Production, Trade and Exchange Rates in Large Experimental Economies

Charles Noussair, Charles Plott and Raymond Riezman[1]

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Abstract

We construct experimental economies for the purpose of studying market equilibration. The economies are the most complex laboratory economies studied to date and are "international" in economic structure. The economies have twenty-one markets and due to the fact that they have on the order of 50 agents, the economies are characterized by several hundred equations. In spite of the complexity and interdependence of the economy, the results demonstrate substantial power of the general equilibrium model of perfect competition to predict directions of movements of market-level variables. Exploratory analysis yields patterns frequently found in field studies. For example, international trade patterns conform closely to the gravity model and exhibit a strong home bias.

1. Introduction

Under the classical competitive equilibrium model, the simultaneous optimization on the part of all participants in the economy, given prices, incentives and constraints, implies an outcome corresponding to a solution of a system of excess demand equations. Although the concept of equilibrium is static, part of its allure as a predictive model lies in a dynamic interpretation. Once an economy has reached an equilibrium state there is, at least in principle, no systematic tendency for deviation. The empirical relevance of the model is demonstrated in a growing body of experimental work that documents the tendency of markets to converge toward the competitive equilibria of corresponding theoretical models, and for the market activity to stabilize in a neighborhood of the equilibrium prices and quantities. This convergence generalizes to a wide class of experimental economies, including those with multiple markets, small as well as very large numbers of traders, and markets with externalities.

[1] Noussair: Department of Economics, Rich Memorial Building, Emory University, Atlanta, GA, e-mail cnoussa@emory.edu. Plott: Division of the Humanities and Social Sciences, California Institute of Technology, Pasadena, CA 91125 cploltt@hss.caltech.edu. Riezman: Department of Economics, University of Iowa, Iowa City, IA 52242, raymond-riezman@uiowa.edu. We thank Carol McAusland and Zheng Liu for helpful comments. We thank Steven Tucker and Tara Larson for research assistance.

However, experimental economies do not operate close to competitive equilibrium instantaneously. Rather, a dynamic process occurs that leads the variables in the economy in the direction of their equilibrium values while the economy is in operation. Thus, *Equilibration*, a dynamic principle of system behavior, underlies the support for the law of supply and demand obtained in experimental markets (Plott and George, 1990; Anderson et al., 2003). The equilibration process tends to be slower and less complete as economies become more complex, but interacts with the specific interdependencies in different microeconomic structures to produce consistent and replicable empirical patterns. The specific types of market interdependence that have been investigated include production economies with derived demand (Goodfellow and Plott, 1990), exchange economies with two or more commodities (Forsythe et al. 1980; Williams et al., 2001; Chen and Plott, 2001) and small general equilibrium systems with a circular flow of income (Lian and Plott, 1998).

In this paper we investigate the properties of the equilibration process of experimental market economies that are far more complex that any laboratory economies created to date. The complexity is not only in terms of the number of commodities, markets and agents, but also in terms of the nature of the economic activities and their interdependence. Our choice of environment involves very complex and delicate economic structures of the type of interest in international economics. The economy is "international" in a sense recognizable to economists. In international economies, special types of market interdependencies arise because international demand for traded goods influences derived demand for factors of production. Moreover, exchange rates exert direct feedback on all sectors of the economy and the demand and supply of foreign exchange are sensitive to various activities throughout the economy. The feasibility of studying simpler international economies has been established (Noussair et al., 1995, 1997; Riedl and van Winden, 2001), together with a presumption that the equilibration tendencies of systems of markets will survive in even the most complex of environments.

In the experiment reported here, the laboratory world is divided into three countries, where each country is characterized by its own currency, resource endowment, and production technology. There are three output goods, which can be produced in any of the three countries. Two input goods, both of which are required to produce any of the outputs, reside in each of the three countries. These factors of production are immobile, although outputs can be traded internationally. Markets exist for each output, input and currency. The simultaneous trade of several types of goods, factors of production, final goods, and currencies, provides a rich setting to study the principles of behavior of an entire general equilibrium economic system, with interdependencies beyond those that have been previously studied experimentally.

The paper is divided into five sections. The first section is this introduction. The second section describes the experimental environment together with the procedures and parameters. Because of the interest in conducting experiments of this complexity, section two also includes some details of the procedures, interfaces and other aspects of the experiment.

The third section is a summary of the models and terminology that are used in the results section. The analysis is conducted at the aggregate level to identify and explore patterns of behavior of economic *systems* rather than those of individuals. The concept of equilibration is expressed in a testable formulation called the *Equilibration Hypothesis.* The hypothesis has two parts: (1) *Stabilization*: the variance of the variables in the system decreases over time, and (2) *Convergence*: the values of the variables move in the direction of the Competitive Equilibrium values.

The fourth section describes the results from the experiment and the last section presents and discusses the conclusions. The overall conclusions are easy to summarize. After evaluating the equilibration hypothesis, which is supported in our data, the empirical characteristics of the equilibration process are explored. The behavior of variables such as national production, international trade, prices, wages, and exchange rates, are studied. Some properties of the equilibration process that appear in our data and that we believe are fairly general are identified. Patterns noted in field data, such as volumes of bilateral international trade consistent with the gravity model (Anderson, 1979; Bergstrand, 1985,1989; Deardorff, 1998), the presence of home bias in trade (McCallum, 1995; Trefler, 1995; Anderson, 2000), greater variance of input than output prices (Clark, 1999), and volatile exchange rates (Obstfeld and Rogoff, 2001) are also present in the experimental economy. The presence of these properties raises the possibility that at least some of the factors that can cause these phenomena in the field are also present in the experimental economy. Any patterns observed in the experiments are merely characteristics of the equilibration process of markets when they exist in economies with the structure of our experiment, and are not be due to shocks to the environment, to government policies, or to changes in institutional structure. Of course, this does not mean that data patterns observed in the field are not influenced or caused by shocks or policy, but it does raise the possibility that the patterns have a more fundamental cause, namely that they are a characteristic of the process of market equilibration.

2. The Experiment

2a. Overview of the Economy

The economies we constructed all had the structure shown in figure 1. There were three countries, *A*, *B*, and *C*. In each country there were agents who were *suppliers*. Suppliers were endowed with the ability to supply two resources *l* and *k* to input markets. In each country there were also agents who were *producers*. Each producer was endowed with a production capability and could produce one of three outputs *x*, *y*, and *z* using the inputs *l* and *k*. Finally, there were *consumers* who could purchase *x*, *y*, and *z* from producers on the output markets.

The final goods *x*, *y*, and *z* could trade freely internationally but the inputs *l* and *k* could not trade internationally. Each country had its own currency, labeled as *A*, *B*, or *C,* and all transactions within a country were required to take place in terms of domestic currency. Only domestic currency had value to residents of a given country, and at the close of the market period all foreign currency was removed from the inventory of all agents. Therefore, in principle, the only sources of demand for currency were the importation of goods or intra-period speculation in the currency market.

A cash-in-advance constraint was in effect on international transactions in addition to domestic transactions. Imports into country *J* could occur only when a resident of country *J* transported a good into country *J*. It was not possible for a resident of country *J* to transport goods produced in *J* to country *K* for sale there. This meant that a prospective purchaser from country *K*, who wished to purchase a good produced in country *J*, had to obtain currency *J* before international trade could take place. To obtain foreign currency, agents could use currency markets that were operating in all three countries. The cash in advance constraint ensured that the currency markets would be active if international trade occurred, and facilitated the calculation of equilibrium by precisely determining the equilibrium demand for foreign currency.

For the economy to maximize gains from trade, the following pattern of activity must occur. Suppliers sell inputs *l* and *k* to producers in their own country. Producers purchase domestic *l* and *k* and use them in the production of the outputs *x*, *y*, or *z*. Producers then sell the outputs to domestic and foreign consumers. Consumers purchase *x*, *y*, and *z* from domestic and/or foreign producers. To purchase a good from a foreign producer the consumer first buys the currency of the country from which he wishes to import. Supply of the foreign currency originates from foreign consumers who also wish to import goods into their own country.

[Figure 1: About Here]

2b. Parameters

Subjects had several sources of incentives. Consumers' valuations for outputs *x*, *y*, and *z* were induced by assigning them exogenous values in terms of domestic currency. If a consumer purchased and later consumed a unit at a price below its valuation to him, he would earn a profit on the unit. The marginal valuations for an individual consumer for the outputs decreased as he consumed more. Suppliers' costs to supply the inputs *l* and *k* were also induced.[2] They were required to pay a marginal cost for each unit they wished to sell, and would make a profit on a unit if the price at which it sold was greater than its marginal cost.

Incentives for consumption activities are denoted as $U(x,y,z)$. Consumers had induced values for the three goods. The preferences were polynomial in each good and separable across goods. The utilities were in terms of home currency, which would be converted into U.S. dollars at the end of the experiment. The induced preferences of a consumer *i*, in terms of U.S. dollars, has the form:

$$U_i = \alpha^i \,[\beta^i x_i + .5\delta^i\,(x_i)^2 + \gamma_i y^i + .5\eta^i\,(y^i)^2 + \kappa^i z^i + .5\upsilon^i\,(z^i)^2] \qquad (1)$$

α^i is the conversion rate for subject *i* from the currency of the country in which he resides to his final payment in US dollars. The utility function is separable in the three goods and quadratic in each of the goods. When presented to subjects, consumer incentives were expressed in terms of integer quantities of home currency and marginal utilities, $[1/\alpha^i]\,[U_i(q) - U_i(q\text{-}1)]$ where *q* is one of the consumption goods.

Supplying resources is costly to the supplier and thus enters as a negative in a utility calculation. The cost of supplying resources is denoted as $C_i(l,k)$. The incentives of suppliers are derived from their ability to acquire resources at a cost in terms of home currency and sell them for home currency at a profit. The induced cost to suppliers of inputs is quadratic, separable in the two inputs and is approximated with the following functional form:

$$C^i = \varphi^i v^i + \theta^i (v^i)^2 + \mu^i w^i + \tau^i (w^i)^2. \qquad (2)$$

Each producer had the capacity to transform the two resources into one of the three outputs. This ability to transform goods represents a production capability. By purchasing the resources with home currency, producing the output and selling it for home currency the producer could make a profit in terms of home currency, which would be converted to dollars. Therefore, producers had an incentive to maximize profits in terms of home currency. Let $f_J^m(k,l)$ denote the production function of a producer in country J for output m. The production functions were of the form:

$$f_J^m(k,l) = A_J^m l^{.25} k^{.25} \quad (3)$$

Each participant was assigned one of twelve possible types. The types indicated their country of residence and the incentives and production technologies at their disposal. Most types had more than one role as consumer, producer or supplier, although no subject was both a producer and a supplier, and no subject was both a producer and a consumer of the same good. These restrictions ensured that all inputs used in production and all outputs consumed were traded between different individuals so that the price of every unit transacted of every good could be measured and recorded. Table 1 contains a list of all parameters used in the incentive and production functions.

