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Trading in a Pure Exchange Economy without an Auctioneer: An Experimental Approach

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Abstract

This paper explores alternatives to the Walrasian Auctioneer for the allocation of resources in a pure exchange economy lacking a bilateral coincidence of wants. We have created three different computerized trading processes called BARTER, NUMERAIRE, and CARE (acronym for Computer Assisted Resource Exchange). CARE is a "smart market" in the sense that it contains computer algorithms that assist users in finding a coincidence of wants. The experimental results show that CARE outperforms BARTER and NUMERAIRE by extracting most of the gains from exchange with fewer contracts, lower volume, smaller utility swings, and lower variances in final utility positions.

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1 Introduction

> It is perhaps surprising that, up to quite recently, economists have paid relatively little attention to the process of exchange itself. Closely analyzed, this process is found to involve inevitable costs and imperfections. It is as an attempt to cope with these imperfections that the crucial institution of ***money*** comes into existence (together with banks, credit cards and other puzzling phenomena of our modern world) ...
> Jack Hirschleifer in *Price Theory and Applications* (1976)

For more than two centuries, at least since the publication of Adam Smith's famous treatise, the virtues of voluntary trading have been unanimously understood. Two or more parties exchange commodities if and only if there are gains from exchange for all of them. But it is also well established that different rules or mechanisms of exchange will produce different outcomes (see Groves and Ledyard (1988) for a survey). Furthermore, as the number of commodities to be exchanged and/or the number of individuals in the market increases, the organizational problems can increase dramatically.

The general question that this paper addresses is: given a pure exchange economy, how do you implement an efficient trading mechanism? There exists a large literature in economics focusing on the existence of competitive equilibria [see for example, Arrow

*We gratefully acknowledge the financial support from the Flight Projects Office of the Jet Propulsion Laboratory. All of the software design and implementation are the work of Wesley Boudville. Without his infinite patience and expert programming skills the Cassini Resource Exchange would not be a reality. We also thank John Casani and Dennis Matson who are the driving force for this new form of science management, and especially John Ledyard for his many comments and encouragement.

and Debreu (1954) or Debreu (1959)]; but most of these results rarely address how equilibrium is achieved. The price formation process assumes the existence of a Walrasian Auctioneer that adjusts a price signal until all the buyer's and seller's orders match. We are interested in alternatives to the Walrasian Tatonnement auction mechanism. There are several reasons for investigating new variations:

1. The Walrasian process requires that the market is called at specific times to aggregate orders and adjust prices until markets clear. In some applications, like the market described in the next section, this is not practical.

2. The number of messages or iterations necessary to clear the market may be large. Scarf (1960) has constructed examples of globally unstable equilibrium positions to indicate some of the limitations to the scope of stability of the tatonnement mechanism in a competitive environment.

3. Strategic underrevelation can cause problems with the convergence of the adjustment rule and losses in efficiency [see Hurwicz (1972), Otani and Sicilian (1990) and Bronfman et al. (1992)].

Before looking at possible alternatives it is important to keep in mind a few of the tasks that an adequate trading system must perform (these are the criteria that we will use to evaluate the quality of trading institutions):

i. The main task for any exchange mechanism is to find Pareto-efficient reallocations. If the economy is not at an efficient allocation, there exists a feasible utility increasing reallocation of resources. If the mechanism is able to identify this reallocation, send the proper signals to the individuals and coordinate the trades, then we will say that it solves the problem of coincidence of wants.

ii. A second desirable feature of the trading mechanism is to achieve Pareto improving reallocations at low transaction costs. We define low transaction costs as a combination of low trading volumes, few number of transactions and low exposure to undesirable utility changes (e.g. utility reducing interim trades).

The following techniques or institutions have been suggested in the past as alternative coordination devices to determine a coincidence of wants in a pure exchange economy:

1. Barter exchanges [see Edgeworth (1881)].

2. Use of one of the commodities in the exchange as a numeraire [see Walras (1954)].

3. Introduction of money or fiat currency [see Wicksell (1961) and Hirshleifer (1976)].

We suggest a fourth alternative: a smart or computer assisted market.

In a pure exchange economy, "money" is either one of the goods acting as a numeraire or tokens with no consumption value. McCabe (1989), in an experimental study on the use of fiat money, shows that this approach presents serious problems. If the closing date of the market is common knowledge and there is not an overlapping generation, a simple backward induction analysis of the situation yields no trading as the predicted outcome. McCabe found that, as time approaches the closing date of the market, the volume of trade diminishes significantly (in some cases it collapses completely).

The selection of one of the commodities as a numeraire has the potential to eliminate the problem described above concerning the use of fiat money. However, it introduces additional problems. In the numeraire case, agents buy and sell combinations of resources in exchange for a certain amount of the numeraire good. The numeraire acts as a bilateral accounting device. But it might be the case that not every individual has the same preferences over the numeraire commodity. For some agents this good may not be attractive. If those individuals want to execute a utility increasing transaction not involving the numeraire good, they must complete the trade, transact in the numeraire commodity, and thus engage temporarily in a utility reducing trade. This involves the risk of ending at an undesired allocation and might deter individuals from trading.

This paper describes the development and testing of three different exchange institutions that attempt to solve the coordination problem in pure exchange economies. The first, called BARTER, is a computerized bilateral trading process. The second is a variation of BARTER called NUMERAIRE. In this mechanism one of the resources is chosen as a numeraire and all the trades must be expressed in terms of this commodity. Hence individuals buy and sell combinations of resources and pay in the numeraire good. The final variation is called CARE (Computer Assisted Resource Exchange). This mechanism is a sophisticated variation of BARTER. Computer algorithms have been developed that use computing power to assist users finding a coincidence of wants (bilateral and multilateral reallocations of commodities).

A testbed has been designed to evaluate the performance of the three institutions relative to the criteria established above. An environment lacking a bilateral coincidence of wants has been created to test the abilities of the mechanisms to find utility improving reallocations of resources.

To date there exists very little empirical evidence about the performance of pure exchange economies; especially in the absence of a Walrasian Auctioneer. Albin and Foley (1992) develop models to study the performance of bilateral resource exchange in the absence of an auctioneer. They study how individual agents would broadcast costly messages to indicate their desire to trade. Their computer simulation shows that even when the cost of finding trading partners is significant, the efficiency of bilateral trading systems is high. The approach we take is somewhat different. We have designed real institutions[1] and we use human subjects to test the performance of the mechanisms.

The problem described in this paper was generated by a specific application. The motivation for the project is described in the next section. Section 3 describes the common features of the three institutions (the basic algebra of exchange) and the specific rules and procedures for each mechanism. Section 4 contains the parameters of the testbed and the experimental procedures. Section 5 presents the experimental results. We state our conclusions in Section 6.

2 The Cassini Mission: A Motivation for the Problem

NASA is planning to launch, in 1997, the Cassini mission to Saturn. The Cassini mission consists of a spacecraft carrying a suite of scientific instruments that will orbit Saturn and deliver a probe to Titan, one of Saturn's satellites. The mission is being managed by the Jet Propulsion Laboratory (JPL). In the past, the allocation of resources[2] to the instruments was done centrally at the project office. However, unlike previous JPL missions, Cassini is essentially operating under a fixed price commitment from Congress. This fact has motivated a radically different approach to the management of the science instruments. The project has decentralized the instrument resource allocation process through the use of a fixed commitment policy [see Ledyard (1991)].

In general terms, the fixed commitment policy specifies that all the resources available for science instrument development be distributed at the beginning of the instrument development phase. Every team receives a vector of resources and is responsible for developing an instrument that meets specified minimum quality and performance requirements.[3]

The process of the initial assignment to the science teams is done with incomplete and asymmetric information and is likely to produce an inefficient initial allocation. During the development process new information enters the system. The science teams learn with more precision about the resource profiles that are required for the successful

[1]A variation of CARE is being implemented at NASA for the exchange of resources within the CASSINI Mission. The market opens in 1993. See the next section for more details.

[2]An allocation of resources includes amounts of mass, power and data to be provided by the spacecraft during the mission and a profile of funding in different fiscal years to pay for instrument development.

[3]The mission consists of 13 science instruments, a probe and a spacecraft.

development of their science instrument.[4] As a consequence of this learning process an instrument team might want to change its allocation.

A market has been provided to soften the impact of the initial allocation on the efficiency of the system and the quality of the science instruments. A science team that voluntarily wants to change its allocation can trade with other teams using the market. The market is a computerized barter exchange called the Cassini Resource Exchange (CRE). CRE is a variation of the CARE mechanism described in this paper. It resides on an international computer network and can be accessed by members of the instrument teams. The market is now open.

In the Cassini application an extra feature has been included in the market. The allocations given to the science teams includes funding and "physical" resources like mass, power and data. The initial allocation determines a set of design parameters for the spacecraft. Examples of the parameters are: center of gravity and moment of inertia related to mass allocations and thermal constraints related to power consumption. There exists an externality problem because when two instruments trade some of these parameters may change. The instrument manager at JPL must decide if the trade is acceptable and determine, if necessary, compensation for the affected agents.

3 The Market Mechanisms

We have created three computerized institutions to trade resources in a standard multi-dimensional pure exchange economy. The institutions are BARTER, NUMERAIRE, and CARE.[5] Although they have different rules and procedures, they share a core of basic features that we call the basic algebra of exchange. These common features are described in the next subsection. The last three subsections describe the particular characteristics of each mechanism.

3.1 The Basic Algebra of Exchange

Let $S = \{1, 2, \ldots, n\}$ denote the set of resource holders in the economy and $G = \{1, 2, \ldots, m\}$ the set of tradable commodities. Every individual possesses an initial allocation in every commodity. Person i's initial allocation is denoted by the vector $\mathbf{w_i^o} = (w_{i1}^{\bullet}, \ldots w_{im}^{o})$, where w_{ik}^{o} represents the initial amount of commodity k that i owns. The market opens at a time t^{o} and closes at a time t^{*}. This is common knowledge among the resource holders. At any time t, individual i's allocation is denoted as:

[4] During the development phase the science teams not only learn with more precisi●n their preferences over design resources; but they must also adapt to changes in the state-of-the-art technology.

[5] Manuals, software, and documentation can be obtained from the authors.

$\mathbf{w_i(t)} = (w_{1i}(t), \ldots, w_{mi}(t))$. At any time the allocation of every individual is public; i.e., there is complete information about who owns what.

The current allocation of any participant changes with every trade. There is a constraint on the range of allocations that are permissible in the system (and thus in the range of trades that an individual can execute):

$$[R1] \qquad \text{For every } t^* \geq t \geq t^\bullet \;\; \mathbf{w_i(t)} \geq \mathbf{0}$$

i.e., negative allocations in any dimension are forbidden and a trade is to be performed if and only if all the parties have enough resources to pay for their share of the trade. There is no short-selling.

The total amount of resources is fixed in time. $\mathbf{tot_j} = \sum_s w^\bullet_{ji}$ is the total amount of commodity j in the economy. $\mathbf{tot} = (tot_1, \ldots, tot_m)$ describes the dimensions of the commodity space.

