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On Money as a Medium of Exchange when Goods Vary by Supply and Demand

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Abstract

Models of the exchange process based on search theory can be used to analyze the features of objects that make them more or less likely to emerge as "money" in equilibrium. These models illustrate the trade-off between endogenous acceptability (an equilibrium property) and intrinsic characteristics of goods, such as storability, recognizability, etc. In this paper, we look at how the relative supply and demand for various goods affect their likelihood of becoming money. Intuitively, goods in high demand and/or low supply are more likely to appear as commodity money, subject to the qualification that which object ends up circulating as a medium of exchange depends at least partly on convention. Welfare properties are discussed.

1. Introduction

Models of the exchange process based on search theory can be used to analyze the features of objects that make them more or less likely to emerge as "money" in equilibrium. Features that are important include the intrinsic properties of an object, which determine how good it is as a store of value, and its acceptability, which determines how good it is as a medium of exchange. Acceptability depends on the behavior of individuals in the economy, since the objects that one chooses to accept as money depend at least in part on what others are accepting (that is, acceptability is a property of an equilibrium more than an intrinsic property of an object).

Search models illustrate the trade-off between endogenous acceptability and intrinsic properties. Several versions of the model have been constructed, focusing on different intrinsic properties that have been suggested as important in the traditional literature (see, e.g., Jevons (1875) and Menger (1892) for early discussions of the desirable intrinsic properties of money). For instance, Kiyotaki and Wright (1989), Aiyagari and Wallace (1991), Cuadras-Morató (1994b), and Burdett et al. (1994) look at what may be thought of as various forms of storability, durability, or portability; and Williamson and Wright (1994), Trejos (1993a), Cuadras-Morató (1994a), and Li (1995) look at what may be thought of as homogeneity or recognizability. We continue this line of research by looking at how the relative supply and demand for various goods affect their likelihood of emerging as media of exchange; that is, we ask how the number of producers and consumers of the different commodities influence whether

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they become money. Both "scarcity" (a relatively low supply) and "intrinsic utility" (a relatively high demand) have often been identified in the traditional literature as crucial factors determining if a good may serve as a commodity money (see, e.g., Jevons (1875), who seems to argue that demand is the most important factor).

To pursue this, we construct a search model where agents are specialists in production but generalists in consumption. On the one hand, an agent of a particular type always produces the same commodity, and the distribution of types thereby determines the relative supply of the different goods. On the other hand, agents of every type have tastes that change over time according to some common distribution, and this determines the relative demand for the different commodities. Otherwise, all goods and individuals are perfectly symmetric, and, in particular, all goods are perfectly and costlessly storable, recognizable, and so on. Individuals meet in a bilateral exchange process where trade is quid pro quo. They always accept a good that they wish to consume, and the interesting question is whether they accept commodities that they are currently not interested in consuming. A high probability of wanting to consume a good encourages an individual to accept it even if he does not want to consume it now, not only because he is more likely to want to consume it next period, but also because, even if he doesn't, trading partners may be more likely to want it next period. Hence, goods in high demand seem more likely to end up serving as money. At the same time, if the number of producers of a good is large, holding demand constant, individuals may be less likely to accept it now since it is easy to acquire when needed. Hence, goods in scarce supply also seem more likely to end up as money. But, again, what agents accept as money also depends on what they

think others are likely to accept. The purpose of this paper is to sort out the details of these effects.

A model that considers similar issues is contained in Jones (1976). However, there are two drawbacks to that model from our current perspective. First, individuals in Jones' model choose and commit to a sequence of trades before the exchange process starts, rather than using optimal sequential strategies to determine when to trade as a function of who you meet and what you both have. Second, he does not generally impose rational expectations concerning the distribution of goods held by other traders in equilibrium (further analyses of Jones' model by Iwai (1988) and Oh (1989) go only part way to addressing these problems). Another related model is described in Wright (1995). However, that model adopts the very special assumption that each type i specializes in the consumption of good i and production of good i+1 (modulo the number of types), which obviously precludes the independent investigation of supply and demand effects. The attempt to generalize that model to study these effects introduced several complications, and led to the rather different model presented here.

In terms of results, the first thing we show is that all types use the same trading strategies in equilibrium. This is important not only because it reduces the set of candidate equilibria rather dramatically, but also because it means that if an object is used as money it is used as money universally (i.e., all agents use the same objects). The next thing we show is that goods are more likely to be accepted as money if and only if holding them implies a higher probability of consumption next period. This is very convenient in terms of solving the model, although note

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that the relevant probability is still endogenous because the likelihood that you consume next period of course depends on the trading strategies of others. We then show that high demand for a good is a necessary condition for it to serve as money, in the following sense: if the demand for a good is sufficiently small then there exists no equilibrium where it is used as a medium of exchange. Indeed, a sufficiently high demand always guarantees that a good will emerge as money. We also show that a high supply of a good does not preclude it from being used as money, nor do low values of supply guarantee it will be used as money. Given supply and demand parameters, multiple equilibria with different media of exchange are possible for the reason to which we earlier alluded: the use of money is at least partly a convention. We show one agent is always better off than another agent if we are in an equilibrium where the former's production good is used as money and the latter's is not. We also show that equilibria are not generally efficient; examples demonstrate that several equilibria may coexist with one being dominated by some other.

2. The model

The economy is populated by a [0,1] continuum of infinite-lived agents. There are 3 types of agents and 3 consumption goods (3 is the minimum number that makes things interesting). These goods are costlessly storable and indivisible. We assume that type i can produce good i, and only good i, at a cost in terms of disutility denoted by D. Let σ_i denote the fraction of the population that are type i, $\Sigma_i \sigma_i = 1$, and let $\sigma = (\sigma_1, \sigma_2, \sigma_3)$. Then σ describes the

relative supplies of the goods.[1]

Although agents are specialists in production they are generalists in consumption. In this model, we assume that at every date $t = 0,1,2...$, each agent gets a taste shock (independent across agents and across time) that determines the good he desires that period. If an agent desires good i, he gets utility U from consuming it and no utility from consuming any other good. In what follows we write $u = U-D$ for the net utility from consumption and production. Let δ_i be the probability that any agent desires good i, $\Sigma_i \delta_i = 1$, and let $\delta = (\delta_1, \delta_2, \delta_3)$. Then δ describes the relative demands for the goods.[2]

If we endow everyone with a single unit of their production good at the initial date, and assume that thereafter agents can produce iff they consume, then every agent will always be holding one unit of one of the goods. If an agent realizes a desire for the good he is holding, he consumes it, produces a new unit of his production good (assuming that D is not too large), and waits for the next period. If he realizes a desire for something other than what he is holding, he enters a trading process, or a *market*, wherein he is randomly matched with another agent who also demands a good other than what he is holding. If both agree to trade, they swap

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[1]Actually, σ_i is a measure of the <u>potential</u> supply of good i, for although it equals the number of agents who can produce it, this is in general different from the number who actually do produce good it each period, or from the number of agents with it in inventory.

[2]Related to the previous footnote, actually δ is a measure of the <u>potential</u> demand for good i, for although it equals the number of agents who would like to consume it each period, this is in general different from the number who actually do consume it, or from the number who accept it in trade.

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inventories one-for-one (since the goods are indivisible); otherwise, they part company and wait for the next period.

