How do firms transition between monopoly and competitive behavior? An Agent-based Economic Model

Michael de la Maza
Redfire Capital Management Group
950 Massachusetts Ave., Suite 209
Cambridge, Massachusetts 02139
RedfireGrp@aol.com

Ayla Oğuş
Department of Economics
Boston College
Chestnut Hill, Massachusetts 02167
ogus@bc.edu

Deniz Yuret
Artificial Intelligence Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
deniz@mit.edu

Abstract

Artificial life has long held out the promise of revolutionizing how scientists approach a variety of problems. In this paper we describe an application of artificial life techniques to the study of a fundamental problem in economics: How does a firm transition from monopoly behavior to competitive behavior as other firms enter the market? Solving traditional economic models provides the equilibrium, but does not give the path to equilibrium.The firms in our artificial life simulation do not have access to any global information about the market. The resulting global behavior that arises from this local price-setting behavior is the equilibrium predicted by the traditional analytical models. Hence, our simulation provides a proof by example that simple, local rules of interaction can create the global regularities observed and predicted by economists, thus providing a relatively low upper bound on how complex firm agents must be to reach equilibrium. In this paper we describe the various agents in the model–firms, consumers, capital suppliers, labor suppliers–and present the outcome of several simulations of the model.

Introduction

For over a decade, artificial life proponents have suggested that artificial life techniques will revolutionize our understanding of the way the world works. Seminal ideas, such as the notion that global regularities can arise from many local interactions, have the potential to provide theoretical underpinnings for many fields, particularly those in the social sciences.

An economic model is a set of decision-making mechanisms, organizational arrangements, and rules for allocating society's scarce resources. An economic model can be as simple as one agent on an island (a Robinson Crusoe economy), or as complex as the everyday decisions of the 5 billion people in the world, the interactions between all firms in all countries and the actions of all governments. The traditional approach to economic modeling is geared towards obtaining an equilibrium solution. This involves solving the maximization problems of all agents to yield market-clearing prices (markets clear when demand is equal to supply) for all goods and also the quantities that are exchanged at these prices. One assumption imposed for analytic tractability that rarely captures the economic phenomenon we observe is homogeneity of agents. Relaxing this assumption is not possible in a lot of economic models and, if it can be relaxed, the level of heterogeneity that can be modeled is still very restricted. Moreover, equilibrium solutions are not always very informative for policy purposes. For policy makers, the path to equilibrium is just as important as the equilibrium itself.

In this paper, we present an agent-based general equilibrium model of a simple transition economy (an economy, such as those of Poland and Hungary, that is moving from a centrally planned system to a competitive market system) that draws on methods developed in the field of artificial life. The agents in our artificial life model use only local information to arrive at the equilibrium price. The dynamics of reaching the equilibrium price are of particular interest when studying transition economies. Because of the generality of artificial life methods, our model is not restricted to homogeneous agents like most standard economic models are. As a result of these enhancements, macroeconomic outputs of our simulated economy, such as production, pricing, and profits, qualitatively resemble those of real-world transition economies.

Modeling the transition from centrally planned to market economies of former communist countries poses a particular challenge. Economies in transition are economies that are making marked changes in their market structure. Since the demise of the Soviet Union, this has become a relevant and hot research topic. Many countries have begun to move away from a centrally planned economy to a more market-based economy. The transition from communism can be analyzed in terms of four basic tasks of economic reform (Sachs 1996) :

- Systemic Transformation: The institutional, legal, political, and administrative change of the economic system from state-ownership and central planning to private ownership and market allocation of resources.
- Financial Stabilization: The end of the pre-reform monetary overhang, high inflation, and large fiscal deficits.
- Structural Adjustment: The initial reallocation of resources in the economy following the introduction of market forces.
- Implementation of a Framework to Promote Rapid Economic Growth.

The transition economies of Eastern Europe and the former Soviet Union have demonstrated that it is possible to introduce the institutions of a market economy within five years. According to Jeffrey Sachs (Sachs 1996):

> ...liberalization of the economy surely proved to be the quickest and most effective area of change. In the fastest-reform economies, currency convertibility was quickly established; prices were freed, and shortages eliminated; and international barriers were cut, resulting in significant growth of trade.
>
> ...Without question the most difficult aspect of institutional reform has been privatization.

