $b \leq M$ in the budget constraint is perfectly sensible. What happens when M exceeds the buyer's value? Why should the market organizers restrict her currency to $M \leq v$? Of course they have no *reason* to do so, and they have no *capacity* to do so. The market organizers don't care if a buyer brings more money to the market than her value for her intended purchase. Even if they did have a reason to impose this restriction, they don't know the value(s) of a buyer, and typically they will not know the amount of money that a buyer brings to the market, so they couldn't carry out this restriction if they had the desire to do so. The restriction that $M \leq v$ is entirely unnatural.[8] The combination of the legitimate constraint $b \leq M$ and the fallacious constraint $M \leq v$ leads to their restriction that bids must be no more than the buyer's value. Most importantly, this fallacious constraint is the basis of their argument that its enforcement is a form of market discipline, which in turn leads to their conclusions that "the convergence of price to equilibrium and the extraction of almost all the total surplus seem to be consequences of the double auction rules" (p. 135).

2.3 Individual rationality and market efficiency

We've now established that the constraints Gode and Sunder impose are neither budget constraints nor a form of market discipline. Section 3 demonstrates that their constraints conform to individual rationality constraints.[9] Their ZI-C simulations – in which their agents exhibit individual rationality – achieve Pareto optimal allocations; their unconstrained (ZI-U) traders do not reach Pareto optimal outcomes. The different performance of the ZI-C and ZI-U traders – combined with the fact that their constraints can only be meaningfully interpreted as aspects of trader behavior rather than budget constraints or as a form of market discipline – demonstrates that it is trader behavior that generates price convergence and efficiency in the CDA, not the structure of the market rules.

3 An exchange economy formulation of induced costs and values

In Section 3.1 we construct a buyer's quasi-linear utility function from a vector of values and show that constrained maximization of the utility function yields a demand function that is dual to the vector of values. In Section 3.2 we follow a similar procedure for sellers. In Section 3.3 we use these constructions to demonstrate that the constraints imposed by Gode and Sunder are in fact individual rationality constraints.

3.1 Induced values and quasi-linear utility

Each buyer $j \in J$ has a vector of values $v_j = (v_j^1, v_j^2, \ldots, v_j^{n_j})$ for units of the commodity Y, where $v_j^1 \geq v_j^2 \geq v_j^3 \geq \cdots \geq v_j^{n_j} > 0$. The total redemption value to buyer j when she purchases y units is

$$r_j(y) = \begin{cases} 0, & y = 0; \\ \sum_{\gamma=1}^{\min\{y,n_j\}} v_j^{\gamma}, & y = 1, 2, 3, \ldots . \end{cases}$$

[8] Surely this constraint isn't a part of any conceivable free market: its enforcement would require interrogation, unrestricted searches, and confiscation of assets; even so it could be evaded if a buyer simply misrepresents her value.

[9] Following Luce and Raiffa [1957, pp. 192 – 193], by *individual rationality* we mean that an agent only attempts to take part in a trade that increases, or at least leaves constant, his own utility.

We use the buyer's redemption value function $r_j(\cdot)$ to develop the buyer's quasi-linear utility function. Define the consumption space of buyer j as $X \times Y$, and let $(x_j, y_j) \in X \times Y$ denote the units of currency X and commodity Y held by buyer j. The utility function of buyer j is

$$u_j(x,\, y) = x + r_j(y) + M_j \tag{1}$$

where M_j is a constant.[10] Equation (1) is linear in the currency (X) and additively separable in the currency and commodity, i.e., it is quasi-linear.[11] The currency endowment $x_j^0 \geq \sum_{\gamma=1}^{n_j} v_j^\gamma$ is sufficient to guarantee that buyer j would be able to purchase each unit at any price at or below the value of the unit.

Theorem 1 The demand for Y by buyer j – derived from maximization of equation (1) for a sufficiently large endowment – is dual to v_j.