If you meet someone in the trading process who has the good that you desire and wants to trade, then obviously you trade. The interesting question is whether you should agree to a trade for a good you do not currently desire. To formalize this, let V_{ij} denote the value function for a type i individual, at the end of a period, holding a good j other than the one currently desired for consumption. One can interpret V_{ij} as the value for individual i of good j as an asset. Since taste shocks are independent over time, V_{ij} does not depend on the good that is desired in the current period. Also, since we consider only stationary equilibria, V_{ij} does not depend on time.

The strategic problem faced by an agent of type i can be summarized in the following way: he wants to trade good j for good k iff $V_{ij} < V_{ik}$, that is, iff the value of k as an asset is larger than the value of good j as an asset.[3] Hence, once we rank the three value functions we know which trades agent i wants to make. For example, if $V_{11} < V_{12} < V_{13}$ then, assuming he did not want to consume the good he was currently holding, type 1 would trade good 1 for good 2, good 1 for good 3, and good 2 for good 3. He would not make any other trades, except of course to acquire a good that he currently desires for immediate consumption.

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[3]We assume agents do not trade if they are indifferent; however, as long as we restrict attention to pure strategy equilibria, this is innocuous because $V_{ij} = V_{ik}$ only on a set of measure zero in parameter space.

We can describe behavior of agents of a particular type by a strategy vector, denoted s^i = $(...s^i_{jk}...)$, where s^i_{jk} = 1 if type i wants to trade good j for good k and s^i_{jk} = 0 otherwise. In fact, since s^i_{jk} = 1 $\leftrightarrow$ V_{ik} > V_{ij}, the vector s^i is completely summarized by any three independent elements, say $\hat{s}^i$ = $(s^i_{12}, s^i_{23}, s^i_{31})$. Given $\hat{s}^i$, we know how to rank the value functions, which gives us all the s^i_{jk}. Provided we restrict our analysis to equilibria in which agents of the same type use the same strategies, we can summarize the behavior of all agents by S = (s^1, s^2, s^3), which describes the strategies of each type.

Let p_{ij} denote the measure of type i agents with good j at the start of a period, $\Sigma_j p_{ij}$ = σ_i, and let p = $(...p_{ij}...)$. The measure of agents with good j is P_j = $\Sigma_i p_{ij}$, and the measure of agents with good j who go to the market is $(1-\delta_j) P_j$, since every agent with good j has probability δ_j of being able to consume without trading. Then the total number of agents in the market is N = $\Sigma_j (1-\delta_j) P_j$, and the fraction of agents in the market who have good i and want good j $\neq$ i is π_{ij} = $P_i \delta_j/N$. Since meetings are random, π_{ij} is the probability of meeting someone who has good i and wants good j. Given S, the distribution p evolves according to some law of motion p' = f(p;S); for now, we simply note that a steady state distribution is a solution to p = f(p;S) (see the Appendix for details). If we know p, we can determine the steady state value of π = $(...\pi_{ij}...)$ as a function of S (given σ and δ). Agents have rational expectations regarding these meeting probabilities.

We now derive the value function for type 1 with an inventory of good 1, looking forward to the next period, for given strategies of others as described by S. This derivation is

somewhat tedious due to the many possible things that can happen to an individual in a period. Propositions 1 and 2 below will simplify the analysis considerably, but it is necessary to consider the general situation before proving these results. To proceed, we partition the different things that can happen to an individual by considering each of three events in turn.

Event 1: With probability δ_1 he desires good 1. In this case, he does not need to go to the market but simply consumes his inventory and produces a new unit of good 1, for a payoff as follows

$$W_1 = u + V_{11}$$

Event 2: With probability δ_2 he desires good 2. Then he goes to the market, where several things can happen. With probability $\pi_{12} + \pi_{13}$ he meets a partner who also has good 1 and they cannot trade, which yields payoff V_{11}. With probability π_{21} he meets a partner with good 2 who wants good 1 and they trade, which yields payoff $u + V_{11}$. With probability $(\delta_3/N)p_{12}$ he meets a partner of type 1 who holds good 2 but wants good 3, and they trade iff this partner is willing to exchange good 2 for good 1, which yields an expected payoff of $s^1_{21}(u + V_{11}) + (1-s^1_{21})V_{11}$. A similar argument can be applied to the case where he meets agents of type 2 and type 3 holding good 2 and wanting to consume good 3. With probability π_{31} he meets a partner with good 3 who wants good 1 and they trade iff our agent is willing to exchange good 1 for good 3, which yields expected payoff $s^1_{13}V_{13} + (1-s^1_{13})V_{11}$. With probability $(\delta_2/N)p_{23}$ he meets a partner of type 2 holding good 3 who wants good 2, and they trade iff $s^1_{13} = 1$ and $s^2_{31} = $

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1. A similar argument applies when our agent meets an agent of type 3.[4] This yields payoff

$s^1_{13}(p_{13}s^1_{31}+p_{23}s^2_{31}+p_{33}s^3_{31})V_{13} + [(1-s^1_{13})(p_{13}s^1_{31}+p_{23}s^2_{31}+p_{33}s^3_{31})+p_{13}(1-s^1_{31})+p_{23}(1-s^2_{31})+p_{33}(1-s^3_{31})]V_{11}$.

Putting all of this together, the expected payoff in Event 2 is

$$W_2 = \left(\pi_{12}+\pi_{13}\right)V_{11}+\pi_{21}\left(u+V_{11}\right)$$

$$+\frac{\delta_3}{N}\left\{\left(p_{12}s^1_{21}+p_{22}s^2_{21}+p_{32}s^3_{21}\right)\left(u+V_{11}\right)+\left[p_{12}\left(1-s^1_{21}\right)+p_{22}\left(1-s^2_{21}\right)+p_{32}\left(1-s^3_{21}\right)\right]V_{11}\right\}$$

$$+\pi_{31}\left[s^1_{13}V_{13}+\left(1-s^1_{13}\right)V_{11}\right]+\frac{\delta_2}{N}\left\{s^1_{13}\left(p_{13}s^1_{31}+p_{23}s^2_{31}+p_{33}s^3_{31}\right)V_{13}\right.$$

$$\left.+\left[\left(1-s^1_{13}\right)\left(p_{13}s^1_{31}+p_{23}s^2_{31}+p_{33}s^3_{31}\right)+p_{13}\left(1-s^1_{31}\right)+p_{23}\left(1-s^2_{31}\right)+p_{33}\left(1-s^3_{31}\right)\right]V_{11}\right\}$$

Event 3: With probability δ_3 he desires good 3. A similar analysis to the previous case implies the expected payoff in Event 3 is

$$W_3 = \left(\pi_{12}+\pi_{13}\right)V_{11}+\pi_{31}\left(u+V_{11}\right)$$

$$+\frac{\delta_2}{N}\left\{\left(p_{13}s^1_{31}+p_{23}s^2_{31}+p_{33}s^3_{31}\right)\left(u+V_{11}\right)+\left[p_{13}\left(1-s^1_{31}\right)+p_{23}\left(1-s^2_{31}\right)+p_{33}\left(1-s^3_{31}\right)\right]V_{11}\right\}$$

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[4]Obviously, no trade will take place when agent of type 1 holding good 1 and wishing to consume good 2 meets another agent of type 1 holding good 3 and wishing also to consume good 2, because s^1_{13} and s^1_{31} can never be both equal to one.