Economic theories do not provide definite answers to the questions that are most central: What is the optimal speed of reforms and what is the best sequencing of reforms? The "shock therapy" proponents favor simultaneous reforms throughout the economy (Lipton & Sachs 1990; Boycko 1992; Frydman & Rapaczynski 1994; Sachs 1993), whereas "gradualists" emphasize the sequencing of reforms (Portes 1991; McKinnon 1991; Dewatriport & Roland 1992; Murrell 1992).

Empirical evidence shows important similarities and differences in the experiences of transitioning economies which contribute to the lack of consensus. Gross Domestic Product (GDP) in a lot of transition economies has followed a U-shaped pattern, an initial decline followed by growth. However, the severity of the fall and its duration has differed (Blanchard 1996). The private sector's share of the GDP has increased, but the increase has been anywhere from double to tenfold (Selowsky & Martin 1997). Countries that have adopted similar reform packages have differed drastically in their responses (Frye & Schleifer 1997).

Examining phenomena such as the U-shaped pattern in output requires modeling the dynamics of the economy. We adopt an artificial life methodology that lends itself with greater ease to modeling these dynamics.

Artificial life techniques hold out the promise of overcoming some of the problems associated with the traditional approach. Artificial life researchers have shown that local rules of behavior can lead to identifiable global regularities. The emphasis on exploiting local information, emergent behavior, and self-organization make artificial life techniques an ideal tool for studying transition economies.

In this paper, we take a first step towards addressing some of the vexing problems posed by transition economies. We present a general equilibrium model of a simple transition economy. It is a general equilibrium model, not because the solution assumes equilibrium, but in the traditional sense that all prices and quantities are determined within the model. We focus on the behavior of firms in a single market, but we also have markets for labor and capital. We analyze the transition from a controlled economy where production is undertaken by one state-owned enterprise (SOE) to a market economy. The agents in this economy do not have access to global information and act on simple rules. We show that equilibrium can be reached. We are also able to replicate qualitatively the U-shaped pattern of output observed in transition economies.

Model

This section describes the decision-making processes of the agents in an economy with one product market,and two input markets (capital and labor). Firms are the only agents we model explicitly and they interact with the three markets. There is a special firm, namely the state-owned enterprise (SOE), which has different constraints than the rest of the firms. All firms, including the SOE produce identical products. We do not explicitly model consumer agents but rather impose specific input supply functions and an output demand function.

This model can be solved analytically if firm agents are assumed to be homogeneous. All of the functions are differentiable, so the solution involves simultaneously solving the equilibrium conditions and all the first order conditions to the maximization problems, to get market-clearing prices and quantities. However, heterogeneous agents are a defining component of transition economies so this simplification would rob the simulation of all potential interest.

Firms

The private firms maximize profits at every period, taking prices of their output and inputs as given. The firms' objective function is:

$$\max_{K,L} \Pi = \max_{K,L} PF(K,L) - rK - wL$$

where $F(K,L) = AK^aL^b$ (Cobb-Douglas production function).

L is labor demand, K is capital demand, and, P, w and r are the market-clearing prices of output, labor services and capital services, respectively. If the parameters of the Cobb-Douglas production function (A, a, and b) are the same across firms, the firms are homogeneous.

Typically, the standard economic approach to solving such a maximization problem is to use calculus. In our simulation, the firm agents instead use local methods, drawn from the field of artificial life, which are described in the Simulation Details section. In particular, the firm agents use locally available prices instead of the market-clearing prices.

The State-Owned Enterprise (SOE)

The SOE maximizes profits at every period but it has to satisfy an employment constraint. The labor demanded in the industry has to be at least $\bar{L}$. The SOE's objective function is:

$$\max_{K,L} \Pi = \max_{K,L} PF(K,L) - rK - wL$$

subject to

$$Q_L^D \geq \bar{L}$$

where Q_L^D is industry labor demand. The production function, F, is also Cobb-Douglas, the parameters of which may be different than those of private firms.