Proof The vector v_j of values is non-increasing, so that the total value function $r_j(y)$ is (weakly) concave for $y \in Y$. Therefore the utility function $u_j(x,\, y) = x + r_j(y) + M_j$ is (weakly) quasi-concave. The theorem of the maximum implies that for any given price p of good Y, the set of values that maximize $u_j(\cdot)$ is convex.

Let $y_j(p)$ be the demand of buyer j at price p, i.e., the solution to the maximization problem for $u_j(x,\, y)$. We complete the proof by showing that the demand $y_j(p)$ has the same graph as the vector v_j of values. If $p = v_j^k$, then $y_j(p) \in \{k-1,\, k\}$. If $p \in (v_j^{k+1},\, v_j^k)$, then $y_j(p) = k$. ■

3.2 Induced costs and quasi-linear utility

Seller i has a marginal cost schedule that is represented as a vector $c_i = (c_i^1,\, c_i^2,\, \ldots,\, c_i^{m_i})$, where the commodity endowment for seller i is $y_i^0 = m_i$. Element c_i^k is the marginal cost incurred by seller i when he produces his k^{th} unit. The marginal cost of any unit beyond m_i is infinite. For $k \in \{0,\, 1,\, 2,\, \ldots,\, m_i\}$ the redemption value for seller i when he sells k units is

$$r_i(k) = \begin{cases} 0, & k = 0; \\ -\sum_{\iota=1}^{k} c_i^\iota, & k = 1,\, 2,\, \ldots,\, m_i. \end{cases}$$

We use the redemption value function of seller i to define his quasi-linear utility function as

$$u_i(x,\, y) = \; x + r_i(m_i - y), \quad 0 \leq y \leq m_i. \tag{2}$$

Theorem 2 Seller i's supply of Y – derived from maximization of equation (2) – is dual to c_i.

Proof The vector c_i of costs is non-decreasing, so that the total value function $r_i(k)$ is (weakly) concave for $k \in \{1,\, 2,\, \ldots,\, m_i\}$, as is $r_i(m_i - y)$ for $y \in \{1,\, 2,\, \ldots,\, m_i\}$. Therefore the utility function

[10] The constant M_j has no theoretical implications but is relevant to experimental studies. If buyer j has the initial endowment $(x_j^0,\, 0)$ and $M_j = -x_j^0$ then $u_j(x_j^0,\, 0) = 0$ so that the autarky outcome has payoff 0.

[11] Our rationalization of the induced demand schedule as the solution to the constrained maximization of a quasi-linear utility function is similar to the construction by Smith [1982, p. 932]. Smith derives the induced demand curve by maximizing the utility function $u_j(x,\, y) = x + r_j(y)$ subject to the budget constraint $x + p\, y \leq 0$ where $x \leq 0$ and $y \geq 0$. In contrast, we define finite positive endowments of X for buyers and of Y for sellers that are consistent with the typical specification of consumer choice problems.

$u_i(x, y) = x + r_i(m_i - y)$ is (weakly) quasi-concave. The theorem of the maximum implies that for any given price p of good Y, the set of values that maximize $u_i(\cdot)$ is convex.

Let $y_i(p)$ be the supply of seller i at price p, i.e., the solution to the maximization problem for $u_i(x, y)$. We complete the proof by showing that the supply $y_i(p)$ has the same graph as the vector c_i of costs. If $p = c_i^k$, then $y_i(p) \in \{k-1, k\}$. If $p \in (c_i^k, c_i^{k+1})$, then $y_i(p) = k$. ■

3.3 Individual rationality from the exchange economy perspective

The final step in our argument demonstrates that a buyer who only proposes bids or accepts asks that are at or below his unit value exhibits individual rationality, as does a seller who only proposes asks or accepts bids that are above his unit cost. We've carried out our utility function construction for buyers and sellers with one or more units to trade at the equilibrium price. In the ZI simulations each buyer has a positive value for one unit and each seller has only one unit available, so we apply our construction to this case.