$$\div \pi_{21}\Big[s_{12}^{1}V_{12}\div\big(1-s_{12}^{1}\big)V_{11}\Big]\div\frac{\delta_{3}}{N}\Big\{s_{12}^{1}\big(p_{12}s_{21}^{1}\div p_{22}s_{21}^{2}\div p_{32}s_{21}^{3}\big)V_{12}$$

$$\div\Big[\big(1-s_{12}^{1}\big)\big(p_{12}s_{21}^{1}\div p_{22}s_{21}^{2}\div p_{32}s_{21}^{3}\big)\div p_{12}\big(1-s_{21}^{1}\big)\div p_{22}\big(1-s_{21}^{2}\big)\div p_{32}\big(1-s_{21}^{3}\big)\Big]V_{11}\Big\}$$

The value function V_{11} satisfies

$$V_{11}=\frac{1}{1+r}\sum_{j}\delta_{j}W_{j}\ ,$$

where $r>0$ is the rate of time preference. Substituting the W_{j} formulae into V_{11} and simplifying, we arrive at

$$rV_{11}=\gamma_{1}u\div\delta_{2}s_{13}^{1}\Big[\pi_{31}\div\frac{\delta_{2}}{N}\big(p_{13}s_{31}^{1}\div p_{23}s_{31}^{2}\div p_{33}s_{31}^{3}\big)\Big]\big(V_{13}-V_{11}\big)$$

$$\div\delta_{3}s_{12}^{1}\Big[\pi_{21}\div\frac{\delta_{3}}{N}\big(p_{12}s_{21}^{1}\div p_{22}s_{21}^{2}\div p_{32}s_{21}^{3}\big)\Big]\big(V_{12}-V_{11}\big) \tag{1}$$

where

$$\gamma_{1}=\delta_{1}\div\delta_{2}\Big[\pi_{21}\div\frac{\delta_{3}}{N}\big(p_{12}s_{21}^{1}\div p_{22}s_{21}^{2}\div p_{32}s_{21}^{3}\big)\Big]\div\delta_{3}\Big[\pi_{31}\div\frac{\delta_{2}}{N}\big(p_{13}s_{31}^{1}\div p_{23}s_{31}^{2}\div p_{33}s_{31}^{3}\big)\Big] \tag{2}$$

is the probability of consumption next period conditional on holding good 1, either because good 1 is desired or because something else is desired and acquired in exchange for good 1.

By similar reasoning (or, more efficiently, by appropriately modulating the subscripts), one can derive

$$rV_{12} = \gamma_2(u + V_{11} - V_{12}) + \delta_1 s_{23}^1 \left[\pi_{32} + \frac{\delta_1}{N} \left(p_{13} s_{32}^1 + p_{23} s_{32}^2 + p_{33} s_{32}^3 \right) \right] (V_{13} - V_{12})$$

$$+ \delta_3 s_{21}^1 \left[\pi_{12} + \frac{\delta_3}{N} \left(p_{11} s_{12}^1 + p_{21} s_{12}^2 + p_{31} s_{12}^3 \right) \right] (V_{11} - V_{12}) \tag{3}$$

where

$$\gamma_2 = \delta_2 + \delta_3 \left[\pi_{32} + \frac{\delta_1}{N} \left(p_{13} s_{32}^1 + p_{23} s_{32}^2 + p_{33} s_{32}^3 \right) \right] + \delta_1 \left[\pi_{12} + \frac{\delta_3}{N} \left(p_{11} s_{12}^1 + p_{21} s_{12}^2 + p_{31} s_{12}^3 \right) \right] \tag{4}$$

and

$$rV_{13} = \gamma_3(u + V_{11} - V_{13}) + \delta_2 s_{31}^1 \left[\pi_{13} + \frac{\delta_2}{N} \left(p_{11} s_{13}^1 + p_{21} s_{13}^2 + p_{31} s_{13}^3 \right) \right] (V_{11} - V_{13})$$

$$+ \delta_1 s_{32}^1 \left[\pi_{23} + \frac{\delta_1}{N} \left(p_{12} s_{23}^1 + p_{22} s_{23}^2 + p_{32} s_{23}^3 \right) \right] (V_{12} - V_{13}) \tag{5}$$

where

$$\gamma_3 = \delta_3 + \delta_1 \left[\pi_{13} + \frac{\delta_2}{N} \left(p_{11} s_{13}^1 + p_{21} s_{13}^2 + p_{31} s_{13}^3 \right) \right] + \delta_2 \left[\pi_{23} + \frac{\delta_1}{N} \left(p_{12} s_{23}^1 + p_{22} s_{23}^2 + p_{32} s_{23}^3 \right) \right] . \tag{6}$$

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Using the same reasoning, we can derive similar expressions for the value functions for types 2 and 3. Having done all of this, we are in position to prove that agents of different types necessarily rank the value functions in the same order, and hence use the same strategies.

<u>Proposition 1</u> *For any two types h and i and two goods j and k,* $V_{hj} > V_{hk} \Leftrightarrow V_{ij} > V_{ik}$.

<u>*Proof*</u> After solving the system of linear equations (1), (3), and (5) for the V_{1j} (and the similar system for agents of type 2 and type 3), we get the following result:

$$V_{i1} - V_{i2} > 0 \quad iff$$

$$(\gamma_1 - \gamma_2)(r + \gamma_3 + \delta_2 s_{31}^i \epsilon_1 + \delta_1 s_{32}^i \epsilon_2) + (\gamma_1 - \gamma_3)\delta_1 s_{23}^i \epsilon_3 + (\gamma_3 - \gamma_2)\delta_2 s_{13}^i \epsilon_4 > 0 \quad (7)$$

$$V_{i2} - V_{i3} > 0 \quad iff$$

$$(\gamma_2 - \gamma_3)(r + \gamma_1 + \delta_3 s_{12}^i \epsilon_5 + \delta_2 s_{13}^i \epsilon_4) + (\gamma_2 - \gamma_1)\delta_2 s_{31}^i \epsilon_1 + (\gamma_1 - \gamma_3)\delta_3 s_{21}^i \epsilon_6 > 0 \quad (8)$$

$$V_{i1} - V_{i3} > 0 \quad iff$$

$$(\gamma_1 - \gamma_3)(r + \gamma_2 + \delta_3 s_{21}^i \epsilon_6 + \delta_1 s_{23}^i \epsilon_3) + (\gamma_2 - \gamma_3)\delta_3 s_{12}^i \epsilon_5 + (\gamma_1 - \gamma_2)\delta_1 s_{32}^i \epsilon_2 > 0 \quad (9)$$

where

$$\epsilon_1 = \pi_{13} + \frac{\delta_2}{N}(p_{11} s_{13}^1 + p_{21} s_{13}^2 + p_{31} s_{13}^3) > 0$$

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$$\epsilon_2 - \pi_{23} + \frac{\delta_1}{N}(p_{12}s_{23}^1 + p_{22}s_{23}^2 + p_{32}s_{23}^3) > 0$$

$$\epsilon_3 - \pi_{32} + \frac{\delta_1}{N}(p_{13}s_{32}^1 + p_{23}s_{32}^2 + p_{33}s_{32}^3) > 0$$

$$\epsilon_4 - \pi_{31} + \frac{\delta_2}{N}(p_{13}s_{31}^1 + p_{23}s_{31}^2 + p_{33}s_{31}^3) > 0$$

$$\epsilon_5 - \pi_{21} + \frac{\delta_3}{N}(p_{12}s_{21}^1 + p_{22}s_{21}^2 + p_{32}s_{21}^3) > 0$$

$$\epsilon_6 - \pi_{12} + \frac{\delta_3}{N}(p_{11}s_{12}^1 + p_{21}s_{12}^2 + p_{31}s_{12}^3) > 0$$