Like the private firms, the SOE uses an optimization method that requires only local information to maximize this objective function.

Input Supply

The supply functions of inputs are increasing (at a decreasing rate) functions of the input prices.

$$Q_L^S = A_L w^p,\ p < 1 \text{ and } A_L > 0$$

$$Q_K^S = A_K r^q,\ q < 1 \text{ and } A_K > 0$$

where Q_L^S is quantity supplied in the labor market and Q_K^S is quantity supplied in the capital market.

Consumer Demand

The market demand for the firms' output is linear[1]:

$$P = A_D Q^D + D,\ D > 0 \text{ and } A_D < 0$$

As with the input suppliers' supply curves, this market demand function is provided exogenously.

Equilibrium Conditions

Demand in every market is equal to supply in every market. There are three markets: two input (capital and labor) markets and one output market. The equilibrium conditions for these three markets are:

$$\begin{aligned} Q^D &= Q^S \\ Q_L^D &= Q_L^S \\ Q_K^D &= Q_K^S \end{aligned}$$

where Q^D is the quantity demanded in the output market and the subscripts L and K refer to the labor and capital markets.

[1] Linear demand can also be expressed as: $Q^D = d + A_d P,\ d > 0$ and $A_d < 0$

Simulation Details

In this section, we describe how the firm agents in our simulation make decisions and interact with the three markets. In contrast to traditional economic modeling where the objective functions are optimized simultaneously, our agents act in sequence. The simulation runs as follows:

- Until the stopping criterion is met:

1. For every firm:
   (a) Labor and capital markets provide prices based on recent sales.
   (b) The firm decides the price of its product.
   (c) The product market provides quantity demanded from this firm at this price. The firm produces this amount, provided that it makes a profit. Otherwise, the firm produces the profit-maximizing amount. In doing so, the firm purchases capital and labor at the price computed in step 1a.
2. Firms enter and exit the market.

One cycle through this loop is referred to as a period.

The quantity exchanged does not always have to be equal to the quantity demanded. It will be the minimum of the two: quantity produced or quantity demanded. If there is excess demand, it is left unsatisfied.

Firm Agents

Firms optimize profit by continuously changing price in small increments (1%) in the direction they think will increase profit. They only know the last change they made in price and the last change they observed in profit. If there was an increase in profits they change the price in the same direction; otherwise, they change the price in the opposite direction. This hill-climbing approach to uncovering the optimal price is successful because the firms' objective function has a single maximum.

Product Market

The quantity demanded from a single firm at a given price is computed such that the exponential average of quantity exchanged stays on the curve. Specifically, the quantity demanded is given by:

$$\max\left(\frac{P_m - D}{A_D} - q_{avg,m}(n-1), 0\right)$$

where P_m is the price submitted by the current firm, n is the number of firms and:

$$q_{avg,m} = (1-\beta^{1/n})q + \beta^{1/n} q_{avg,m-1}$$

where q is the last quantity exchanged, m denotes the mth exchange, and β, the exponential constant, is 0.1.

Capital and Labor Markets

The rent at which a firm can purchase capital is computed as follows:

1. Total capital rented in that period is estimated using the exponential average of the capital rented.
2. The rent at which this amount of capital would be supplied is computed from the supply function.
3. If the last rent was lower the rent is increased; if the last rent was higher the rent is decreased subject to a maximum 1% change[2].

The exact formulation is:

$$r = \left(\frac{nk_{avg,m}}{A_K}\right)^{1/q}$$

where n is the number of firms and :

$$k_{avg,m} = (1-\beta^{1/n})k + \beta^{1/n} k_{avg,m-1}$$

where k is the last capital exchange, m is the mth exchange, and β, the exponential constant, is 0.1.

The wage is determined by the same algorithm, using the average labor hired and the last wage in the following relationship:

$$w = \left(\frac{nl_{avg,m}}{A_L}\right)^{1/p}$$

where n is the number of firms and :

$$l_{avg,m} = (1-\beta^{1/n})l + \beta^{1/n} l_{avg,m-1}$$

where l is the last labor exchanged, m is the mth exchange, and β, the exponential constant, is 0.1.

