16

Intertemporal General Equilibrium Models

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1. Introduction

In this chapter we shall explore the properties of two simple intertemporal general equilibrium models, a model with a finite number of infinitely lived consumers, and an overlapping generations model with an infinite number of finitely lived consumers. Both models contain a complete set of markets. The Arrow–Debreu formulation of the Walrasian equilibrium model can, of course, be given a dynamic interpretation in which goods are indexed by date. The models that we study differ from the standard Arrow–Debreu model in that we allow an infinite number of goods. As we shall see, models with infinite numbers of goods can possess very different properties from models with finite numbers of goods. Such models are best regarded as idealizations, however: their properties are interesting in so far as they provide insights into models with large, but finite, numbers of goods.

The model with a finite number of infinitely lived consumers shares three important properties with the standard Arrow–Debreu model: first, all equilibria are Pareto-efficient; second, there is no role to be played by outside money, unbacked nominal debt; and, third, there are, in general, a finite number of locally unique equilibria. In contrast, the overlapping generations model may violate each of these three properties: it may have equilibria that are not Pareto-efficient; it may have equilibria in which outside money plays an important role; and it may have a robust continuum of equilibria. We shall see that there is a close relationship between the possibility of inefficiency of equilibria and the role for outside money. The possibility of indeterminacy of equilibria is a relatively separate issue, however, except in models in which consumers live for only two periods and there is only one good in each period.

Intertemporal general equilibrium models are becoming increasingly important in economic theory, particularly in macroeconomics. The trend

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there has been to use small general equilibrium models to analyse macroeconomic issues (see, for example, Lucas 1981, and Kydland and Prescott 1982). Not all macroeconomists have been caught up in this trend, however, and the use of explicit general equilibrium models in macroeconomics has been the subject of much controversy, in which one side accuses the other of using *ad hoc* and unrealistic models. Many commentators have interpreted this controversy as an idealogical debate between monetarists and Keynesians. This interpretation is probably unfortunate. An explicit general equilibrium framework imposes a discipline and assures internal consistency. This makes it easy for us to organize our thinking about economic phenomena and to communicate this thinking to others, mostly because the assumptions of the model have well understood implications in this framework. The phrase *ad hoc* is much misused in economics. It has become a synonym for 'yours' and 'bad' and an antonym for 'mine' and 'good'. Most good economic models are *ad hoc* in the strict sense that they are designed for a particular purpose and produce results that follow closely from a particular set of assumptions. The advantage of using explicit general equilibrium models is that they provide a framework in which sets of assumptions are easily understood and compared.

The potential disadvantage is, of course, that the general equilibrium framework can become an intellectual straightjacket. Fortunately, however, this framework is rich enough to allow a wide variety of results. To illustrate this, we employ both of our models to answer Barro's (1974) question of whether government bonds are net wealth. Different models can produce very different answers to this question. There is a close relationship between these answers and the sets of assumptions that distinguish these models.

The models that we study in this paper are both pure-exchange models with no production or storage. Time is discrete and there is no uncertainty. Furthermore, both models are stationary in that the structure of preferences and endowments is constant over time. These models are the simplest to analyse. We indicate, however, how our results extend to more complicated models. We also compare the structures of the two models. On one hand, the overlapping generations model has similar properties to a model with a finite number of infinitely lived consumers who face borrowing and lending constraints. On the other, a model with a finite number of infinitely lived consumers has similar properties to an overlapping generations model in which parents leave bequests to their children.

2. An Infinitely Lived Consumer Model

We begin by analysing an economy with a finite number of agents who consumer over an infinite number of time-periods. There are n goods,

which cannot be stored, in each period and h consumers. Consumer j is characterized by a utility function

$$\sum_{t=1}^{\infty} \gamma_j^{t-1} u_j(c_{1t}^j, \ldots, c_{nt}^j) \tag{1}$$

and an endowment vector $w^j = (w_1^j, \ldots, w_n^j)$, which he has claim to in each period. Here the discount factor γ_j satisfies $1 > \gamma_j > 0$; the momentary utility function u_j is continuously differentiable of the second order for all positive consumption vectors, strictly concave, and monotonically increasing; and the endowment vector w^j is strictly positive.

There are two interpretations of this model. The first is the traditional Walrasian interpretation in which all trades, including those that involve future delivery of goods, take place in the first period. In this interpretation time plays no explicit role and t can be thought of as merely another index on commodities. The consumer's budget constraint is

$$\sum_{t=1}^{\infty} p_t' c_t^j \leq \sum_{t=1}^{\infty} p_t' w^j. \tag{2}$$

Here $p_t = (p_{1t}, \ldots, p_{nt})$ is the vector of futures prices in period t and $p_t' c_t^j$ is the inner product $\sum_{i=1}^{n} p_{it} c_{it}^j$.

In the second interpretation trades take place over time, but there are perfect capital markets and rational expectations. In this simple model the assumption of perfect capital markets means only that consumers can borrow and lend as much as they want at a competitively determined interest rate, and the assumption of rational expectations means that consumers have perfect foresight. Let $q_t = (q_{1t}, \ldots, q_{nt})$ be the vector of spot prices in period t; let r_t be the interest rate between t and $t+1$; and let m_t^j be the net lending done by consumer j between t and $t+1$. We can interpret m_t^j as inside money. Consumer j faces a sequence of budget constraints

$$\begin{aligned} q_1' c_1^j + m_1^j &\leq q_1' w^j \\ q_2' c_2^j + m_2^j &\leq q_2' w^j + (1+r_1) m_1^j \\ &\vdots \\ q_t' c_t^j + m_t^j &\leq q_t' w^j + (1+r_{t-1}) m_t^j \end{aligned} \tag{3}$$

Dividing the budget constraint in period t by $(1+r_1)(1+r_2)\cdots(1+r_{t-1})$, $t = 2, \ldots, T$, and adding up, we obtain

$$\sum_{t=1}^{T} p_t' c_t^j + m_T^j/(1+r_1)(1+r_2)\cdots(1+r_{T-1}) \leq \sum_{t=1}^{T} p_t' w^j \tag{4}$$

where $p_t = q_t/(1+r_1)(1+r_2)\cdots(1+r_{t-1})$. In the limit this produces the same budget constraint as does the first interpretation as long as

$$\lim_{T\to\infty} m_T^j/(1+r_1)(1+r_2)\cdots(1+r_{T-1}) = 0. \tag{5}$$

To ensure that this condition holds, we need to put some constraint on the real level of debt that we allow consumer j to incur. We shall see that, with such a constraint, (5) must hold in any equilibrium.

Let us return to the first interpretation of the model. An equilibrium is a sequence of price vectors $(\hat{p}_1, \hat{p}_2, \ldots)$ and a sequence of consumption vectors $(\hat{c}_1^j, \hat{c}_2^j, \ldots)$ for each consumer, $j = 1, \ldots, h$, such that each consumer maximizes utility subject to his budget constraint (2) and demand is equal to supply:

$$\sum_{j=1}^{h} \hat{c}_t^j = \sum_{j=1}^{h} w^j, \qquad t = 1, 2, \ldots \tag{6}$$

Notice that any equilibrium must be such that $\sum_{t=1}^{\infty} \hat{p}_t' w^j$ converges; otherwise the consumer would have infinite income, and his utility maximization problem would have no solution. Because u_j is monotonically increasing, he would want to consume infinite amounts of at least one good, which would make equilibrium impossible.

Since every consumer has finite income, the value of the aggregate endowment must also be finite:

$$\sum_{t=1}^{\infty} \hat{p}_t'\Big(\sum_{j=1}^{h} w^j\Big) = \sum_{j=1}^{h}\Big(\sum_{t=1}^{\infty} \hat{p}_t' w^j\Big). \tag{7}$$

This implies that any equilibrium must be Pareto-efficient. The argument is due to Debreu (1954). Suppose, to the contrary, that there is a Pareto-superior allocation plan $(\bar{c}_1^j, \bar{c}_2^j, \ldots)$:

$$\sum_{t=1}^{\infty} \gamma_j^{t-1} u_j(\bar{c}_t^j) \geqslant \sum_{t=1}^{\infty} \gamma_j^{t-1} u_j(\hat{c}_t^j), \qquad j = 1, \ldots, h, \tag{8}$$

with strict inequality for some j, that is feasible:

$$\sum_{j=1}^{h} \bar{c}_t^j \leqslant \sum_{j=1}^{h} w^j, \qquad t = 1, 2, \ldots \tag{9}$$

Then the consumption sequence $(\bar{c}_1^j, \bar{c}_2^j, \ldots)$ must cost at least as much as the consumer's income, and strictly more for some consumer; otherwise $(\hat{c}_1^j, \hat{c}_2^j, \ldots)$ would not be utility-maximizing. Consequently,

$$\sum_{j=1}^{h}\Big(\sum_{t=1}^{\infty} \hat{p}_t' \bar{c}_t^j\Big) > \sum_{j=1}^{h}\Big(\sum_{t=1}^{\infty} \hat{p}_t' w^j\Big) = \sum_{t=1}^{\infty} \hat{p}_t'\Big(\sum_{j=1}^{h} w^j\Big). \tag{10}$$

Since the Pareto-superior allocation is feasible, however,

$$\sum_{j=1}^{h}\Big(\sum_{t=1}^{\infty} \hat{p}_t' \bar{c}_t^j\Big) = \sum_{t=1}^{\infty} \hat{p}_t'\Big(\sum_{j=1}^{h} \bar{c}_t^j\Big) \leqslant \sum_{t=1}^{\infty} \hat{p}_t'\Big(\sum_{j=1}^{h} w^j\Big). \tag{11}$$

This contradiction establishes that there can be no allocation that is Pareto-superior to the competitive allocation and is also feasible.