If an individual wants to change her distribution of resources, she needs to trade with other individuals. Users list proposed trades, called *bids*, on the system in the hope that some other user will accept them. A bid can be represented as a vector in R^m defined as $\mathbf{x_k} = (x_{k1}, \ldots, x_{km})$. A bid contains the following information:

1. $k \in N$ is the bid number. If two bids are different then they have different bid numbers. Two bids are different if they were placed at a different time or by a different person. In particular, if $\mathbf{x_{k1}}, \mathbf{x_{k2}}$ $k2 > k1$ then $\mathbf{x_{k2}}$ was placed after $\mathbf{x_{k1}}$; i.e., the index k increases with time.
2. Given a bid $\mathbf{x_k}$, if $x_{kj} \geq 0$ for some $j \in G$ then x_{kj} represents the amount of good j requested by the trade. If $x_{kj} < 0$ then x_{kj} is the amount of commodity j offered.

Let $B(t) = \{\mathbf{x_{ka}}, \mathbf{x_{kb}}, \ldots, \mathbf{x_{kr}}\}$ be the finite set that contains all the bids at any given time t. The bid $\mathbf{x_k} \in B(t)$ iff $\mathbf{x_k}$ was placed at a time $t' < t$ and $\mathbf{x_k}$ has not been deleted[6] at a time $t' \leq t$. At any time t, a participant can only accept bids that were not placed by him.

If a bid is accepted a trade occurs. The software executes the desired transfer of resources and updates all the relevant information. Note that an individual accepts a bid if and only if he wants to perform the trade described in the bid.

[6]To delete a bid is to retire it from the set of bids that can be accepted. A bid is deleted if: a) the bid was accepted, or, b) the individual who placed the bid retires it from the system before it is accepted. Some rules describing this point are given below.

Let $Ow(\mathbf{x_k}) : B \rightarrow S$ be a function that maps every bid into the person who placed it.

There is a natural rule concerning the process of deleting bids:

[R2] if $Ow(\mathbf{x_k}) = i$ then only i is able to delete $\mathbf{x_k}$ and i can delete $\mathbf{x_k}$ at t iff $\mathbf{x_k}$ has not been traded at a $t' < t$.

This rule is necessary to ensure consistency in the philosophy of voluntary trading. A trade is to be reversed or nullified if and only if all the parties involved in the operation agree to do so. A trade $\mathbf{x_k}$ can be reversed by executing the opposite operation: $-\mathbf{x_k}$.

[R1] imposes a constraint on the kinds of bids that can belong to $B(t)$. If $\mathbf{x_k} \in B(t)$ and $Ow(\mathbf{x_k}) = i$, then $w_i(t) + \mathbf{x_k} \geq \mathbf{0}$; i.e., i cannot place a bid if he does not possess enough resources to pay for the trade. This follows logically from [R1] and the definition of $B(t)$.

$B_i(t) = \{\mathbf{x_k} | \mathbf{x_k} \in B(t) \text{ and } Ow(\mathbf{x_k}) = i\}$ is the set that contains the standing bids of i at time t. Note that $\bigcup_{i \in s} B_i(t) = B(t)$.

3.2 BARTER

This mechanism, as its name indicates, is a bilateral exchange process. No additional constraints are added to the procedures described in the previous subsection. Every individual can place as many bids as she desires. The only constraint is that she has enough resources to cover the trade described by her bids.

3.3 NUMERAIRE

In this institution, before the opening of the market, one of the commodities is designated as the numeraire. The same commodity is used as the numeraire for the entire operational life of the market. Hence, individuals buy and sell combinations of resources and pay or are paid in the numeraire good.

NUMERAIRE provides a bid-ask spread for every dimension. Appendix C contains examples of different computer screens and data formats for market data for BARTER, NUMERAIRE and CARE.

It is important to realize that strictly speaking NUMERAIRE is a subset of BARTER. Every NUMERAIRE bid and acceptance can be executed in BARTER but the opposite is not true.

3.4 CARE: Algorithms and Underlying Principles

The concepts of placing, accepting and deleting bids are the fundamental features of the market; the cornerstones that make possible the voluntary exchange of resources. Nevertheless, there are two severe obstacles that may impede the performance of the market: the difficulty in finding a coincidence of wants and an excessive amount of information processing. As the number of resources in the economy increases, the probability of finding a utility increasing bilateral transaction decrease. Because an individual must take into account all the possible trades that he could execute in order to select the best option in the market, the limited capability of the human mind might impede the optimal performance of the market.

CARE deals with these problems. A smart unit is a procedure or algorithm that takes the information available in the system and transforms it into a specific format. It provides every user with a set of tools that facilitates the search of information in the message space.

SMART UNIT I: The Set of Potential Bids

At any time t, the set of i's standing bids $B_i(t)$ can be transformed into the set $B_i^*(t)$ that contains the set of all the potential bids that i is offering. Note for example, that if $i \in S$ is offering two bids $\mathrm{x_k}$ and $\mathrm{x_h}$ then i is willing to reach any of the following allocations:

$$\begin{array}{rl} \text{i.} & \mathrm{w_i} + \mathrm{x_k} \\ \text{ii.} & \mathrm{w_i} + \mathrm{x_h} \\ \text{iii.} & \mathrm{w_i} + \mathrm{x_k} + \mathrm{x_h}. \end{array}$$

The process to generate $B_i^*(t)$ is given by:

1. Let $B_i'(t) = \{C | C \subseteq B_i(t),\ C$ is not the empty set$\}$. This set contains all the subsets of i's bids that could be traded simultaneously.

2. Given $C = \{\mathrm{x_1}, \mathrm{x_2}, \ldots, \mathrm{x_m}\}$ s.t. $\mathrm{x_i} \in R^m, \sum(C) : C \rightarrow R^m$ is a function given by $\mathrm{sum}(C) = \sum_c \mathrm{x_k}$. Let $B_i''(t) = \{\mathrm{x_k} | \mathrm{x_k} = \mathrm{sum}(C)$ for all $C \in B_i'(t)\}$. This step combines all the subsets above into one bid.

3. Let $B_i'''(t) = \{\mathrm{x_k} | \mathrm{x_k} \in B_i''(t)$ and $\mathrm{w_i} + \mathrm{x_k} \geq 0\}$. This step verifies that [R1] is not violated by any combination of bids.

4. Let $B_i^*(t) = \{\mathrm{x_k} | \mathrm{x_k} \in B_i'''(t)$ and $\mathrm{tot} \geq \mathrm{w_i} + \mathrm{x_k}\}$. This last step excludes bids that are asking for an amount of resources greater than the quantity available in

the economy. It eliminates non-feasible trades. In the example above $B_i^*(t) = \{\mathbf{x_k}, \mathbf{x_h}, \mathbf{x_k} + \mathbf{x_h}\}$.

The purpose of these algorithms is:

(a) The user is able to verify how his standing bids and their contingencies map into possible final allocations.

(b) The set $B_i^*(t)$ is required for the generation of chains (a procedure described below).

SMART UNIT II: The Set of Potential Trades

At any given time an individual $i \in S$ is faced with a set of potential trades that is the result of all the possible combinations of subsets of bids of the other players.

Let $C_i(t) = \{\mathbf{x_k} | \mathbf{x_k} \in B_j^*(t) \text{ for some} j \neq i\}$, the set containing all the proposed trades facing i. $C_i(t)$ can be transformed into $F_i^*(y)$, the set that contains all the possible allocations that i can reach as a result of accepting a feasible combination of bids by other players.

The procedure to generate this set is the following:

1. Let $C_i^*(t) = \{G | G \subseteq C_i(t) \text{ and if } \mathbf{x_k}, \mathbf{x_h} \in C_i^*(t) \text{ then } Ow(\mathbf{x_k}) \neq Ow(\mathbf{x_h})\}$. This set generates subsets of $C_i(t)$ that do not contain more than one bid per player. It is important that two bids of a same player are not included because $B_j^*(t)$ already contains all the possible combinations of bids that j is offering.

2. Let $D_i^*(t) = \{\mathbf{x_k} | \mathbf{x_k} = \text{sum}(G) \text{ for all } G \in C_i^*(t)\}$.

3. Let $E_i^*(t) = \{\mathbf{x_k} | \mathbf{x_k} = \in D_i^*(t) \text{ and } w_i + w_k \geq 0\}$. This step eliminates allocations that individual i cannot afford.

4. Let $F_i^*(t) = \{\mathbf{x_k} | \mathbf{x_k} \in E_i^*(t)$ and for all $\mathbf{x_k} \in F_i^*(t)$ there does not exist $x_h \in F_i^*(t)$ such that $\mathbf{w_i(t)} + \mathbf{x_h} \geq \mathbf{w_i(t)} + \mathbf{x_k}$ and for some commodity j, $(\mathbf{w_i(t)} + \mathbf{x_h})_j > (\mathbf{w_i(t)} + \mathbf{x_k})_j\}$. This operation excludes a bid $\mathbf{x_k}$ if there exists a bid x_h that is a strictly better for i than $\mathbf{x_k}$.

The purposes of this procedure are:

a) A user looking for a favorable trade is presented with a "purified" set of all possible final allocations. It is then straightforward to choose the trade in $F_i^*(t)$ that maximizes the user preferences.

b) It assists i in generating his bidding strategy because it contains all the information about other individuals' stated preferences or proposed trades.

c) $F_i^*(t)$ is used in the generation of the chain algorithm that we will discuss next.

SMART UNIT III: Chains

The concept of chains is most easily introduced with an example. Assume $\mathbf{x_1} = (10, 0, -10)$, $\mathbf{x_2} = (0, -10, 15)$, $\mathbf{x_3} = (-10, 10, -5)$, $Ow(\mathbf{x_1}) =$ Wes, $Ow(\mathbf{x_2}) =$ Frank and $Ow(\mathbf{x_3}) =$ Tom. Furthermore, assume that these are the only bids in the market. The reader can easily verify that $\mathbf{x_1} + \mathbf{x_2}$, $\mathbf{x_1} + \mathbf{x_3}$, and $\mathbf{x_2} + \mathbf{x_3}$ are all different from 0 implying that no one in the economy is able to improve his allocation through bilateral trading with another resource holder. Nevertheless, $\mathbf{x_1} + \mathbf{x_2} + \mathbf{x_3} = \mathbf{0}$. This is a perfect example of a lack of bilateral coincidence of wants. The sum of wants equals to the sum of offers (see Figure 1 below).

[Figure 1 about here]

Given $\mathbf{x_k} \in B_i^*(t)$ and $\mathbf{x_h} \in F_i^*(t)$, the two element set $\{\mathbf{x_k}, \mathbf{x_h}\}$ is an i-chain if $\mathbf{x_k} + \mathbf{x_j} = \mathbf{0}$. $Ch_i^*(t) = \{\{\mathbf{x_k}, \mathbf{x_h}\} \,|\, \{\mathbf{x_k}, \mathbf{x_h}\}$ is an i-chain as defined above $\}$. To generate this set it is necessary to take every potential bid that i is offering and add it to every potential trade that i is facing. If they add up to zero then the chain is included in $Ch_i^*(t)$. If $\mathbf{x_k} + \mathbf{x_h} \geq 0$ then for a subset of the agents the sum of the offers is greater than the sum of the wants. In this case $\mathbf{x_k} + \mathbf{x_h} \in F_i^*(t)$ (the set of potential trades facing i) for every individual i. Anyone can pick up the surplus by executing the trade.