SOE agent

The SOE behaves like the firms, but with an additional employment constraint. After it decides how much labor to hire, it checks to see if its estimate of total employment is at least $\bar{L}$. If not, it hires the difference.

Results

In this section we describe four experiments of increasing complexity.

Effects of market size: This experiment attempts to reproduce well known classical results in our simulation environment. In a simple market with identical firms, we show the monopoly, the oligopoly and the competitive outcome.

[2] Without this restriction, some systems are unstable. We see increasing oscillations in prices and quantities rather than convergence to equilibrium.

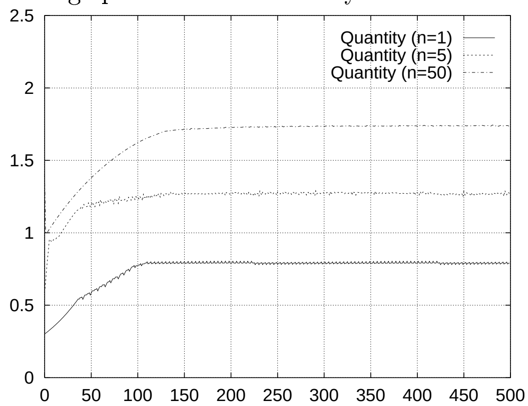
Imposing minimum employment: During liberalization, the government may want to prevent unemployment by imposing a minimum employment constraint on the SOE. This experiment demonstrates that an artificially imposed employment level may reduce market efficiency.

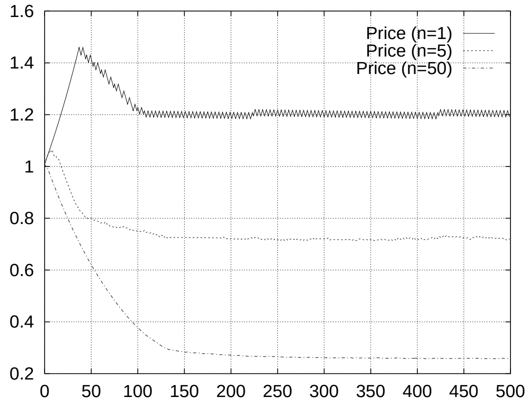
Liberalization of the market: This experiment analyzes the effects of liberalization in a market where all firms are identical.

Introducing heterogeneous firms: This experiment analyzes the effects of liberalization in a market where firms have varying degrees of efficiency.

Effects of market size

Figure 1 shows how the market reacts to an increase in the size of the private sector. We present plots of total quantity produced in the market, average price and average profit under a monopoly ($n = 1$), an oligopoly ($n = 5$) and perfect competition ($n = 50$). We observe that quantity increases as price and profits fall when the number of firms in the market increases. This is exactly what is predicted by economic theory: competition increases the quantity produced and decreases the average profits in the industry.





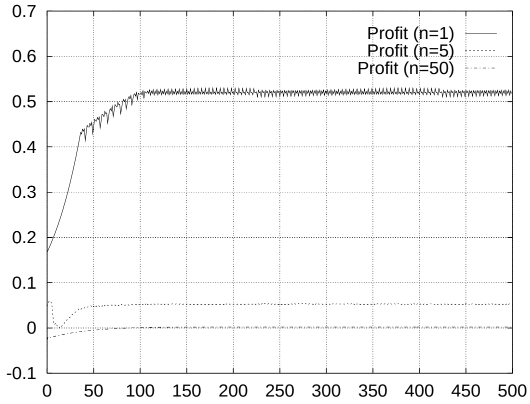
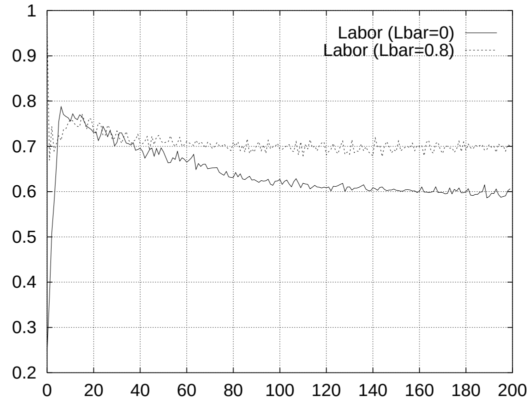


Figure 1: Dynamics of quantity, price, and profit in markets of different sizes.