[Table 1: About Here]

Earnings of each participant i in each period were given by $M_d^{Fi} - M_d^{Bi}$. M_d^{Fi} is i's holding of domestic currency at the end of the period, while M_d^{Bi} is the holding of domestic currency at the beginning of the period. $M_d^{Fi} - M_d^{Bi}$ is equal to $U_k(x,y,z) - C_k(l,k) + R(x,y,z,l,k,M_f) - E(x,y,z,l,k,M_f)$. $U_k(x,y,z)$ and $C_k(l,k)$ are included in the final total holding of domestic currency because the value of an individual's consumption was added to his cash balance and the cost of supplying inputs was deducted from his cash balance. $R(x,y,z,l,k,M_f)$ and $E(x,y,z,l,k,M_f)$ are the revenues from sales to and the expenditures on purchases from other agents. All agents were free to purchase and resell in any market and therefore could speculate on price changes within a period. M_f denotes foreign currency, which could be bought and sold with domestic currency.

2c. The Interface

In the experimental economies, 21 markets, in which all subjects could participate at all times, were in operation. There were seven markets located in each country. Each country contained a market for each of the three outputs x, y, and z, and for each of the two inputs l and k.

[2] The variable names V and W were used in the experiment to refer to the inputs. To facilitate their interpretation as factors of production for purposes of exposition in this paper we refer to V as l and W as k.

Each country also contained two currency markets. In each currency market, domestic currency could be exchanged for one of the two foreign currencies. All markets followed continuous double auction rules. The experiment was computerized and used the Marketscape platform developed at the California Institute of Technology. The computer program was written in PERL and runs on the LINUX operating system. Each subject accessed the markets using a web browser. The principal interface for the subjects was the *Market Summary Screen*, illustrated in figure 2.

[Figures 2 and 3: About Here]

There was one market screen corresponding to each country and links on the bottom of the screen that allowed the user to move between countries. Subjects could submit offers to buy or sell by filling out the rightmost portion of the screen. The subject specified whether the offer was to buy or sell, the good offered, the number of units, the price, and the time period for which the offer was to be available. The order book for each good was displayed on a screen that subjects reached if they selected the name of the market on their main screen. To accept an offer another participant submitted, an agent could select a box next to the offer she was accepting.

To induce values and costs, consumers and suppliers had access to private markets, in which there were only two participants, the experimenter and the specific individual who had access to the market. To reach a private market, subjects could select the market, as for example by clicking *Private X1* shown in figure 2. The subject would then observe an order book in which the experimenter entered offers at the beginning of the period. The experimenter's offers remained the same in each period. Therefore, the demand functions of consumers for final goods and the supply functions of suppliers for inputs were stationary. Consumers could sell units of x, y, and z to the experimenter, and receive cash in return. These sales were considered consumption and the cash received for the sale, which was added to the cash balance of the consumer, represented the utility of consumption. Similarly, suppliers could purchase units of l and k from the experimenter at predetermined prices for resale to producers. The price the supplier paid for each unit represented the marginal cost of supplying that unit and was deducted from the supplier's earnings.

The links in figure 2 illustrate the information available at any time to participants. At any time, subjects could access the current offers available to every domestic and foreign market. In addition to being able to view all current offers in all markets, they could go to pages that would list their own history of offers and a history of transactions for each good for the current and all previous periods of the experiment. The latter information was available in both text and graphical form. They could also select *Announcements* and receive public messages from the experimenter.[3]

A producer's production function was displayed in the manner shown in figure 3. The numbers in the table correspond to the total output that could be produced with given quantities of the two inputs within a period. The numbers in the table form an isoquant map of the producer's production function. Production was restricted to integer amounts. Over the course of a period, as inputs were used in production, a highlighted cursor would track input use from the origin outward. This facilitated the calculation of the current marginal product at any point in time. To produce output subjects used another, interactive screen that allowed them to calculate hypothetically the quantity they could produce with different combinations of inputs before they committed themselves to the irreversible production decision. To produce, they typed input quantities in designated fields.

2d. The Sessions

Three independent experiments were conducted. Experiment 1 took place during three three-hour sessions on three different days, and experiments 2 and 3 during two four-hour sessions on two different days. The same subject took part in all of the sessions that made up an individual experiment, but no subject took part in more than one experiment. In experiment 1, there were 60 participants, 46 of whom were undergraduates at Purdue University and 14 of whom were undergraduates at the California Institute of Technology. In experiment 1, all subjects were located in the economics laboratories at Purdue University and the California Institute of Technology during the sessions. In experiments 2 and 3, there were 40 and 57 subjects, respectively, who were all undergraduate students at Caltech. Sessions 2 and 3 were conducted remotely with all subjects connecting from outside the laboratory over the Internet using a web browser. The experiments consisted of a sequence of periods. All markets were open for the entire duration of each period. In each period all values of the parameters were reinitialized to the same starting values so that the underlying parameters remained the same within each period of a given experiment. Thus there was no ability to carry over inventories or to accumulate capital from period to period. Experiment 1 consisted of 12 periods and experiments 2 and 3 consisted of 16 periods. Each period was between 20 and 30 minutes in length. The time remaining in the current period was always common knowledge.

[3] When the experimenter sent a message to subjects that could be read on the Announcements page, an alert appeared on the main screen indicting that there was a new message for the subject from the experimenter.

Table 1 contains the continuous approximations of the functions of the goods defining each type of agent and the number of agents of each type that there were in each experiment. The actual discrete parameter functions given to each type are available from the authors.

2e. Competitive equilibrium

Application of the model of perfect competition can be used to produce market demand functions for each commodity in each country. These are themselves complex, being derived from individual maximization theory, inverted and summed across agents. Thus, the summary equations (21) – (44) in this section represent a major simplification of the economic environment that existed.

The demand functions of individual consumers for the three outputs in each of the three countries were discrete approximations to (4) – (12), and are calculated from the incentives described in equation (1). p_i^J is the price of good i in country J, and $d_i^J(p_i^J)$ denotes the demand function of a consumer of good i in country J. The demand functions, defined for non-negative quantities and prices, are denominated in domestic currency.

$$d_x^A(p_x^A) = 3.5 - .005p_x^A \quad (4)$$
$$d_y^A(p_y^A) = 8.25 - .005p_y^A \quad (5)$$
$$d_z^A(p_z^A) = 9.5 - .005p_z^A \quad (6)$$
$$d_x^B(p_x^B) = 4.75 - .00125p_x^B \quad (7)$$
$$d_y^B(p_y^B) = 4.875 - .00125p_y^B \quad (8)$$
$$d_z^B(p_z^B) = 7 -.00125p_z^B \quad (9)$$
$$d_x^C(p_x^C) = 6 -.0005p_x^C \quad (10)$$
$$d_y^C(p_y^C) = 6.25 - .0005p_y^C \quad (11)$$
$$d_z^C(p_c^C) = 8 - .0005p_z^C \quad (12)$$

The production technologies available to producers were approximations of (13) and (14). Country A had a comparative (as well as an absolute) advantage in the production of x, B in y, and C in z. $f_i^J(k,l)$ denotes the production function for output i in country J.

$$f_x^A(k,l) = f_y^B(k,l) = f_z^C(k,l) = 4l^{.25}k^{.25} \quad (13)$$
$$f_y^A(k,l) = f_z^A(k,l) = f_x^B(k,l) = f_z^B(k,l) = f_x^C(k,l) = f_y^C(k,l) = 2l^{.25}k^{.25} \quad (14)$$

The supply functions of individual suppliers of input were as given in (15)-(20) for non-negative quantities and prices. The supply function of a supplier of factor i in country J is denoted as $s_i^J(w_i^J)$

$$s_l^A(w_l^A) = .25w_l^A - 6.5 \tag{15}$$
$$s_l^B(w_l^B) = w_l^B/30 - 1.6 \tag{16}$$
$$s_l^C(w_l^C) = .01w_l^C - 3 \tag{17}$$
$$s_k^A(w_k^A) = .1w_k^A - 1 \tag{18}$$
$$s_k^B(w_k^B) = w_k^B/15 - 11/3 \tag{19}$$
$$s_k^C(w_k^C) = w_k^C/40 - 5.5 \tag{20}$$

The competitive equilibrium of the economy can be found by solving the system of 23 equations given in (21)-(43). The first nine equations are market-clearing conditions in the output market. $D^J{}_i(p^J{}_i) = \Sigma\, d^J{}_i(p^J{}_i)$ and $S^J{}_i(p^J{}_i) = \Sigma s^J{}_i(p^J{}_i)$ denote market demand and supply for good i in country J respectively.[4] $IMP^J{}_i$ is equal to the imports of good i into country J. The equations say that the amount of a commodity that is consumed in a country equals the net imports of the commodity into the country plus the home production of the commodity.[5]

$$D^A{}_x(p^A{}_x) = S^A{}_x(p^A{}_x) - IMP^B{}_x - IMP^C{}_x \tag{21}$$
$$D^A{}_y(p^A{}_y) = S^A{}_y(p^A{}_y) + IMP^A{}_y \tag{22}$$
$$D^A{}_z(p^A{}_z) = S^A{}_z(p^A{}_z) + IMP^A{}_z \tag{23}$$

$$D^B{}_x(p^B{}_x) = S^B{}_x(p^B{}_x) + IMP^B{}_x \tag{24}$$
$$D^B{}_y(p^B{}_y) = S^B{}_y(p^B{}_y) - IMP^A{}_y - IMP^C{}_y \tag{25}$$
$$D^B{}_z(p^B{}_z) = S^B{}_z(p^B{}_z) + IMP^B{}_z \tag{26}$$

[4] The supply of outputs and the demand for inputs are calculated from the production functions in a straightforward manner. An individual firm producing output M residing in country J has a factor demand for input k with the form: $d_k^J(\boldsymbol{p},\boldsymbol{w}) = (Ap_M{}^J)^2/(16(w_k{}^J)^{1.5}(w_l{}^J)^{.5}))$, where A = 4 for x in country A, y in country B, and z in country C. A = 2 for all other goods. The market level demand for an input in each country is calculated by summing the demand of the factor over all firms. The market supply of a firm selling output M in country J is given by $s_M{}^J(\boldsymbol{p},\boldsymbol{w}) = A^2p_M{}^J/((w_k{}^J)^{.5}(w_l{}^J)^{.5}$. A country's market supply for an output is calculated by summing the supply of individual firms.