CARE: Rules and Procedures

The three smart units described above are algorithms included to enhance the performance of the market. As a mechanism, these smart units are a group of simple operations over sets. But although their definition and interpretation present no conceptual problems, their implementation into a computer program is not so trivial.

CARE easily generates the first two procedures. The chain algorithm is the unit that presents some implementation problems. The challenge is not the complexity of the operations required to generate the chain-set but the number of computations. Let a market have m resource holders placing n bids. The number of computations required is approximately (for $n \geq 2$):

$$\sum_{k=2}^{n} \frac{n!(2^m - 1)^k}{(n-k)!k!}$$

This number increases exponentially in both n and m.

CARE is the combination of BARTER, the three smart units and a few rules regarding the process of placing and deleting bids in the market. The set of rules described below reduces the number of bids that an agent can place and thus it reduces the number of combinations necessary to generate chains. These rules force individuals to act in a way that enhances orderly convergence to a trade. These rules are generalizations of the bid-ask-spread improvement rule found in the double-auction mechanism. We selected these rules because the double-auction mechanism has been found to generate high efficiencies in the laboratory [see Smith (1982)]. The rules are:

RULE I: THE PLACEMENT OF BIDS

a) At any given time any individual may have only one standing bid in the market (the purpose of this rule is to reduce the number of computations).

b) At the opening of the market, every individual i has a default bid $\mathbf{z_i} = \mathbf{0}$.

c) Any person can modify his standing bid but he must comply with the following IMPROVEMENT RULE:
Let x be the standing bid and y be the new bid. y is acceptable if and only if $\sim (\mathrm{y} > \mathrm{x})$.
i.e., to ask for more in one dimension the individual must reduce the request in another dimension.

RULE II: UPDATING THE SYSTEM

a) Every time there is a trade all the bids are set into the default bid ($\mathbf{z_i} = \mathbf{0}$).

b) Every time a bid changes, CARE updates all the information (smart units, accounting, etc.) using the new bid information.

RULE III: TRADING

a) Any person can accept at any time a bid from the set of potential trades facing him or a chain from her i-chair set.

4 Experimental Design

4.1 Parameters of the Testbed

Our objective is to compare the performance of the three market institutions described above. This requires the use of a common testbed.

We create a six-person-three-commodity pure exchange economy. We generate the preferences with induce values [see Smith (1976)] by providing monetary payments to subjects proportional to their final utility. The amount paid is equal to the value of their respective payoff functions at the allocation held when an experimental period ends. The induced value functions that we use are a combination of a Cobb-Douglas utility function and a step function in one of the dimensions. Table 1 shows the initial allocation and payoff functions of three types of subjects. Individuals 1 and 4 are called type one traders; 2 and 5 are type two traders and 3 and 6 are type three traders. Notice that if agents face positive price vectors, the type 1 traders do not buy or sell A, type 2 traders do not deal in B, and type 3 traders do not exchange C.

[Table 1 about here]

The system has a competitive equilibrium (C.E.). The payoffs are normalized so that every individual makes 7 dollars at the C.E. and zero dollars at the initial allocation. Table 2 contains the C.E. prices with commodity C as the numeraire. Table 3 describes the competitive equilibrium transactions for each trader type. Notice that the C.E. reallocation cannot be reached using only bilateral utility increasing trades. All the feasible utility increasing trades take the form of chains. This is the most important feature of the design because we want to test the relative performance of the mechanism under a severe coincidence of wants problem. Note that if the CE allocation is to be represented by one trade, this trade must be executed in the form of a chain.

[Table 2 and Table 3 about here]

4.2 Experimental Procedures

Subjects were recruited from the undergraduate population at Caltech. A prerequisite to be in the experiment was to have participated in a training session the day prior to the experiment. In the training session the individuals learned the market procedures of the mechanism being tested and the structure of the experiment. They were familiarized with the software and received their initial allocations and payoff functions. The subjects received five dollars for participating in the training session.

Every mechanism was tested for 12 experimental periods. An experimental period is structured as follows:

1. At the beginning of the period every individual is given her respective initial allocation.
2. At $t = 0$ the market opens.
3. At $t = 20$ minutes the market closes. For every player, the payoff for the experimental period is determined by the final allocation of that period.

A given group of six individuals participated in four consecutive experimental periods of a given mechanism. Hence, 18 different people participated in the testing of each institution for a total of twelve periods per institution.

The players' total earnings for participating in the experiment is equal to the sum of the payoffs in the four experimental periods plus the five dollars for the training session. The subjects were paid at the end of the experiment.

Note the following points about the information distribution in the system:

1. Although the players might know the identity of the other players, all the communication is done through computer terminals.
2. The only private information is the individual's payoff function.

The instructions consisted of two parts. The first part was a description of the experiment. Appendix A contains a copy of a typical package handed to a participant. A set of instructions, payoff sheet, computer passwords, and login instructions and an accounting sheet was included. The second part was necessary to teach the subjects how to use the software. A fifteen minute demonstration plus a ten minute practice period for the subjects was provided.

5 Experimental Results

In this section we analyze the results of the experiments described in Section 4. We have divided the presentation in four subsections dealing with trading efficiency, trading dynamics and final allocations, and competitive equilibrium predictions. The lost subsection provides a summary of the experimental results.

5.1 Efficiency Measures

We look at two possible measures of efficiency. The first one is the coefficient of resource utilization (CRU) [see Debreu (1951)]. The other one is the Euclidean distance between a point in the commodity space and the competitive equilibrium allocation defined by the point.

5.1.1 CRU: a measure of resource utilization.

Let $\mathbf{x} = (\mathbf{x}^1, \ldots, \mathbf{x}^n)$ be an allocation for the economy, $\mathbf{x}^*$ the allocation for which we want to compute the CRU, $\mathbf{p}^e(\mathbf{x}^*)$the CE-price vector at $\mathbf{x}^*$ and $\mathbf{tot}$ the dimensions of the Edgeworth Box. The CRU is of the economy calculated as follows:

$$CRU(\mathbf{x}^*) = \frac{V(\mathbf{x})}{\mathbf{p}^e(\mathbf{x}^*) \cdot \mathbf{tot}}$$

where

$$V(\mathbf{x}) = \min_{\mathbf{x}} \sum_{i=1}^{n} \mathbf{p}^e(\mathbf{x}^*) \cdot \mathbf{x}^i$$

subject to:

$$\begin{array}{ll} i) & u^i(\mathbf{x}) = u^i(\mathbf{x}^*) \\ ii) & \mathbf{x} \leq \mathbf{x}^* \end{array}$$

[$u^i(\cdot)$ is the utility of person i.]

Thus, the CRU is a measure of the maximum value of resources, weighted by the CE-price vector, that are being wasted in the economy. Notice that the CRU takes values between 0 and 1, and that the CRU is equal to one only at a Pareto optimal allocation. A low value of CRU implies that valuable resources are being wasted because we can find a reallocation in which everybody stays on the same indifference curve without utilizing all the available commodities.

Figure 2 shows the mean per period CRU for each mechanism. Notice that if the CRU is one, then all the gains from exchange have been extracted and the value of the net gains from exchange (NGFE) would be one. We define the net gains from exchange for a particular allocation as the percentage of the gains from exchange that have been extracted. It is calculated as follows:

$$NGFE = \frac{\text{Final CRU - Initial CRU}}{0.15}$$

where 0.15 is the maximum possible increase of the CRU. Notice that each trading system results in high levels of the CRU. That should be expected since the CRU at the initial allocation is 0.85. From Figure 2 it is clear that each institution is extracting some gains from exchange.

[Figure 2 about here]

Result 1: Compared to BARTER and CARE, the NUMERAIRE mechanism results in the largest amount of resource waste.

Support:
The average CRU and the average net gains from exchange for each mechanism is provided below:

Mechanism	Average CRU	Average Net Gains from Exchange
CARE	.99	.93
BARTER	.98	.87
NUMERAIRE	.94	.6[illegible]

A paired comparison of the CARE and BARTER mechanisms against NUMERAIRE yields a t-statistic of 1.91 (p-value of .06).

Result 2: There is no change in the CRU for CARE and BARTER over time.

Support:
The average CRU for periods 1 and 2 versus periods 3 and 4 is provided below:

Mechanism	Average CRU Periods 1-2	Average CRU Periods3-4
CARE	.99	.99
BARTER	.98	.98
NUMERAIRE	.95	.93

5.1.2 Euclidean distance to the C.E.

As an extension of the notation used above, let $\mathbf{x}^{\mathbf{e}}(\mathbf{x}^*)$ denote the CE-allocation determined by $\mathbf{x}^*$. The new measure of efficiency denoted by $D(\mathbf{x}^*)$ is given by:

$$D(\mathbf{x}^*) = [(\mathbf{x}^* - \mathbf{x}^{\mathbf{e}}(\mathbf{x}^*)) \cdot (\mathbf{x}^* - \mathbf{x}^{\mathbf{e}}(\mathbf{x}^*))]^{1/2}$$

$D(\mathbf{x}^*)$ is equal to zero only at a Pareto optimal allocation. A bigger value of $D(\mathbf{x}^*)$ indicates a lower efficiency. The value of the coefficient at the initial allocation is 472. Figure 3 shows the time series for the coefficient.

[Figure 3 about here]

Result 3: The distance-efficiency measurements for CARE indicate a much higher distance-efficiency than BARTER or NUMERAIRE.

Support: See Figure 3.

Result 4: For CARE, the value of $D(\mathbf{x}^*)$ improves with time. The $D(x^*)$-time series for BARTER and NUMERAIRE do not exhibit any clear trends.

Support: See Figure 3.

In our experiments each measure provides the same ordinal ranking of the institutions. In decreasing level of efficiency the ranking is: CARE, BARTER, and NUMERAIRE. But if we consider net gains from exchange and distance efficiency, CARE shows significantly larger cardinal values.

5.2 Trading Dynamics and Final Allocations

Although the three mechanisms exhibit strong tendencies not to waste resources, the final allocation and the trading paths are quite different.

In each mechanism, when a trade occurs each party to the trade moves to a new level of utility. Figure 4 shows distribution of the changes in utility per trade for each trading mechanism. The boxplots show the median, inter and outer quartiles, along with the 10 and 90 percent outlyers.

[Figure 4 about here]

Result 5: In both the BARTER and NUMERAIRE trading mechanisms agents engage in a significant number of utility reducing trades during the trading period. The distribution tightens with experience, but large changes in utility are required to reach the final allocation. In contrast, CARE allows traders to reach an efficient allocation without exposing themselves to large swings in utility (most trades are utility increasing for CARE).

Support: See Figure 4.

In terms of final utility positions we find that each mechanism behaves quite differently. Table 4, provides the final utility (earnings position) for each of the trader types. Recall that, at the competitive equilibrium, profits should be equalized at seven dollars across trader types.

[Table 4 about here]

From Table 4 we obtain the following results:

Result 6: Each of the exchange mechanisms has wide ranges in profits for each trader type. The largest spreads occur in NUMERAIRE and then BARTER.