Imposing minimum employment

This set of simulations shows a state owned enterprise (SOE) coexisting with a fixed number of identical firms. We observe how the behavior of the SOE, which has to maintain employment in the industry above $\bar{L}$, changes when the number of private firms in the industry changes.

Figure 2 shows how the SOE's employment constraint affects the total labor employed by the industry, total quantity and average price. Without a labor constraint, the equilibrium labor usage is approximately 0.6. When $\bar{L}$ is set to 0.8, the SOE is forced to employ more labor than it would have liked and total labor usage in the industry increases but remains below 0.8 due to averaging errors in the calculation. The labor constraint is binding which results in a less efficient outcome, illustrated by a lower equilibrium quantity and a higher equilibrium price.



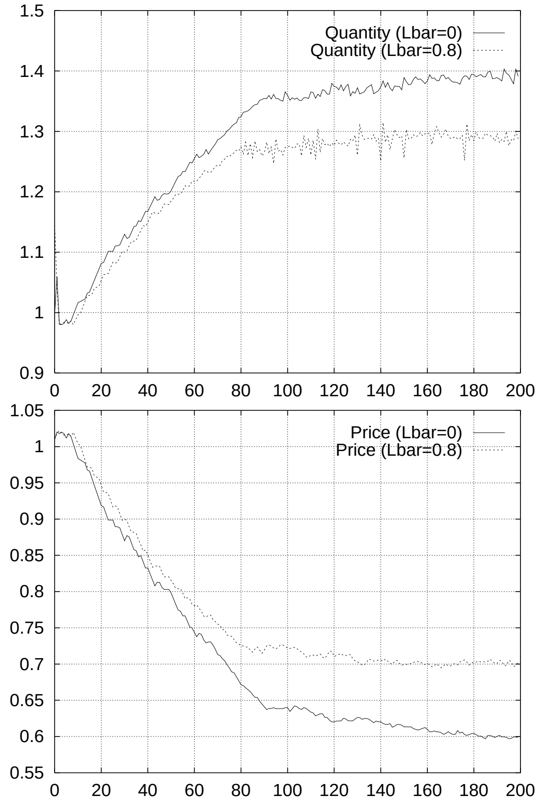


Figure 2: Imposing minimum employment decreases efficiency.

Liberalization of the market

This set of experiments differs from the first experiment in one important sense: firms are allowed to enter and exit the market.

Figure 3 shows how our simulated economy smoothly transitions from a protected environment to perfect competition. During the first 500 periods, entry into this market is prohibited and the SOE is the only firm in the industry (i.e., $n = 1$). The market is liberalized in the 501st period. High profits attract new firms and we observe an increase in the number of firms. This reduces firms' profits. In addition, quantity increases as the price declines. These findings are consistent with economic theory. All of the firms are identical to the SOE in this experiment and a minimum employment constraint is not imposed. The SOE's production can be approximated by dividing total quantity by the number of firms in the industry. The SOE's price and profit are almost identical to the average price and average profit in Figure 3. The significance of this experiment is that the simple SOE agent exhibits monopoly and competitive behavior in an emergent and endogenous manner. The SOE's behavior rules are the same in both monopoly and competitive environments. It is the interaction with the other agents that causes the decline in average price.