If buyer j only submits bids $b_j \leq v_j$, this is equivalent to $x_j^0 - b_j + v_j + M_j \geq x_j^0 + M_j$. For buyer j with the utility function $u_j(x, y)$ in equation (1) and endowment $(x_j^0, 0)$ of the currency and the consumption good, $r_j(1) = v_j$ and $r_j(0) = 0$ so $x_j^0 - b_j + r_j(1) + M_j \geq x_j^0 + r_j(0) + M_j$. From the definition of the utility function in equation (1), this is equivalent to $u_j(x_j^0 - b_j, 1) \geq u_j(x_j^0, 0)$. With indivisible units of the consumption good as in the experiments, this is the individual rationality constraint.

The argument for seller i is similar. Suppose that seller i only considers asks $a_i \geq c_i$. Assume that seller i has the utility function in equation (2). Since $r_i(0) = 0$ and $r_i(1) = -c_i$, the condition $a_i \geq c_i$ is equivalent to the condition $a_i + r_i(1-0) \geq r_i(1-1)$. This is equivalent to $u_i(a_i, 0) \geq u_i(0, 1)$, which is the individual rationality constraint with indivisible units.

4 Conclusions

In Section 2.2 we showed that the constraints that Gode and Sunder impose cannot be interpreted as budget constraints; in Section 3.3 we showed that they are individual rationality constraints. Gode and Sunder demonstrate that (ZI-C) traders reach approximate Pareto optimal allocations, and that unconstrained (ZI-U) traders do not reach a Pareto optimal allocation. This establishes that individual rationality is both necessary and sufficient to reach a Pareto optimal allocation.[12]

[12] Hurwicz, Radner, and Reiter [1975] show that in any general equilibrium economy without externalities, random individually rational behavior leads to Pareto optimal allocations in a simple trading institution called the B-process. The B-process is defined generally enough so that the double auction with discrete units is a special case. With a discrete commodity space, as in a market experiment, random sequences of proposed trades submitted from each agent result in a sequence of net trades. An element of the trade sequence is non-zero if submitted proposals include a compatible trade (i.e., there is at least one trade proposal for which the net trade sums to zero). Hurwicz, Radner, and Reiter show under weak conditions on preferences and technologies that if at every iteration of the bargaining process, each individual only submits individually rational trade proposals, then the process converges to a Pareto optimal allocation in finite time. In effect, Gode and Sunder show that in a special case the B-process converges to a Pareto optimal allocation, although they either did not recognize or did not acknowledge that they had imposed an individual rationality constraint.

Price adjustment and convergence is a fundamental economic problem. Economists almost exclusively formulate their price theories as equilibrium models, but price adjustment is by its nature a disequilibrium phenomenon. Substantial market disruptions, such as shocks to demand or supply, frequently disconnect price expectations from the actual market equilibrium price. Experiments have provided much insight into how trade activity realigns expectations and trading strategies of buyers and sellers with the market conditions that prevail after the disruption.

Practical problems of this sort are common. At a national scale, the closures of nine refineries in the aftermath of hurricane Katrina in August 2005 led to a 27% reduction in domestic oil production and a 21% reduction in U.S. oil refining capacity (Yergin [2006]), which destabilized prices of petroleum products for months. At a regional scale, almost every market was disrupted as infrastructure was destroyed and hundreds of thousands of people relocated. In neighboring cities, housing and labor market conditions were both greatly affected by the influx of displaced persons. Economists do not have theories that indicate how prices will stabilize after such a disruption. Even in more prosaic situations, such as a large expansion of an auto manufacturing plant in a medium sized city, equilibrium models do not offer much insight into the path of price adjustment in labor markets, housing markets, or even markets for goods and services.

Price paths during these adjustment periods will affect the profits that accrue to sellers, which in turn will affect the rate of capacity investment by firms. Changes to capacity will affect market supply and further impact price adjustment processes. This long-run market adjustment problem has not been addressed experimentally, nor do we have good models of its dynamics. This says nothing of the interactions across markets, that is, the general equilibrium adjustment issues. These are serious economic problems, and they call for serious economic models, even if those models require some work to develop and to understand. Experimental economics and learning models are particularly well positioned to make substantive contributions to these issues, but first we have to move beyond the simplistic view of market adjustment in the zero-intelligence model.

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