Result 7: Each of the mechanisms end up at profit positions by trader type that are significantly different. For NUMERAIRE, net suppliers of the numeraire, at the C.E., fare significantly better than net demanders of the numeraire.

Result 8: Each of the mechanisms exhibits significant changes across periods. The profit range tightens and the profit differences across types decreases. CARE exhibits the strongest tendency towards profit equality over time.

Each mechanism takes a very different trading path. It is also clear from results 5-8 that each institution generates a different final allocation. In order to organize the data, and take into account these differences, two specific models are proposed. The first, and most obvious model, is the competitive equilibrium prediction. The second uses the strategic Nash equilibrium prediction of underrevelation of demand and supply [see Hurwicz (1972) and Otani and Sicilian (1990)].

5.3 Competitive Equilibrium Predictions

5.3.1 Allocations

For our experimental testbed the Competitive Equilibrium provides a precise prediction of the final allocation that should be achieved. Hence, it also provides predictions on the direction each trader type should move in order to reach the C.E.

5.3.1.1 Final Trader Positions

In Figure 5 we show the deviation from the CE of the final allocations for each of the trading mechanisms and trader type. Recall that type 1 traders only trade in goods B and C, type 2 trades in goods A and C, and type 3 in goods A and B.

[Figure 5 about here]

From Figure 5 we obtain the following result:

Result 9: In all the trading mechanisms the traders move in the direction of the C.E. Experience also moves the allocations closer to the C.E. in all the mechanisms. However, CARE provides the smallest deviations from C.E. and NUMERAIRE the largest. The dispersion of outcomes around the C.E. are large for all the mechanisms.

Result 10: The final allocations are different by trader type and mechanism with under revelation by type 3 trades in CARE and type 1 traders in NUMERAIRE. BARTER shows no major underrevelation properties.

Support: See Table 5. It describes the mean deviation from the predicted allocation at the CE by trader type and mechanism.

[Table 5 about here]

5.3.1.2 Relative Prices

The following regression was estimated for each trading mechanism:

$$C_{jt} = \alpha A_{jt} + \beta B_{jt} + \epsilon$$

where C_{jt} is the C amount provided in trade j in period t. The equilibrium predictions are : α= -1.72; β= -1.66. Table 6 supplies the estimates of α and β.

[Table 6 about here]

Result 11: We cannot reject that the BARTER and CARE prices are equal to the competitive prices; they are significantly different for NUMERAIRE.

Support:
The 95% confidence intervals for period 4 are given below:

Mechanism	α	β
CARE	(-1.35,-1.95)	(-1.22,-1.60)
BARTER	(-1.70,-2.06)	(-1.47,-1.91)
NUMERAIRE	(-1.30,-1.42)	(-1.30,-1.50)

The selection of a numeraire good significantly reduces the relative prices in the NUMERAIRE mechanism and thus provides profits to those who are net sellers at the competitive price. Indeed, this implies that there is potential underrevelation on the part of the net sellers of the numeraire. The time series of trades can be found in Appendix B.

5.3.2 Volume of Trade

In order to reach the competitive equilibrium predicted allocation a certain volume of trading must occur. Table 6 describes the volume of trading at the C.E. allocations and the average volume of trading in each mechanism.

[Table 7 about here]

Result 12: In terms of the average volume of trading, CARE is closest to the C.E. prediction. However, for every dimension and mechanism the volume of trade is greater than the CE-predicted volume of trade.

Support: See Table 7.

Result 13: The composition of the volume of trade is different across the mechanisms. Since good C was selected as the numeraire, it shows significant volume in the NUMERAIRE mechanism. However, the volume of trade is lower for good, A and B with the NUMERAIRE. The total volume of trade is lowest with CARE.

Support: See Table 7.

Result 14: There is a significant increase in the volume of trade over time with NUMERAIRE, but not for BARTER or CARE.

Support: The average volumes for the last period of the experiments are provided in Table 8.

[Table 8 about here]

Recall, with CARE individuals can execute chains. Figure 6 shows the distribution of contracts in terms of chain behavior (1-chains are bilateral trades, 2-chains are three person trades, etc.).

Result 15. With CARE, over 40% of the trades are 3 or 4 person chains. However the majority of trades are bilateral.

Support: See Figure 6.

[Figure 6 about here]

5.4 Experiment Summary: What Was Learned From the Experiments?

The experiments were designed to test the most basic trading mechanisms in an environment where there is a significant lack of a coincidence of wants. In addition, the exponents provided a method to determine a proof of concept for a new and untested "smart market" — CARE. First, the CARE system posed no major learning issues for participants. In terms of the experimental results CARE consistently outperformed BARTER and NUMERAIRE in terms of gains from exchange, transactions volume, smooth changes in utility positions, and relative profitability of traders. Thus, we have developed an institution that holds the promise of coping with the cost and imperfections associated with pure barter-type exchanges. In the process of comparing the performance of the basic trading institutions, we have found that the use of a numeraire good as a bilateral coordination and account device hampers barter exchange due to the strategic underrevelation abilities of those who placed a relatively high use value on the numeraire.

6 Conclusions

To date very little evidence exists on the performance of barter and numeraire trading institutions. This paper fills that gap by supplying an experimental examination of these mechanisms in a pure exchange setting in which utility increasing trades must occur in three-person, three good transaction chains. Since the main problem facing an institution in a pure exchange environment is solving the coincidence of wants problem, we created a computer-assisted pure exchange trading mechanism (CARE) that determines trading chains and allows users to execute combinations of bilateral trades simultaneously.

The data from our experiments demonstrate that although these mechanisms tend to exhaust the gains from exchange: they extract these gains in entirely different ways. CARE and BARTER are similar but CARE has fewer contracts and volume, lower utility swings from trades, and tighter profit distributions. NUMERAIRE does not provide the type of coordination needed to smooth the market. Those individuals for which the numeraire does not provide direct utility do much better than those individuals who are net demanders of the numeraire.

The motivation for our investigation is the market established by the Jet Propulsion Laboratory (JPL) for the exchange of Cassini mission resources (mass, power, data rate, and instrument development funding) among science teams. In that market trades will likely involve series of science teams exchanging packages of resources (they will be multilateral allocations). The algorithms and procedures used in the CARE mechanism have been implemented into the Cassini Resource Exchange.

Computer assisted markets, such as CARE, are likely to emerge in the future. The allocation of resources internal to a firm and across divisions are potential candidates for such a mechanism. Immediate applications could include the market for the swaps of financial instruments (e.g. interest rate and foreign exchange) and the trading of packages of environmental emissions. As more and more applications utilizing market mechanisms to solve resource allocation problems are brought forward, new and improved institutions will be required. The power of the computer and the development of fast search algorithms can enhance the performance (lower the transactions costs) of proposed allocation schemes.

Appendix A

INSTRUCTIONS

a. Timing of the Experiment

This experiment lasts for two hours. During these two hours we are going to run four identical periods. Every period will run for twenty minutes.

b. Description of the Experiment

The following is a description of a trading period. (Recall that you are going to participate in four trading periods.)

You have been given an initial allocation in three fictitious commodities. These commodities are labeled: A, B, and C. There are five other participants in the experiment. Each one of them has been given an initial allocation in these three commodities.

Your package contains a payoff function that translates your allocation of resources into payoffs convertible into U.S. dollars. You make money by increasing the value of your payoff function. The only way to do this is to make trades with the other participants. Your payoff table is your own private information. It is very important that you do not reveal your payoff table to the other participants.

How do you trade? You can make trades with other participants using your computer. In a few moments the experimenter will show you how to use the system.

All the trades must be expressed in terms of the commodity C. Hence you buy combinations of commodities A and B and pay in C and sell combinations of A and B and get paid in C.

Example:

1.	BUY A	Bid
	Want 10 A	10 A
	Offer 5 C	-5 C
2.	SELL A	Bid
	Want 10 C	10 C
	Offer 10 A	-10 A
3.	SELL A AND BUY B	
	Sell A for C	
	Buy B using C	

The program restricts you to hold only non negative allocations in every commodity.

The structure of a trading period is the following:

Minute	Description
0	The market opens. Each participant is given their initial allocation of A, B, and C.
0-20	Participants place bids and make trades.
20	The market closes. No more bids are to be placed or trades to be performed. Your payoff for the period is fixed by your final allocation. The market is reinitialized to your original allocation.

Your earnings for the experiment are the sum of the individual payoffs for the four periods plus a five dollars bonus for participating.

c. Remark

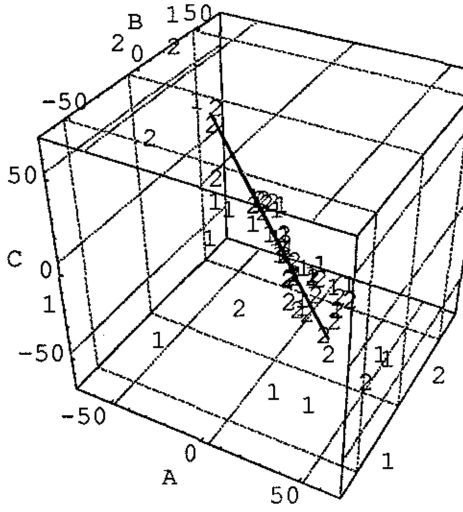
This experiment runs under the honor system. You are not allowed to show your payoff function to the other players, or to collude, or to form cartels, etc.

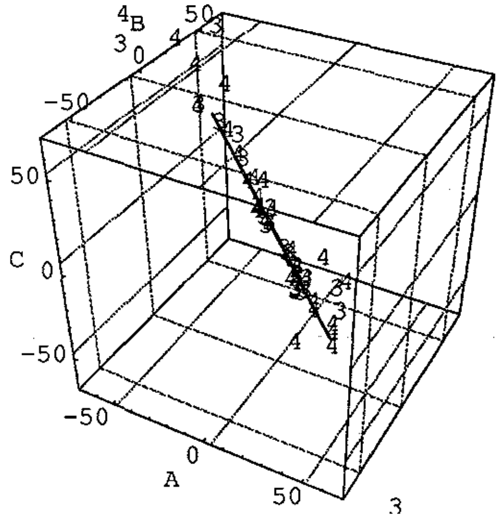
Appendix B

Notes: Trades are listed as a 3 tuple (A,B,C) where a negative number is the amount offered in the trade and a positive number is the amount received from the trade. The numbers in the graphs correspond to the period the contract was made and the line in the figure is the Competitive Equilibrium price prediction.