That the value of the aggregate endowment is finite also implies that there can be no equilibrium with outside money, unbacked debt. Suppose, to the contrary, that there is an allocation that is feasible in which each consumer satisfies the budget constraint

$$\sum_{t=1}^{\infty} \hat{p}_t' \hat{c}_t^j = \sum_{t=1}^{\infty} \hat{p}_t' w^j + m^j, \qquad j = 1, \ldots, h \tag{12}$$

where

$$m = \sum_{j=1}^{h} m^j \neq 0. \tag{13}$$

(If $m = 0$ but $m^j \neq 0$, this is just an equilibrium with transfer payments.) Here m is the stock of outside, or fiat, money, which can be positive or negative. Summing these budget constraints over consumers, we obtain

$$\sum_{j=1}^{h}\Big(\sum_{t=1}^{\infty} \hat{p}_t' \hat{c}_t^j\Big) = \sum_{j=1}^{h}\Big(\sum_{t=1}^{\infty} \hat{p}_t' w^j\Big) + m. \tag{14}$$

Multiplying the feasibility conditions (6) by prices and summing, however, we obtain

$$\sum_{t=1}^{\infty} \hat{p}_t'\Big(\sum_{j=1}^{h} \hat{c}_t^j\Big) = \sum_{t=1}^{\infty} p_t'\Big(\sum_{j=1}^{h} w^j\Big). \tag{15}$$

Consequently, $m = 0$, which contradicts the assumption that there is an equilibrium with outside money.

This same argument can be used to show that the sequence of budget constraints (3) are equivalent to the single intertemporal budget constraint (2). For consumer j to have a well defined maximization problem, and for the concept of equilibrium to make any sense, the limit in (5) would have to exist. Here, unlike the outside money case that we have just examined, the variables m_t^j are chosen by the consumers. Since utility is monotonically increasing, every consumer would want to choose $(m_1^j, m_2^j, \ldots)$ so that the limit in (5) is negative. The same argument that precludes an equilibrium with outside money also precludes this possibility.

For an equilibrium to exist, however, we must impose a constraint on the real level of debt that we allow consumer j to incur:

$$m_t^j / \|p_t\| \geqslant b, \qquad t = 1, 2, \ldots \tag{16}$$

for some $b < 0$. Otherwise, the consumer would try to run a Ponzi scheme, rolling over an exponentially increasing amount of debt and making the limit in (5) as negative as possible. In such a case, as was argued above, no equilibrium can exist. Any sort of bound on the real level of debt, no matter how large in absolute value, precludes this possibility.

In general, this model has a finite number of locally unique equilibria. To see this, we transform the equilibrium conditions using an approach developed by Negishi (1960b) and applied to intertemporal models by Bewley (1982). To simplify the exposition, we ignore the possibility of corner solutions to the consumer's utility maximization problem. This can be justified by imposing an additional restriction on u_j (see Kehoe and Levine 1985a). The solution to the consumer's utility maximization problem is characterized by the conditions

$$\gamma_j^{t-1} Du_j(c_t^j) = \lambda_j p_t' \tag{17}$$

for some Lagrange multiplier $\lambda_j > 0$, and the budget constraints (2). (Here $Du_j(c_t^j)$ is the $1 \times n$ vector of partial derivatives of u_j.) An equilibrium is, therefore, characterized by (2) and (17), which are the utility maximization conditions, and (6), which are the market-clearing conditions that demand be equal to supply. This is a system with an infinite number of equations and unknowns.

Consider now the Pareto problem of maximizing a weighted sum of individual utility functions subject to feasibility constraints:

$$\begin{aligned} &\max \sum_{j=1}^{h} \alpha_j \sum_{t=1}^{\infty} \gamma_j^{t-1} u_j(c_t^j) \\ &\text{s.t.} \sum_{j=1}^{h} c_t^j = \sum_{j=1}^{h} w^j, \qquad t = 1, 2, \ldots \end{aligned} \tag{18}$$

Here $\alpha_1, \ldots, \alpha_h$ are positive utility weights. A solution to this problem is characterized by the conditions

$$\alpha_j \gamma_j^{t-1} Du_j(c_t^j) = \pi_t, \qquad j = 1, \ldots, h, \quad t = 1, 2, \ldots \tag{19}$$

for some sequence of vectors of Lagrange multipliers $\pi_t = (\pi_{1t}, \ldots, \pi_{nt}) > 0$, and the feasibility constraints (6). Notice that, if we divide (19) by α_j, then it becomes the same as (17). This is an alternative way of seeing that any competitive equilibrium is Pareto-efficient, that the First Theorem of Welfare Economics holds.

The Second Theorem holds as well: any solution to the Pareto problem (18) satisfies all of the conditions for a competitive equilibrium except the individual budget constraints (2). Such a solution can, therefore, be viewed as competitive equilibrium with transfer payments. The competitive prices are, of course, the Lagrange multipliers π_t. We can compute the transfer payments needed to implement as a competitive equilibrium the Pareto-efficient allocation associated with the welfare weights $\alpha = (\alpha_1, \ldots, \alpha_h)$:

$$t_j(\alpha) = \sum_{t=1}^{\infty} \pi_t(\alpha)'[c_t^j(\alpha) - w^j], \qquad j = 1, \ldots, h. \tag{20}$$

Setting these transfers payments equal to 0 produces a characterization of equilibria in a finite number of equations and unknowns.

Using the strict concavity of u_j, we can demonstrate that transfer functions t_j are continuous. Also, t_j is homogeneous of degree 1 in α because π_t is homogeneous of degree 1 and c_t^j is homogeneous of degree 0; if we double α, for example, the sequences of consumption vectors that solve the problem do not change, but the Lagrange multipliers double. Furthermore, the transfer functions satisfy

$$\sum_{j=1}^{h} t_j(\alpha) \equiv 0 \tag{21}$$

because any solution to the Pareto problem satisfies the feasibility constraints.

The conditions that characterize the equilibria of this model are formally equivalent to those that characterize the equilibria of a static, pure-exchange model with h goods. Indeed, the functions $f_j(\alpha) = -t_j(\alpha)/\alpha_j$ have all of the properties of the excess demand functions of a pure-exchange model: they are continuous; they are homogeneous of degree 0; and they obey Walras's Law, $\sum_{j=1}^{h} \alpha_j f_j(\alpha) \equiv 0$. Debreu (1970) has demonstrated that, if the excess demand functions f_j are continuously differentiable, then almost all economies have a finite number of locally unique equilibria. The phrase 'almost all' is, of course, given a precise mathematical meaning. We can use either the transfer functions t_j or the demand functions f_j to characterize the equilibria of the intertemporal model that we are considering here. Kehoe and Levine (1985a) have shown that Debreu's reasoning extends to this model. Furthermore, by imposing another, fairly weak, condition on u_j, they are able to demonstrate that t_j is indeed continuously differentiable.

The proof of Debreu's result relies on fairly complex mathematical machinery. The intuition behind it is very simple, however. It is, in fact, the same intuition as Walras had when he counted equations and unknowns: There are h equations, $t_j(\alpha) = 0$, in h unknowns, α_j. Because of homogeneity, one of the weights α_j is redundant. Because of the adding-up restriction (21), however, one of the equations is also redundant. Consequently, the equilibrium conditions can be viewed as a syetem of $h-1$ equations in $h-1$ unknowns. Suppose that these equations are independent in the sense that $t_j(\hat{\alpha}) = 0$, $j = 1, \ldots, h-1$, and the $(h-1) \times (h-1)$ matrix of partial derivatives

$$J = \begin{bmatrix} \dfrac{\partial t_1}{\partial \alpha_1}(\hat{\alpha}) & \cdots & \dfrac{\partial t_1}{\partial \alpha_{h-1}}(\hat{\alpha}) \\ \vdots & & \vdots \\ \dfrac{\partial t_{h-1}}{\partial \alpha_1}(\hat{\alpha}) & \cdots & \dfrac{\partial t_{h-1}}{\partial \alpha_{h-1}}(\hat{\alpha}) \end{bmatrix} \tag{22}$$

is non-singular. (We have imposed the normalization $\alpha_h = 1$ and dropped the equation $t_h(\alpha) = 0$.) Then the inverse function theorem of elementary calculus says that, in some open neighbourhood of $\hat{\alpha}$, it is the only solution to the equilibrium conditions; that is, $t^{-1}(0) = \hat{\alpha}$. Using the compactness of the set of possible equilibria and the continuity of the equilibrium conditions, we can easily prove that there is a finite number of equilibria if J is non-singular at every equilibrium.

If J is singular at some equilibrium, then the intuition says that the slightest perturbation in the functions t_j either make it non-singular or else make it impossible for there to be a solution near $\hat{\alpha}$. Figure 16.1 illustrates some possibilities in an economy with two consumers.