The argument now proceeds by contradiction. Suppose that two agents rank the value functions differently and hence use different strategies. For instance, suppose $s^1 = (0,0,1)$ and $s^2 = (1,0,0)$. Then, $V_{11} > V_{12}$, and, by (7), $(\gamma_1-\gamma_2)(r+\gamma_3+\delta_2\epsilon_1+\delta_1\epsilon_2) > 0$, which implies $\gamma_1 > \gamma_2$. Also, $V_{22} > V_{21}$, and, again by (7), $(\gamma_1-\gamma_2)(r+\gamma_3+\delta_1\epsilon_2)+(\gamma_3-\gamma_2)\delta_2\epsilon_4 < 0$, which implies $\gamma_2 > \gamma_3$ (given $\gamma_1 > \gamma_2$). Also, $V_{21} < V_{23}$, and, by (9), $(\gamma_1-\gamma_3)(r+\gamma_2)+(\gamma_2-\gamma_3)\delta_3\epsilon_5+(\gamma_1-\gamma_2)\delta_1\epsilon_2 < 0$, which implies $\gamma_3 > \gamma_1$. This contradicts $\gamma_1 > \gamma_2$ and $\gamma_2 > \gamma_3$. Consequently, we cannot have $s^1 = (0,0,1)$ and $s^2 = (1,0,0)$. Following an identical procedure, one can derive similar contradictions whenever $s^2 \neq (0,0,1)$. One can do the same thing whenever $s^3 \neq (0,0,1)$. Hence, if $s^1 = (0,0,1)$ then $s^2 = s^3 = (0,0,1)$. A similar argument applies to any s^1. This completes the proof. □

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Proposition 1 simplifies things a lot, because we only need to analyze situations in which agents rank the goods in the same order, and we can summarize S by one vector. The following result further simplifies the analysis.

<u>Proposition 2</u> $V_{ij} > V_{ik} \Leftrightarrow \gamma_j > \gamma_k$.

<u>*Proof*</u>: Since all types use the same strategies by Proposition 1, we can substitute $s_{jk} = s^i_{jk}$ in (7)-(9). Then, using $s_{jk} \cdot s_{kj} = 0$, we get the following results for agents of type 1

$$V_{11} > V_{12} \quad iff$$

$$(\gamma_1 - \gamma_2)(r + \gamma_3 + \delta_2 s_{31} \pi_{13} + \delta_1 s_{32} \pi_{23}) + (\gamma_3 - \gamma_2)\delta_2 s_{13} \pi_{31} + (\gamma_1 - \gamma_3)\delta_1 s_{23} \pi_{32} > 0 \quad (10);$$

$$V_{12} > V_{13} \quad iff$$

$$(\gamma_2 - \gamma_3)(r + \gamma_1 + \delta_3 s_{12} \pi_{21} + \delta_2 s_{13} \pi_{31}) + (\gamma_1 - \gamma_3)\delta_3 s_{21} \pi_{12} + (\gamma_2 - \gamma_1)\delta_2 s_{31} \pi_{13} > 0 \quad (11);$$

$$V_{13} > V_{11} \quad iff$$

$$(\gamma_3 - \gamma_1)(r + \gamma_2 + \delta_1 s_{23} \pi_{32} + \delta_3 s_{21} \pi_{12}) + (\gamma_2 - \gamma_1)\delta_1 s_{32} \pi_{23} + (\gamma_3 - \gamma_2)\delta_3 s_{12} \pi_{21} > 0 \quad (12)$$

Given (10)-(12), choose any ranking $V_{ih} > V_{ij} > V_{ik}$, and substitute the implied s. Then, check that $\gamma_h > \gamma_j$ and $\gamma_j > \gamma_k$ are necessary and sufficient conditions for the V's to be ranked in the assumed way (these computations involve simple algebra which is available upon request). $\square$

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Given Propositions 1 and 2, we are now ready to define an equilibrium.

<u>Definition</u> A steady state, pure strategy, equilibrium is a vector s that satisfies $s_{ij} = 1$ iff $\gamma_j > \gamma_i$, where the γ's are defined by (2), (4) and (6).

In terms of intuition, Proposition 2 says that the only value to holding an asset is its use in facilitating future consumption. This is because ultimately all that agents care about is consumption. Proposition 1 says that, irrespective of their production types, all agents rank the goods the same way in terms of their asset value. This is because all agents draw their taste shocks from the same distribution, and so, conditional on holding the same good, they all have the same chance of consuming next period. Of course, once they consume they will be in different positions if they produce different goods, but this does not affect their trading strategies.

In terms of monetary economics, we can say the following. If $\gamma_i > \gamma_j > \gamma_k$, then good i is the best asset and hence is always accepted in trade even if the recipient does not want to consume it; good j is the second best asset and hence is accepted in some trades where the recipient does not want to consume it but not others; and good k is the worst asset and hence is never accepted in trade unless the recipient wants to consume it. According to standard definitions (see, e.g., Kiyotaki and Wright (1989) and the references contained therein), this means that good i serves as a universally accepted commodity money, good j serves as a partially accepted commodity money, and good k never serves as money.

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We now consider some special cases where supply or demand parameters take on certain extreme values (e.g., $\sigma_i = 1$ or $\delta_j = 0$) which allow us to say quite a bit analytically. Although the model is not very interesting at these extreme values (e.g., at $\sigma_i = 1$ there is only one type), by continuity we know that for parameter values not too different from these extremes the results will be qualitatively similar. The following result says that when demand for a particular good is very small the only possible equilibria are those where it is the worst asset, and therefore it can never be used money.

Proposition 3 *When demand for good i is very small, it must be the worst asset, and either of the other two goods will be the best asset depending on which has the greater demand relative to supply (in a sense to be made precise in the proof).*

Proof: We prove this result for the case of a very low demand for good 3; exactly the same argument applies to any other good. Consider the limiting case where $\delta_3 = 0$. Then it is easy to show $P_j = p_{jj} = \sigma_j$ for all j (all types exclusively hold their production good, because, e.g., given $\delta_3 = 0$, type 1 either demands good 1, in which case he consumes and produces a new unit of good 1, or demands good 2, in which case the only trade he ever makes is for immediate consumption). This implies $N = 1 - \sigma_1 \delta_1 - \sigma_2 \delta_2$, $\pi_{12} = \sigma_1 \delta_2 / N$, $\pi_{13} = 0$, $\pi_{21} = \sigma_2 \delta_1 / N$, and $\pi_{23} = 0$ (we will not need π_{3j}). From these one can solve for

$$\gamma_1 = \frac{\delta_1 (1 - \sigma_1 \delta_1)}{1 - \sigma_1 \delta_1 - \sigma_2 \delta_2}$$

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$$\gamma_2 = \frac{\delta_2(1-\sigma_2\delta_2)}{1-\sigma_1\delta_1-\sigma_2\delta_2}$$

$$\gamma_3 = \frac{\delta_1\delta_2(\sigma_1 s_{13}+\sigma_2 s_{23})}{1-\sigma_1\delta_1-\sigma_2\delta_2}$$

It is now easy to see that equilibria where good 3 ranks as the first or second best asset do not exist. Consider, for instance, $s=(0,1,1)$, which requires $\gamma_1 > \gamma_3 > \gamma_2$. Using $\delta_1 = 1-\delta_2$ one can show that $\gamma_3 - \gamma_2 > 0$ iff $\sigma_2 > 1$ which is a contradiction. Similar contradictions can be derived for all equilibria which imply that good 3 would be ranked as best or second best asset, and so the only possible equilibria have $\gamma_3 = 0$, and good 3 is the worst asset.