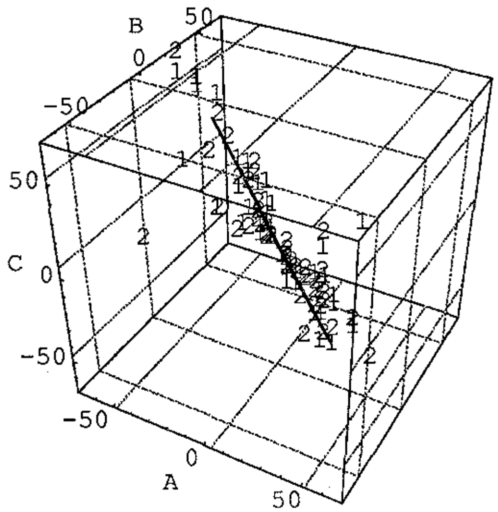
Appendix B

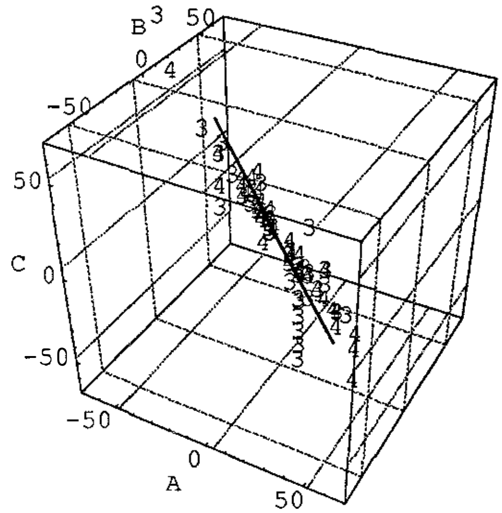
Barter Experiments



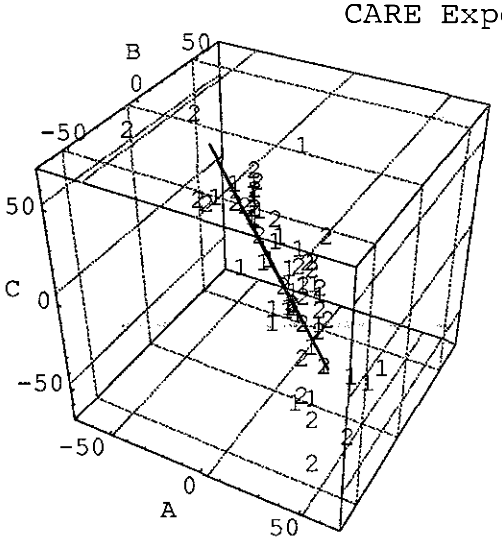


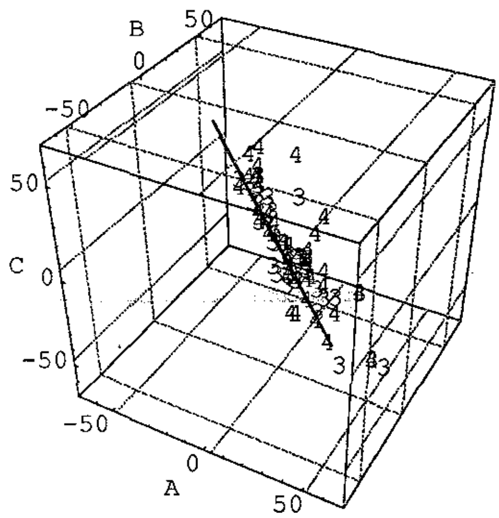
Numeraire Experiments





CARE Experiments



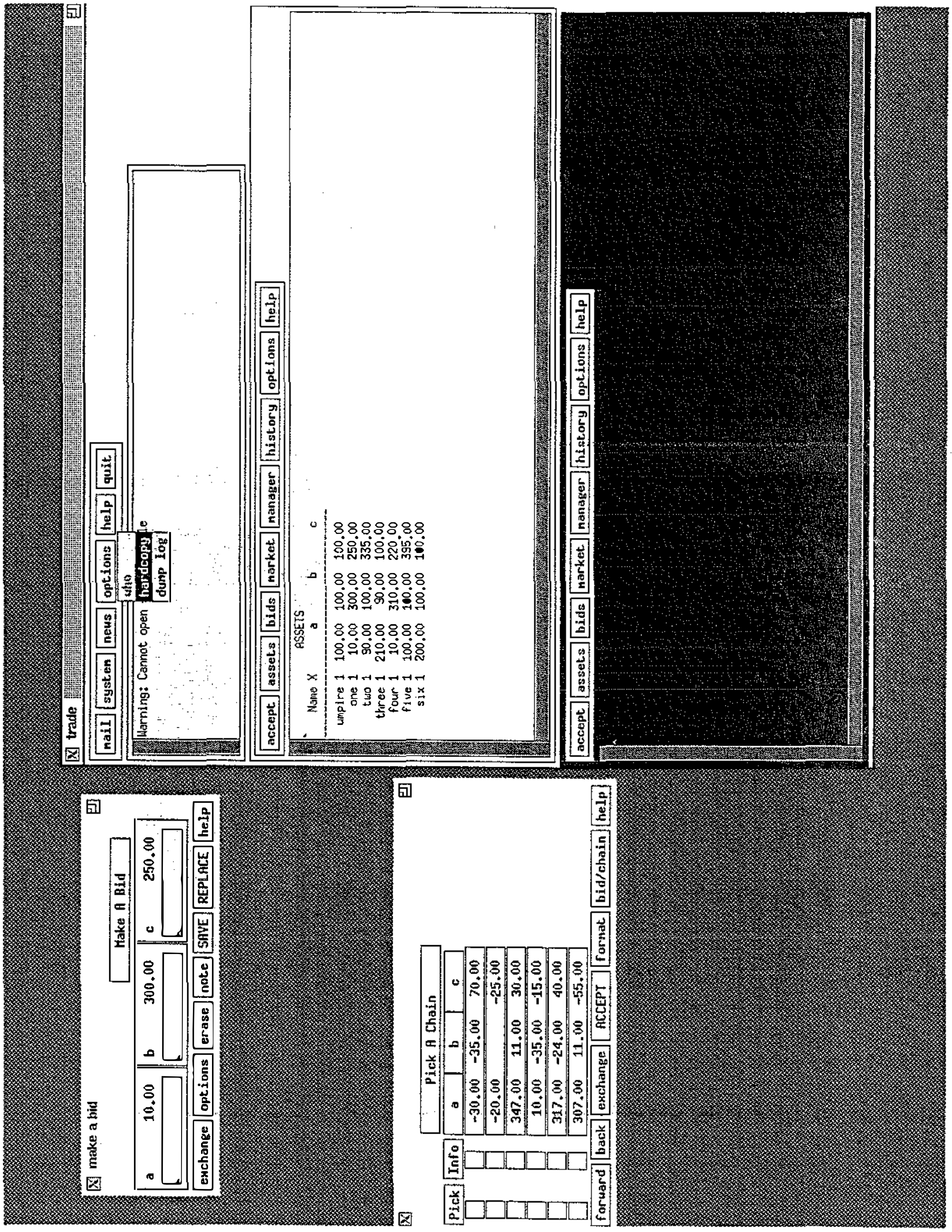


1 - Period 1
2 - Period 2
3 - Period 3
4 - Period 4

______ **CE Price**

Appendix C

Basic computer trading screens used by subjects in the experiments.