[5] Since countries A, B, and C have comparative advantages in x, y, and z respectively, in equilibrium they each export that good. These means that country A imports y and z, B imports x and z, and C imports x and y. In the system of equations (21) – (43), $IMP_x{}^A$, $IMP_y{}^B$, and $IMP_z{}^C$ are constrained to be zero. If they are unconstrained, the solution is identical.

$$D^C{}_x(p^C{}_x) = S^C{}_x(p^C{}_x) + IMP^C{}_x \quad (27)$$

$$D^C{}_y(p^C{}_y) = S^C{}_y(p^C{}_y) + IMP^C{}_y \quad (28)$$

$$D^C{}_z(p^C{}_z) = S^C{}_z(p^C{}_z) - IMP^A{}_z - IMP^B{}_z \quad (29)$$

Equations (30) – (35) are market-clearing conditions for the two inputs in the three countries. They say that the wage of a factor is such that the quantity of the factor demanded in a country is equal to the amount that is supplied in that country. There are no exports or imports of the inputs *k* and *l* permitted.

$$D^A{}_l(w^A{}_l) = S^A{}_l(w^A{}_l) \quad (30)$$

$$D^A{}_k(w^A{}_k) = S^A{}_k(w^A{}_k) \quad (31)$$

$$D^B{}_l(w^B{}_l) = S^B{}_l(w^B{}_l) \quad (32)$$

$$D^B{}_k(w^B{}_k) = S^B{}_k(w^B{}_k) \quad (33)$$

$$D^C{}_l(w^C{}_l) = S^C{}_l(w^C{}_l) \quad (34)$$

$$D^C{}_k(w^C{}_k) = S^C{}_k(w^C{}_k) \quad (35)$$

Equations (36) – (41) are *Law of One Price* conditions. They require that prices of outputs in different countries be equal, adjusting with the appropriate exchange rate. There are no transportation costs in this economy. r^B is the exchange rate of currency *B* for currency *A* (r^B units of currency *B* trade for one unit of currency *A*). r^C is the exchange rate of currency *C* for *A*.

$$p^B{}_x = r^B * p^A{}_x \quad (36)$$

$$p^B{}_y = r^B * p^A{}_y \quad (37)$$

$$p^B{}_z = r^B * p^A{}_z \quad (38)$$

$$p^C{}_x = r^C * p^A{}_x \quad (39)$$

$$p^C{}_y = r^C * p^A{}_y \quad (40)$$

$$p^C{}_z = r^C * p^A{}_z \quad (41)$$

The final three equations reflect the *flow of funds theory* of exchange rates. They require that exchange rates adjust so that the demand for foreign exchange as dictated by imports equals the supply of foreign exchange as dictated by exports. Since the third equation is a linear combination of the first two, only (42) and (43) are used to compute the competitive equilibrium.

$$p^A{}_x * (IMP^B{}_x + IMP^C{}_x) = p^B{}_y * IMP^A{}_y / r_B + p^C{}_z * IMP^A{}_z/r_C \quad (42)$$

$$p^B{}_y * (IMP^A{}_y + IMP^C{}_y) = p^A{}_x * IMP^B{}_x * r_B + p^C{}_z * IMP^B{}_z *r_B/r_C \quad (43)$$

$$p^C{}_z * (IMP^A{}_z + IMP^B{}_z) = p^A{}_x * IMP^C{}_z * r_C + p^B{}_y * IMP^C{}_y *r_C/r_B \quad (44)$$

Market demands and supplies can be calculated in a straightforward manner from the individual demands and the data in table 1. Table 2 contains the solution to the equations (21) – (43) for each experiment. The solution defines a set of testable predictions, to which we shall refer as the *Competitive Model*, which are the competitive equilibrium values of the variables. These differ between the experiments because of the different numbers of agents of each of the twelve types. From the values in the table, the quantities of production and consumption of outputs, as well as the quantity of each input employed in the production of each output under the Competitive Model, can be calculated.

[Table 2: About Here]

2f: An Alternative: The Autarky Model

An alternative model to the competitive equilibrium, which we call the autarky model, assumes that there is no international trade and that the currency markets are inactive. Within each country, prices and wages clear the domestic markets. The predictions of the autarky model are calculated as the solution of (21) – (35), with all of the international trade terms IMP_k^J constrained to equal zero. In other words, the autarky model is the Walrasian equilibrium of each country *J*'s economy under the assumption that it is completely isolated from other countries. The predictions of the autarky model for each of the three experiments are given in table 2, along with those of the competitive model.

In these economies, the autarky model is not as unreasonable a predictive model as one might think at first glance. International trade includes some risks. An importer must first purchase foreign currency, which has no value to him at the end of the trading period, in order to make purchases in a foreign country. The currency market purchases must be of a sufficient quantity to allow the importer to complete the foreign purchases, yet not be of such a large quantity that unspent foreign currency cannot be resold for domestic currency before the end of the period. If an insufficient number of agents are willing to engage in international trade, the currency markets may become thin, eventually discouraging all traders from using them and as a consequence the disappearance of international trade.

3. Statistical Methodology

The Equilibration Hypothesis has two components, *stabilization* and *convergence*. Stabilization is a notion of decreasing variability of the value of a market-level variable over time, where a unit of time is defined as a market period. It can be defined for any input price, output price, exchange rate, or quantity produced, traded and consumed of any good at either the national or international level.

To evaluate whether or not stabilization is occurring, we calculate the normalized standard deviation of prices, wages, exchange rates, production, and international trade flows. We divide the data from each experiment into two segments of equal length, and designate the two segments as the early and the late periods of the experiment. For experiment 1, the early and late periods comprise periods 1-6 and 7-12, respectively. In experiments 2 and 3, the early and late periods correspond to periods 1-8 and 9-16, respectively. For price variables; output prices, wages and exchange rates, the normalized standard deviation is defined as $\sigma_{im}{}^{L}/\mu_i{}^{L}$, where $\sigma_{im}{}^{L}$ is the standard deviation of all transaction prices in market *i* during the late periods of experiment *m*, and $\mu_{im}{}^{L}$ is the average transaction price in the late periods of experiment *m*. σ_j^E and $\mu_i{}^{E}$ are analogous variables for the first half (the early periods) of the experiments. For trade flows and production, the same variables are calculated, although the total quantity imported or produced in each period is the unit of observation, rather than the individual transaction.

We say that a market has stabilized if $\sigma_{im}{}^{L}/\mu_i{}^{L} < \sigma_{im}{}^{E}/\mu_i{}^{E}$, that is, if the normalized standard deviation is lower in the late periods than in the early periods. We say that the economy as a whole is stabilizing if (a) the percentage of market prices that are stabilizing is significantly greater than 50%, and (b) the percentage of market quantity variables that are stabilizing is significantly greater than 50%. To test for stabilization we use a sign test of the hypothesis that the median value of $\sigma_{im}{}^{L}/\mu_i{}^{L} - \sigma_{im}{}^{E}/\mu_i{}^{E}$, over the relevant variables, is greater than or equal to zero. If the hypothesis is rejected it means that a significant majority of the variables are stabilizing and therefore that the economy is stabilizing.

Convergence occurs when prices are closer to the competitive equilibrium values in late periods than in early periods. We will say that convergence of a variable occurs if the inequality $|\mu_m{}^{L} - m^*| < |\mu_m{}^{E} - m^*|$ holds, where m^* denotes the competitive equilibrium prediction of variable *m*. As with stabilization, we say that an economy is converging if a significant majority of both price and quantity variables exhibit convergence.

For any variable that exhibits equilibration we can estimate the exact value to which the variable would converge asymptotically if the data in the experiment were extrapolated into the infinite future. Even if equilibration is observed and the variables move in the direction of their equilibrium values, it is possible that they converge asymptotically to values other than those of equilibrium. To estimate these values, we use the model in equation (45), first employed in Noussair et al. (1995). The equation is a natural specification for panel data where there is heterogeneity between the data series at the beginning of the time horizon the data covers, but where the dependent variable converges to a common asymptote near the end of the time horizon, a common pattern in experimental studies of markets.

$$y_{it} - y_i^* = \beta_{11}\frac{D_1}{t} + \beta_{12}\frac{D_2}{t} + \beta_{13}\frac{D_3}{t} + \beta_2\frac{t-1}{t} \tag{45}$$

In the above equation, y_{it} denotes the value of one of the variables in the economy in period t of the ith experiment, and y_i^* is the competitive equilibrium value of the variable. y_i^* has no index for time because the competitive equilibrium predictions remain the same over time within an experiment, but differ between experiments. D_i is a dummy variable for experiment i and t denotes time period within the experiment. For example, D_i equals 1 if the data are from experiment i. The model allows for the estimation of the value of the dependent variable at the beginning of each horizon and the value to which the series is converging. In the first period of experiment i, $D_i/t = 1$ and all of the other variables equal 0. Therefore, β_{11} is the estimated value of the time series at the beginning of experiment 1, and β_{12} and β_{13} are analogous. In later periods of experiment i the D_i/t term decreases toward 0, while the variable $(t-1)/t$ increases toward 1. If t were projected to the infinite future, $(t-1)/t$ would converge to 1. Therefore β_2 can be interpreted as the asymptote to which the time series is converging. We will refer to the β_2 estimate as the *convergence value* of the variable. The specification assumes that there is a common value to which the time series is converging for all experiments. We will say that we cannot reject the hypothesis that a variable converges to its competitive equilibrium value if the estimated β_2 is not significantly different from zero. The standard errors are corrected for heteroscedasticity to account for stabilization, which would decrease the variance of the error terms for later periods in the sessions.

4. Results

4.1. The equilibration hypothesis

Figures 4 – 6 illustrate the price patterns observed in experiment three, which are typical for the three economies we studied. Figure 4 shows the average transaction prices for the three outputs during each period in each of the three countries in experiment 3 in comparison with the competitive equilibrium prices. Figure 5 contains the analogous data from input prices. Figure 6 illustrates the average exchange rate, as well the competitive equilibrium exchange rate and the level that would be consistent with purchasing power parity given the actual average prices in the three countries. It is apparent from the figures that the values of many of the variables differ substantially from the competitive equilibrium levels. For example, the price of *z* in country *B* is roughly 50% higher than the competitive equilibrium level for most of the experiment. The prices of *y* and *z* in country *C* are higher than the equilibrium by similar percentages. The exchange rate of currency *C* to *A* is roughly 40% higher than the predicted rate of 5.17. However, the time series also suggest that many of the variables are closer to the equilibrium levels in the late periods than in the early periods, suggesting that equilibration, as defined in section 1, may be taking place. For example, in country C, the prices of *k*, *x,* y, and *z* are noticeably closer to their equilibrium levels in the late periods of the experimental session than early on. The same is true for *l* and *x* in country A and *k* and *x* in country B. Result 1 and its supporting discussion summarize the balance of the evidence on equilibration in our data.

[Figures 4-6: About Here]

Result 1: The equilibration hypothesis is supported.

Support for result 1: Table 2 contains the competitive model predictions for each of 23 system level variables in the experiment. In addition, the competitive equilibrium implies a level of production of each good in each country, yielding predictions for 9 more variables. Since there are three independent experiments, these data make up 96 time series. The equilibration hypothesis asserts that (a) the variance in the variables of the economy declines over time (stabilization) and (b) the variables attain values closer to the equilibrium over time (convergence). Operationally, as described in section three, we define an economy to be equilibrating is significantly more than 50% of the price and quantity variables exhibit declining variance and means closer to the competitive equilibrium in the late periods than in the early periods.

We find that stabilization is occurring in the experimental economies. $\sigma_{im}{}^{L}/\mu_i{}^{L} < \sigma_{im}{}^{E}/\mu_i{}^{E}$ for 23 of 27 output prices (3 outputs*3 countries*3 experiments), 15 of 18 wage rates, 5 of 6 exchange rates, 17 of 18 trade variables ($IMP_k{}^{J}$ quantities) and 24 of 27 production variables. In other words, 43 of 51 prices and 41 of 45 quantities are stabilizing. We reject at $p < .01$ the hypothesis that 50% or less of the price variables are stabilizing and the hypothesis that 50% or less of the quantity variables are stabilizing at the same level of significance.