To make some of the concepts that we have discussed in this section more concrete, let us consider a simple model with one good in each period and two consumers. Suppose that $u_1(c_t) = u_2(c_t) = \log c_t$ and that $w^1 = w^2 = 1$. The only difference between the two consumers is that $\gamma_1 < \gamma_2$. A solution to the utility maximization is characterized by the conditions

$$\gamma_j^{t-1}/c_t^j = \lambda_j p_t \tag{23}$$

$$\sum_{t=1}^{\infty} p_t c_t^j = \sum_{t=1}^{\infty} p_t. \tag{24}$$

An equilibrium satisfies these conditions and the condition that demand

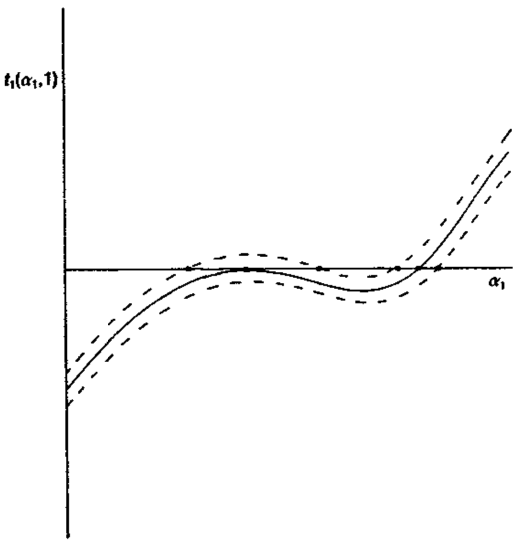

Fig. 16.1

equals supply:

$$c_t^1 + c_t^2 + 2, \qquad t = 1, 2, \ldots \tag{25}$$

The Pareto problem is

$$\max \alpha_1 \sum_{t=1}^{\infty} \gamma_1^{t-1} \log c_t^1 + \alpha_2 \sum_{t=1}^{\infty} \gamma_2^{t-1} \log c_t^2 \tag{26}$$
$$\text{s.t. } c_t^1 + c_t^2 = 2, \qquad t = 1, 2, \ldots$$

A solution to this problem is characterized by the conditions

$$\alpha_j \gamma_j^{t-1}/c_t^j = \pi_t, \qquad j = 1, 2, \tag{27}$$

and (25). These equations can easily be solved to yield

$$c_t^j = \frac{2\alpha_j \gamma_j^{t-1}}{\alpha_1 \gamma_1^{t-1} + \alpha_2 \gamma_2^{t-1}}, \qquad j = 1, 2, \tag{28}$$

$$\pi_t = (\alpha_1 \gamma_1^{t-1} + \alpha_2 \gamma_2^{t-2})/2. \tag{29}$$

The transfer payments needed to implement as a competitive equilibrium the allocation associated with the weights α_1 and α_2 are therefore

$$\begin{aligned} t_1(\alpha_1, \alpha_2) &= \sum_{t=1}^{\infty} \pi_t (c_t^1 - 1) = \left(\frac{\alpha_1}{1-\gamma_1} - \frac{\alpha_2}{1-\gamma_2}\right)/2 \\ t_2(\alpha_1, \alpha_2) &= \sum_{t=1}^{\infty} \pi_t (c_t^2 - 1) = \left(\frac{\alpha_2}{1-\gamma_2} - \frac{\alpha_1}{1-\gamma_1}\right)/2 \end{aligned} \tag{30}$$

Notice that these functions are continuously differentiable, are homogeneous of degree 1, and sum to 0.

The unique equilibrium of this model is found by setting these transfer payments equal to 0. It is $\alpha_1 = (1-\gamma_1)/(1-\gamma_2)$, $\alpha_2 = 1$. Notice that the value of the aggregate endowment is finite since

$$\begin{aligned} \sum_{t=1}^{\infty} \pi_t (1+1) &= 2 \sum_{t=1}^{\infty} \left(\frac{1-\gamma_1}{1-\gamma_2} \gamma_1^{t-1} + \gamma_2^{t-1}\right)\Big/2 \\ &= \frac{2}{1-\gamma_2}. \end{aligned} \tag{31}$$

There is, of course, no outside money in this model. There is, however, inside money: consumer 1, who is more impatient than consumer 2, spends more than his endowment early in his life. Later he consumes less, paying back his debt. In the limit, his consumption in each period approaches 0 and consumer 2's consumption approaches 2.

3. An Overlapping Generations Model

In this section we consider an overlapping generations model in which there is a single good in each period and a single consumer, who lives for two periods, in each generation. This is the model originally developed by Samuelson (1958) and analyzed extensively by Gale (1973). In the next section we discuss more general models.

The consumer born in period t, $t=1, 2, \ldots$, solves the utility maximization problem

$$\begin{aligned}&\max u(c_t^t, c_{t+1}^t)\\ &\text{s.t. } p_t c_t^t + p_{t+1}c_{t+1}^t = p_t w_1 + p_{t+1}w_2.\end{aligned} \tag{32}$$

We make the same sort of assumptions on u and (w_1, w_2) as in the previous section. As in the previous model, we can also think of this consumer as facing two budget constraints:

$$\left.\begin{aligned}&q_t c_t^t + m^t = q_t w_1\\ &q_{t+1}c_{t+1}^t = q_{t+1}w_2 + (1+r_t)m^t.\end{aligned}\right\} \tag{33}$$

If we normalize the spot prices so that $q_{t+1} = q_t = 1$, divide the second constraint by $(1+r_t)$, and add both together, we can produce a single budget constraint in which $p_t/p_{t+1} = (1+r_t)$.

The solution to this problem is characterized by the conditions

$$\left.\begin{aligned}&\frac{\partial u}{\partial c_t^t}(c_t^t, c_{t+1}^t) = \lambda_t p_t\\ &\frac{\partial u}{\partial c_{t+1}^t}(c_t^t, c_{t+1}^t) = \lambda_t p_{t+1}\end{aligned}\right\} \tag{34}$$

and the budget constraint in (32). Given the strict concavity of u, this consumer has continuous excess demand functions $y(p_t, p_{t+1}) = c_t^t - w_1$ when young and $z(p_t, p_{t+1}) = c_{t+1}^t - w_2$ when old. The form of the budget constraint implies that these functions are homogeneous of degree 0 in (p_t, p_{t+1}) and obey Walras's Law:

$$p_t y(p_t, p_{t+1}) + p_t z(p_t, p_{t+1}) \equiv 0. \tag{35}$$

Consider, for example, the case where $u(c_t^t, c_{t+1}^t) = \log c_t^t + \gamma \log c_{t+1}^t$. The excess demand functions can easily be computed using (32) and (34). They are

$$\left.\begin{aligned}y(p_t, p_{t+1}) &= \frac{p_t w_1 + p_{t+1}w_2}{(1+\gamma)p_t} - w_1 = \frac{-\gamma p_t w_1 + p_{t+1}w_2}{(1+\gamma)p_t}\\ z(p_t, p_{t+1}) &= \frac{\gamma(p_t w_1 + p_{t+1}w_2)}{(1+\gamma)p_{t+1}} - w_2 = \frac{\gamma p_t w_1 - p_{t+1}w_2}{(1+\gamma)p_{t+1}}.\end{aligned}\right\} \tag{36}$$

Notice that these functions do indeed satisfy continuity, homogeneity, and Walras's Law.

In addition to the consumers born in periods $1, 2, \ldots$, there is a consumer who is alive only in period 1 and who solves the problem

$$\begin{aligned}&\max u_0(c_1^0)\\ &\text{s.t. } p_1 c_1^0 = p_1 w_2^0 + m.\end{aligned} \tag{37}$$

Here m, which can be positive, negative, or zero, is the stock of outside money held by generation 0. If m is non-negative, then it is easily interpreted as fiat money. Even if it is negative, however, there are institutional stories to go with it. Think of an institution that makes loans to consumers when they are young. The institution collects the repayments of these loans when the consumers are old and uses them to make loans to the young consumers in the next generation. There are, of course, many other interpretations.

Since this consumer has preferences for, and endowment of, only the first good, we need not be careful about specifying u_0 or w_2^0. The excess demand function for this consumer is

$$z_0(p_1, m) = \frac{m}{p_1}. \tag{38}$$

An equilibrium of this model is a stock of outside money $\hat{m}$ and a price sequence $(\hat{p}_1, \hat{p}_2, \ldots)$ that satisfies the conditions that excess demand be equal to 0 in every period:

$$z_0(\hat{p}_1, \hat{m}) + y(\hat{p}_1, \hat{p}_2) = 0 \tag{39}$$

in period 1 and

$$z(\hat{p}_{t-1}, \hat{p}_t) + y(\hat{p}_t, \hat{p}_{t+1}) = 0 \tag{40}$$

in period t, $t = 2, 3, \ldots$.

One way to compute the equilibria of this model, developed by Gale (1973) and Cass, Okuno, and Zilcha (1979), is to use the offer curve, the image of $[y(p_t, p_{t+1}), z(p_t, p_{t+1})]$. This curve passes through the origin, stays always in the second and fourth quadrants, and intersects rays through the origin only once (except at the origin itself). In fact, Walras's Law (35) tells us that

$$z(p_t, p_{t+1})/y(p_t, p_{t+1}) = -p_t/p_{t+1}; \tag{41}$$

that is, the point where it intersects the ray with slope $-p_t/p_{t+1}$ has as its coordinates excess demands at (p_t, p_{t+1}). In addition, the offer curve always satisfies $y > -w_1$ and $z > -w_2$.

For example, in our simple log-linear example, we can use the formula for $y(p_t, p_{t+1})$ in (36) to solve for p_t/p_{t+1} in terms of y and substitute the result into the formula for $z(p_t, p_{t+1})$ to obtain the offer curve:

$$z = \frac{\gamma w_1 w_2}{(1+\gamma)^2 y + (1+\gamma)\gamma w_1} - \frac{w_2}{1+\gamma}. \tag{42}$$

The result is pictured in Figure 16.2.

In general, there are two steady states, inflation factors $\beta > 0$, such that the price sequence $p_t = \beta^t$ satisfies

$$z(\beta^{t-1}, \beta^t) + y(\beta^t, \beta^{t+1}) = z(1, \beta) + y(1, \beta) = 0. \tag{43}$$

These are given by the two intersections of the offer curve with the line through the origin with slope -1, $z = -y$. There is only one steady state in the degenerate case where the slope of the offer curve is -1 at the origin.