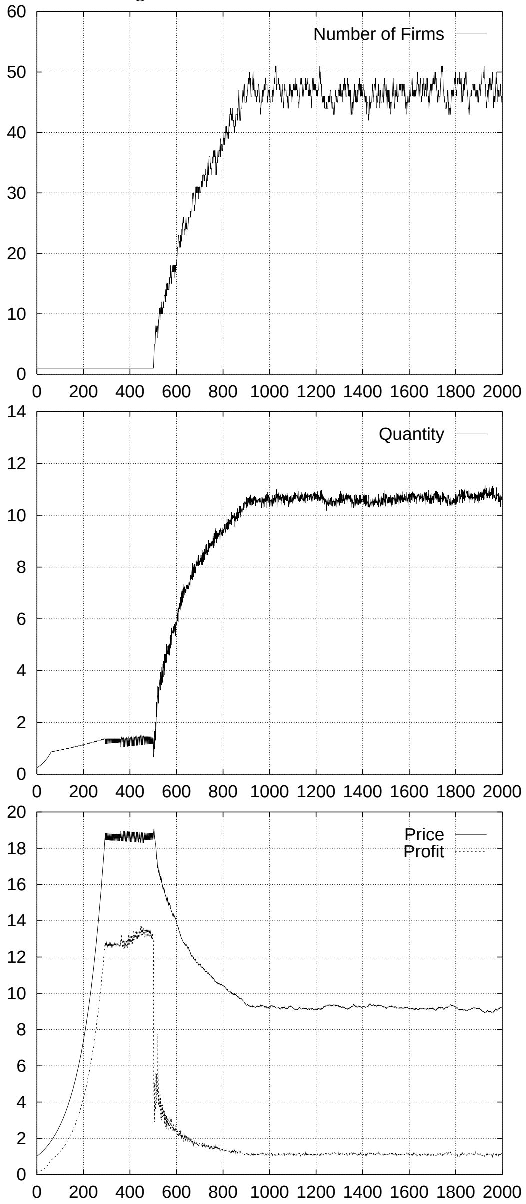


Figure 3: Liberalization in a market with identical firms at period 500.

Introducing heterogeneous firms

The SOE operates alone for the first 500 periods and reaches the monopoly equilibrium. These 500 periods simulate the centrally planned interval of a transition economy. After 500 periods, the market is liberalized and other firms start entering because of high profits in the industry. The probability that a new firm will want to join the market during a period is an increasing function of average profits in the market. Firms only produce in the feasible region of their supply function, so they never make negative profits. If they do not produce for two periods in a row, they exit the market. For these experiments, the SOE does not have an employment constraint because we discovered that, in the scenarios we analyzed, it was rarely binding.

In Figure 4, the heterogeneity of the firms enables us to observe how price and wage evolve as the industry becomes increasingly dominated by more efficient firms. Rent and wage follow a similar pattern so we only provide a plot for wage. Initial entrants to the market are not necessarily very efficient, because with a high profit margin even inefficient firms can survive. Competition results in lower prices, reducing profit margins so only those firms with more efficient production technologies enter the market as price declines and the inefficient firms exit. As more efficient firms enter the market, labor and capital become more productive so wage and rent are bid up.

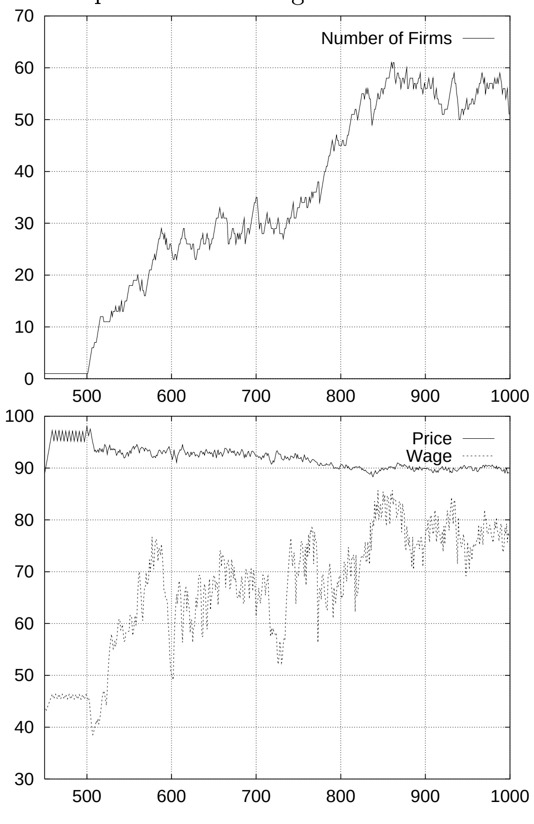


Figure 4: Competition between heterogeneous firms leads to lower price and higher wages after liberalization at period 500.