Convergence is also occurring. Prices, wages, exchange rates, production, and magnitudes of international trade are closer to the equilibrium predictions late in the sessions than early in the sessions. The inequality $|\mu_{im}{}^{L} - p^*| < |\mu_{im}{}^{E} - p^*|$, where p^* denotes the competitive equilibrium price, holds for 20 of 27 output prices, 13 of 18 input prices, and 5 of 6 exchange rates. The inequality $|\mu_{im}{}^{L} - q^*| < |\mu_{im}{}^{E} - q^*|$, where q^* denotes the competitive equilibrium quantity, is satisfied for 17 of 18 international trade flow variables, and 17 of 27 production variables. Thus, for 41 of 51 prices and 34 of 45 quantities, convergence is occurring. We reject the hypotheses that 50% or fewer of the prices (at $p < .01$) and that 50% or fewer of the quantities (at $p < .05$) are converging. Therefore, convergence is also taking place in the economies.□

Thus, although the pattern is less obvious than in previous experimental studies of simpler economies, there exists evidence that the economic variables are closer in the late periods than in the early periods to a common attractor, their equilibrium values. They also exhibit less variation in the late than in the early periods. A natural question arises about what patterns might be observed if the experiment were conducted over a much longer horizon. In particular, would the variables in the economy converge *to* and not merely *toward* their equilibrium values? We consider this issue with estimation of equation (45), which can provide estimates of the precise values toward which the data series are converging if extrapolated into the infinite future. The particular equation seems to be a reasonable specification to capture the structure of the data in light of the presence of stabilization and convergence. The estimated coefficients for output prices are shown in table 3. The estimates of the same model for input prices and exchange rates are given in table 4. Those for imports of goods into each of the three countries and the production of each country are in table 5.

[Tables 3 – 5: About Here]

The tables show that many of the convergence values, described by the β_2 coefficients, are significantly different from zero, indicating that even if we extrapolate our data to the distant future, we cannot conclude that they converge asymptotically to values precisely equal to the competitive equilibrium. Thus, assuming the convergence process follows the structure of (45), there appears to be some degree of deviation from the competitive equilibrium, even in the long run. This is consistent with the visual impression gained from observation of figures 4 – 6. Nevertheless, the regressions support the notion that an equilibration process, albeit incomplete, is taking place in the economy. The β_2 coefficients are closer to zero than the β_{1j} coefficients for 16 of 27 prices (where each comparison is between a β_2 and one of the β_{1j} coefficient from the same estimated equation), 12 of 18 wages, and 6 of 6 exchange rates. The convergence is more evident for quantities transacted. For 15 of the 18 import variables and 21 of 27 of the production variables β_4 is closer to zero than the corresponding $\beta_1, \ldots, \beta_3$ terms. The result that convergence in the direction of equilibrium is stronger for quantities than for prices is also obtained in the international economies studied by Noussair et al. (1995, 1997).

4.2. Properties of the equilibration process

In this subsection we conduct an exploratory analysis of the production, trade and price data, and study the empirical characteristics of the equilibration process in our economies. We investigate whether the equilibration process is characterized by consistent and regular dynamics. We first consider properties of real activity in the economy and focus on production and trade and their behavior over time in relation to patterns documented in field studies. In the second subsection, we consider the relationships between prices, wages and exchange rates and their dynamics in relation to field data. In the third subsection we describe other interesting patterns in our data that appear to be general characteristics of laboratory markets.

4.2.1 Production and Trade

The regressions in tables 3 - 5 reveal several interesting patterns about the nature of the equilibration process. The first pattern is that the estimated β_2 coefficients tend to deviate from the equilibrium in the direction of autarky. Under autarky, the prices of the goods that would be exported under free trade, x^A, y^B and z^C, are lower than in the competitive equilibrium, and the quantity of these goods produced is below the competitive equilibrium level. The output prices and quantities produced for the remaining six outputs are higher in autarky than in the competitive equilibrium. The import variables are all equal to zero in autarky and positive in the competitive equilibrium. The convergence values tend to lie between the competitive equilibrium and the autarky levels. This pattern is analogous to the home bias often noted in the study of field data, since it reveals the presence of lower international trade than the fundamentals of the economies would predict, as well as the price patterns characteristic of a home bias. We will refer to the tendency of the economies to deviate from their equilibria in the direction of autarky as the *home bias* property.

Property 1: The Home Bias Property – A home bias in trade exists. Observed trade and production levels deviate from competitive model predictions in direction of autarky.

Support for property 1: All of the β_4 coefficients in table 5 for the variables indicating import quantities and the location of the production of the three goods differ from zero in the direction of autarky. The levels of imports are all lower than in the competitive equilibrium, as are the levels of production of the goods that a country exports (the variables $Prod_x^A$, $Prod_y^B$, $Prod_z^C$). All of the other production levels are greater than in the competitive equilibrium, indicting that more production of these goods for domestic consumption occurs than predicted. Six of eight β_4 coefficients for output prices deviate from the competitive model in the direction of autarky (p_y^B is not significantly different from the competitive level at the 5% level of significance). □

This "Home Bias Puzzle" has given rise to many alternative theories to explain why there is less international trade than theory predicts. Among those explanations are imperfect contract enforcement (Anderson and Marcouiller, 1999,) differences in legal systems (Turrini and Van Ypersele, 2001,) intermediate goods trade (Hillberry and Hummels, 2002,) and information/networks (Rauch, 2001.) While these explanations may be plausible for accounting for the field data, none of these are factors in our laboratory experiments. This suggests that it is possible that the home bias in international trade may be due to more fundamental causes than previously thought.

The second property of the equilibration process concerns changes in production over time. Output increases as the economies equilibrate. The increase is due to higher factor utilization, as the quantity of inputs employed grows over time, as well as to rising productivity, the amount of output that is produced with given a quantity of input. Although there are no changes in the production function over the life of our economies, there can be changes in productivity because the economies generally operate strictly inside their production possibility frontiers. Increased productivity in these economies results from better choices of combinations of l and k on the part of individual firms, as well as an improved allocation of l and k between firms.[6]

The Gross National Product of a country J in terms of domestic currency can be calculated as:

$$GNP_J = (p_x^J x^J + p_y^J y^J + p_z^J z^J) \qquad (46)$$

Property 2 is that national GNP's are growing over time. The growth is due to increases over time in both the quantity and the efficiency of resource utilization.

Property 2: GDP growth property - Total output is increasing over time. The increases are due to rising productivity as well as to higher factor utilization.

Support for property 2: The actual world GDP attained in the experiments as a fraction of the competitive equilibrium world GDP is illustrated in figure 7. The figures show that there is a general increasing trend over time in world GDP. In the late periods of all three experiments world GDP is higher as well as closer to the Competitive Model level than in the early periods.[7] Overall, GDP grows at an average of 4% per period in the three economies.

[Figure 7: About Here]

We can measure the component of GDP growth that is due to factor utilization and the amount that is due to productivity growth in the economy. We calculate a version of the Solow residual, which is the component of increased output that greater utilization of factors cannot explain. For our data, the Solow residual (Solow, 1957) for period t is given by:

$$\frac{\Delta \ln(TP_J)}{\Delta t} = \frac{\Delta \ln(GDP_J)}{\Delta t} - \pi_l^{t-1,J} \frac{\Delta \ln(l_J)}{\Delta t} - \pi_k^{t-1,J} \frac{\Delta \ln(k_J)}{\Delta t} \qquad (47)$$

the $\Delta\ln(TP_J)/\Delta t$ term is the increase in total factor productivity in country J between periods t-1 and t. The $\pi^{t-1,J}_l$ and the $\pi^{t-1,J}_k$ terms are the relative weights of labor and capital in production. In

[6] The firms have decreasing returns to scale at the individual level. This does not mean, however, that each firm has an incentive to produce at the smallest possible scale. This is because the number of firms is fixed so that entry into any of the industries is impossible.

[7] In one experiment, World GDP is at times higher than the CE level, and this is possible because the countries' output is weighted by PPP exchange rates based on actual prices and the possibility that

our data they are calculated as $\pi^{t-1,J}_{l} = l^{t-1,J}/(l^{t-1,J} + k^{t-1,J})$, where $l^{t-1,J}$ is the quantity of input l used in country J in period t-1. The increase in input utilization from period t-1 to period t is expressed as $\pi_l^{tJ}\dfrac{\Delta\ln(l)}{\Delta t} - \pi_k^{tJ}\dfrac{\Delta\ln(k)}{\Delta t}$, and the change in productivity as $\dfrac{\Delta\ln(TP_J)}{\Delta t}$. The differences are calculated between one period and the next and defined at either the national or the world level. The increases in both variables are most rapid in the early periods of the sessions. At the world level, factor utilization increases by an average of 14.14% per period from periods 1 to 3 and .58% per period thereafter. Productivity increases an average of 7.87% per period from periods 1 to 3 and .65 % per period thereafter.□

Much of the increase in production over time is comprised of goods that are eventually exported. In the first two periods, the rapidly rising GNP is mostly reflected in increasing production for local consumption and the volume of international trade is low. In later periods the location of production changes to reflect countries benefiting from their comparative advantages and the volume of international trade rises rapidly. Export growth thus tends to increase by greater percentages than GNP growth.

International economists have noted a relationship between national GDPs and the value of international trade called the gravity model. One version of the model posits the relationship:

$$\ln(V_{JK}) = a + b(GNP_J + GNP_K) \tag{48}$$

where V_{JK} denotes the value of trade between two countries J and K. V_{JK} is given by:

$$V_{JK} = \sum_{i=x,y,z} p_i^{\ J} IMP_i^{JK} / r_J + \sum_{i=x,y,z} p_i^{\ K} IMP_i^{KJ} * r_J / r_k \tag{49}$$

IMP_i^{JK} denotes the imports of good i from country K into country J ($r^A = 1$, since currency A is the numeraire currency). In analyses using field data, the distance between the two countries and the idiosyncratic features of the country pair are typically included in the specification and have significant effects. In our experiment, there is no notion of distance between countries, and there are no special features specific to any country-pair. However, the data suggest that the gravity

suppliers sell more than the competitive equilibrium quantity of input resulting in production greater than the equilibrium level.

model relationship in (48) holds in the experimental economy with a remarkable degree of accuracy. While the linear relationship is difficult to explain, the fact that trade increases faster than GDP is related to the fact that there is very little trade early in the experiments. Initially, agents focus on domestic markets. When prices begin to stabilize, agents become aware of international arbitrage opportunities and large increases in trade occur.

Property 3: The Gravity Model Property - International trade becomes a larger fraction of the economy over time. The value of trade between two countries is approximately linear in the product of their GDPs.

Support for property 3: The share of international trade in the world economy increases over time from an average of 12.9% of world GNP in period 1 to 29.4% of World GDP in period 16. From period 3 on, while world GNP grows at only 1.22% per period, the value of international trade increases on average 15% from one period to the next. Figure 8 illustrates the relationship between V_{JK} and $(GNP_J + GNP_K)$ for the pooled data from all three experiments. The gravity model predicts a positive linear relationship between the two variables shown in the graph. The slope is given by the parameter b in (48). The data in the figure show a pattern that appears quite consistent with a linear specification with a positive slope. □

[Figure 8: About Here]

Our results suggest that the widespread use of the gravity model to describe patterns of international trade is justified. In addition, our results suggest that there is some fundamental principle concerning market size that is important in explaining the patterns of international trade.