trade
mail
system
news
options
help
quit
who
hardcopy
dump log
Warning: Cannot open
accept
assets
bids
market
manager
history
options
help
ASSETS
Name X a b c
umpire 1 100.00 100.00 100.00
one 1 10.00 300.00 250.00
two 1 90.00 100.00 335.00
three 1 210.00 90.00 100.00
four 1 10.00 310.00 220.00
five 1 100.00 100.00 395.00
six 1 200.00 100.00 100.00
make a bid
Make A Bid
a 10.00
b 300.00
c 250.00
exchange
options
erase
note
SAVE
REPLACE
help
Pick A Chain
Pick
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a b c
-30.00 -35.00 70.00
-20.00 -25.00
347.00 11.00 30.00
10.00 -35.00 -15.00
317.00 -24.00 40.00
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ACCEPT
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bid/chain
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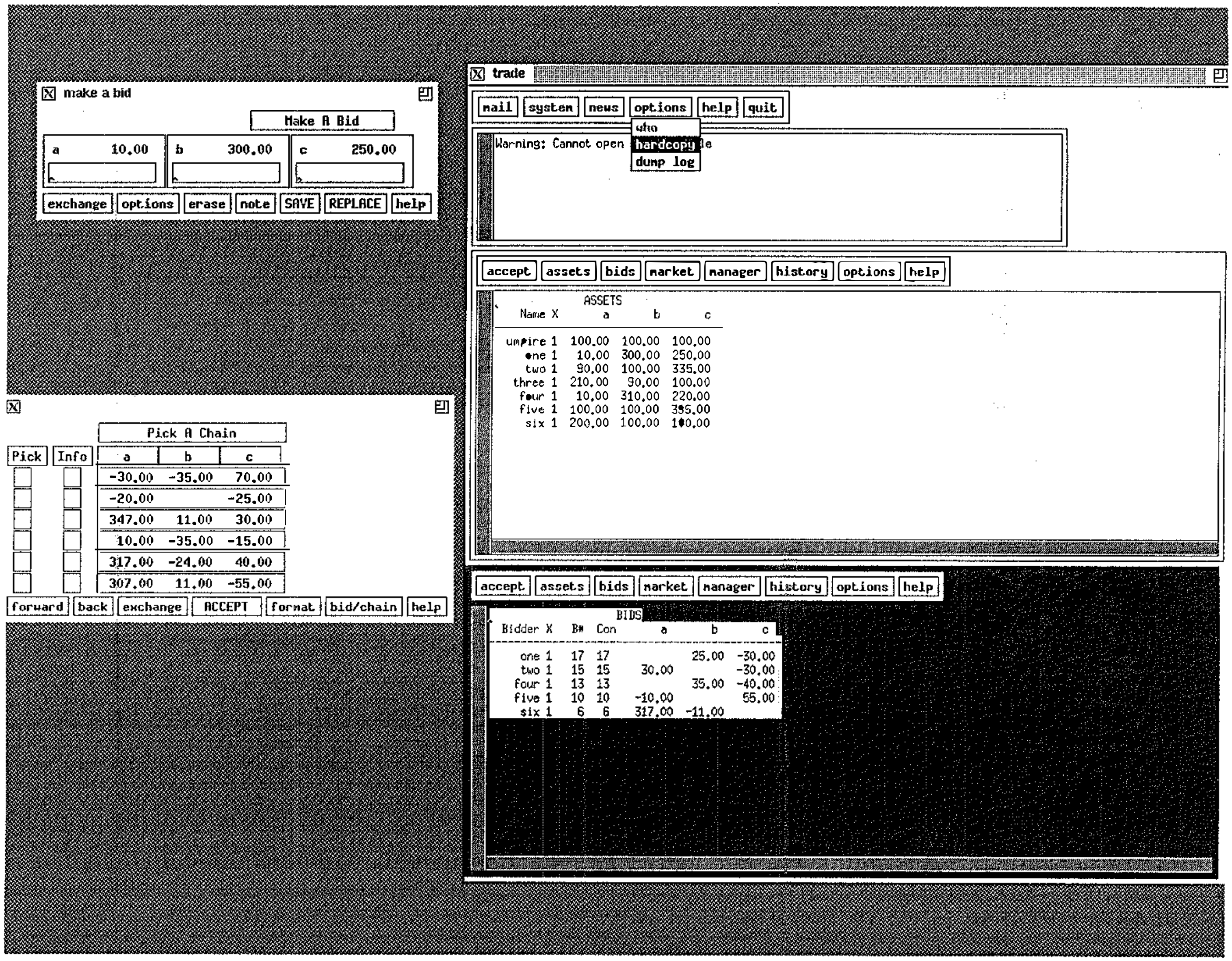
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10.00 -35.00 -15.00
317.00 -24.00 40.00
307.00 11.00 -55.00
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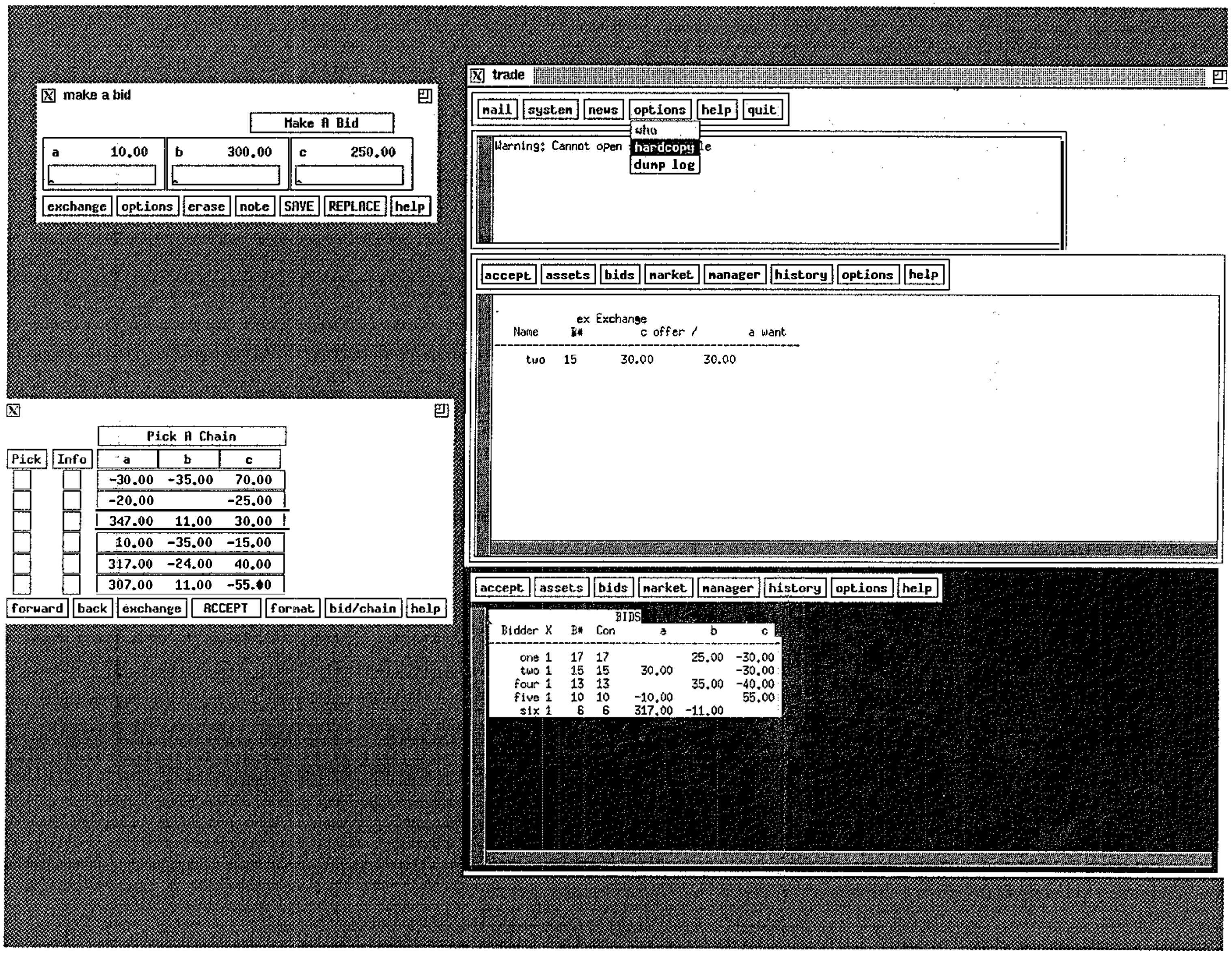
accept assets bids market manager history options help
BIDS
Bidder X B# Con a b c
one 1 17 17 25.00 -30.00
two 1 15 15 30.00 -30.00
four 1 13 13 35.00 -40.00
five 1 10 10 -10.00 55.00
six 1 6 6 317.00 -11.00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Make A Bid
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Pick A Chain
Pick
Info
a b c
-30.00 -35.00 70.00
-20.00 -25.00
347.00 11.00 30.00
10.00 -35.00 -15.00
317.00 -24.00 40.00
307.00 11.00 -55.00
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ACCEPT
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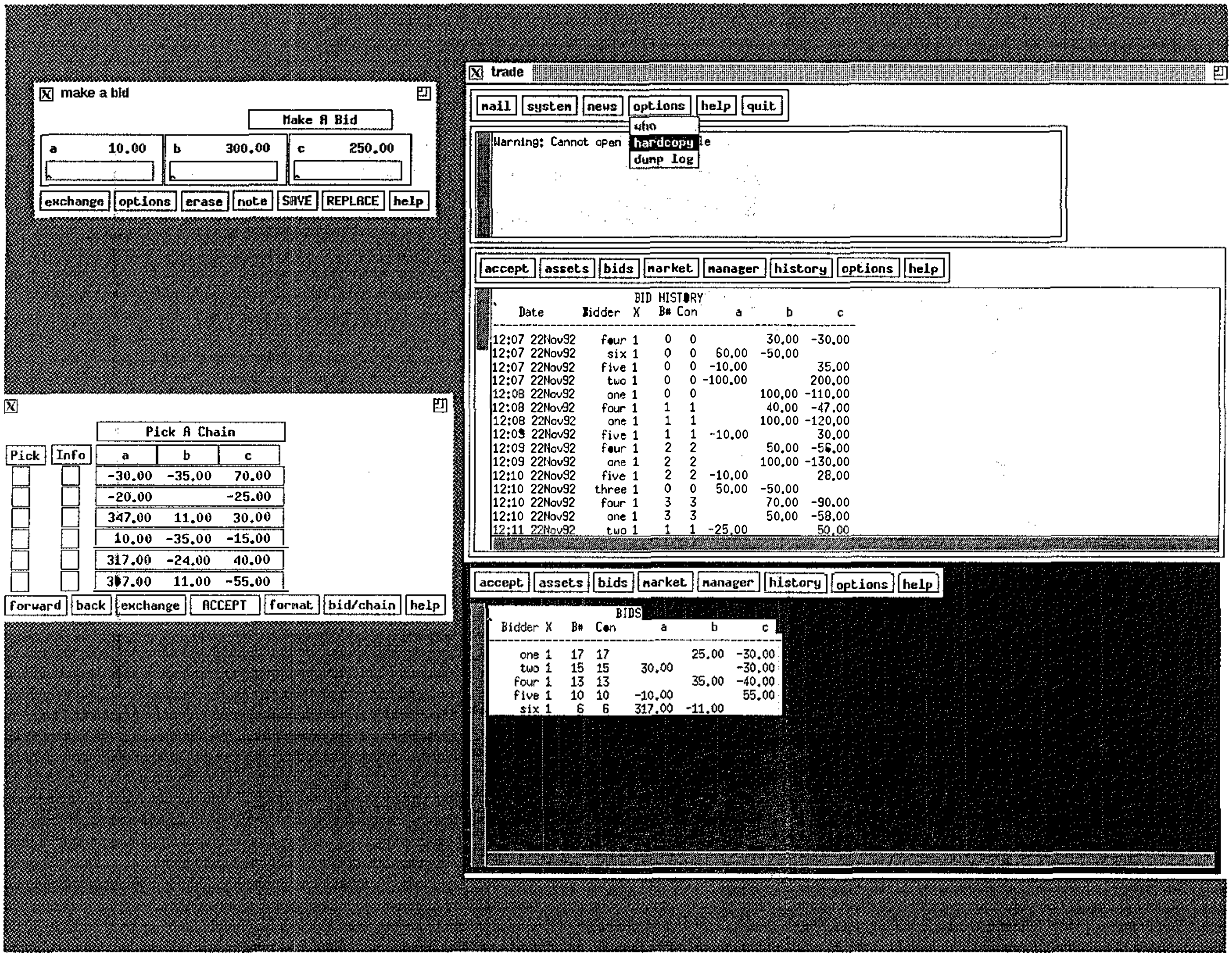
BIDS
Bidder X B# Con a b c
one 1 17 17 25.00 -30.00
two 1 15 15 30.00 -30.00
four 1 13 13 35.00 -40.00
five 1 10 10 -10.00 55.00
six 1 6 6 317.00 -11.00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Make A Bid
a 10.00
b 300.00
c 250.00
exchange options erase note SAVE REPLACE help
Pick A Chain
Pick Info a b c
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-20.00 -25.00
347.00 11.00 30.00
10.00 -35.00 -15.00
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3?7.00 11.00 -55.00
forward back exchange ACCEPT format bid/chain help
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mail system news options help quit
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Warning: Cannot open
accept assets bids market manager history options help
BID HISTORY
Date Bidder X B# Con a b c
12:07 22Nov92 four 1 0 0 30.00 -30.00
12:07 22Nov92 six 1 0 0 60.00 -50.00
12:07 22Nov92 five 1 0 0 -10.00 35.00
12:07 22Nov92 two 1 0 0 -100.00 200.00
12:08 22Nov92 one 1 0 0 100.00 -110.00
12:08 22Nov92 four 1 1 1 40.00 -47.00
12:08 22Nov92 one 1 1 1 100.00 -120.00
12:09 22Nov92 five 1 1 1 -10.00 30.00
12:09 22Nov92 four 1 2 2 50.00 -56.00
12:09 22Nov92 one 1 2 2 100.00 -130.00
12:10 22Nov92 five 1 2 2 -10.00 28.00
12:10 22Nov92 three 1 0 0 50.00 -50.00
12:10 22Nov92 four 1 3 3 70.00 -90.00
12:10 22Nov92 one 1 3 3 50.00 -58.00
12:11 22Nov92 two 1 1 1 -25.00 50.00
accept assets bids market manager history options help
BIDS
Bidder X B# Con a b c
one 1 17 17 25.00 -30.00
two 1 15 15 30.00 -30.00
four 1 13 13 35.00 -40.00
five 1 10 10 -10.00 55.00
six 1 6 6 317.00 -11.00

Table 1. Testbed Parameters

	Initial Allocation			
Type	A	B	C	Payoff Function
1	10	200	400	$K_1 \ (0.7\log B + 0.3\log C)$ Where K_1=0 if $X < 10$ and $K_1 = 1$ otherwise
2	200	100	200	$K_2 \ (0.3\log A + 0.7\log C)$ Where K_2=0 if $Y < 100$ and $K_2 = 1$ otherwise
3	100	200	100	$K_3 \ (0.7\log A + 0.3\log B)$ Where K_3=0 if $Z < 100$ and $K_3 = 1$ otherwise

Table 2: C.E. Prices

Commodity	Price
A	1.72
B	1.66
C	1

Table 3: C.E. Trades (Buy+, Sell-)

	Commodity		
Type	**A**	**B**	**C**
1	0	109	-181
2	-105	0	181
3	105	-109	0

Table 4. Payoff ($) by Trader Type and Period

		Type 1		Type 2		Type 3	
Mechanism	Period	Average	Range	Average	Range	Average	Range
CARE	1	6.80	[1.5, 10]	4.30	[-1.1, 9.6]	4.00	[1.3, 6.7]
	2	7.53	[4.1, 11]	4.67	[-2.2, 11]	4.11	[-3, 6.8]
	3	7.66	[4.4, 10]	5.67	[2.5 , 10]	4.42	[2.9, 6.5]
	4	6.95	[4.3, 11]	5.80	[3.8, 9.1]	5.33	[3.0, 6.7]
BARTER	1	5.80	[-5, 17]	5.00	[-5, 10]	7.15	[1.1, 13]
	2	4.63	[1.1, 10]	2.01	[-5 , 10]	8.53	[5.0, 13]
	3	4.00	[-1 , 10]	5.33	[2.5, 10]	6.16	[5.0, 8.5]
	4	3.80	[1.2, 7.0]	5.83	[0.5, 10]	6.10	[5.0, 7.0]
NUMERAIRE*	1	9.30	[1.1, 18]	4.34	[-5.0,7.2]	1.20	[-6, 7.1]
	2	8.83	[2.5, 18]	1.79	[-6.0,5.4]	4.25	[-5, 10]
	3	7.12	[-2, 10]	2.02	[-5.3,5.0]	5.11	[-5, 9.5]
	4	7.45	[4.9,9.1]	2.85	[-5.5,5.2]	5.78	[3.1, 10]

* Type 1 traders are net sellers of the numeraire at the C.E., Type 2 traders are net demanders of the numeraire, and Type 3 are neither.