Figure 5 shows the U-shaped output curve that immediately follows liberalization. The U-shaped pattern of output was observed in the transition economies in Eastern Europe and still puzzles economists. The simulation allows us to vary a large number of parameters, and we are able to replicate this result qualitatively for certain ranges of parameter values.

The decline in output after liberalization is due to a decline in the output of the SOE which is not offset by the output of new private firms. The initial entrants to the market are inefficient, and they lure resources away from the more efficient SOE. This is the reason for the initial decline in quantity, the corresponding fall in wage, and rent (not shown here).

Econometric evidence suggests that the start of growth is due to improved resource allocation, both within SOEs and through utilization of assets by new private firms as SOEs are downsized or liquidated (Barbone, Marchetti, & Paternostro 1996; Pinto, Belka, & Krajewski 1993).

This is illustrated here as well. The increase in quantity coincides with the increase in the efficiency of new firms. At the end of each period, one firm can enter but more than one firm can exit. As a result, n initially increases steadily because even inefficient firms can enter and survive. Later on, n declines as firms exit in large numbers and entry to the market becomes less frequent. As more efficient firms dominate the market, inefficient firms exit and the average price declines. In Figure 4, the equilibrium has not been reached yet, but the declining trend in average price is apparent. The increases in rent and quantity show that the greater efficiency in production increases the total quantity produced and the prices of the inputs.

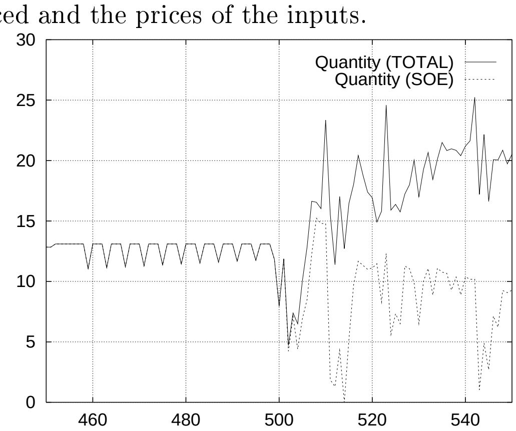


Figure 5: The U shaped output curve after liberalization at period 500.

Related Work

The field of computational economics is a young and growing field. While this paper presents the first agent-based model of transition economies, many others researchers have begun to draw on ideas from the field of artificial life to model economic phenomena. Critically, the emergent behavior exhibited by many artificial life systems has the potential to explain how large-scale economic behavior arises from local interactions among a multitude of heterogeneous agents (Arthur De Vany, personal communication).

One of the most complete artificial life models of an economy is the Aspen system developed by Richard Pryor and colleagues at Sandia National Labs (Basu *et al.* 1996). Aspen has a rich set of agents, including households, firms in four different sectors, a realtor, a capital goods producer, banks, and a government. The firms use a genetic algorithm to select a price that maximizes profits. The Aspen model duplicates several results first described by Modigliani in his research on the FMP model.

Sugarscape, a versatile system that has become a testbed for studying problems in the social sciences, has been used to examine simple trading models. In these trading models, agents in a two-dimensional landscape trade two goods (sugar and spice) that the agents then metabolize. The agents endogenously determine the prices of sugar and spice, and the quantities exchanged. This simulation replicates several findings described in standard economic literature. For example, the number of agents that can exist on a landscape increases when trading is added to the simulation. However, the Sugarscape simulations also demonstrate that, under certain conditions, prices do not converge to the general equilibrium price, a result that differs from standard economic theory.