Given this, we now proceed to rank goods 1 and 2. Observe that $\gamma_1 - \gamma_2$ is proportional to $H(\delta_1) = (\sigma_1-\sigma_2)\delta_1^2 - 2(1-\sigma_2)\delta_1 + 1 - \sigma_2$. Since $H(0) > 0 > H(1)$ and $H'(\delta_1) < 0$ for all $\delta_1 \in (0,1)$, there is a unique δ_1° such that $\gamma_2 > \gamma_1$ iff $\delta_1 < \delta_1^\circ$, where:

$$\delta_1^\circ = \begin{cases} \dfrac{1}{2} & \text{if } \sigma_1 = \sigma_2 \\[2ex] \dfrac{1}{\sigma_1-\sigma_2}\left(1-\sigma_2-\sqrt{(1-\sigma_1)(1-\sigma_2)}\right) & \text{if } \sigma_1 > \sigma_2 \\[2ex] \dfrac{1}{\sigma_1-\sigma_2}\left(1-\sigma_2+\sqrt{(1-\sigma_1)(1-\sigma_2)}\right) & \text{if } \sigma_1 < \sigma_2 \end{cases}$$

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We conclude that when $\delta_3 = 0$, good 3 is the worst asset, and either good 1 will be the best asset iff it has a greater demand relative to supply than good 2 in the sense that $\delta_1 > \delta_1^\circ$; in particular, if good 1 and good 2 are supplied equally $(\sigma_1 = \sigma_2)$, then good 1 is the best asset iff $\delta_1 > \delta_2$. This establishes the desired results for the limiting case $\delta_3 = 0$. By continuity, the equilibrium will be qualitatively similar if δ_3 is strictly positive but not too big. $\square$

The above argument actually implies that any of the possible strategy profiles can be an equilibrium for the appropriate choice of δ, regardless of σ. Consider, e.g., the case $V_{i1} > V_{i2} > V_{i3}$. If we make δ_3 sufficiently small and δ_1 sufficiently big, then this is an equilibrium. Moreover, it implies the following: as demand for good j gets sufficiently big ($\delta_1 \to 1$, which requires δ_2 and $\delta_3 \to 0$), good 1 will necessarily be the best asset. Hence, high enough demand always guarantees that good 1 will emerge as money in equilibrium.

The next result implies that we cannot rule out the existence of equilibria in which goods in very high supply are used as money, or guarantee that goods in low supply are used as money. We proceed by characterizing the set of equilibria in the extreme case of $\sigma_1 = 1$ (which might suggest that good 1 is be the worst asset since it is so plentiful).

Given $\sigma_1 = 1$, it is easy to see that $p_{11} = 1$ and $p_{ij} = 0$ unless $i = j = 1$. Therefore, $P_1 = 1$, $P_2 = P_3 = 0$, $N = 1 - \delta_1$, $\pi_{12} = \delta_2 / (1 - \delta_1)$, $\pi_{13} = \delta_3 / (1 - \delta_1)$. Now the general formulae for γ_j reduce to:

$$\gamma_1 - \delta_1 = 1 - \delta_2 - \delta_3$$

$$\gamma_2 = \frac{\delta_2 + \delta_3(1 - \delta_2 - \delta_3)s_{12}}{\delta_2 + \delta_3}$$

$$\gamma_3 = \frac{\delta_3 + \delta_2(1 - \delta_2 - \delta_3)s_{13}}{\delta_2 + \delta_3}$$

This means that $\gamma_i - \gamma_j$ is proportional to D_{ij}, where:

$$D_{21} = (\delta_2 + \delta_3)^2 - \delta_3 + \delta_3(1 - \delta_2 - \delta_3)s_{12}$$

$$D_{31} = (\delta_2 + \delta_3)^2 - \delta_2 + \delta_2(1 - \delta_2 - \delta_3)s_{13}$$

$$D_{32} = \delta_3 - \delta_2 + \delta_2(1 - \delta_2 - \delta_3)s_{13} - \delta_3(1 - \delta_2 - \delta_3)s_{12}$$

We now look for equilibria of various types. First, suppose good 1 is the best asset. For one such case, let $V_{i1} > V_{i2} > V_{i3}$, which means $s_{12} = s_{13} = 0$ and requires $D_{21} < 0$, $D_{31} < 0$, and $D_{32} < 0$. Inserting $s_{12} = s_{13} = 0$ into D_{ij} yields:

$$D_{21} = (\delta_2 + \delta_3)^2 - \delta_3 < 0 \quad \textit{iff} \quad \delta_2 < \sqrt{\delta_3} - \delta_3$$

$$D_{31} = (\delta_2 + \delta_3)^2 - \delta_2 < 0 \quad \textit{iff} \quad \delta_3 < \sqrt{\delta_2} - \delta_2$$

$$D_{32} = \delta_3 - \delta_2 < 0 \quad \textit{iff} \quad \delta_2 > \delta_3.$$

These conditions hold, and hence $V_{i1} > V_{i2} > V_{i3}$ is an equilibrium, in the region labeled A in Fig. 1. The other case where good 1 is the best asset is $V_{i1} > V_{i3} > V_{i2}$, and, by symmetry,

it is an equilibrium in the region labeled A'.

Now suppose good 1 is the second best asset. One case is $V_{i2} > V_{i1} > V_{i3}$, which means $s_{12} = 1$ and $s_{13} = 0$ and requires $D_{21} > 0$, $D_{31} < 0$, and $D_{32} > 0$. Inserting $s_{12} = 1$ and $s_{13} = 0$ yields:

$$D_{21} = \delta_2(\delta_2 + \delta_3) > 0 \textit{ for all } \delta$$

$$D_{31} = (\delta_2 + \delta_3)^2 - \delta_2 < 0 \quad \textit{iff} \quad \delta_3 < \sqrt{\delta_2} - \delta_2$$

$$D_{32} = -\delta_2 + \delta_2\delta_3 + \delta_3^2 < 0 \quad \textit{iff} \quad \delta_2 > \frac{\delta_3^2}{1 - \delta_3}.$$

It can easily be shown that $D_{31} < 0$ implies $D_{32} > 0$, and therefore this equilibrium exists iff $\delta_3 < \sqrt{\delta_2} - \delta_2$, which holds in the union of regions A, A', and B in the figure. Symmetrically, the other equilibrium where good 1 is second best, $V_{i3} > V_{i1} > V_{i2}$, exists in the union of regions A', A, and B' in the figure.