4.2.2. Prices, Wages and Exchange Rates

Properties 1 - 3 concern quantities of goods supplied, produced and exported in our economies. Properties 4 – 5 below describe the behavior of transaction prices. We have already noted that prices tend to deviate from the Competitive Model predictions in the direction of autarky. However, in addition to the mean prices following a particular pattern relative to the equilibrium level, we also find that the variances in input and output prices exhibit consistent patterns. These are summarized as property 4. The normalized standard deviations of transaction prices are generally greater for input than for output prices. This is consistent with empirical studies of field data (see for example, Clark 1999) that find that prices for primary and intermediate goods, as measured by the Producer Price Index, tend to be more volatile than for final goods, measured by the Consumer Price Index. Furthermore, normalized standard deviations also tend to be greater for exchange rates than for either input or output prices. The volatility of exchange rates has been a topic of interest in international finance. It has been noted that changes in exchange rates are not fully reflected in prices of goods in different countries, leading to failures of the Law of One Price and of Purchasing Power Parity (see for example Obstfeld and Rogoff, 2000). In our data we also find that exchange rates tend to be more volatile than other prices.

Property 4: The Input/Output/Exchange Price Variance Property – Transaction Price variability is higher for producer prices (inputs) than for consumer prices. (outputs) Exchange rates exhibit more variability than the prices of other goods.

Support for property 4. To provide a measure of consumer prices, we calculate the pooled average normalized standard deviation across the two input markets in each country. This is given by $\frac{\sigma^J_{inputs}}{\mu^J_{inputs}} = \sqrt{((n_l - 1)\sigma^J_l / \mu^J_l + (n_k - 1)\sigma^J_k / \mu^J_k) \big/ (n_l + n_k - 2)}$, where n_m is the number of units of input *m* traded. We calculate as well as the pooled average normalized standard deviation over the three output markets in each country, which is given by $\frac{\sigma^J_{outputs}}{\mu^J_{outputs}} = \sqrt{((n_x - 1)\sigma^J_x + (n_y - 1)\sigma^J_y + (n_z - 1)\sigma^J_z) \big/ (n_x + n_y + n_z - 3)}$. We consider the late periods of each experiment. In experiment 1, the pooled normalized standard deviation of prices in the input markets is greater than that of output markets in each of the three countries. In experiments 2 and 3, the input markets exhibit greater pooled normalized standard deviations than the output markets in 2 of the 3 countries. Thus, in seven of nine possible cases, there is more variability in producer prices than in consumer prices.

We also calculate the pooled average normalized standard deviation of prices in the late periods in the currency markets and compare them to those from pooling prices in the six world input markets (two markets in each country) and the nine world output markets. In each of the three experiments, the normalized standard deviation of prices is greater in the currency markets than in the input markets and in the output markets. □

Thus, it appears that input and output markets behave differently in some respects from each other and from foreign exchange markets. The greater price variance in input than in output markets may reflect a relatively slow speed of adjustment of markets, such as factor or foreign exchange markets, where demand is derived rather than exogenous as in the output markets. Such a principle is consistent with the high variance observed in exchange rates, since demand for foreign exchange is also derived. The markets tend to stabilize "backwards", beginning with the final goods market, and followed by input markets. Thus, a version of the "Swingback Hypothesis" (Forsythe et al. 1982) observed in experimental asset markets appears to be at work in our economies.[8]

Markets for foreign exchange are of special interest to economists. It has been noted in field studies that exchange rates exhibit persistent departures from purchasing power parity levels. As the support of property five documents, there are deviations from purchasing power parity in our data as well, but they tend to diminish over time. Figure 6 illustrates this pattern, and shows that during the convergence process exchange rates track ever more closely over time the level that corresponds to Purchasing Power Parity, the exchange rate that would equalize purchasing power in the two countries. We define r_B^{ppp}, the Purchasing Power Parity exchange rate, as the following:

$$r_B^{PPP} = \frac{p_x^B \sum_j x_j + p_y^B \sum_j y_j + p_z^B \sum_j z_j}{p_x^A \sum_j x_j + p_y^A \sum_j y_j + p_z^A \sum_j z_j} \tag{50}$$

The price indices for each country in the numerator and the denominator of (50) use the world production (which is always equal to world consumption) of each good as the weight for the good in the consumption bundle. We find that the exchange rates tend to converge toward the PPP level, even when the PPP level departs from the competitive equilibrium. Although the output markets might be in disequilibrium, the currency market prices adjust in the direction of equalizing purchasing power in the two countries. While the movement of exchange rates is toward PPP, this convergence is not complete since even asymptotically. As table 5 reveals the exchange rate of currency C for A does not reach the PPP level. Of course, since prices in the

[8] In repeated markets for two-period assets, the final period transaction price tends to converge to near its rational expectations equilibrium price before the first period transaction price does.

goods markets are not at equilibrium levels in all markets, at least some of the Law of One Price equations, given by (39) – (44), will fail to hold.

Property 5: Purchasing Power Parity Convergence - Exchange rates tend to move in the direction of purchasing power parity levels. However, convergence is incomplete and purchasing power parity is not reached.

Support for property 5: Table 6 contains the regression results for the variable (r_A - r_A^{PPP}) and (r_B – r_B^{PPP}). For both variables, the β_4 terms are closer to zero that any of the other three coefficients. For the variable $r_B - r_B^{PPP}$, the β_4 term is not significantly different from zero. However, the β_4 term for r_A - r_A^{PPP} is significantly different from zero at the $p < .05$ level. □

[Table 6: About Here]

4.2.3 Other Properties of the Equilibration Process

Property 6 encompasses two characteristics of prices of final goods. The first is that final goods prices tend to be greater than the competitive model predictions. This is consistent with previous experimental work on multiple-market economies (Goodfellow and Plott, 1990; Noussair et al., 1995). The second is that the greater consumer surplus is, relative to the competitive equilibrium revenue in the market, the further the average transaction price is above the competitive prediction. Since all demand curves for final goods are linear in our economies, the statement is equivalent to the assertion that the steeper the demand function for a given competitive equilibrium price and quantity, the more the price exceeds the competitive prediction. This pattern is somewhat reminiscent of the rent asymmetry effect studied by Smith and Williams (1982). They note that prices in single market economies tends to converge to equilibrium prices from above when equilibrium consumer surplus exceeded producer surplus and from below when producer surplus is greater than consumer surplus. In essence, prices in our markets are higher relative to equilibrium prices when they have upward flexibility, that is, when they do have relatively small consequences on the quantity exchanged.

Property 6: The Surplus Price Adjustment Property - Output prices are higher than in the competitive equilibrium. The difference between observed and equilibrium output prices tends to be greater, the greater the ratio of consumer surplus to equilibrium expenditure.

Support for property 6: Consider a weighted average of consumer prices, $P_J = \dfrac{p_x^J x^J + p_y^J y^J + p_z^J z^J}{x^J + y^J + z^J}$, for country *J*. The index has a value greater than the competitive equilibrium value in each period, in each country, and in each experiment except for one (that is, in 131 of 132 instances). The exception is in country *A* in period 1 of experiment 1. Therefore output prices are generally higher than the competitive model predictions.

We compare the correlation between the following two variables for each good in each country (nine total goods). The first variable is $\left(\int_0^{q_m^J*} (D_m^J)^{-1}(q_m^J) - p_m^{*J} dq_m^{*J}\right) / (p*_m^J \, q*_m^J)$, the ratio of competitive equilibrium consumer surplus to competitive equilibrium expenditures for good *m* in country *J*. The second is p_m^J/p_m^J*, the ratio of the observed to the equilibrium price of good *m* in country *J*. The observed price is defined by adding the estimated value of β_4 in table 3 to the equilibrium price, so that $p_m^J/p_m^J* = \dfrac{p_m^J * + \beta_4}{p_m^J *}$. We rank the nine goods (three goods in three countries) by their values of the two variables, which are pooled across sessions, and calculate the correlation between the two rankings. The correlation between the two rankings is .636. Furthermore, the goods p_x^C, p_x^B, and p_y^C have the first, second, and third highest values of both variables, and p_x^A has the lowest value of both variables. The ratio of consumer surplus to competitive equilibrium expenditure and the percentage that the price exceeds the equilibrium level are highly positively correlated. □

Property 7 is a relationship between output and input prices that was previously observed in the economies that Noussair et al. (1995) studied. The relationship also appears here. Noussair et al. observed that the ratio of input to output prices was below the competitive equilibrium ratio in their data. They explained the deviation from the competitive equilibrium ratios as a compensation for a risk that producers undertook, and referred to the price pattern as the Risk Compensated Input/Output Price Adjustment Property. The source of the risk lies in the fact that producers must commit themselves to purchase inputs that have no value other than in irreversible production of an output to be sold later at a price that is unknown at the time of the input purchase. To compensate for the risk they bear, producers earn a premium over the amount they would earn in the competitive equilibrium. Riedl and van Winden (2001) observe a similar empirical pattern in their study. We find that the property generalizes in a straightforward way to the economies studied here. This risk premium, along with the inefficiencies in production arising from the misallocation of input between firms and suboptimal input mixes within firms, appears to account for the fact that output prices exceed the competitive predictions. When demand is relatively inelastic, the upward shift is greater in magnitude.

Property 7: The Risk Compensated Input/Output Price Adjustment Property - Wage/Price ratios are lower than the competitive equilibrium level.

Support for property 7: The ratio of wages to prices in a country, $\frac{W_J}{P_J}$, where W_J = $\frac{w_l^J l^J + w_k^J k^J}{l^J + k^J}$ and P_J is defined as previously, is less than the competitive equilibrium level in 101 of 132 instances (the number of observations is one ratio in each of three countries for 44 periods). Thus, we can reject the hypothesis that $\frac{W_J}{P_J}$ is greater than or equal to the competitive equilibrium price ratio at the $p < .01$ level of significance. □

The final property of the equilibration process is a behavioral regularity that has been observed in some previous experimental studies, the *Sawtooth* property of transaction prices (see Plott 2002 for a detailed discussion). The Sawtooth property is a characteristic of the time series of transaction prices in a goods market within a period. Here the pattern appears to manifest itself with much greater force than in simpler experimental economies. In almost all markets for both outputs and inputs, and in all of the experiments, prices are declining *within* a market period.

Property 8: The Sawtooth Property - Within a market period, input and output markets exhibit the "sawtooth" property. Transaction prices decline within the period. This pattern is consistent with a higher option value for goods acquired earlier in the period.

An example is shown in figure 9. We believe that declining prices within periods in these markets (resale of units purchased is permitted in any of the markets) occurs at least in part because of the option of resale later in the period increases the value of units obtained early in the periods. The observation that the Sawtooth Property does not appear in our foreign exchange markets supports this interpretation. Unlike in an input or an output market, the option value of resale of foreign currency exists for both parties to the transaction. Each party to a foreign exchange transaction is a “purchaser” of a “good”, a foreign currency (domestic currency can be thought of as the money used to purchase the good). The premia resulting from the option value of resale for the two parties may thus have a tendency to offset, and the result is the absence of the Sawtooth pattern in the currency markets.

[Figure 9: About Here]

5. Conclusions

Experimental economics has produced a growing body of evidence supporting a principle of market convergence toward the equilibrium of the competitive model. The competitive equilibrium is defined as a solution to a system of simultaneous equations and is thus a static concept. However, the equilibration process is dynamic and is influenced by human behavior resulting from bounded rationality, heterogeneous beliefs, learning and errors. These uncontrolled features of behavior interact with technological and institutional constraints such as irreversible production, cash-in-advance constraints, undiversifiable risk, and the particular institutions of exchange in effect to produce a dynamic process of activity over time. With some notable exceptions (stability references), our understanding of this convergence process is empirical so a natural question exists about the robustness of the stylized facts of market convergence.