The steady state where $\beta = 1$ Pareto-dominates the steady state at the origin. One way to see this is to show that the consumption plan found by solving the representative consumer's maximization problem when $p_t = p_{t+1}$ also solves the problem of maximizing the utility of a steady-state consumption plan:

$$\begin{aligned} &\max u(c_1, c_2) \\ &\text{s.t. } c_1 + c_2 = w_1 + w_2. \end{aligned} \tag{44}$$

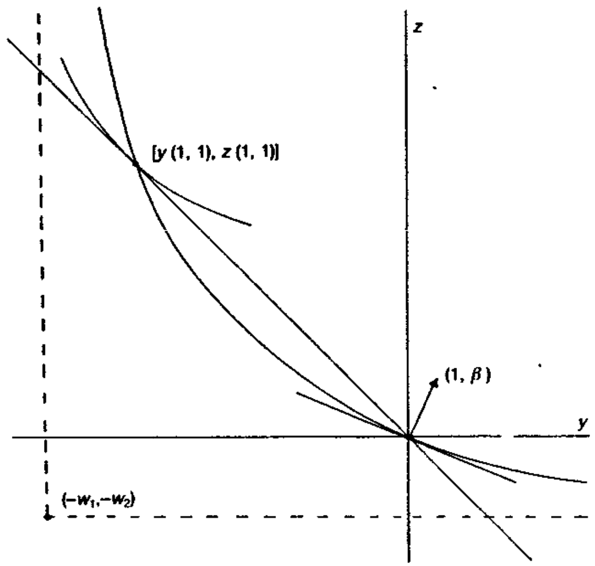

Fig. 16.2

Alternatively, notice that, since no trade is always feasible, the consumer can only be better off if he chooses to trade. Indeed, a simple revealed preference argument implies that the consumer prefers the net trade $[y(1, 1), z(1, 1)]$ to any point that lies on or to the left of the line with slope -1. (Look at Figure 16.2 again.)

To compute equilibria besides the two steady states, we start with $z_0 = \hat{m}/\hat{p}_1$ and read horizontally to the line with slope -1 to find the value of y for which $y(\hat{p}_1, \hat{p}_2) = -z_0$. We then read vertically to the offer curve to find the point $[y(\hat{p}_1, \hat{p}_2), z(\hat{p}_1, \hat{p}_2)]$. We now continue by reading horizontally to the ray with slope -1 to find the value of y for which $y(\hat{p}_2, \hat{p}_3) = -z(\hat{p}_1, \hat{p}_2)$. This process is illustrated in Figure 16.3. The offer curve in the figure corresponds to the case where $\gamma w_1 > w_2$. Notice that, for any value of z_0 such that $z_0 = \hat{m}/\hat{p}_1 < z(1, 1)$, there is an equilibrium that converges to the autarkic steady state in which there is no trade. (There is a natural lower bound on $\hat{m}/\hat{p}_1$ provided by $-w_2^0$, but this is independent of the offer curve of (y, z).) The price sequence is computed by normalizing $\hat{p}_1 = 1$, then using the slope of the line through the origin passing through the offer curve at $[y(\hat{p}_1, \hat{p}_2), z(\hat{p}_1, \hat{p}_2)]$ to find $\hat{p}_2$, using the slope of the line through the origin passing through the offer curve at $[y(\hat{p}_2, \hat{p}_3), z(\hat{p}_2, \hat{p}_3)]$ to find $\hat{p}_3$, and so on. Notice that every equilibrium of this model, except for the one that starts at $\hat{m}/\hat{p}_1 = z(1, 1)$, involves inflation. At the autarkic steady state β, which is the

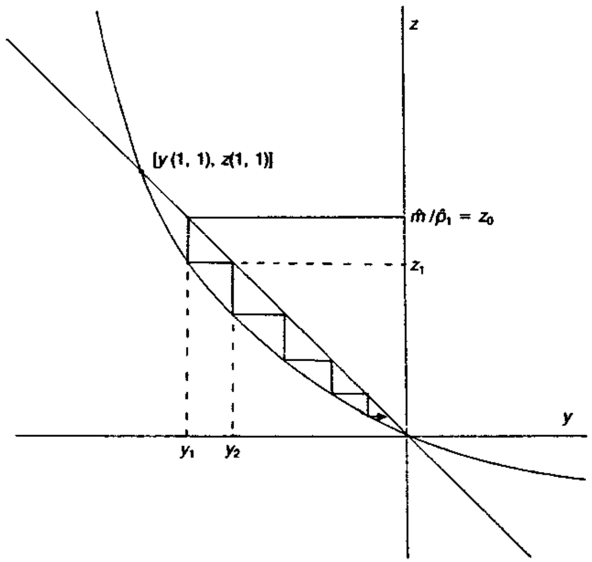

Fig. 16.3

negative of the reciprocal of the slope of the offer curve at the origin, is $\gamma w_1/w_2 > 1$.

Not only is there a continuum of equilibria in this example, but outside money plays a crucial role and equilibria are not necessarily Pareto-efficient. Observe that any equilibria that starts with $0 < \hat{m}/\hat{p}_1 < z(1, 1)$ is Pareto-dominated by the equilibrium with $\hat{m}/\hat{p}_1 = z(1, 1)$: the first generation prefers the highest z_0 possible, and subsequent generations are worse off the further they are from $[y(1, 1), z(1, 1)]$ and the closer they are to autarky. In fact, equilibria with higher $\hat{m}/\hat{p}_1$ Pareto-dominate those with lower starting-points. In the next section we shall see that the equilibria with $\hat{m}/\hat{p}_1 < 0$, although not necessarily Pareto-dominated by equilibria with $\hat{m}/\hat{p}_1 = z(1, 1)$, are not Pareto-efficient. As Shell (1971) has indicated, this failure of the First Welfare Theorem depends on the double infinity of consumers and goods. Although it is possible to mimic this failure of the First Welfare Theorem in a model with incomplete markets, as done, for example, by Cass and Yaari (1966), it should be stressed that it occurs even if all markets are complete.

Figure 16.4 depicts the offer curve for the log-linear model where $\gamma w_1 < w_2$. Notice that, for any values of $\hat{m}/\hat{p}_1$ such that $\hat{m}/\hat{p}_1 < 0$, there is an equilibrium that converges to the steady state where $\beta = 1$. There is also an equilibrium that starts with $\hat{m}/\hat{p}_1 = 0$ and stays at the autarkic steady state. Here $\beta = \gamma w_1/w_2 < 1$. This equilibrium is Pareto-efficient

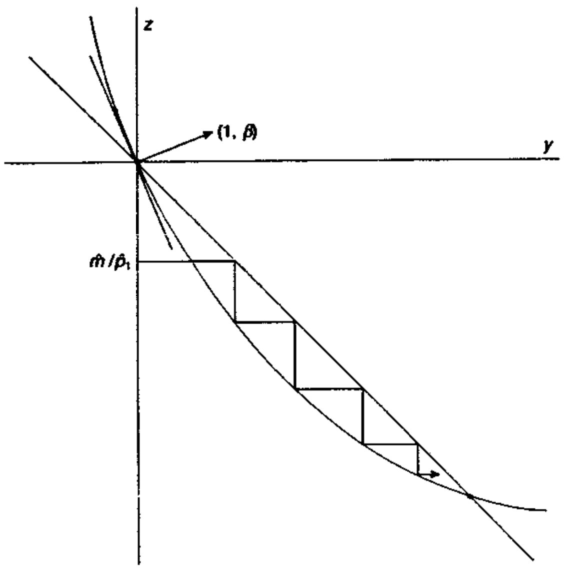

Fig. 16.4

since the value of the aggregate endowment is finite:

$$w_2^0 + w_1 + \sum_{t=2}^{\infty} \beta^{t-1}(w_1 + w_2) = w_2^0 + w_1 + \frac{\beta}{1-\beta}(w_1 + w_2). \tag{45}$$

As we shall see in the next section, all of the equilibria of this model are Pareto-efficient.

These two examples suggest three hypotheses. First, any indeterminacy of equilibrium is connected to inflation if there is positive outside money. Second, all equilibrium price paths converge to some steady state. Third, any indeterminacy of equilibrium is associated with a non-zero stock of outside money. We now study counter-examples to the first two propositions. In the next section we shall see that the third, although true in any model with one good in each period and consumers who live for two periods, fails in more general models.

The log-linear examples that we have analysed have the property that, as the price ratio p_t/p_{t+1} increases, $y(p_t, p_{t+1})$ decreases and $z(p_t, p_{t+1})$ increases. This means that the demand functions y and z exhibit gross substitutability. Consider the offer curve depicted in Figure 16.5. Here gross substitutability fails in the backwards-bending section of the offer curve. Notice that, for any value of $\hat{m}/\hat{p}_1$ sufficiently close to $z(1, 1)$, there is an equilibrium that converges to the steady state where $\beta = 1$. The crucial feature of this offer curve is that the slope of the offer curve

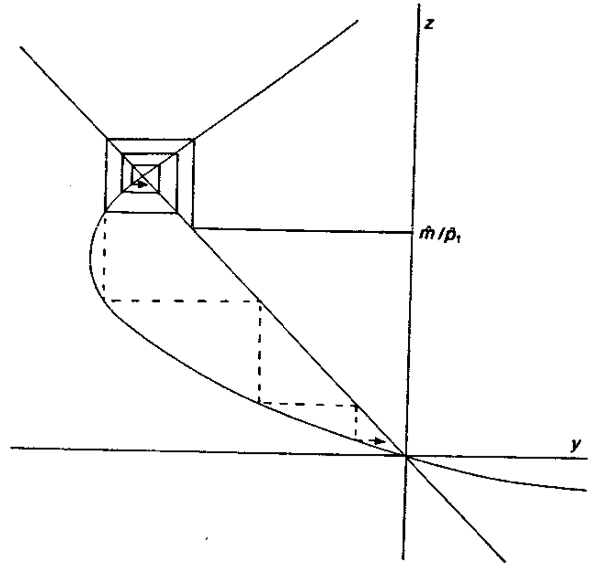

Fig. 16.5

at $[y(1, 1), z(1, 1)]$ is positive and less than one. There are also equilibria that start with $\hat{m}/\hat{p}_1$ near, or even equal to, $z(1, 1)$ and converge to the autarkic steady state: whenever there are two values of z that correspond to a single y, we have a choice of two ways to read from the line with slope -1 to the offer curve.