Finally, suppose good 1 is the worst asset. One case is $V_{i2} > V_{i3} > V_{i1}$, which means $s_{12} = 1$ and $s_{13} = 1$ and requires $D_{21} > 0$, $D_{31} > 0$, and $D_{32} < 0$. Inserting $s_{12} = s_{13} = 1$ yields

$$D_{21} = \delta_2(\delta_2 + \delta_3) > 0 \textit{ for all } \delta$$

$$D_{31} = \delta_3(\delta_2 + \delta_3) > 0 \textit{ for all } \delta$$

$$D_{32} = \delta_3^2 - \delta_2^2 < 0 \quad \textit{iff} \quad \delta_2 > \delta_3$$

Hence, this equilibrium exists in the union of regions A, B, and C in the figure. By symmetry, the other equilibrium where good 1 is the worst asset, $V_{i3} > V_{i2} > V_{i1}$, exists in the symmetric region, the union of regions A', B', and C'. In particular, notice that for all δ there is an equilibrium for which good 1 is the worst asset, and either good 2 or good 3 is the best asset depending only on δ_2-δ_3. Although we have verified this for the limiting case where $\sigma_1 = 1$, by continuity, Fig.1 looks similar and the same economics applies if σ_1 is strictly less than 1 but sufficiently large.

The economics of large σ_1 can be explained as follows: if δ_1 is very high, which occurs near the origin in Fig.1, then good 1 can be 1st, 2nd or 3rd best asset; if δ_1 is less high, then good 1 can be the 2nd or the 3rd best but not the best asset; and, finally, if δ_1 is low then good 1 must be the worst asset. Given high supply, high demand is a necessary but not sufficient condition for good 1 to be used as money, in the sense that there always exists an equilibrium where good 1 is the worst asset. Hence, high supply makes it less likely that good 1 will be money; it could be money, but demand for that good has to be high and also beliefs have to be right (in the sense that whenever there is an equilibrium where good 1 is used as money there

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is another equilibrium where it is not).[5] We summarize certain relevant aspects of the above analysis as follows.

Proposition 4 *Even if the supply of good i is very high (low), there is always a value of δ for which it is (is not) used as money.*

The last result of this section concerns welfare. It says that, in equilibrium, the producers of the most accepted good are better off than the producers of the second most accepted good, and the latter are better off than the producers of the least accepted good. Hence, in a given equilibrium, producing a good that is used as money gives a higher payoff.

Proposition 5 *If $\gamma_i > \gamma_j$, then $V_{im} > V_{jm}$ for all m; that is, type i agents are better off than type j agents (holding the same good) in any equilibrium where good i is ranked above good j.*

Proof: The proof involves simple but tedious algebra. We need to solve a system of nine linear equations, composed of (1), (3) and (5) for type 1 and something similar for types 2 and 3, in which we insert for s_{ij} the values implied by the γ's. Given the solution, it is easy to check

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[5] A natural way of introducing fiat money in our model could be as follows: suppose $\sigma_j = \delta_j = 0$, but we start off with the initial condition that the fraction of agents holding good j is positive. We could construct an equilibrium in which good j has value in a general model where we have n (n > 2) consumer goods and fiat money (good j). In our particular three-good version of the model, however, once we assume $\sigma_j = \delta_j = 0$ we have only two consumer goods and, hence, fiat money would not alleviate the problem of double coincidence of wants and would not take on value.

that $V_{im} > V_{jm} > V_{km}$ for m = 1,2,3 (details are available upon request). ☐

Multiple equilibria with different media of exchange exist for a large set of parameter values for supply and demand. In general, we cannot Pareto rank those equilibria[6], but we can construct examples where some of the equilibria are inefficient. Consider the case where $\delta=(0.18,0.10,0.72)$ and $\sigma=(0.1/9,0.1/9,8.8/9)$. It can be shown that the following ranking of assets are equilibria: a) $V_{i1} > V_{i2} > V_{i3}$, b) $V_{i2} > V_{i3} > V_{i1}$, c) $V_{i3} > V_{i1} > V_{i2}$, and d) $V_{i1} > V_{i3} > V_{i2}$. It is easy to prove that c) is inefficient because all agents are better off in equilibrium a). The intuition for this is the following: an equilibrium in which a good in very high supply performs the role of main medium of exchange is Pareto dominated by another equilibrium in which this same good is the worst asset. This shows that there exist equilibria in which an ill-suited object is used as money (e.g. one in very high supply), but this is inefficient and everyone would be better off if they could coordinate on a different equilibrium with different money.

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[6]We define the payoff function of type agents i as

$$U_i - \sum_i \frac{p_{ij}}{\sigma_i} V_{ij}$$

Note that, by Proposition 5, $\gamma_i > \gamma_j \Rightarrow U_i > U_j$.

3. Numerical analysis

In the previous section we presented some analytic results displaying how the set of equilibria behaved for certain extreme values of parameters (high or low demand for a good, and high supply of a good). Here we consider a range of other parameter values. The method we use for finding equilibria is as follows. First, choose a ranking for good 1, 2 and 3. Then compute π numerically using the formulae in the Appendix. Then compute γ and check whether it is consistent with the ranking we started with. Whether it is will depend on the supply and demand parameters σ and δ (since γ depends on δ directly, and on π, which itself depends on σ and δ). In fact, due to the symmetry of the model, for most of our analysis we need only focus on a single case. To see this, note that if $\hat{s}$ is an equilibrium for parameters σ and δ and ρ is a permutation operator, then $\rho(\hat{s})$ is an equilibrium for parameter $\rho(\sigma)$ and $\rho(\delta)$. For example, fix $\sigma = (\sigma_1, \sigma_2, \sigma_3)$ and $\delta = (\delta_1, \delta_2, \delta_3)$ and suppose that $\hat{s} = (0,0,1)$ implies $\gamma_1 > \gamma_2 > \gamma_3$, which means that $\hat{s} = (0,0,1)$ is an equilibrium. Then for the permutation $\rho(\sigma) = (\sigma_3, \sigma_2, \sigma_1)$ and $\rho(\delta) = (\delta_3, \delta_2, \delta_1)$ it is clear that $\rho(\hat{s}) = (1,1,0)$ implies $\gamma_3 > \gamma_2 > \gamma_1$, since this is merely a change in notation, and therefore $\hat{s} = (1,1,0)$ is an equilibrium. Hence, if we find the set of (σ, δ) parameters such that $\hat{s} = (0,0,1)$ is an equilibrium, we know the set of parameters such that any other s is an equilibrium simply by permuting the subscripts.

We focus on the case $\hat{s} = (0,0,1)$, which means $\gamma_1 > \gamma_2 > \gamma_3$. For this particular case, the steady state distribution of inventories is described as follows (see the Appendix for more details). First, the producers of good 1 never trade it (except for a good they consume), and so

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$p_{11} = \sigma_1$ and $p_{12} = p_{13} = 0$. Second, the producers of good 2 trade it for good 1 but not for good 3, and $p_{21} = (\sigma_2/\sigma_3) p_{31}$, $p_{22} = \sigma_2 - p_{21}$, and $p_{23} = 0$, where p_{31} is defined next. The values of p_{31} and p_{32} are found by solving

$$P_1(\sigma_3 - p_{31})\delta_2\delta_3 = [N\delta_1 + P_2\delta_2(1-\delta_2) + P_3\delta_3(1-\delta_3)]p_{31}$$

$$P_2 P_3\delta_1\delta_3 = [N\delta_2 + P_1\delta_2(1-\delta_1) + P_3\delta_3(1-\delta_3)]p_{32}.$$

where

$$P_1 = \sigma_1 + \frac{\sigma_2 + \sigma_3}{\sigma_3}p_{31}; \quad P_2 = \sigma_2 - \frac{\sigma_2}{\sigma_3}p_{31} + p_{32}; \quad P_3 = \sigma_3 - p_{31} - p_{32}.$$

For what values of (σ,δ) is $\hat{s} = (0,0,1)$ an equilibrium? To answer this question, for all points on a grid in the set $\Theta = \{(\sigma,\delta): \sum_i\sigma_i = \sum_i\delta_i = 1\}$, we compute γ_i and check when $\gamma_1 > \gamma_2 > \gamma_3$. Notice that this does not require specifying values for the preference parameters u and r.

