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PARTIALLY-REVEALING RATIONAL EXPECTATIONS EQUILIBRIA IN A GENERAL EQUILIBRIUM ECONOMY: AN EXAMPLE WITHOUT NOISE

by

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Preliminary

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Research over the past two decades has established many remarkable results about the rational expectations equilibrium (REE). The generic existence of fully-revealing REE's has been proven for general equilibrium models in which the state space is finite (Radner, 1979), and in which the number of dimensions to the state space is less than the number of prices (Allen, 1981a and 1982). Nongeneric examples of nonexistence of equilibrium have also been demonstrated in this "lower dimensional case" (e.g., Kreps, 1977). The generic nonexistence of fully-revealing REE's has been shown for general equilibrium models in which the number of dimensions to the state space is greater than the number of prices, when we restrict attention to well-behaved price functions (Jordan, 1983). Meanwhile, the generic existence of almost-fully-revealing REE's has been demonstrated in this "higher dimensional case" when we permit price functions which are discontinuous on dense sets (Jordan, 1982). Existence results for closely related equilibrium concepts (with, possibly, partial revelation) have been proven for general equilibrium models where: (a) agents form "irrational" inferences which are arbitrarily close to the rational expectations inference (e.g., Allen, 1983, Anderson and Sonnenschein, 1982, and Ausubel, 1984); or (b) markets do not clear, but they come arbitrarily close to fully clearing (e.g., Allen, 1985).

Unfortunately, the state of our understanding of strict rational expectations equilibria with <u>partial</u> revelation is much more disappointing. Allen (1981b) constructs a class of economies with two dimensions of information but just one price. Each of the two agents is privately informed of one coordinate of that information and can infer the other coordinate from price. Thus, price together with private information is fully revealing;

however, price, by itself, is only partially revealing. This rids us of the paradox (see Grossman and Stiglitz, 1980) that no agent need ever look at her private information, but still leaves us in a situation where information is symmetric in equilibrium.

A few papers do achieve asymmetric information in equilibrium, but only at the cost of introducing "noise" -- unobserved variation of another factor. In Lucas (1972) and Grossman-Stiglitz (1980), for example, the presence of a second (intrinsically irrelevant) random variable prevents uninformed agents from inverting the price function to fully infer the variable they care about. Diamond and Verrecchia (1981), Verrecchia (1982), Ausubel (1984) and Laffont (1985) utilize noise to produce examples in which price "partially aggregates" the information of the economy.

Four criticisms can be leveled at this line of analysis. First, "noise" is an artificial construct which is preferably avoided in general equilibrium models. Second, all of the known examples with nontrivial asymmetry of information are at least moderately complex to describe, obscuring the message behind the models. Third, the asymmetric information examples also rely crucially on producing closed-form solutions, in a way which provides little hope that any of these examples are "robust". Fourth, most of these examples (e.g., Grossman-Stiglitz, 1980, Diamond-Verrecchia, 1981, and Verrecchia, 1982) use exponential utility functions together with normally-distributed random variables. This prevents consideration of wealth effects, and leaves us with the nagging suspicion that the model is internally inconsistent for realizations at the tail of the distribution (where endowments are negative).[1]

In this paper, we present a class of examples of general equilibrium economies where: (a) there does not exist a fully-revealing REE; (b) there does exist an extremely simple and transparent partially-revealing REE; and

(c) there is nontrivial asymmetry of information in the REE. The equilibrium is unique within a class of REE's with well-behaved price functions. Moreover, the examples avoid the use of noise: every piece of uncertainty is both economically relevant and known by at least one agent in the economy. We use neither exponential utility functions nor normally-distributed random variables. Finally, in preliminary sections of this paper, we give some indication of: how one might prove that these examples are "robust" in the sense that there probably exist open sets of economies around the examples which have qualitatively-similar equilibria; and how the examples may lead to some type of more general existence proof. But these issues will not be resolved at least until later iterations of the paper.

1. The Basic Example

The following general equilibrium economy, which displays a partially-revealing REE (and no fully-revealing REE) was inspired, in general, by the nonexistence example of Kreps (1977), and, in particular, by the simplification of that example in Allen (1984). The relationship to that literature will become apparent.