The research reported here created an economic system far larger and more complex than anything studied experimentally in the past and is focused on two issues. The first is the robustness of the most basic principles of market behavior to matters of scale. We consider whether behaviors observed in small-scale laboratory economies are also observed at a larger, more complex scale. Are larger scale economies orderly and similar to smaller scale versions or does chaos ensue with scale? Do new and different principles emerge to govern system behavior or do the same principles observed operating in smaller economies still apply?

Our data demonstrate that chaos does not necessarily ensue as the complexity of the economy increases. An equilibration process is clearly evident in the sense that the movements of economic variables are in the direction of the general competitive equilibrium of the appropriate model together with decreasing variance. Although the equilibration process is slower and less complete than in simpler economies, there are no qualitative differences. The same principles are in operation at both scales.

The second issue is the reliability of the model as developed to deal with the particular production, preference, and market interdependencies that are characteristic of international economies. We conclude that the essential elements of the special theory that has evolved to address complex issues of international trade and finance are operating. The general equilibrium model in the form of a classical theory of international economics predicts much of what is observed. In the sense of the movement of magnitudes of variables such as trade flows and exchange rates, the general theory of international trade and finance emerges with much supporting evidence.

Our experiments contribute to a third issue, which was not part of our planned research but is nevertheless important. We ask whether empirical patterns frequently observed in field settings appear in the experiments. If such patterns are observed it demonstrates that explanations of field events are not forced by logic to special institutions, parameters or theories, for explanations of what they have observed. The theoretical principles of the general equilibrium model coupled with the properties of the market equilibration process may provide appropriate explanations in some cases. Indeed, some well-known empirical patterns typically found in data from field studies of international trade and finance are also found in the experimental data. Both output and productivity are increasing over time. A nation's international trade rises proportionally more rapidly than its income. Bilateral trade patterns between countries conform to the gravity model. A home bias in trade is observed. Exchange rates and prices converge toward purchasing power parity levels, albeit not completely. Exchange rates exhibit proportionally more variance than input or output prices. The variance of input prices exceeds that of output prices. At least in our economies, these properties appear to be properties of the equilibration process as opposed to consequences of special institutions, policy variables or technological change. In principle, the methodology we have used here, to explore the laboratory data for patterns that appear in field data, may be successfully applied in reverse. In particular, the patterns of activities observed in the experiments can be used to motivate conjectures about patterns of field data produced from naturally occurring economies.

We close with the conjecture that the patterns of convergence we observe in our experiments will be observed operating at much larger scales than we were able to create for this study. We saw nothing about the operation of these economies that would suggest that the basic principles of economics are wrong or will be severely modified by scale. The results reported here suggest that much larger market systems are beyond neither human capacities nor beyond the reach of laboratory experimental methods.

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Table 1: Number of Participants of Each of the Twelve Types and Their Functions

Type	Country	Role	Parameter Values	# in exp 1	# in exp 2	# in exp 3
1	A	Producer of X Consumer of Y	$f_x^A(k,l) = 4l^{.25}k^{.25}$ $U(y) = 1650y - 100y^2$	5	3	5
2	A	Producer of Y Consumer of X and Z	$f_y^A(k,l) = 2l^{.25}k^{.25}$ $U(x,z) = 700x - 100x^2 + 1900z - 100z^2$	5	3	5
3	A	Producer of Z Consumer of X and Y	$f_z^A(k,l) = 2l^{.25}k^{.25}$ $U(x,y) = 700x - 100x^2 + 1650y - 100y^2$	5	3	4
4	A	Supplier of L and K Consumer of Z	$C(l,k) = 26l + 2l^2 + 10k + 5k^2$ $U(z) = 1900z - 100z^2$	5	3	5
5	B	Producer of X Consumer of Y and Z	$f_x^B(k,l) = 2l^{.25}k^{.25}$ $U(y,z) = 3900y - 400y^2 + 5600z - 400z^2$	5	4	5
6	B	Producer of Y Consumer of X	$f_y^B(k,l) = 4l^{.25}k^{.25}$ $U(x) = 3800x - 400x^2$	5	4	5
7	B	Producer of Z Consumer of X and Y	$f_Z^B(k,l) = 2l^{.25}k^{.25}$ $U(x,y) = 3800x - 400x^2 + 3900y - 400y^2$	5	4	4
8	B	Supplier of L and K Consumer of Z	$C(l,k) = 48l + 15l^2 + 4.091k + 7.5k^2$ $U(z) = 5600z - 400z^2$	5	4	5
9	C	Producer of X Consumer of Y and Z	$f_x^C(k,l) = 2l^{.25}k^{.25}$ $U(y,z) = 13500y - 1000y^2 + 16000z - 1000z^2$	5	4	5
10	C	Producer of Y Consumer of X and Z	$f_y^C(k,l) = 2l^{.25}k^{.25}$ $U(x,z) = 12000x - 1000x^2 + 16000z - 1000z^2$	5	3	5
11	C	Producer of Z	$f_z^C(k,l) = 4l^{.25}k^{.25}$	5	2	4
12	C	Supplier of L and K Consumer of X and Y	$C(l,k) = 300l + 50l^2 + 220k + 20k^2$ $U(x,y) = 12000x - 1000x^2 + 13500z - 1000z^2$	5	3	5

Table 2: Competitive Equilibria in the Experiments

Variable	Competitive Model			Autarky Model		
	Exp. 1	Exp. 2	Exp. 3	Exp. 1	Exp. 2	Exp. 3
p_x^A	539	567	497	205	206	184
p_y^A	795	724	773	1036	1036	981
p_z^A	1035	1008	1142	1193	1193	1275
p_x^B	1095	1249	1006	2034	2016	2111
p_y^B	1614	1594	1564	855	850	851
p_z^B	2101	2219	2312	2994	2984	3847
p_x^C	3329	4000	2567	7269	6587	7325
p_y^C	4906	5106	3993	7569	8181	7629
p_z^C	6385	7108	5902	4405	6187	5477
$w^A{}_l$	143	142	139	139	139	134
$w^A{}_k$	209	208	203	203	203	179
$w^B{}_l$	537	544	514	531	527	557
$w^B{}_k$	391	396	375	387	384	406
$w^C{}_l$	1942	2110	1811	1898	2024	1948
$w^C{}_k$	1235	1351	1162	1217	1295	1248
$IMP^B{}_x$	22	15	16	0	0	0
$IMP^C{}_x$	33	21	34	0	0	0
$IMP^A{}_y$	20	15	16	0	0	0
$\mathrm{IMP}^C{}_y$	22	17	32	0	0	0
$\mathrm{IMP}^A{}_z$	13	9	11	0	0	0
$\mathrm{IMP}^B{}_z$	23	15	25	0	0	0
r^B	2.03	2.2	2.02	-	-	-
r^C	6.17	7.06	5.17	-	-	-

Table 3: Estimates of Regression for Output Prices

Variable	β_1	β_2	β_3	β_4	R^2
p_x^A	-26.8 (36.4)	-229.5* (24.0)	-206.0* (85.6)	-31.2* (12.0)	.65
p_y^A	273.8* (121.4)	557.8* (146.6)	-146.7 (148.8)	149.2* (25.4)	.76
p_z^A	-181.8 (133.6)	124.2 (111.1)	-242.1 (136.8)	213.2* (27.6)	.62
p_x^B	1915.6* (495.8)	1307.6* (338.0)	557.3 (417.9)	734.3* (79.6)	.86
p_y^B	72.4 (76.8)	-155.2 (165.9)	-114.7 (132.1)	45.8 (24.7)	.11
p_z^B	2008.8* (714.5)	-153.9 (121.0)	280.1 (182.2)	1263.1* (87.5)	.91
p_x^C	5966.6* (1144.0)	1434.8 (914.6)	2543.1* (657.5)	2241.1* (171.8)	.89
p_y^C	-1196.2 (1639.5)	1687.2* (771.7)	1566.4 (1422.4)	2087.0* (228.6)	.76
p_z^C	-6210.1* (2732.9)	-2155.8 (1191.2)	2696.2 (1351.3)	1055.2* (328.7)	.49

Table 4: Estimates of Regression for Input Prices and Exchange Rates

Variable	β_1	β_2	β_3	β_4	R^2
w_l^A	440.2* (151.0)	163.8* (42.8)	13.9 (37.1)	54.0 (14.8)	.74
w_k^A	564.5* (161.1)	35.9 (44.4)	-33.5 (38.6)	15.8 (15.7)	.70
w_l^B	707.1* (257.1)	-167.8* (45.3)	-82.2 (78.0)	104.1* (28.5)	.63
w_k^B	657.2* (227.9)	-106.8 (63.8)	-41.7 (81.0)	171.9* (26.7)	.74
w_l^C	-264.4* (127.2)	-477.3 (330.9)	-116.3 (367.0)	89.4 (58.1)	.14
w_k^C	-210.4* (90.9)	51.8 (122.7)	69.8 (139.6)	210.0* (29.8)	.59
r^B	1.33 (.90)	-1.71* (.52)	2.53* (.51)	.62* (.14)	.50
r^C	-15.06* (2.49)	-7.84* (1.45)	6.36* (1.42)	1.63* (.38)	.72

Table 5: Estimates of Regression for Imports and Production by Country

Variable	β_1	β_2	β_3	β_4	R^2
IMP_x^B	-27.4* (5.6)	-15.7* (2.3)	-6.9 (4.6)	-8.1* (0.9)	.89
IMP_x^C	-31.9* (2.5)	-26.7* (4.3)	-20.7* (2.3)	-15.2* (1.0)	.93
IMP_y^A	-29.4* (7.1)	-17.8* (4.5)	9.8 (7.3)	-5.2* (1.2)	.73
IMP_y^C	-23.4* (3.5)	-12.9* (2.7)	-41.2* (7.1)	-13.6* (1.1)	.92
IMP_z^A	-11.6* (2.1)	-16.6* (5.7)	-3.1 (3.9)	-1.9 (1.2)	.44
IMP_z^B	-25.4* (4.1)	-13.1* (1.8)	-30.9* (4.6)	-13.6* (0.9)	.95
$Prod_x^A$	-49.4* (5.1)	-41.6* (6.6)	-18.7* (7.1)	-22.1* (1.5)	.93
$Prod_y^A$	-12.2* (2.9)	2.6 (3.1)	16.7* (1.6)	2.3* (0.8)	.59
$Prod_z^A$	-34.2* (10.8)	-6.8 (4.6)	12.8 (8.1)	4.9* (1.6)	.54
$Prod_x^B$	-1.1 (1.7)	-13.1* (2.7)	12.9 (8.0)	6.6* (1.0)	.69
$Prod_y^B$	-53.0* (5.6)	-28.6* (2.5)	-33.0* (3.0)	-18.0* (1.0)	.58
$Prod_z^B$	-15.9* (2.4)	-6.2* (3.0)	1.5 (1.2)	3.5 (0.7)	.53
$Prod_x^C$	-11.7* (3.7)	2.2 (1.2)	14.2* (3.8)	13.6* (0.9)	.90
$Prod_y^C$	-13.5* (4.2)	3.3* (1.3)	6.5 (3.8)	9.9* (0.7)	.84
$Prod_z^C$	-59.2* (4.0)	-29.9* (1.8)	-53.2* (1.4)	-17.1* (1.1)	.74