Figures 2, 3, and 4 show the set of δ for which, given values of σ, the equilibrium where $\gamma_1 > \gamma_2 > \gamma_3$ exists. Recall that in this equilibrium, good 1 is a generally accepted medium of exchange and good 2 is a partially accepted medium of exchange. Each of Figures 2, 3 and 4 differ in the relative supply of goods, σ. Notice that when supply of goods 1 and 2 is markedly scarcer than that of good 3, this equilibrium exists for a much larger region (Fig. 3). When the supply of good 1 is large (Fig. 4), the region where this equilibrium exists is small, and

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corresponds very closely to region A in Fig. 1.

Figures 5, 6, and 7 display values of the parameters σ for which the same equilibrium exists, given different values for δ. For high enough demand for goods 1 and 2, this equilibrium exists for a large region (Fig. 5 and 6), while for very low demand for goods 1 and 2, this equilibrium exists only for very few values of σ (Fig 7).

We can also use numerical methods to look at the changes that occur in Fig. 1 when we move away from the extreme assumption $\sigma_1 = 1$ used in constructing that diagram analytically. In Figures 8, 9, and 10 we fix $\sigma = (0.70, 0.15, 0.15)$, and show the set of δ for which the following equilibria exist: respectively, $\gamma_1 > \gamma_2 > \gamma_3$, $\gamma_2 > \gamma_1 > \gamma_3$, and $\gamma_2 > \gamma_3 > \gamma_1$. These figures show regions in the parameter space which should be compared with the corresponding regions showed in Fig. 1 (respectively A, the union of A, A', and B, and the union of A, B, and C). What these figures indicate is that when the supply of good 1 goes down there are more values of δ such that good 1 serves as general medium of exchange (Fig. 8) and fewer values such that good 1 is the least valued asset (Fig. 10).

To conclude the numerical analysis, we compare different equilibria and also different economies as to their degree of monetization. In order to do this, we propose the following measure, m for the equilibrium with $\gamma_1 > \gamma_2 > \gamma_3$ (simply modulating the subscripts gives a similar expression for the other equilibria):

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$$m - p_{33}\delta_3(P_2\delta_1+P_1\delta_2)+(p_{22}+p_{32})\delta_2\delta_3 P_1 - P_3\delta_3(P_2\delta_1+P_1\delta_2)+P_2\delta_2\delta_3 P_1$$

In the specified equilibrium, type 1 agents never make any trades for a good they do not consume immediately. Type 2 agents sometimes accept good 1 as medium of exchange when they are holding good 2, while type 3 agents accept good 1 and good 2 as money, provided they are holding good 3. What m measures is the frequency with which goods are accepted to be used as money and not for immediate consumption.

One conclusion from the experiments we ran is that economies in which agents are relatively equally distributed in terms of both supply and demand parameters are more highly monetized than economies in which the distribution is polarized. An example serves to illustrate the general idea. An economy with a high level of monetization $m=0.0390728$ is given by $\delta=(0.31,0.34,0.35)$ and $\sigma = (0.31,0.34,0.35)$. An economy with a low degree of monetization $m=0.00000293$ is given by $\delta = (0.98,0.01,0.01)$ and $\sigma = (0.98,0.01,0.01)$. In the latter case, agents very often produce goods that they consume, yielding little trade. In the former case, production and consumption are not closely linked, implying the need for trade and the use of media of exchange in equilibrium. This result is reminiscent of the observation dating back at least to Adam Smith that specialization leads to a greater role for money (see Kiyotaki and Wright (1993) and Siandra (1991)).

4. Conclusion

This paper provides a model that allows one to study the influence of relative supply and demand on the equilibrium choice of commodity money. The model tends to confirm the intuition that goods with relative high demand and/or low supply are more likely to be used as commodity money. Nevertheless, a good may be used as money if agents believe that it will be acceptable, as long as it does not have too low demand. In fact, we show that if the demand for a good is sufficiently small then there exists no equilibrium where it is used as a medium of exchange and, at the same time, a sufficiently high demand always guarantees that a good will emerge as money. On the supply side, we could not make analogous statements, in the sense that high supply of a good does not preclude it from being used as money, and low supply does not guarantee its use as medium of exchange. We show that there are multiple equilibria for large regions of the space of parameters, although some of them are not efficient. Perhaps the main contribution has been to show that a very natural model, which on the surface seems exceedingly complicated, can actually be analyzed in a fairly clean and simple way.

Appendix

This appendix shows how to compute the steady state distribution p for the case of s = (0,0,1). We must solve the following system of equations, which are derived by setting the flow in to a state equal to the flow out. For type 1,

$$p_{12}\left[N\delta_2 + P_1(\delta_1\delta_2 + \delta_3\delta_2) + P_3(\delta_3\delta_2 + \delta_3\delta_1)\right] - P_2 p_{13}\delta_3\delta_1 \quad (13)$$

$$p_{13}\left[(\delta_1\delta_3 + \delta_2\delta_3)P_1 + (\delta_2\delta_3 + \delta_1\delta_3)P_2 + N\delta_3\right] - 0 \quad (14)$$

For type 2,

$$p_{21}\left[N\delta_1 + (\delta_2\delta_1 + \delta_2\delta_3)P_2 + (\delta_3\delta_1 + \delta_3\delta_2)P_3\right] - P_1(\sigma_2 - p_{21})\delta_3\delta_2 \quad (15)$$

$$p_{23}\left[(\delta_1\delta_3 + \delta_2\delta_3)P_1 + (\delta_2\delta_3 + \delta_1\delta_3)P_2 + N\delta_3\right] - 0 \quad (16)$$

For type 3,

$$p_{31}\left[N\delta_1 + (\delta_2\delta_1 + \delta_2\delta_3)P_2 + (\delta_3\delta_1 + \delta_3\delta_2)P_3\right] - P_1(\sigma_3 - p_{31})\delta_3\delta_2 \quad (17)$$

$$p_{32}\left[N\delta_2 + P_1(\delta_1\delta_2 + \delta_3\delta_2) + P_3(\delta_3\delta_2 + \delta_3\delta_1)\right] - P_2(\sigma_3 - p_{31} - p_{32})\delta_3\delta_1 \quad (18)$$

From (14) it is obvious that $p_{13} = 0$. Then (13) implies $p_{12} = 0$. From (16), $p_{23} = 0$. From (15) and (17), $p_{21} = (\sigma_2/\sigma_3) p_{31}$. Consequently, $p_{11} = \sigma_1$ and $p_{22} = \sigma_2 [(1-(p_{31}/\sigma_3)]$. We can now use

this to get the following expressions for P_i's.