We consider a pure exchange economy with three agents, two goods (i.e., one relative price), and two independent components to uncertainty. The first component to uncertainty, denoted β , is continuous, and is uniformly distributed over $[0,1]$. The second component to uncertainty, denoted γ , is dichotomous, taking on "heads" (H) or "tails" (T) with probability $1/2$. The uncertainty is relevant to agents because it enters into their (state-dependent) utility functions. The distributions of β and γ are common knowledge to all agents, but agents do not necessarily know the true realizations of β and γ .

The three agents are labeled 1a, 1b, and 2 because agents 1a and 1b share the same utility function. [In our equilibrium, they also possess the same information, and so they also form the same demands.] Each agent is assumed to be a price taker (or, alternatively, each "agent" is actually a composite of a continuum of identical agents). An agent is specified by his private information, his endowment, and his (state-dependent) utility function over the two goods. Agents maximize expected utility, given their information.

Let (x,y) denote the quantities of the first and second goods, respectively. Let prices be normalized to sum to one, and let p denote the price of the first good.

Agent 1a:

- Privately informed of γ , but not informed of β .
- Endowment is $(\frac{1}{2}, \frac{1}{2})$.
- Let $h(\cdot)$ satisfy: $h(0) = 0$
  $h(1) = 1$
  $h(\beta) \neq \beta$, for all $0 < \beta < 1$
  h strictly monotone and h^{-1} twice continuously differentiable
- State-dependent utility given by:

$$U_1(x,y;\beta,H) = h(\beta) \log x + [1 - h(\beta)] \log y$$
$$U_1(x,y;\beta,T) = \beta \log x + (1 - \beta) \log y$$

Agent 1b:

- Privately informed of β , but not informed of γ .
- Otherwise, same as agent 1a.

Agent 2:

- Not privately informed.
- Endowment is (1,1).
- State-dependent utility given by:

$$U_2(x,y;\beta,H) \;=\; \beta \log x + (1-\beta) \log y \;=\; U_2(x,y;\beta,T)$$

Definition 1: By a rational expectations equilibrium (REE), we mean a price function $p : [0,1] \times \{H,T\} \to [0,1]$ (where $p(\beta,\gamma)$ denotes the price of the first good, and $1 - p(\beta,\gamma)$ denotes the price of the second good, in state (β,γ)) such that:

(a) every agent maximizes utility in every state of the world, given the price vector $(p,1-p)$, given the agent's private information, and given the additional information inferable from price (i.e., that $(\beta,\gamma) \in \{(\beta,\gamma) \text{ s.t. } p(\beta,\gamma) = p\}$); and

(b) markets clear in every state of the world.

Note that some researchers have applied slightly more stringent definitions to the REE, but that the equilibrium constructed in this paper typically satisfies these more stringent requirements.

We first prove a lemma which shows that the example is interesting:

Lemma 2: There does not exist a fully-revealing REE for this model.

Proof: Suppose there does exist one. Let $0 < \beta < 1$, and let $D_1(x|\beta,\gamma)$ denote the sum of agents 1a's and 1b's demands for good x in state (β,γ). We calculate full-information demands for agents 1 and 2 in state (β,H):

$$D_1(x|\beta,H) \;=\; \frac{h(\beta)}{p(\beta,H)}$$

$$D_2(x|\beta,H) \quad = \quad \frac{\beta}{p(\beta,H)}$$

Then, by market clearing:

$$D_1(x|\beta,H) + D_2(x|\beta,H) \quad = \quad 2$$

$$\frac{h(\beta)}{p(\beta,H)} + \frac{\beta}{p(\beta,H)} \quad = \quad 2$$

$$\Longrightarrow \qquad p(\beta,H) \quad = \quad \frac{h(\beta) + \beta}{2}$$

Meanwhile, define $\beta' \;=\; [h(\beta) + \beta] \;/\; 2 \;\neq\; \beta$. Then, in state (β',T) :

$$D_1(x|\beta',T) \quad = \quad \frac{\beta'}{p(\beta',T)} \quad = \quad D_2(x|\beta',T)$$

$$\frac{\beta'}{p(\beta',T)} + \frac{\beta'}{p(\beta',T)} \quad = \quad 2$$

$$\Longrightarrow \qquad p(\beta',T) \quad = \quad \beta' \quad = \quad \frac{h(\beta) + \beta}{2}$$

Hence, under the hypothesis of full relevation, $p(\beta,H) \;=\; p(\beta',T)$, yet agent 2 displays different demands in states (β,H) and (β',T) . This is a contradiction.