This example also has equilibria that do not converge to any steady state. Consider the offer curves in Figure 16.6. Here there is a two-period cycle $z_0, z_1, z_0, z_1, \ldots$. The second offer curve is the reflection of the first across the line with slope -1. Cycles are points where these two

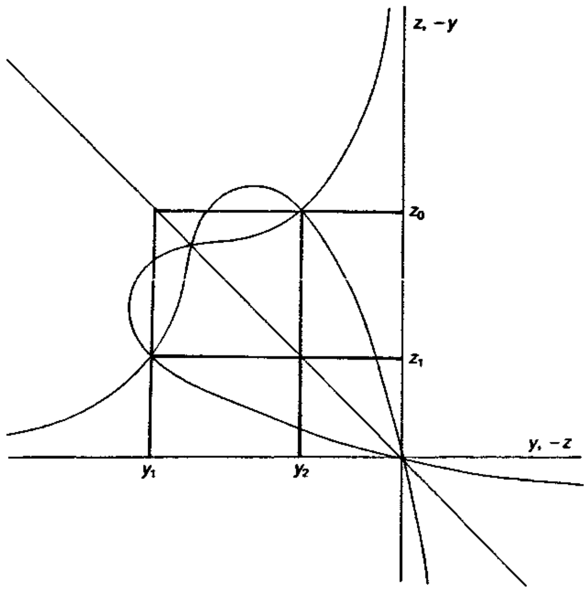

Fig. 16.6

curves intersect, where

$$[y(\hat{p}_1, \hat{p}_2), z(\hat{p}_1, \hat{p}_2)] = [-z(\hat{p}_2, \hat{p}_1), -y(\hat{p}_2, \hat{p}_1)]. \tag{46}$$

This implies that $\hat{m}$ and $(\hat{p}_1, \hat{p}_2, \hat{p}_1, \hat{p}_2, \ldots)$ are an equilibrium of this model. The possibility cycles in this sort of model was first pointed out by Gale (1973). Benhabib and Day (1982) have shown that there are also examples with equilibria that do not converge to any steady state or to a cycle of any length. The possibility of such strange behaviour, often referred to as chaotic dynamics, has been analysed extensively by Grandmont (1985).

4. General Overlapping Generations Models

We now turn our attention to overlapping generations models with many goods in each period and many consumers in each generation. If we allow many goods and many consumers, the assumption of two periods of life is completely general: Balasko, Cass, and Shell (1980) present a simple procedure for redefining periods and generations that converts a model in which consumers live for any finite number of periods into one in which they live for only two. Suppose that consumers live for k periods. Then redefine generations so that generations $-k+2, -k+3, \ldots, 0$ become generation 0, generations $1, 2, \ldots, k-1$ become generation 1, and so on. Redefine periods in the same way. Figure 16.7 illustrates this procedure for the case $k = 4$. Notice that each generation lives for just two redefined periods. If there are n goods in each original period, there are $(k-1)n$ goods, indexed by date, in each redefined period. If there are h consumers in each original generation, there are $(k-1)h$ consumers in each redefined generation.

The model with many consumers and many goods has the same potential for equilibria that are Pareto-inefficient and equilibria with unbacked nominal debt as does the simple model of the previous section.

Generation	1	2	3	4	5	6	7	8	9	
−2	X	0	0	0	0	0	0	0	0	0
−1	X	X	0	0	0	0	0	0	0	
0	X	X	X	0	0	0	0	0	0	
1	X	X	X	X	0	0	0	0	0	1
2	0	X	X	X	X	0	0	0	0	
3	0	0	X	X	X	X	0	0	0	
4	0	0	0	X	X	X	X	0	0	2
5	0	0	0	0	X	X	X	X	0	
6	0	0	0	0	0	X	X	X	X	
7	0	0	0	0	0	0	X	X	X	3
8	0	0	0	0	0	0	0	X	X	
9	0	0	0	0	0	0	0	0	X	
Period		1			2			3		

Fig. 16.7

It has even more potential for indeterminacy of equilibria. Consumer j in generation t solves the problem

$$\begin{aligned}&\max u_j(y_t^j + w_1, z_t^j + w_2)\\ &\text{s.t. } p_t'y_t^j + p_{t+1}'z_t^j = 0.\end{aligned} \tag{47}$$

Here y_t^j, z_t^j, w_1, w_2, p_t, and p_{t+1} are all n-dimensional vectors. If his excess demand functions are $y^j(p_t, p_{t+1})$ and $z^j(p_t, p_{t+1})$, then the aggregate excess demand functions for generation t are $y(p_t, p_{t+1})$ and $z(p_t, p_{t+1})$ where, for example,

$$y(p_t, p_{t+1}) = \sum_{j=1}^{h} y^j(p_t, p_{t+1}). \tag{48}$$

We assume that y and z are continuously differentiable for all strictly positive price vectors (p_t, p_{t+1}), are homogeneous of degree 0 in (p_t, p_{t+1}), and obey Walras's law,

$$p_t'y(p_t, p_{t+1}) + p_{t+1}'z(p_t, p_{t+1}) \equiv 0. \tag{49}$$

In addition, there is an old generation, alive only in the first period, that has the aggregate excess demand function $z_0(p_1, m)$. We assume that z_0 is continuously differentiable for all strictly positive price vectors p_1 and an open interval of money stocks m that includes 0, is homogeneous of degree 0 in (p_1, m), and obeys Walras's law,

$$p_1'z_0(p_1, m) \equiv m. \tag{50}$$

An equilibrium of this model again is a stock of outside money $\hat{m}$ and a sequence of price vectors $(\hat{p}_1, \hat{p}_2, \ldots)$ that satisfies (39) and (40) where the variables are reinterpreted as vectors. To see the possibility of indeterminacy, let us count equations and unknowns in the equilibrium conditions. The equilibrium condition in the first period,

$$z_0(\hat{p}_1, \hat{m}) + y(\hat{p}_1, \hat{p}_2) = 0, \tag{51}$$

contains n equations in $2n+1$ unknowns. Since the equations are all homogeneous, we can impose a normalization to reduce this to $2n$ unknowns. The equilibrium conditions in subsequent periods,

$$z(\hat{p}_{t-1}, \hat{p}_t) + y(\hat{p}_t, \hat{p}_{t+1}) = 0, \qquad t = 2, 3, \ldots, \tag{52}$$

each add n equations and n unknowns. The entire system therefore has n degrees of freedom. If we set $\hat{m} = 0$ *a priori*, there is one fewer unknown, and this reduces the degrees of freedom to $n-1$. The idea is that we choose $\hat{m}$, $\hat{p}_1$, and $\hat{p}_2$ to satisfy (51) and then use (52) as a nonlinear difference equation to determine $\hat{p}_3, \hat{p}_4, \ldots$.

The problem with simply counting equations and unknowns is that we do not always know whether we can use (52) to continue an equilibrium price sequence for arbitrary $(\hat{p}_1, \hat{p}_2)$. In Figure 16.3, for example, if we

start with any value of $\hat{m}/\hat{p}_1$ above $z(1, 1)$, we can continue the equilibrium for a few periods but eventually we reach a situation where we cannot continue because z exceeds w_1 and there is no offer curve to read to vertically! In general, we want to avoid situations where we cannot use (52) to compute a positive value of $\hat{p}_{t+1}$ as a function of $\hat{p}_{t-1}$ and $\hat{p}_t$. One way to do this is to require that the equilibrium price sequence converge to a steady state at which the matrix of partial derivatives of $y(p_t, p_{t+1})$ with respect to p_{t+1} is non-singular. This implies that in some open neighbourhood of the steady state, for fixed $(\hat{p}_{t-1}, \hat{p}_t)$, the function $z(\hat{p}_{t-1}, \hat{p}_t) + y(\hat{p}_t, \cdot)$ is invertible. The implicit function theorem tells us that in this neighbourhood $\hat{p}_{t+1}$ can be computed uniquely as a function of $(\hat{p}_{t-1}, \hat{p}_t)$. Restricting our attention to this t-1
neighbourhood of the steady state, we can avoid the problem illustrated in Figure 16.5, where there may be more than one $\hat{p}_{t+1}$ that satisfies the equilibrium conditions. This restriction may force us, however, to ignore some equilibria.

A steady state of this model is a vector of relative prices p and an inflation factor β such that $\hat{p}_t = \beta^t p$ satisfies (52). There are two types of steady states: nominal steady states, in which there is a non-zero amount of nominal debt transferred from generation to generation, and real steady states, in which there is no such transfer. Notice that in any equilibrium the amount of nominal debt transferred from generation to generation stays constant over time: (50) and (51) imply that $-\hat{p}_1'y(\hat{p}_1, \hat{p}_2) = \hat{p}_1'z_0(\hat{p}_1, \hat{m})$; Walras's Law implies that $\hat{p}_2'z(\hat{p}_1, \hat{p}_2) = -\hat{p}_1'y(\hat{p}_1, \hat{p}_2)$; (51) implies that $-\hat{p}_2'y(\hat{p}_2, \hat{p}_3) = \hat{p}_2'z(\hat{p}_1, \hat{p}_2)$; and so on. The steady-state condition is

$$z(\beta^{t-1}p, \beta^t p) + y(\beta^t p, \beta^{t+1}p) = z(p, \beta p) + y(p, \beta p) = 0. \tag{53}$$

This implies that $p'z(p, \beta p) + p'y(p, \beta p) = 0$. Walras's Law implies that $p'y(p, \beta p) + \beta p'z(p, \beta p) = 0$. Subtracting one from another, we obtain $(1-\beta)p'z(p, \beta p) = 0$. This says that $\beta = 1$ at any nominal steady state. Kehoe and Levine (1984b) prove that almost all economies are such that $\beta \neq 1$ at every real steady state.