$$P_1 = \sigma_1 + \left(1 + \frac{\sigma_2}{\sigma_3}\right)p_{31}$$

$$P_2 = \sigma_2\left(1 - \frac{p_{31}}{\sigma_3}\right) + p_{32}$$

$$P_3 = \sigma_3 - p_{31} - p_{32}$$

Substituting into (17) and simplifying we arrive at

$$p_{31}\left\{\delta_1 - \delta_1^2\left[\sigma_1 + \left(1 + \frac{\sigma_2}{\sigma_3}\right)p_{31}\right] + \delta_2\delta_3\left[\sigma_2\left(1 - \frac{p_{31}}{\sigma_3}\right) + \sigma_3 - p_{31}\right]\right\} = \left[\sigma_1 + \left(1 + \frac{\sigma_2}{\sigma_3}\right)p_{31}\right](\sigma_3 - p_{31})\delta_2\delta_3$$

which is a nonlinear equation with only one unknown, p_{31} and which we can solve numerically

for any δ and σ. Given p_{31} and (δ,σ), we can now solve (18) for p_{32}.

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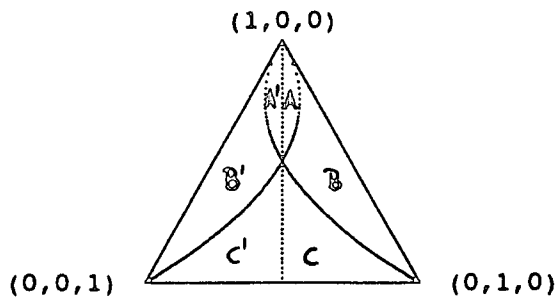
Fig.1 Equilibria when $\delta = (1,0,0)$
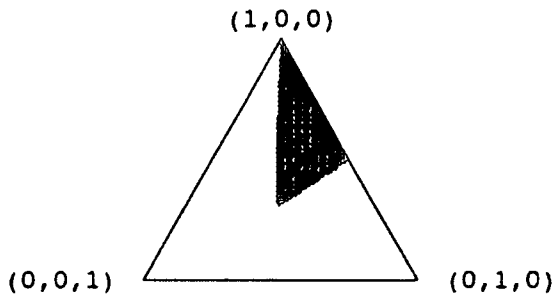
Fig.2 $\sigma = (1/3, 1/3, 1/3)$
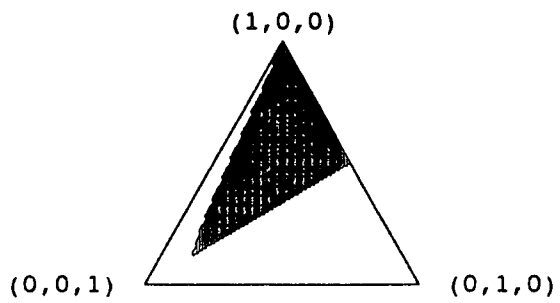
Fig.3 $\delta = (0.1/9, 0.1/9, 8.8/9)$

Fig.4 σ =(0.98,0.01,0.01)

Fig.5 δ =(1/3,1/3,1/3)
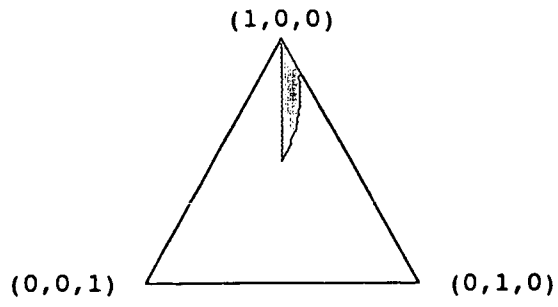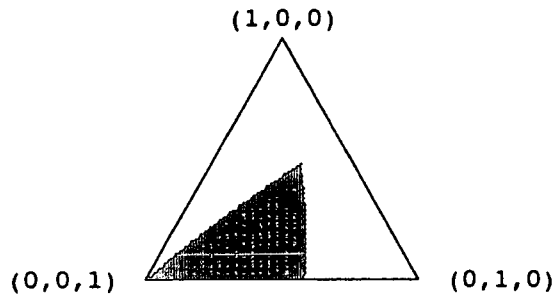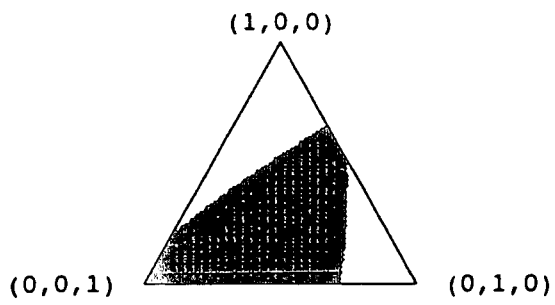
Fig.6 δ =(3.42/9,3/9,2.58/9)
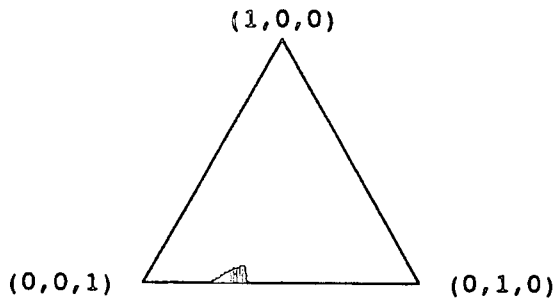
Fig.7 $\delta = (2/9, 3/9, 4/9)$
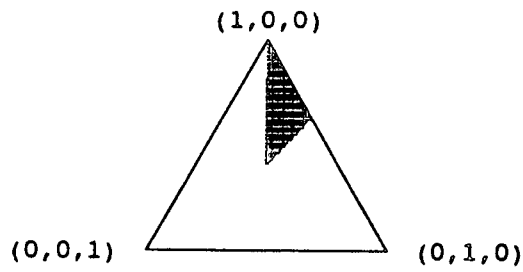
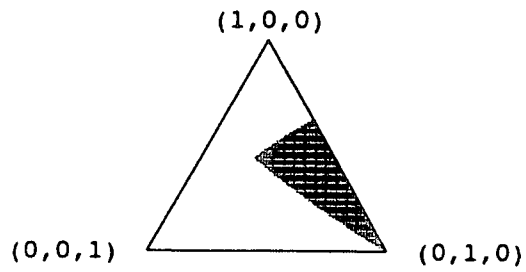Fig.8 Equilibrium $\delta_1 > \delta_2 > \delta_3$
when $\sigma = (0.70, 0.15, 0.15)$

Fig.9 Equilibrium $\delta_2 > \delta_1 > \delta_3$
when $\sigma = (0.70, 0.15, 0.15)$
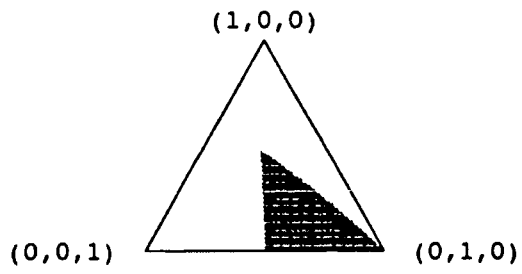
Fig.10 Equilibrium $\delta_2 > \delta_3 > \delta_1$
  when $\sigma = (0.70, 0.15, 0.15)$

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