Table 5. Periods 3 and 4 Mean Deviation from CE Allocation by Good

		CARE		BARTER		NUMERAIRE	
Trader Type	Good	μ	σ	μ	σ	μ	σ
1	B	-20	41	22	49	19	54
	C	-12	49	-26	81	39	90
	A	.9	2.8	.75	1.7	1.67	4.43
2	A	-16	32	3	22	-13	42
	C	18	40	27	120	60	43
	B	.8	2.8	25	61	8.3	25
3	A	18	30	-2	28	19	42
	B	21	23	4	16	-25	34
	C	4.5	10.7	.5	1.4	15	21

Table 6. Regression Estimates of Contract Prices
(t-statistics in parentheses)*

	CARE		BARTER		NUMERAIRE	
Period	α	β	α	β	α	β
1	-1.31	-1.28	-1.12	-0.94	-1.29	-0.72
	(-13.85)	(-23.51)	(-5.25)	(-5.[illegible]4)	(-8.13)	(-8.27)
2	-1.31	-1.13	-1.14	-1.42	-1.27	-0.93
	(-8.56)	(-11.32)	(-8.61)	(-9.43)	(-11.60)	(-13.71)
3	-1.65	-1.39	-1.84	-1.71	-1.31	-1.49
	(-12.20)	(-15.70)	(-21.36)	(-15.79)	(-11.35)	(-16.25)
4	-1.65	-1.42	-1.87	-1.69	-1.37	-1.40
	(-9.62)	(-13.32)	(-20.27)	(-15.28)	(-32.45)	(-29.25)

* The R^2 of these regressions range from .80 to .96.

Table 7. Average Volume of Trading Per Period

	A	B	C	Total
Predicted at the C.E.	210	218	362	780
CARE	241	337	401	979
BARTER	345	303	486	1134
NUMERAIRE	229	246	644	1119

Table 8. Period 4 Volume and Transactions

	Average		Volume
Mechanism	**A**	**B**	**C**
CARE	243	351	411
BARTER	358	289	482
NUMERAIRE	260	240	720