Balasko and Shell (1980) and Burke (1987) have shown that a necessary and sufficient condition for Pareto efficiency of an equilibrium is that

$$\sum_{t=1}^{\infty} \|p_t\|^{-1} = \infty. \tag{54}$$

Here $\|p_t\| = (p_t'p_t)^{1/2}$, the standard Euclidean norm. They impose a uniform curvature condition on indifference surfaces that is natural in a stationary environment. Notice that any equilibrium that converges to a steady state where $\beta > 1$, an inflationary steady state, is Pareto-inefficient since the sum in (54) converges. Any equilibrium that converges to a steady state where $\beta \leq 1$, however, is Pareto-efficient since the sum in

(54) diverges. In fact it is easy to show that if $\beta = 1$ the equilibrium allocation maximizes a weighted sum of utilities of the consumers in a representative generation subject to steady-state consumption constraints.

When there are many goods in each period and many consumers in each generation, there is no need for there to be a unique nominal steady state and a unique real steady state as there are in the example of the previous section. Even with one good in each period, but more than one consumer in each generation, there can be multiple real steady states, although there is a unique nominal steady state. Consider, for example, a static two-person exchange model with multiple equilibria. Such a model is easy to construct in an Edgeworth box; see Shapley and Shubik (1977) for an example. Now convert this into an overlapping generations model in which there are two consumers in each generation with the same preferences for and endowments of the two goods in the two periods of their lives. The multiple equilibria of the static model are real steady states of the overlapping generations model in which each consumer trades only with the other consumer in the same generation. This illustrates the point that real steady states are not, in general, autarkic, as they are in the simple model. With many goods in each period, not even nominal steady states need be unique. Kehoe and Levine (1984b) prove, however, that in general every economy has an odd—in particular, a non-zero—number of nominal steady states and an odd number of real steady states. Furthermore, the matrix of partial derivatives of y with respect to its second vector of arguments is almost always non-singular at every steady state.

To analyse the behaviour of equilibrium price sequences that converge to a steady state, Kehoe and Levine (1985a) linearize the equilibrium conditions (51) and (52). The local stable manifold theorem of dynamical systems theory says that the behaviour of the nonlinear system near the steady state is qualitatively the same as that of the linear system (see Irwin 1980). They consider the set of price pairs $(\hat{p}_1, \hat{p}_2)$ that satisfy the equilibrium condition in the first period and lead to convergence to the steady state when employed as starting conditions for the nonlinear difference equation (52). This set is a manifold, a set of points that is locally equivalent to an open subset of a Euclidean space of dimension smaller than $2n$. (The prototypical manifold is a linear subspace.) Kehoe and Levine demonstrate that this manifold can have dimension as large as n if there is outside money and as large as $n-1$ if there is no money. This manifold can also have dimension as small as 0, in which case it consists of isolated points. (The best linear approximation to this manifold near the steady state is the intersection of the stable subspace of the linearized version of (52) with the set of vectors that satisfy the linearized version of (51).) Almost all economies are such that any small perturbation produces an economy with the same qualitative properties. Kehoe and Levine also prove that there are robust examples of steady states with no equilibria at all that converge to them. This cannot happen with only one good in each period because Walras's Law implies that m and p can be chosen so that the steady-state price vector $(p, \beta p)$ satisfies $z_0(p, m) + y(p, \beta p) = 0$. Consequently, the steady state itself is an equilibrium.

Notice that we can use a similar trick to that used to convert economies with consumers who live for k periods into economies in which they live for two to convert the study of equilibria that converge to cycles of any finite length into the study of equilibria that converge to steady states. Suppose that an economy has a k-period cycle in the sense that $(p_{t+1}, \ldots, p_{t+k}) = (\beta^t p_1, \ldots, \beta^t p_k)$ satisfies (52). Redefine generations so that, for example, generations $1, 2, \ldots, k$ become generation 1. Similarly, redefine goods. A k-period cycle is now a steady state of the redefined model.

5. The Ricardian Equivalence Theorem

In 1817 Ricardo asked the question, Does it make any difference whether a government finances an increase in expenditure by raising taxes or by selling bonds? (See Ricardo 1951: 244–9.) The simple answer that he came up with, although he realized that there were complications, was that it makes no difference, because consumers anticipate that they have to pay more taxes in the future if there is a bond sale so that the government can make interest payments. This is at odds to Keynes's answer to the same question; that a bond-financed increase in government expenditure has the full multiplier effect, but that a tax-financed increase has a much smaller balanced multiplier effect. The crucial distinction between the two analyses is that in one consumers' savings behaviour is altered by the bond issue and in the other it is not. It reduces to, as Barro (1974) puts it, Are government bonds net wealth?

Let us first answer this question using our model with infinitely lived consumers. We introduce into that model a government that purchases goods $g_t = (g_{1t}, \ldots, g_{nt})$ in period t, $t = 1, 2, \ldots$. We require that this expenditure pattern be feasible in that

$$0 \leq g_t \leq \sum_{j=1}^{h} w^j, \qquad t = 1, 2, \ldots \tag{55}$$

Suppose first that these purchases are financed by lump-sum taxes $\tau_t^1, \ldots, \tau_t^h$ so that the government budget balances in every period:

$$\sum_{j=1}^{h} \tau_t^j = p_t' g_t, \qquad t = 1, 2, \ldots . \tag{56}$$

Then the budget constraint faced by consumer j is

$$\sum_{t=1}^{\infty} p_t' c_t^j = \sum_{t=1}^{\infty} (p_t' w^j - \tau_t^j). \tag{57}$$

Suppose, on the other hand, that the government issue bonds b_t, $t = 1, 2, \ldots$, that pay interest at the competitively determined interest rate. It finances these interest payments by lump-sum taxes θ_t^j. The government must balance its budget in the sense that the present discounted value of its expenditures is equal to the present discounted value of its revenues:

$$\begin{gathered} \sum_{t=1}^{\infty} p_t' g_t + \sum_{t=1}^{\infty} b_t = \sum_{t=1}^{\infty} \left(\sum_{j=1}^{h} \theta_t^j + b_t \right) \\ \sum_{t=1}^{\infty} p_t' g_t = \sum_{t=1}^{\infty} \sum_{j=1}^{h} \theta_t^j. \end{gathered} \tag{58}$$

$\sum_{t=1}^{\infty} b_t$ shows up on both sides of the budget constraint since the present discounted value of a bond is equal to sum of the interest payments on it. The consumer's budget constraint becomes

$$\begin{gathered} \sum_{t=1}^{\infty} (p_t' c_t + b_t^j) = \sum_{t=1}^{\infty} (p_t' w^j - \theta_t^j) + \sum_{t=1}^{\infty} b_t^j \\ \sum_{t=1}^{\infty} p_t' c_t = \sum_{t=1}^{\infty} (p_t' w^j - \theta_t^j). \end{gathered} \tag{59}$$

Here b_t^j is the net purchase of bonds by consumer j in period t and

$$\sum_{j=1}^{h} b_t^j = b_t. \tag{60}$$

Notice that, if

$$\sum_{t=1}^{\infty} \tau_t^j = \sum_{t=1}^{\infty} \theta_t^j, \tag{61}$$

these two models are identical in their essentials. In particular, the agents face the same budget constraints. This is the Ricardian Equivalence Theorem. There are a number of important maintained hypotheses. First, there are perfect capital markets. This implies that each consumer faces a single budget constraint. Second, all taxes are lump-sum; Third otherwise, relative prices would be distorted in different ways by different taxation schemes. ~~Fourth~~, taxes are not redistributional. In other words, consumers face the same total tax bill under the two taxation scheme; otherwise, relative prices would change because of income effects.

We are not claiming that the equilibrium is the same as if $g_t = 0$, $t = 1, 2, \ldots$ Since the government is consuming some of the goods that would otherwise have gone to consumers, this cannot be the case. Government fiscal policy always has real effects. It is the way it is financed that is irrelevant.

It is difficult to give the Ricardian Equivalence Theorem an interpretation in an overlapping generations model: alternative tax schemes that time tax collections differently necessarily have redistributional effects because consumers are alive at different times. There are very special situations in which different tax schemes do not affect the equilibria. It does not matter, for example, in which period of life consumers pay taxes as long as each consumer faces a single budget constraint, all taxes are lump-sum, and each consumer faces the same total tax bill under the different schemes. Rather than say that the Ricardian Equivalence Theorem does not hold in an overlapping generations model, we should say that the range of tax schemes that do not affect the equilibria is much more limited in an overlapping generations model than it is in an infinitely lived consumer model.