2. Existence of a Partially-Revealing REE

By Lemma 2, we know that there does not exist an REE where the uninformed agent can fully infer the state of the world from price. However, the uninformed agent can surely infer the coefficient of log x in the informed agents' utility function, in any REE where agents 1a and 1b attain full information. [The argument goes: the uninformed agent must be able to infer his own demand $D_2(x|\beta,\gamma)$ and, hence, can infer $D_1(x|\beta,\gamma) = 2 - D_2(x|\beta,\gamma)$. Multiplying $D_1(x|\beta,\gamma)$ by price $p(\beta,\gamma)$ gives the coefficient of log x.]

Let α denote the coefficient of log x in the informed agents' utility function. Observe that α is a function of the state (β,γ) ; in particular:

$$\alpha(\beta,H) = h(\beta)$$

$$\alpha(\beta,T) = \beta$$

It seems plausible to seek an REE where price reveals to the uninformed agent the value of α , but no more.[2] We may then describe the equilibrium price as a function, ϕ, of α. (The argument of the previous paragraph implies that ϕ is an invertible function of α.) We shall now construct such an REE, later discussing how we may view this as a unique equilibrium for the model.

Let $r(\cdot)$ denote the inverse function of $h(\cdot)$, i.e., $r \equiv h^{-1}$. Suppose that price is an invertible function, ϕ, of α. Then, associated with every price is exactly two states of the world -- one state $(r(\alpha),H)$ and a second state (α,T) . If agent 2 observes the market-clearing price, he can fully infer α, but he can only place probabilistic weights on which of the two states, $(r(\alpha),H)$ or (α,T), are responsible for α. Furthermore, agent 2 crucially cares which state the world is really in: if he knew, with probability one, that he was in the former state, his demand would be $r(\alpha)/\phi(\alpha)$; if he knew that he was in the latter state, his demand would be $\alpha/\phi(\alpha)$. If $0 < \alpha < 1$, observe that $r(\alpha) \neq \alpha$.

Let us compute the probability of heads given α, i.e., the probability that the state is $(r(\alpha),H)$, given α. Observe the graph of β versus α in Figure 1:

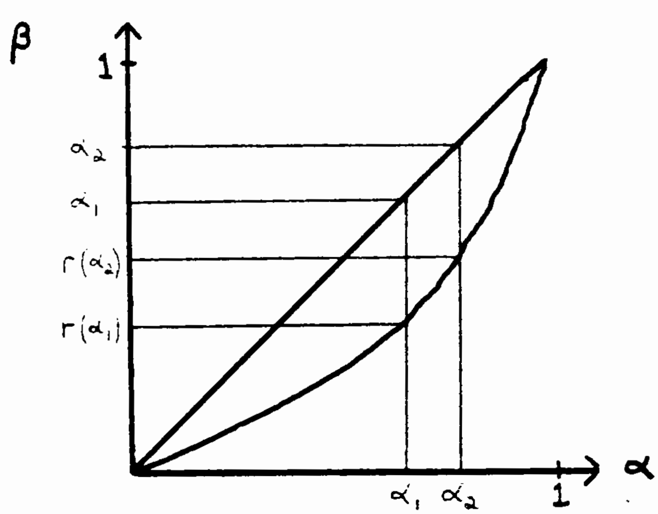

Figure 1

If we are on the "heads branch" ($\gamma = H$) , β is given by $r(\alpha)$; on the "tails branch" ($\gamma = T$) , β is given by the identity mapping of α. Recalling that we have assumed β and γ to be independent random variables, suppose it is known that $\alpha_1 < \alpha < \alpha_2$. If $\gamma = H$, then $r(\alpha_1) < \beta < r(\alpha_2)$; if $\gamma = T$, then $\alpha_1 < \beta < \alpha_2$. For α_2 near α_1, note $r(\alpha_2) - r(\alpha_1) \approx r'(\alpha_1)\cdot[\alpha_2 - \alpha_1]$. Since β is assumed uniformly distributed, and $\text{Prob}(H|\beta) = 1/2 = \text{Prob}(T|\beta)$, we have shown that:

$$\text{(1)} \qquad \text{Prob }(H|\alpha) = \frac{r'(\alpha)}{1 + r'(\alpha)}$$

$$\text{(2)} \qquad \text{Prob }(T|\alpha) = \frac{1}{1 + r'(\alpha)}$$

We can now prove:

<u>Theorem 3</u>: If an REE has equilibrium price function $\phi(\alpha)$, where ϕ is an invertible function of α , then:

$$\text{(3)} \qquad \phi(\alpha) = 1/2\,\alpha + 1/2\left[\frac{r'(\alpha)\cdot r(\alpha) + \alpha}{1 + r'(\alpha)}\right]$$

<u>Proof</u>: Observe that price being given by $\phi(\cdot)$, invertible in α , implies that agents 1a and 1b attain full information in equilibrium. Hence, the sum of their demands for the first good is given by:

$$D_1(x|\alpha) = \frac{\alpha}{\phi(\alpha)}$$

Agent 2 maximizes his expected utility, given $\phi(\alpha)$ and α, by solving:

$$\text{Max } \{\text{Prob}(H|\alpha)\cdot[r(\alpha)\log x + (1-r(\alpha))\log y] + \text{Prob}(T|\alpha)\cdot[\alpha\log x + (1-\alpha)\log y]\}$$

$$\text{subject to:} \quad \phi(\alpha)\cdot x + [1-\phi(\alpha)]\cdot y \leqq 1$$

giving the demand function:

$$D_2(x|\alpha) = \frac{\text{Prob}(H|\alpha)\cdot r(\alpha) + \text{Prob}(T|\alpha)\cdot\alpha}{\phi(\alpha)} = \frac{r'(\alpha)\cdot r(\alpha) + \alpha}{[1 + r'(\alpha)]\cdot\phi(\alpha)}$$

by equations (1) and (2). Market clearance then implies:

$$\frac{\alpha}{\phi(\alpha)} + \frac{r'(\alpha)\cdot r(\alpha) + \alpha}{[1 + r'(\alpha)]\cdot\phi(\alpha)} = 2$$

Algebraic manipulation gives (3), proving the theorem.

Theorem 3 does not complete our work in proving existence, as we have not yet shown that equation (3) provides an invertible function.[3] In the next lemma, we prove that a large class of functions r yield the required invertibility.

Lemma 4: If r is twice continuously differentiable and:

(4) $$\left| r''(\alpha)\cdot[r(\alpha) - \alpha] \right| < 2 \quad , \quad \text{for all } \alpha \ (0 < \alpha < 1)$$

then $\phi(\cdot)$ defined by equation (3) is monotone increasing.

Proof: The derivative of ϕ may be written:

(5) $$\phi'(\alpha) = \tfrac{1}{2}\left\{ \frac{r''(\alpha)\cdot[r(\alpha) - \alpha] + [2 + r'(\alpha) + r'(\alpha)^2]\cdot[1 + r'(\alpha)]}{[1 + r'(\alpha)]^2} \right\}$$

Since $r(\cdot)$ is monotone increasing, $r'(\alpha) \geq 0$. Hence, $\phi'(\alpha) > 0$ iff:

$$r''(\alpha)\cdot[r(\alpha) - \alpha] + [2 + r'(\alpha) + r'(\alpha)^2]\cdot[1 + r'(\alpha)] > 0$$

Furthermore, $[2 + r'(\alpha) + r'(\alpha)^2] \geq 2$ and $[1 + r'(\alpha)] \geq 1$, so if inequality (4) is satisfied, we can conclude that $\phi'(\alpha) > 0$.

Example 5: Consider $r(\alpha) \equiv \alpha^n$, where $1 < n < 2$. Then:

$$r''\cdot[r - \alpha] = n(n - 1)\alpha^{n-2}(\alpha^n - \alpha) = n(n - 1)\alpha^{n-1}(\alpha^{n-1} - 1)$$

Observe that $\left| n(n-1) \right| < 2$, $\left| \alpha^{n-1} \right| < 1$ and $\left| \alpha^{n-1} - 1 \right| < 1$. So the example satisfies Lemma 4, and hence equation (3) gives a partially-revealing REE.