Table 6: Estimates of Regression for Differences Between Observed and PPP Exchange Rates

Variable	β_1	β_2	β_3	β_4	R^2
r_A - r_A^{PPP}	-.738 (.690)	-1.045* (.394)	1.603* (.385)	.240 (.103)	.40
$r_B - r_B^{PPP}$	-6.730* (2.020)	-5.381* (1.175)	2.200 (1.151)	.281 (.311)	.49

Figure 1: The Structure of the Economies

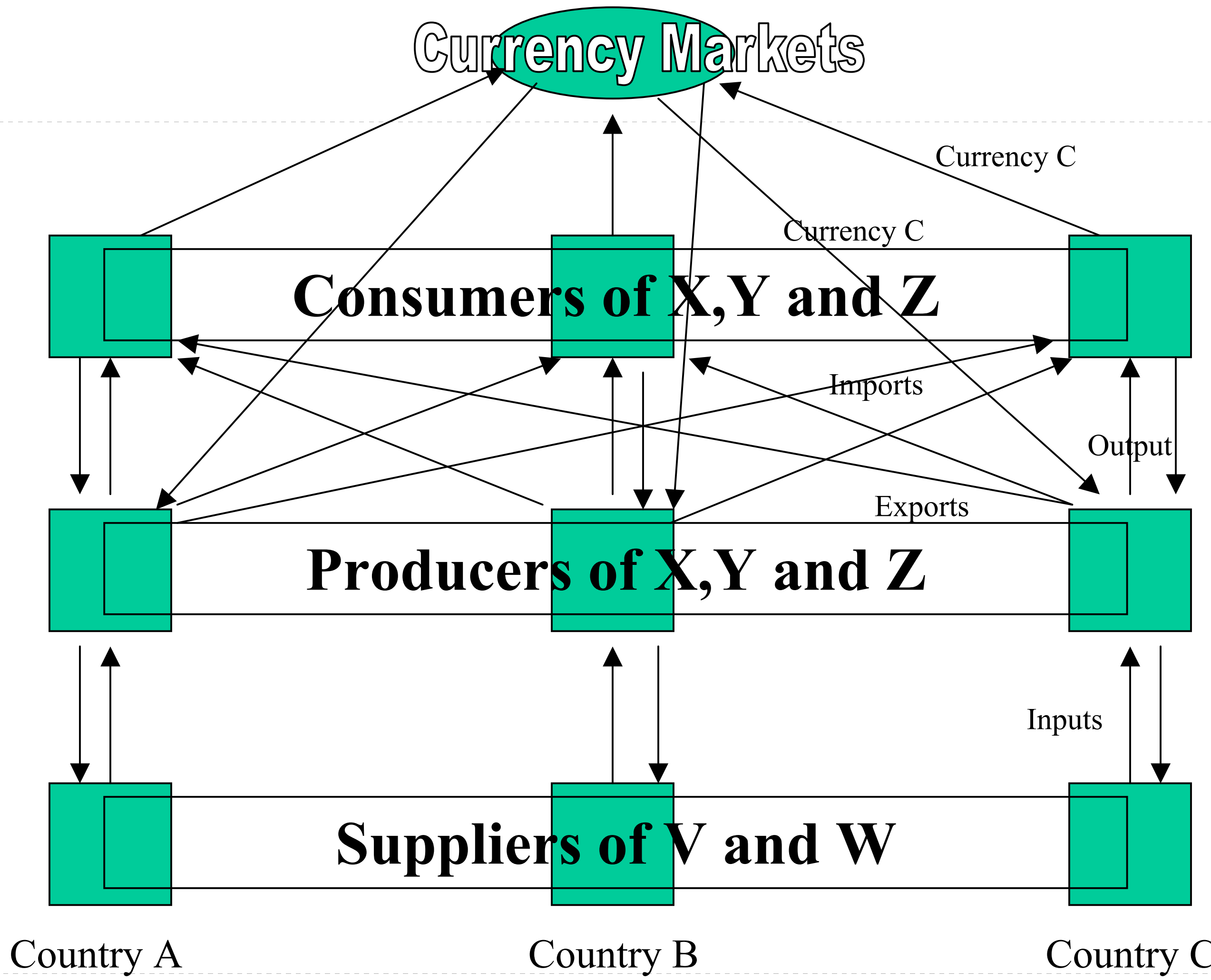


Figure 2: The Market Summary Screen

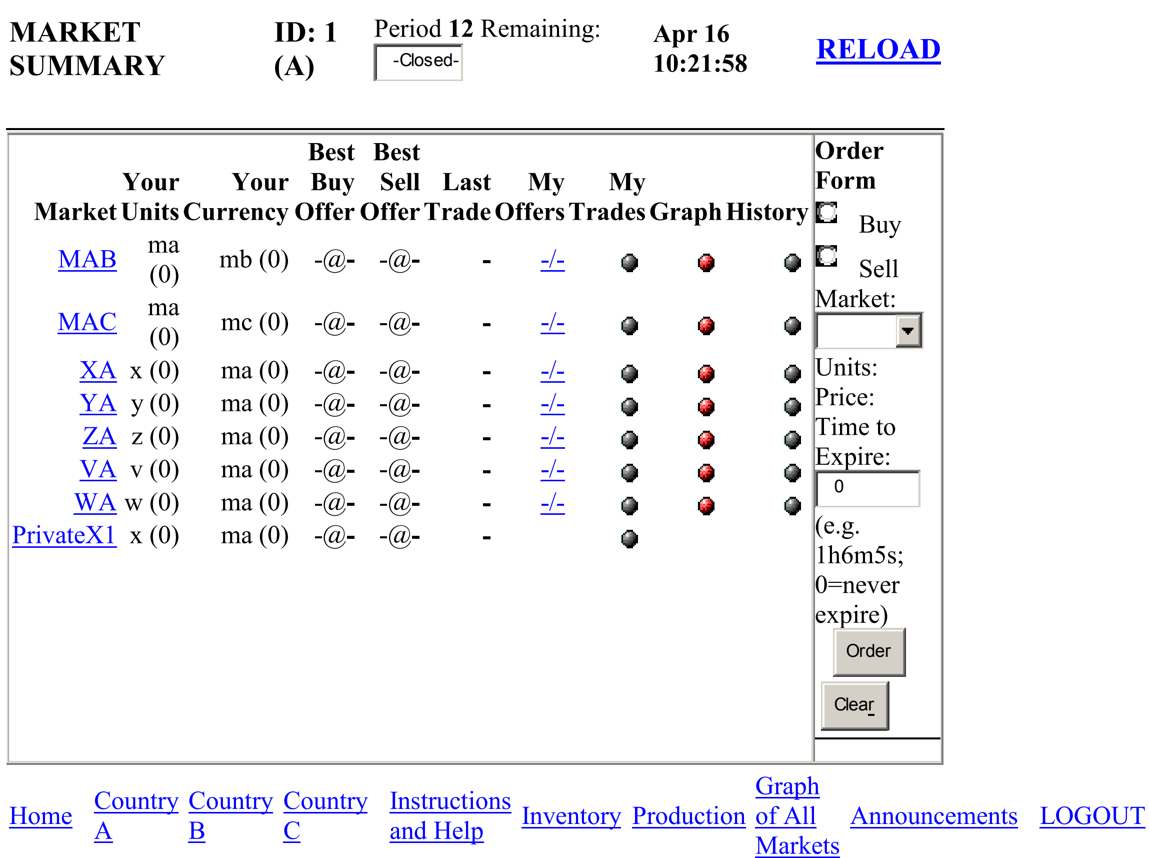


Figure 3: Production Function Display

Table of production of X from V and W

V used	Amount Produced								
8	0	7	8	9	10	10	11	11	12
7	0	7	8	9	9	10	10	11	11
6	0	6	7	8	9	9	10	10	11
5	0	6	7	8	8	9	9	10	10
4	0	6	7	7	8	8	9	9	10
3	0	5	6	7	7	8	8	9	9
2	0	5	6	6	7	7	7	8	8
1	0	4	5	5	6	6	6	7	7
0	0	0	0	0	0	0	0	0	0
	0	1	2	3	4	5	6	7	8
	W used								