Another problem with interpreting the Ricardian Equivalence Theorem in a model with infinite numbers of consumers and goods is, as we have seen, that there is no reason for $\sum_{t=1}^{\infty} p_t' g_t$ to converge. The government can therefore issue bonds that it need never pay back. These bonds act like injections of outside money and are, therefore, net ~~worth.~~ weal Figure 16.8 depicts an example with a steady state in which $g_t = g > 0$ every period. Here inflation erodes the value of the initial stock of outside money at the same rate as that at which the value of the total

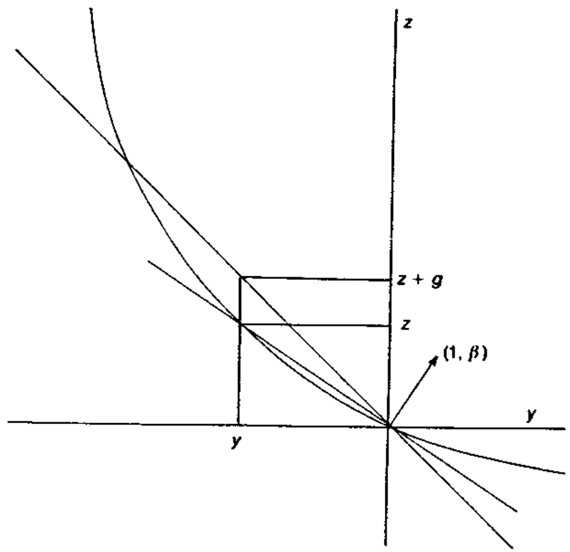

Fig. 16.8

stock of government bonds increases. The total real stock of nominal debt, outside money and bonds, remains constant at $z+g$. The steady state interest rate is $r=1/\beta -1<0$. Notice that, even though the government is consuming $g>0$ of the single good in every period, this equilibrium Pareto dominates the autarkic equilibrium where it consumes nothing. Examples of this sort are discussed by Sargent (1987: Ch. 7).

Barro (1974) has argued that the Ricardian Equivalence Theorem holds for overlapping generations models in which consumers include their offspring's utility in their own utility functions. Since their offspring similarly value the utility of their own offspring, this can make a consumer's utility maximization problem into the problem of maximizing the utility of an infinitely lived family. The problem with this story is that, in general, we have to allow some consumers to pass on debts, as well as bequests, to their offspring. In this case we would want consumers to include their progenitors' utility in their own utility functions. Think of our example of the two infinitely lived consumers with log-linear utility functions as a model of such families. One family of consumers asymptotically consumes nothing. They use almost all of their income to service their family debt, which they inherit from their progenitors and pass on to their offspring. This sort of problem always occurs if different families have different discount factors in their reduced-form utility functions. Institutional arrangements in modern societies make this feature of the bequest story very unrealistic. As Barro himself points out, if a family is at a corner solution because of a non-negativity constraint on bequests, the family faces a sequence of budget constraints that cannot be aggregated into one.

Similarly, a model with infinitely lived consumers who face liquidity constraints can have similar characteristics to an overlapping generations model (see Woodford 1986a, for example.) If we cannot reduce the consumer's utility maximization problem to one with a finite number of budget constraints, then we cannot prove that the value of the aggregate endowment is finite. Consequently, equilibria need not be Pareto-efficient, and there may be equilibria in which outside money plays a role. Even our argument that there is a finite number of equilibria falls apart. The essential feature of that argument is that each consumer is characterized by a single Lagrange multiplier $\lambda_j=1/\alpha_j$. If the consumer cannot equate his marginal utility of income in different periods, then he acts, to some extent, like a sequence of different consumers. There may be a robust continuum of equilibria, and the Ricardian Equivalence Theorem need not hold.

6. Implications for Finite Models

What does our analysis of the overlapping generations model tell us about the properties of models with large, but finite, number of consumers and goods? Suppose that we truncate the model at some period T using a terminal young generation $y_T(p_T, m)$ analogous to the initial old generation $z_0(p_1, m)$. Outside money now corresponds to a transfer from the terminal young generation to the initial old. There is now a finite number of equilibrium conditions:

$$\begin{aligned} z_0(\hat{p}_1, \hat{m}) + y(\hat{p}_1, \hat{p}_2) &= 0 \\ z(\hat{p}_1, \hat{p}_2) + y(\hat{p}_2, \hat{p}_3) &= 0 \\ &\vdots \\ z(\hat{p}_{T-1}, \hat{p}_T) + y_T(\hat{p}_T, \hat{m}) &= 0. \end{aligned} \tag{62}$$

All of the equilibria of this model are Pareto-efficient. In general, there is a one-dimensional continuum of equilibria indexed by the real transfer payment $\hat{m}/\|\hat{p}_1\|$.

This method of truncating this model is often equivalent to specifying expectations of prices in periods after the model ends. For example, we could specify $y_T(p_T, m)$ as $y_T(p_T, \|p_T\|\,\beta p)$ where (p, β) is a steady state. Here, of course, $m=\|p_T\|\,\beta p' z(p_T, \|p_T\|\,\beta p)$. (See Auerbach, Kotlikoff, and Skinner 1983 for an application of this approach.)

Consider a situation where one equilibrium Pareto-dominates another in the infinite horizon model. Each of these can be made an equilibrium of the truncated model with a suitable choice of y_T. Since both of the equilibria of the truncated model are Pareto-efficient, the equilibrium that dominates in the infinite horizon model must assign some members of the terminal generation lower utility than does the inferior equilibrium. Notice that the functions y_T do not necessarily bear any relationship to utility maximization by generation T in the infinite-horizon model. If T is large enough, the model is clear: by sacrificing the welfare of one generation, all others are made better off, and society as a whole is made better off from a utilitarian viewpoint.

In an infinite horizon model there can be n dimensions of indeterminacy if there is outside money and $n-1$ dimensions if there is not. The single dimension of indeterminacy that shows up because of fiat money corresponds to the indeterminacy parametrized by the real transfer payment. What about the other dimensions? To answer this question, let us suppose that we have two equilibrium price sequences, $(\hat{p}_1, \hat{p}_2, \ldots)$ and $(\bar{p}_1, \bar{p}_2, \ldots)$, which both converge to the same steady state. Suppose too that both involve the same real stock of outside money,

$$\frac{\hat{m}}{\|\hat{p}_1\|}=\frac{\bar{m}}{\|\bar{p}_1\|}.$$

If we truncate using a terminal young generation

$$\hat{y}_T(p_T, m) = y_T(p_T, \hat{p}_{T+1}), \tag{63}$$

$m=\hat{m}$, then $(\hat{p}_1, \hat{p}_2, \ldots, \hat{p}_T)$ is an equilibrium. If we truncate with the

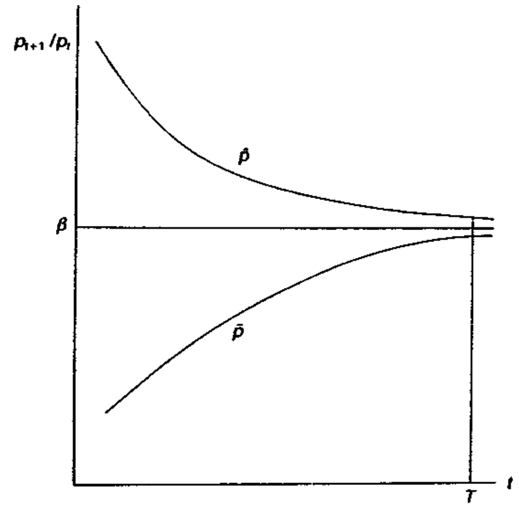

Fig. 16.9

analogous choice of $\bar{y}_T$, then $(\bar{p}_1, \bar{p}_2, \ldots, \bar{p}_T)$ is an equilibrium. Figure 16.9 depicts this sort of situation. For large enough T, $(\hat{p}_T, \hat{p}_{T+1})$ is going to be arbitrarily close to $(\bar{p}_T, \bar{p}_{T+1})$ no matter how far apart are $\hat{p}_1$ and $\bar{p}_1$. Indeterminacy of equilibrium therefore corresponds to sensitivity to terminal conditions, sensitivity of initial prices that becomes more acute as the time horizon T becomes larger. See Kehoe and Levine (1986) for numerical simulations of an example with this propery.

We should point out one other way of reducing an overlapping generations model to a model with a finite time horizon. Suppose that in every period the probability that the world ends before the next period is ρ, $0<\rho<1$. It is then natural to assume that consumer j in generation t solves the expected utility maximization problem

$$\left.\begin{array}{l}\max \rho u_j(y_t^j + w_1) + (1-\rho)v_j(y_t^j + w_1, z_t^j + w_2) \\ \text{s.t. } p_t' y_t^j + p_{t+1}' z_t^j = 0.\end{array}\right\} \qquad (64)$$

Here u_j is his utility function if the world ends before the second period of his life and v_j is his utility function if it does not. Even though the world ends in finite time with probability 1, this model is identical to an overlapping with an infinite horizon. It may have equilibria that are not Pareto-efficient, equilibria in which outside money plays a role, and equilibria with one or more dimensions of indeterminacy.

7. Extensions and Conclusions

The results presented in this paper can be extended to more general models. Kehoe *et al.* (1988) have extended this analysis of the model with a finite number of infinitely lived agents to similar models that allow production and capital accumulation. The only difficulty is in ensuring that the transfer functions used in the equilibrium conditions are continuously differentiable. Muller and Woodford (1985) have extended this analysis of the overlapping generations model to models that include infinitely lived consumers, assets, and production. They find that the presence of infinitely lived consumers or infinitely lived assets can force the value of the aggregate endowment to be finite. This rules out Pareto inefficiency of equilibria and outside money. It does not rule out indeterminacy of equilibria, however.

Do Pareto inefficiency of equilibria and outside money depend on there being an infinite number of consumers or on some consumers having finite life-spans? Kehoe (1986) considers a simple pure-exchange model in which there is an infinite number of consumers who all live for ever. This model has equilibria that are Pareto-inefficient and equilibria with outside money. It also has equilibria with several dimensions of indeterminacy.

As we have seen, indeterminacy is a relatively separate issue from Pareto inefficiency and outside money, Kehoe *et al.* (1986b) consider an abstract model with infinite numbers of consumers and goods. The only prices that are allowed assign finite value to the aggregate endowment. This rules out Pareto inefficiency and outside money. Even so, there are robust examples with any dimension of indeterminacy. The reason for this indeterminacy is that we cannot reduce the equilibrium conditions to a finite number of equations and unknowns. These authors also find that there is a finite number of locally unique equilibria if consumers are similar enough. This generalizes our results on economies with a finite number of consumers.