3. On Uniqueness of Continuous or Monotone Equilibria

I do not, at this time, possess a proof that this model has a unique rational expectations equilibrium (as defined in Definition 1); nor am I certain that the REE is unique. However, there is good reason to restrict attention to REE's with well-behaved price functions, and then it is easy to establish uniqueness.[4]

A restriction to continuous or monotone REE's is desirable on a number of grounds. Observe that if the price function is relatively simple (for example, as in Theorem 3), then the inference process posited by rational expectations is really quite plausible. However, as the price function loses its continuity or monotonicity, the rational expectations exercise becomes increasingly incredible. The observation here is closely related to the recent literature on game-playing automata, which attempts to exclude the possibility of players using excessively-complex strategies.

A related argument is made in Ausubel (1984): it is reasonable to suppose that it is costly for agents to learn the true price function of the economy. Consequently, optimizing agents will find it preferable to work with approximations to the price function. Agents who use approximations will avoid drawing radically-different inferences from similar observed prices; and this will tend to rule out the occurrence of highly discontinuous price functions. Similar conclusions can be reached if we either suppose that price observations are noisy or that markets do not precisely clear. In either case, inversion of a price function which fluctuates wildly over the state space may lead to grossly misleading inferences.

We will also be restricting our attention, in this section, to REE's in which the (informed) agents 1a and 1b attain full information in equilibrium. The easiest way to finesse this assumption is to modify the model to simply say: "There are two types of agents -- agent 1 and agent 2. Agent 2 has no private information but agent 1 has full private information. Otherwise the model is the same as before." Certainly, the uniqueness results of Theorems 6 and 7 apply to the modified model as well. Another equivalent avenue is to modify the model to contain agent 1a (privately informed of γ), agent 1b (privately informed of β), agent 1c (full private information), and agent 2 (no private information). Further assume that demands, as well as price, are observable. Then agents 1a and 1b can infer all the information they need just by observing agent 1c's demand -- their demands then equal the full information demands.

<u>Theorem 6</u>: Equation (3) gives the unique REE in which: (a) the price function, $p(\beta,\gamma)$, is continuous in β at all points in the state space; and (b) agents 1a and 1b attain full information.

<u>Proof</u>: As was argued in the text of the previous section, agent 2 must be able to infer his own demand $D_2(x|\beta,\gamma)$ and, so, he can also infer $D_1(x|\beta,\gamma) = 2 - D_2(x|\beta,\gamma)$. Since agents 1a and 1b attain full information, α is inferable by:

$$\alpha = D_1(x|\beta,\gamma)\cdot p(\beta,\gamma)$$

For every state of the world (β,γ), there are thus two possibilities:

Case 1: There exists exactly one other state of the world with the same price. Then, $p(\beta,\gamma)$ is uniquely given by equation (3), as in the proof of Theorem 3.

Case 2: (β,γ) is the unique state of the world associated with price $p(\beta,\gamma)$. Then, as in the proof of Lemma 2, we have:

$$(6) \qquad p(\beta,H) = \frac{h(\beta) + \beta}{2} \qquad ; \qquad p(\beta,T) = \beta$$

Observe that equations (3) and (6) coincide only at $\beta = 0$ and $\beta = 1$. Then to satisfy the required continuity, $p(\cdot,H)$ must entirely follow either equation (3) or equation (6). But equation (6) leads to the same contradiction as in Lemma 2, leaving equation (3) as the unique equilibrium.

Theorem 7: Equation (3) gives the unique REE in which: (a) the price function, $p(\beta,\gamma)$, is monotone in β at all points in the state space; and (b) agents 1a and 1b attain full information.

Proof: Analogous to the proof of Theorem 6.

4. On Robustness of Equilibrium

So far, we have constructed an example of a noiseless economy in which there exists a partially-revealing REE, which under certain "refinements" to the equilibrium concept is unique. An important question to ask ourselves is whether the example is "robust", in the sense that there exists an open set of economies around our example, each possessing an REE which is qualitatively similar. While I do not yet have a complete answer to this query, I intend in this section to suggest that the answer is affirmative.