Figure 4: Output Prices in the Three Counties, Experiment 3

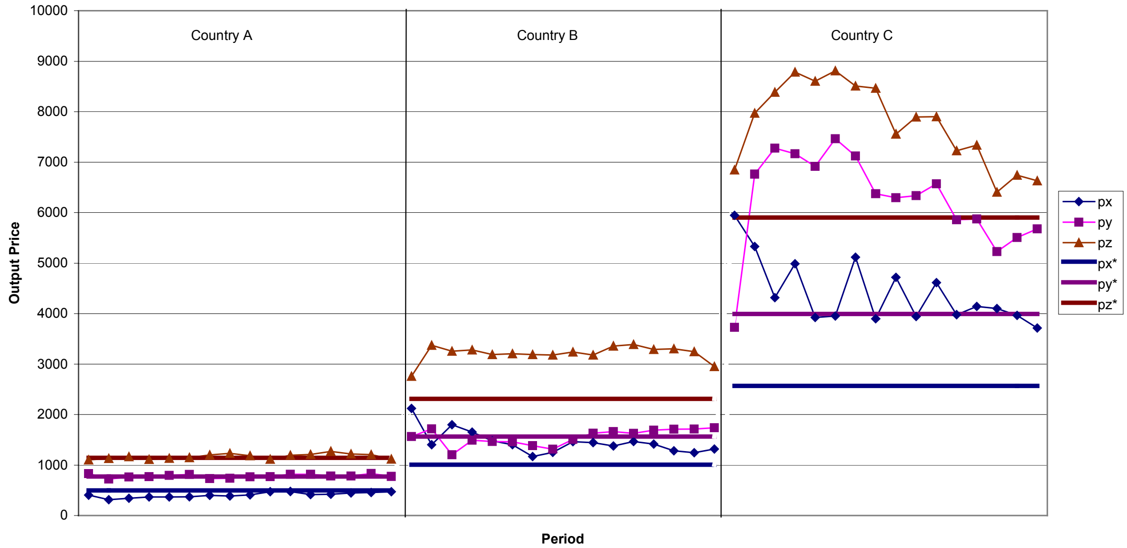


Figure 5: Input Prices in the Three Countries, Experiment 3

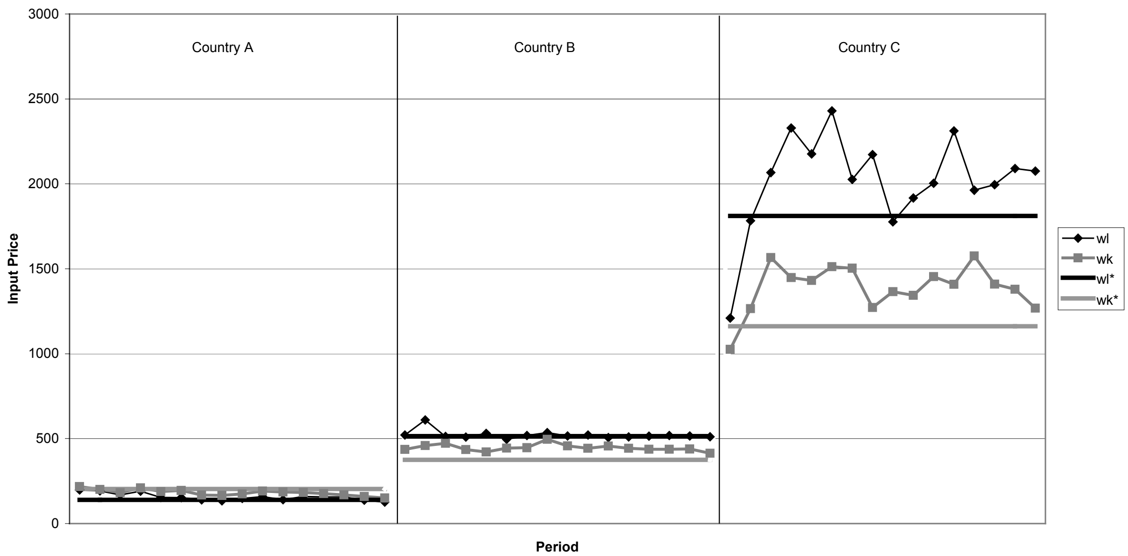
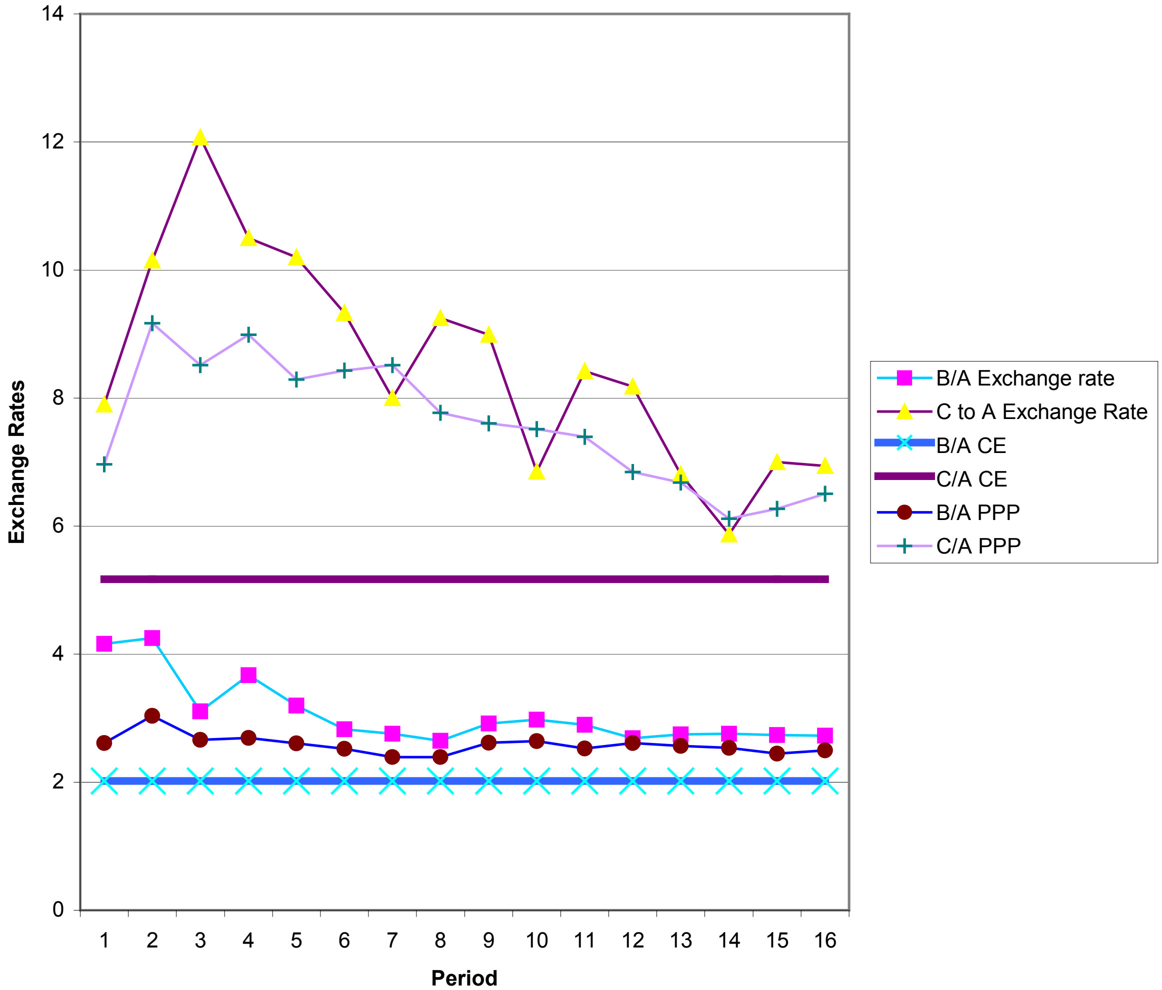


Figure 6: Observed, Equilibrium and PPP Exchange Rates, Experiment 3



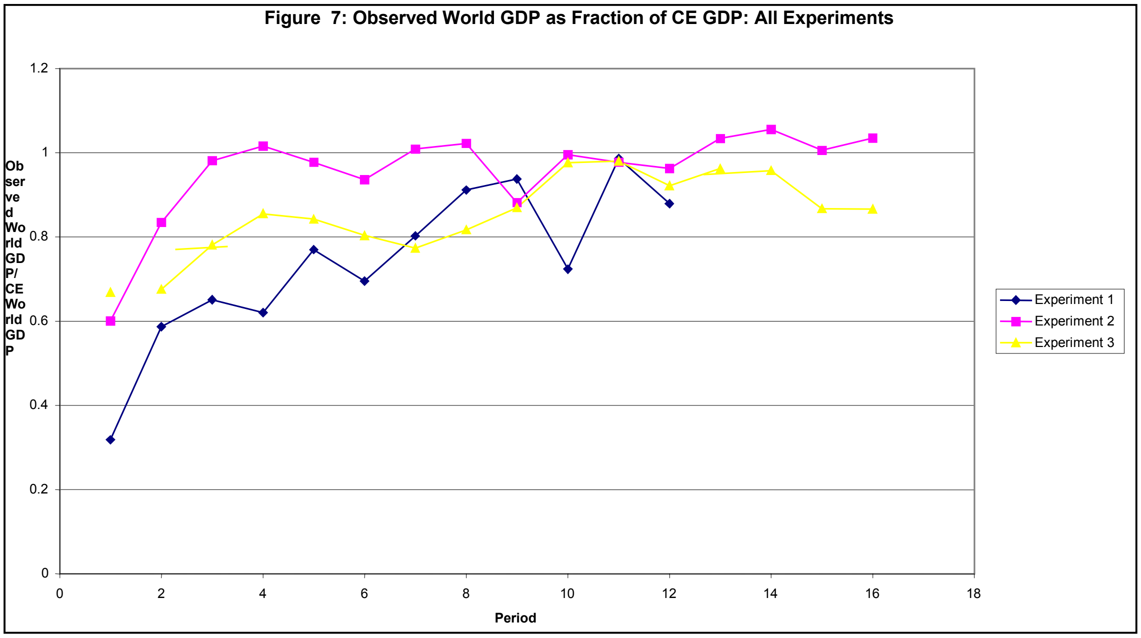


Figure 7: Observed World GDP as Fraction of CE GDP: All Experiments
Observed World GDP/CE World GDP
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
Period
Experiment 1
Experiment 2
Experiment 3

Figure 8: Relationship between value of trade and total GDP of trade partners

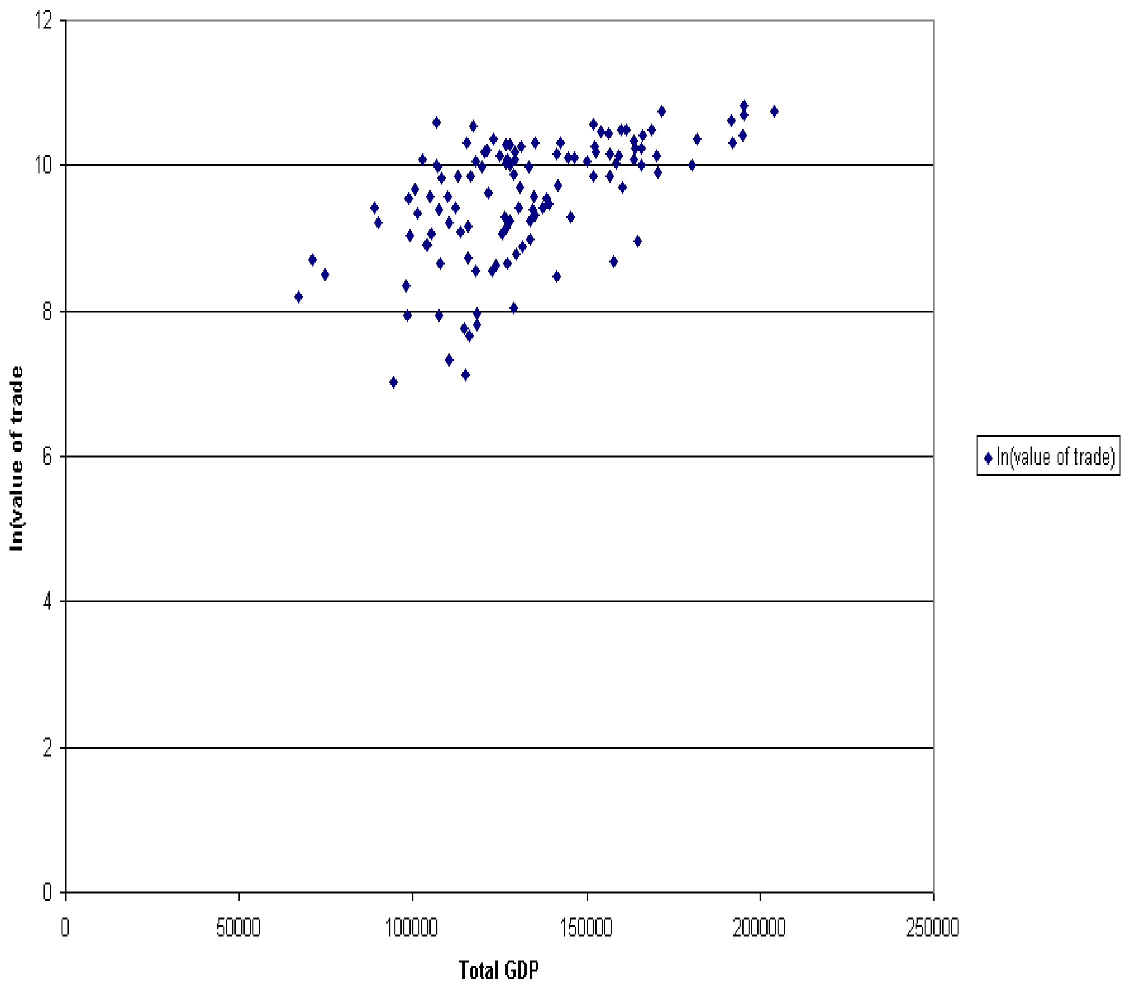


Figure 9: Time series of Wages for L in country A, Experiment 1