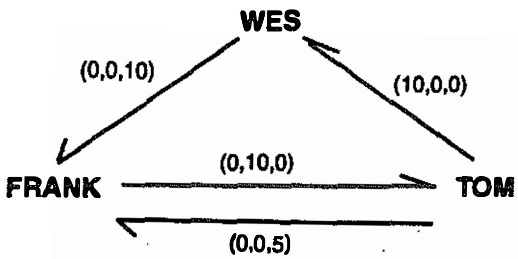


Figure 1. An Example of a Chain

Figure 2. Average Per Period CRU and NGFE by Treatment

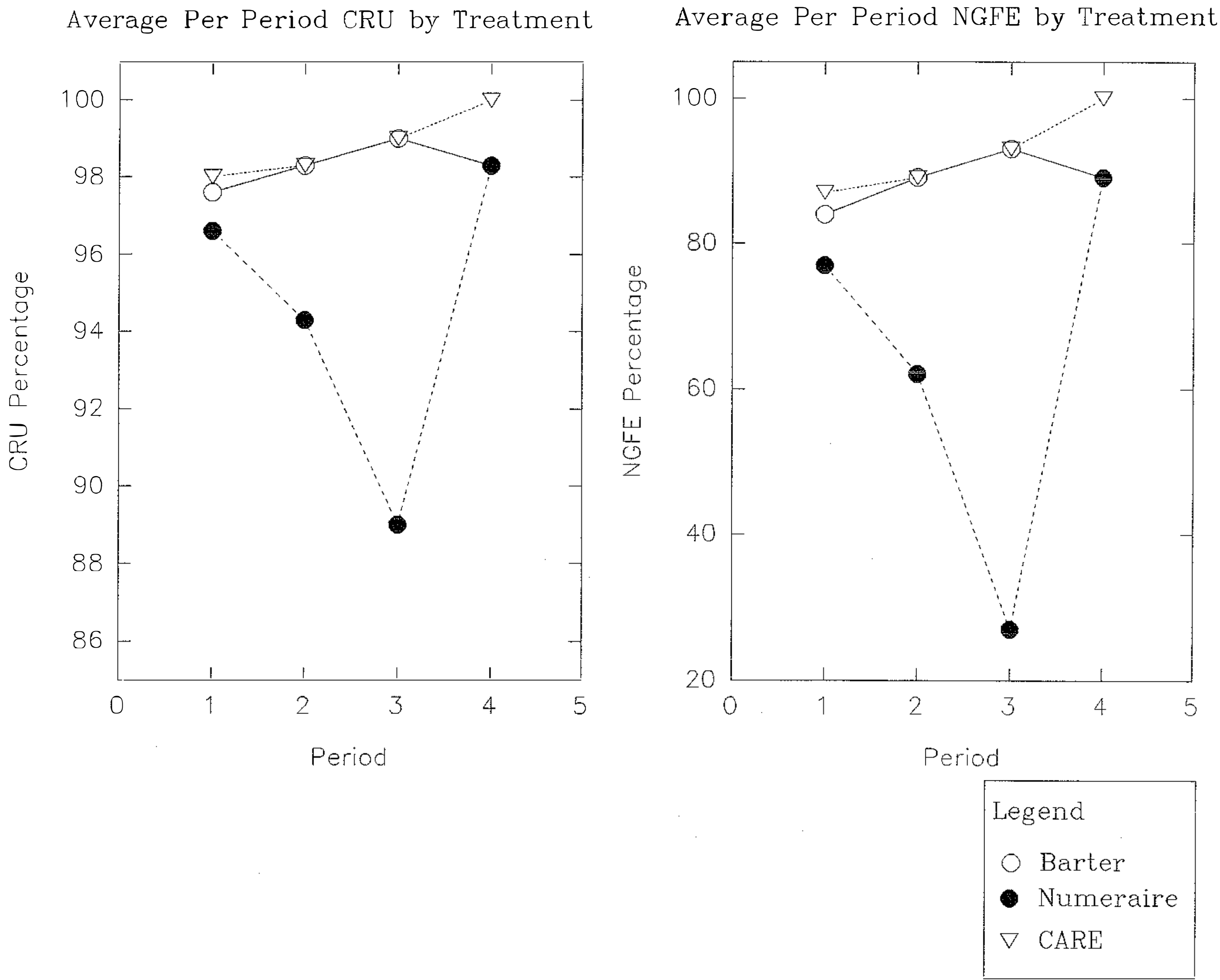


Figure 3. Average Per Period CE Distance by Treatment

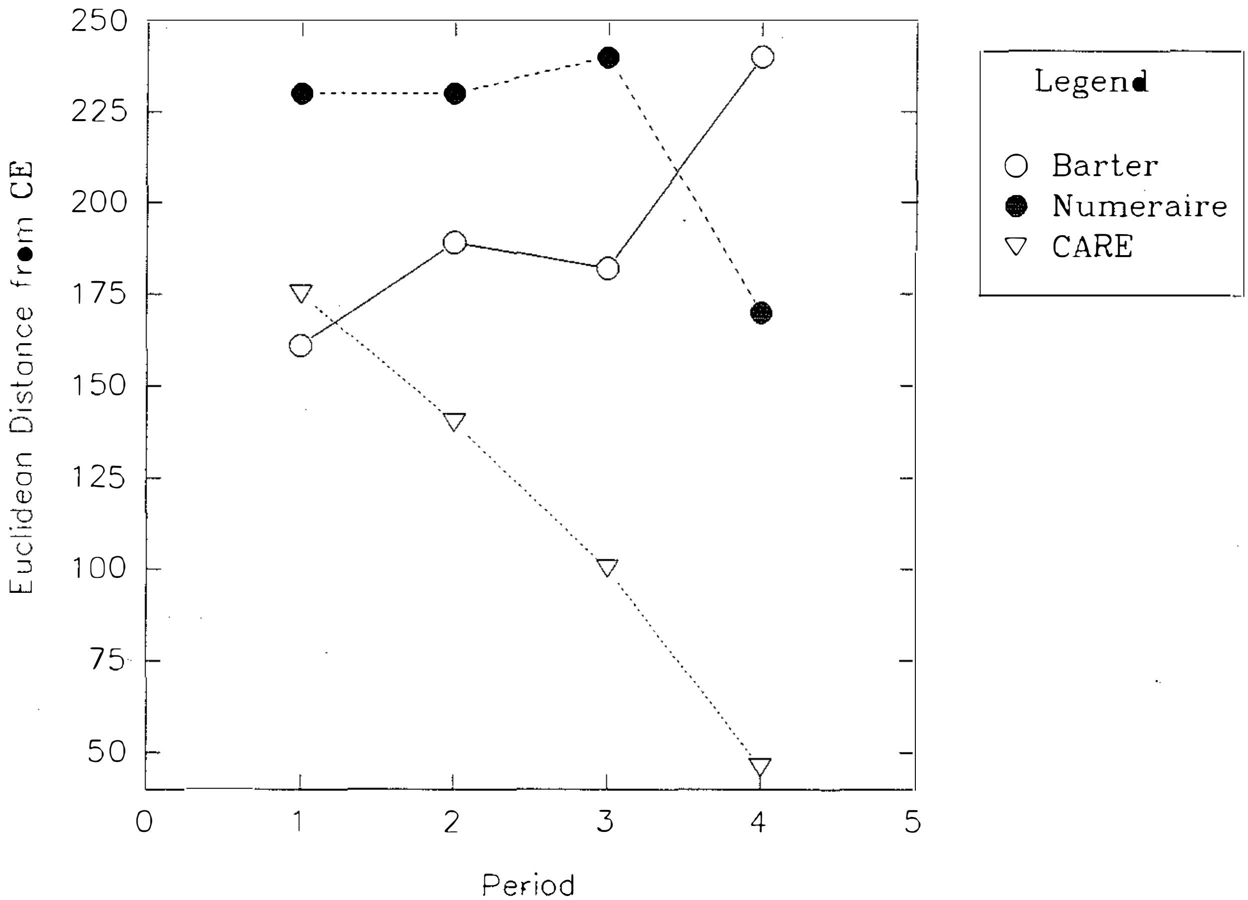


Figure 4. Average Increments in Utility by Trade

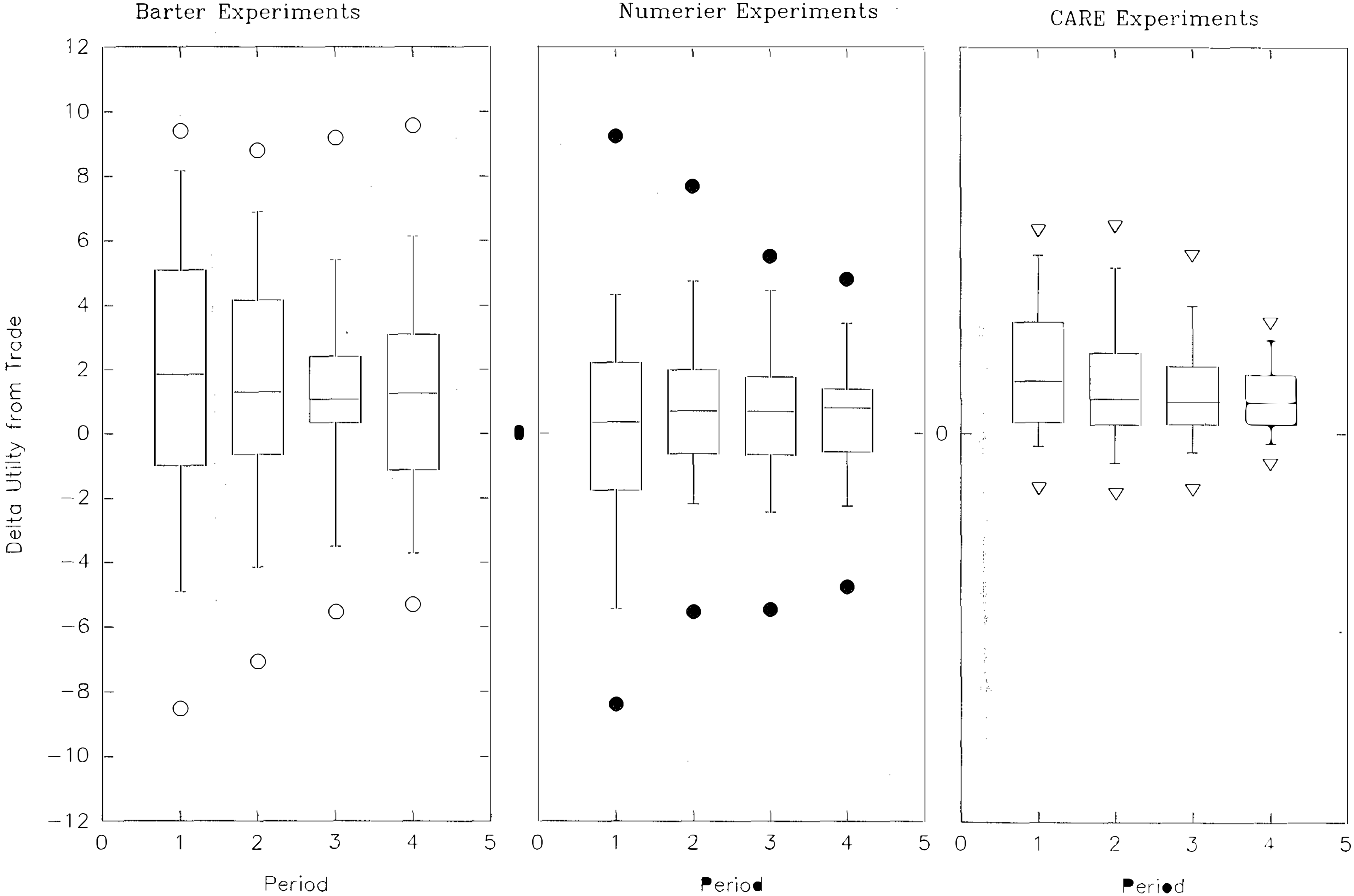


Figure 5. Final Allocation Deviation from the Predicted CE Allocation by Trader Type

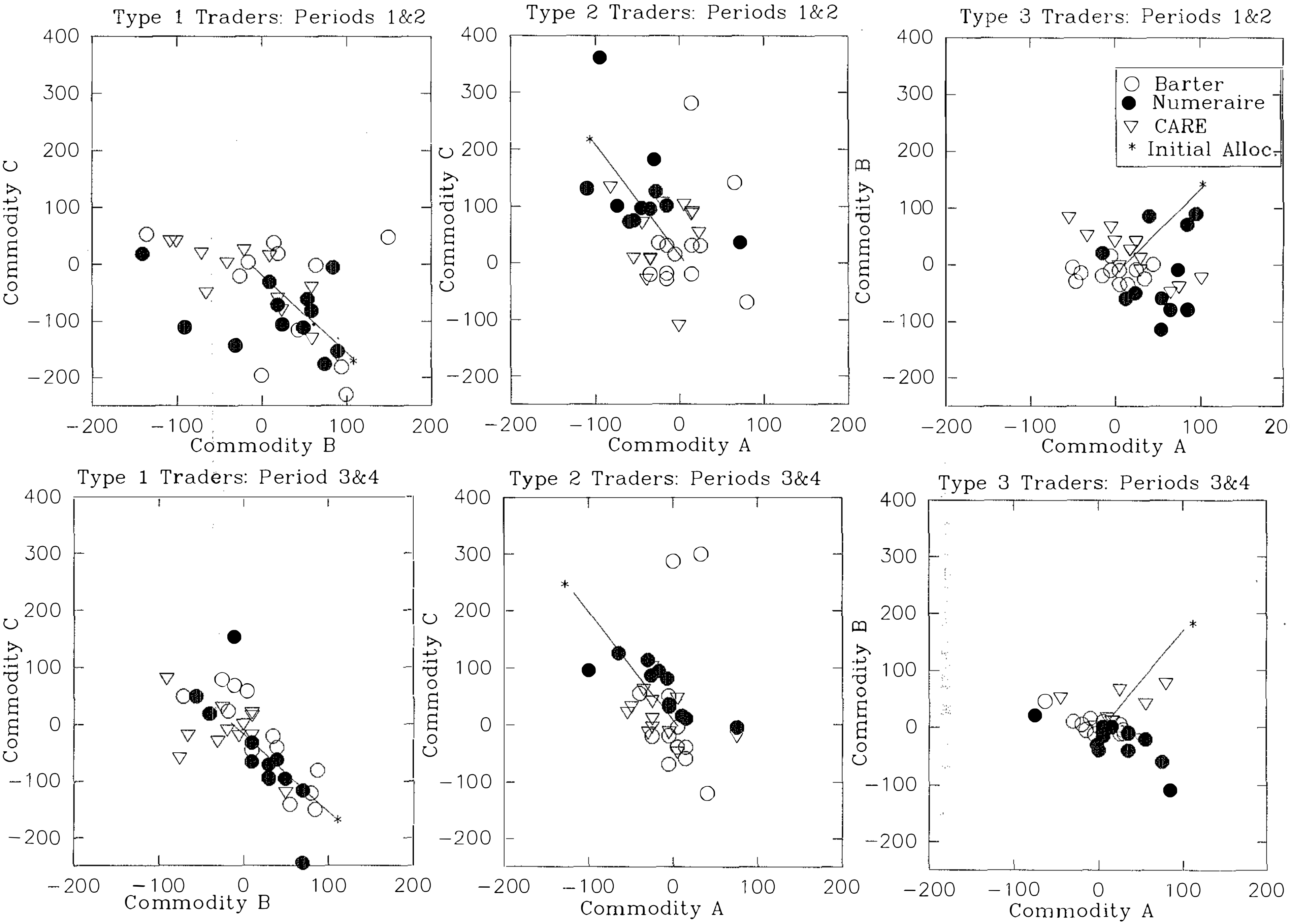
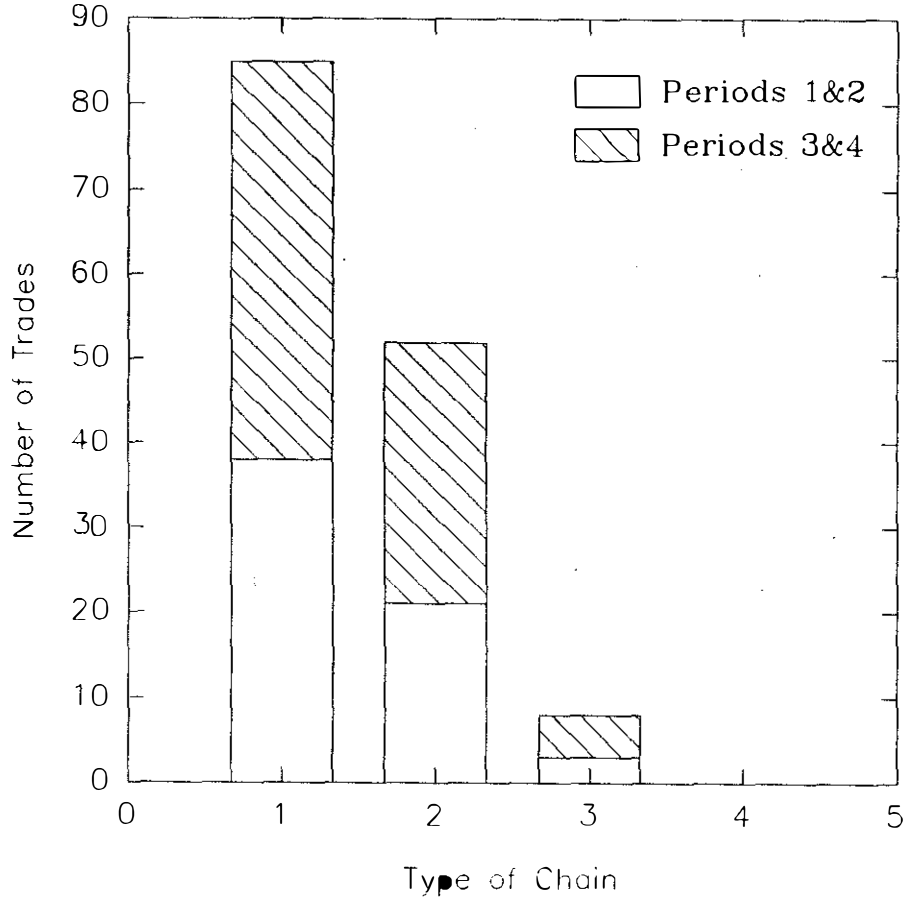


Figure 6. Distribution of Chain Trades in CARE



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