Observe that, in Example 5, we demonstrated that our model with $r(\alpha) = \alpha^{3/2}$ (i.e., $h(\beta) = \beta^{2/3}$) gave a partially-revealing REE. The initial question to ask is whether there is a well-defined way in which we might perturb $r(\cdot)$ around $\alpha^{3/2}$ while preserving this property. This is easily done. Observe that the candidate price function is given by equation (3), and that the candidate yields an REE provided that (3) is strictly monotone. Furthermore, (3) is guaranteed to be strictly monotone if (5) is strictly positive. Now (5) is readily seen to be strictly positive if $r(\alpha) = \alpha^{3/2}$. Furthermore, the right side of (5) is a continuous function of r, r' and r'', whose denominator is bounded away from zero. Hence, if we perturb r in a manner which retains control over r, r' and r'', we are assured that we are left with an economy for which equation (3) still gives an REE price function. This is easily accomplished by using a C^2-norm on r. We have thus shown:

Theorem 8: Let R denote the set of twice continuously differentiable, strictly monotone functions on [0,1] which satisfy: $r(0) = 0$; $r(1) = 1$; and $r(\beta) \neq \beta$ for $0 < \beta < 1$. Let r be an element of R, and further suppose that the right side of equation (5), evaluated using r, is bounded away from zero for all α between 0 and 1. If $\|f\|$ denotes $\sup_{[0,1]} \{|f(x)|, |f'(x)|, |f''(x)|\}$, then there exists a positive ε such that the model has a (partially-revealing) REE with price function:

$$\phi(\alpha) = \tfrac{1}{2}\alpha + \tfrac{1}{2}\left[\frac{s'(\alpha)\cdot s(\alpha) + \alpha}{1 + s'(\alpha)} \right]$$

for all s belonging to:

$$S = \{ s : s \text{ is an element of } R \text{ and } \| s - r \| < \varepsilon \}$$

It would be nice to be able to show that our example is robust to other perturbations in the model; the reasoning behind Theorem 8 suggests that this is possible. However, such a demonstration will not appear at least until later iterations of this paper.

5. Conclusions

This paper has presented a rational expectations equilibrium which is rather intuitively appealing. Agents who start with partial private information attain full information in equilibrium; agents who start with no private information obtain partial information in equilibrium. Everyone learns something from the market-clearing price, but there remains nontrivial asymmetry of information in equilibrium.

The results of this paper suggest at least two directions in which work might continue. First, we may attempt to use this example to prove a more general existence theorem. It has been demonstrated in other areas (see, most recently, Duffie and Shafer, 1985) that the presence of a unique equilibrium for a particular example may imply the existence of at least one equilibrium for a whole class of economies. Let Y be the set of economies, P be the set of "equilibrators", and:

$$X = \{ (p,y) \in P \times Y : p \text{ equilibrates } y \}$$

The reasoning there goes: the Mod 2 Degree Theorem implies that the degree, mod 2, of the projection from X to Y is the same for every regular economy in Y (provided that certain properties are satisfied). The number of equilibria for the example satisfying uniqueness is odd; therefore every regular economy has an odd number of equilibria, guaranteeing existence. The example presented in this paper of existence and uniqueness provides some hope that analogous reasoning may work in the area of partially-revealing rational expectations equilibria (although the usual discontinuity problem makes such an approach more difficult).

Second, the type of equilibrium constructed in this paper, where uninformed agents cannot distinguish between two different states of the world, is nicely suited to modeling the problem of insider trading. Observe that heads may be identified with "takeover in progress" and tails with "no takeover"; uninformed agents cannot fully infer the insiders' information. It may be objected that the REE methodology is inappropriate for modeling trade in the organized financial markets, since rational expectations posits that agents only observe price, whereas in most financial markets, trading volume is widely published as well. However, it should be observed that one of the nicest properties of the current model is that the REE does not change if uninformed agents are permitted to observe the actual demands of informed agents. [In fact, in the equilibrium advocated here, observing $D_1(x|\beta,\gamma)$ is entirely redundant with observing price.] Uninformed agents can observe trade as well as the terms of trade; but even in equilibrium they cannot fully infer the reason for trade.

NOTES

[1]This difficulty is recognized, for example, in Laffont (1985), footnote 9.

[2]By the argument of the previous paragraph, this is the "minimally-revealing" REE in which agents 1a and 1b nevertheless attain full information.

[3]Indeed, Theorem 3 can equally be used to prove the nonexistence of this type of equilibrium, if $\phi(\cdot)$ defined by equation (3) is not invertible.

[4]A proof which attempts to exclude the possibility of <u>any</u> other equilibria satisfying Definition 1 appears to be rather intricate specifically because it must address the issue of price functions which, by any reasonable standards, are truly pathological.

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