Work by Youssefmir, Huberman, and Hogg provides a possible explanation for why markets crash, a particularly timely topic given the market gyrations of 1997 (Youssefmir, Huberman, & Hogg 1996). In their model, a set of heterogeneous agents trade in an asset market based on the agents' expectations of what future prices will be. These expectations are based on two components: the fundamental price and a trend. Each agent has a slightly different perception of the fundamental price, and a trend gets established based on the past behavior of prices. Agents differ in their belief in how long a trend will last. So a rising trend can lead to speculative bubbles since most trend followers are likely to believe strongly in the trend, and some fundamentalists will believe in the trend for a while. As prices move away from the fundamental price, fundamentalist agents will expect the trend to reverse itself and eventually some trend followers will also lose faith in the trend, and the speculative bubble will deflate. The price response to buy/sell orders and the individual trend horizon are set exogenously, and asset prices are determined endogenously. These results show that asset prices can deviate sharply from their fundamental values.

In Tesfatsion's Trade Network Game (TNG), the player set is a collection of traders consisting of pure buyers, pure sellers, and buyer-sellers(Tesfatsion 1997). Buyers repeatedly submit trade offers to sellers, who either refuse or accept these offers. If a seller accepts a trade offer from a buyer, the seller and buyer engage in a risky trade modeled as a standard prisoner's dilemma game. The iterated prisoner's dilemma strategies used by buyers and sellers to conduct their trades are evolved by means of a genetic algorithm. The fact that traders are able to choose and refuse their trading partners makes this a better model of real-world trading than standard game models in which partners are matched randomly or by round robin assignment. Simulations are run for two types of markets: Endogenous-type markets comprising only buyer-sellers; and two-sided markets comprising equal numbers of pure buyers and pure sellers. The findings illustrate how en ante capacity constraints, in the form of buyer offer quotas and seller acceptance quotas, are a primary driving force determining the evolution of trading behavior. For example, given relatively large seller acceptance quotas and relatively small buyer offer quotas, sellers tend to be parasitized by buyers in the sense that buyers are able to latch on to cooperative sellers and successfully defect against them.

Contributions and Future Work

In this paper, we applied artificial life techniques to an outstanding problem in economics. Critically, we have defined and implemented a firm agent that exhibits monopoly and competitive behavior under appropriate conditions. The development of this firm agent, an agent which relies only on local information to make pricing decisions, is the primary contribution of this work.

Our simulation provides an upper bound on the complexity of an agent required to generate the qualitative features of a transition economy. These features include a U-shaped output curve, an increasing share of the private sector in production and efficiency gains in resource allocation. These results give a proof-by-example that an approach to economics that draws on ideas from the field of artificial life may succeed in providing important insights into economic phenomena.

As the next step in developing this approach, we plan to fully model consumer agents who choose consumption and leisure. This will endogenize consumption and labor decisions thus enabling us to address labor market issues. We also plan to calibrate our simulation to a real-world transition economy, such as Poland or Hungary.

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Appendix

Parameter values for Figure 1:

$$F(K,L) = K^{0.5}L^{0.25}$$

$$F(K,L)_{SOE} = K^{0.25}L^{0.2}$$

$$Q_L^S = w^{0.5}$$

$$Q_K^S = r^{0.5}$$

$$P = 2 - Q$$

Parameter values for Figure 2:

$$F(K,L) = K^{0.5}L^{0.25}$$

$$F(K,L)_{SOE} = K^{0.25}L^{0.2}$$

$$Q_L^S = w^{0.5}$$

$$Q_K^S = r^{0.5}$$

$$P = 2 - Q$$

$$n = 10$$

Parameter values for Figure 3:

$$F(K,L) = K^{0.25}L^{0.25}$$

$$F(K,L)_{SOE} = K^{0.25}L^{0.25}$$

$$Q_L^S = w^{0.5}$$

$$Q_K^S = r^{0.5}$$

$$P = 20 - Q$$

Parameter values for Figure 4 and Figure 5:

$$F(K,L) = AK^aL^b$$

$$A \sim uniform(0.1, 2)$$

$$a \sim uniform(0.1, 0.9)$$

$$b \sim uniform(0.1, 0.9)$$

$$F(K,L)_{SOE} = 5K^{0.25}L^{0.2}$$

$$Q_L^S = w^{0.5}$$

$$Q_K^S = r^{0.5}$$

$$P = 100 - 0.25Q$$

Initial wage, rent and price are 1 for all experiments.

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