Santos and Bona (1986) and Geanakoplos and Brown (1985) have extended the results of Kehoe and Levine (1985a) for stationary, pure-exchange, overlapping generations models to models with non-stationary structures. Like Kehoe and Levine, these authors need to restrict their attention to equilibria that remain close to each other in some sense. They find that, even in a non-stationary environment, there are n dimensions of potential indeterminacy if there is outside money and $n-1$ dimensions if there is not.

One disturbing aspect to the potential indeterminacy of equilibria is that it occurs for some values of the parameters of a model but not for others. We would like to somehow classify the parameter values for which indeterminacy does not occur. A first step in this direction has been taken by Balasko and Shell (1981), who consider a model with many goods in each period but a single two-period-lived consumer with a Cobb–Douglas utility function in each generation. They prove that there is no indeterminacy without outside money and only one dimension of indeterminacy with it. Geanakoplos and Polemarchakis (1984) have shown that the essential feature of this analysis is that the single two-period-lived consumer has intertemporally separable preferences. Kehoe and Levine (1984a) have shown further that any small perturbation to a model with a single two-period-lived consumer with intertemporally separable preferences, even if it introduces small heterogeneities among consumers or small interdependencies in consumption over time, results in a model with these same features.

A more significant finding is that of Kehoe *et al.* (1986a), who consider general pure-exchange, overlapping generations economies with many goods in each period and many consumers in each generation, in which all demand functions exhibit gross substitutability. They prove that there is a unique equilibrium if there is no money; although there may be a one-dimensional indeterminacy with outside money, there is at most one equilibrium for each level of real outside money in the first period. Furthermore, their analysis is global rather than local. If the economy is stationary, then there is a unique nominal steady state and there is a unique real steady state, and every equilibrium converges to one of them. Unfortunately, there are plausible examples that violate gross substitutability. Kehoe and Levine (1986) consider a model with a single good in each period and a single three-period-lived consumer in each generation. They give this consumer a constant elasticity of substitution utility function and show that, for plausible parameter values, this model can exhibit indeterminacy without outside money and more than one dimension of indeterminacy with it. Moreover, they choose the crucial parameter, the elasticity of substitution in consumption over time, to agree with empirical evidence.

The present analysis has focused on the differences between models with a finite number of infinitely lived consumers and overlapping generations models. Yet these two types of models have important properties in common. In both, for example, equilibria always exist. Since the equilibrium conditions for a model with a finite number of infinitely lived consumers can be transformed using Negishi's (1960b) approach into those of a model with a finite number of goods, it is straightforward to prove the existence of equilibria in such models. This is done, for example, by Kehoe *et al.* (1988). Proving the existence of equilibria in overlapping generations models involves more subtle issues. Considering the limit of a sequence of truncated economies, Balasko *et al.* (1980) prove the existence of an equilibrium with $\hat{m}=0$ in a pure-exchange, overlapping generations model. For general models with countably many consumers and goods, Burke (1986, 1988) and Wilson (1981) have proven the existence of equilibria. The presence of outside money may be necessary, however, for an equilibrium to exist.

Another property that these two types of models have in common is that the Second Welfare Theorem holds: any Pareto-efficient allocation can be supported as a competitive equilibrium with transfers. This is proven for the overlapping generations model by Balasko and Shell (1980). The role that outside money plays in supporting a Pareto-efficient allocation can be interpreted as such a transfer. Unfortunately, Cass *et al.* (1979) and Millan (1981) have examples in which no Pareto-efficient allocation can be supported as a competitive equilibrium by giving a transfer only to the first generation. Burke (1987), however, shows that a transfer to the first generation does support efficiency if it is followed by a sequence of taxes on subsequent generations. Furthermore, the sum of real tax payments can be made arbitrarily small.

How much of this analysis extends to intertemporal models with uncertainty? If all markets are complete, then the analysis of the model with a finite number of infinitely lived consumers remains the same. In particular, all equilibria are Pareto-efficient, there is no role for outside money, and there is generically a finite number of equilibria. Goods are indexed by histories of states of nature as well by date. (See Kehoe and Levine 1985b for an analysis of a model of this sort.) In a stochastic overlapping generations model the assumption of complete markets is unnatural, however. In a deterministic setting we have argued that it makes no difference whether all trade takes place in the first period or takes place sequentially; in a stochastic setting setting this is no longer the case. Consumers would want to make trades in periods before they are born to insure themselves against being born into unfavourable circumstances. Dutta and Polemarchakis (1985) present an analysis of a simple stochastic overlapping generations model and show the difference between equilibria with complete markets and equilibria where consumers are allowed to trade only during their own lifetimes.

As we have seen, models with infinitely lived consumers who face incomplete markets have similar properties to overlapping generations models. Bewley (1980, 1983), Scheinkman and Weiss (1986), and Levine (1986) analyse simple stochastic models in which there are infinitely lived consumers who are constrained in their borrowing and lending decisions. Not surprisingly, they find that such models have equilibria that are Pareto-inefficient and equilibria in which outside money plays an important role. Presumably, these models also have indeterminate equilibria, but this property has not received much attention.

The most worrying property of the overlapping generations model is probably its potential for indeterminate equilibria even if there is no outside money. There are two reasons for this. First, indeterminacy makes the model unsuitable for comparative statics analysis. Second, it makes the concept of perfect foresight problematical. Multiplicity of equilibria of any sort presents difficulties for an economist interested in using a model to do a comparative-statics analysis of the impact of a change in parameters. Suppose, however, that a model has a finite number of locally unique equilibria that vary continuously with its parameter values. (Almost all static general equilibrium models possess these properties.) Then the economist could hope that, by appealing to history to justify focusing on one particular equilibrium, and to a (usually unspecified) dynamic adjustment process to justify focusing on the displacement of that equilibrium after a change in parameter values, comparative statics still makes some sense. Even these hopes vanish if there is a continuum of equilibria.

The idea underlying perfect foresight in a model with no uncertainty is the same as that underlying the rational expectations hypothesis in a model with uncertainty: the agents know the structure of the model and use it to predict the relevant values of future variables. If the model does not make determinate prediction, then hypothesis of perfect foresight becomes less attractive. If there is a continuum of perfect foresight paths, the theory is incomplete. Geanakoplos and Polemarchakis (1986) argue that indeterminacy leaves room for factors like fixed nominal wages and animal spirits of investors. As we have seen in our discussion of the Ricardian Equivalence Theorem, if there is a continuum of equilibria, some may have Keynesian features and some may not.

One way to try to make the theory complete would be to fix the values of some variables in the first period, for example the real money stock or a relative price. Even this approach fails if $y(p_t, p_{t+1})$ is not always an invertible function of p_{t+1}. With the backwards-bending offer curve in Figure 16.5, for example, there is an infinite number of equilibria even if we fix the value of $\hat{m}/\hat{p}_1$: at every point where there are two values of $\hat{p}_{t+1}$ such that $z(\hat{p}_{t-1}, \hat{p}_t) + y(\hat{p}_t, \hat{p}_{t+1}) = 0$, we have a choice of a different price path to follow.

Modelling expectations has long been a difficulty in economic theory. Keynes (1973/1936), for example, realized the importance of expectations formation, but claimed to work with a model in which the time period was short enough so that expectations could be taken as exogenous. The simplest way of making expectations endogenous is to make them adaptive as done by, for example, Friedman (1968) and Phelps (1967). The equilibria of the overlapping generations models would be generically determinate if we specified expectations as either exogenous or adaptive: since values of past variables can be taken as exogenous in any period, the equilibrium conditions reduce to a system of a finite number of equations in the same finite number of unknowns. Computing the equilibria of such a model would reduce to computing the equilibria of a sequence of models that look like static models.

The indeterminacy of equilibria in the overlapping generations models is all the more worrying because it can be associated with the existence of self-fulfilling prophecies. Even though the preferences, endowments, and technology of an economy are deterministic, a random variable can affect the equilibria merely because agents expect it to. This phenomenon is referred to as a 'sunspot', although actual sunspots may actually affect the technology of an economy (see, Mirowski 1984), and may not be themselves stochastic (see, Weiss 1985). There is a large and growing literature on sunspots. A very incomplete list of references includes: Azariadis (1981), Azariadis and Guesnerie (1986), Cass and Shell (1983), and Farmer and Woodford (1984). Woodford (1986b) presents an example in which agents employ a simple learning rule and the economy converges to a perfect-foresight sunspot equilibrium.

Just as worrying as indeterminacy of equilibria is the possibility that an economy may have no equilibrium that converges to a steady state. If the path followed by equilibrium prices is chaotic or periodic of a very long length, the perfect-foresight hypothesis is unattractive for a different reason: it requires too much computational power of the agents of the model. Any theory of expectations formation that is designed to cope with the problem of indeterminacy of equilibrium must also be able to relax the requirement of perfect foresight when equilibrium price dynamics are chaotic or periodic of very long length. Unfortunately, as Benhabib and Nishimura (1985) and Boldrin and Montrucchio (1986) have shown, even the model with a finite number of infinitely lived agents can have equilibria that exhibit periodic or chaotic dynamics.

The above analysis of intertemporal general equilibrium models has provided us with a clear understanding of why Pareto inefficiency and outisde money occur in the overlapping generations model but not in the model with a finite number of infinitely lived consumers. It is also clear how these properties manifest themselves in a truncated version of the model. Although we have attained some understanding of the possibility of indeterminacy, we are still faced with the dilemma that indeterminacy is symptomatic of an incompleteness of the model. What is needed is a serious theory of expectations formation.

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