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WORKING PAPER NO. 277

ON THE INDETERMINACY OF DETERMINACY AND INDETERMINACY

ANDREAS BEYER,
ROGER E. A. FARMER

SEPTEMBER 2003

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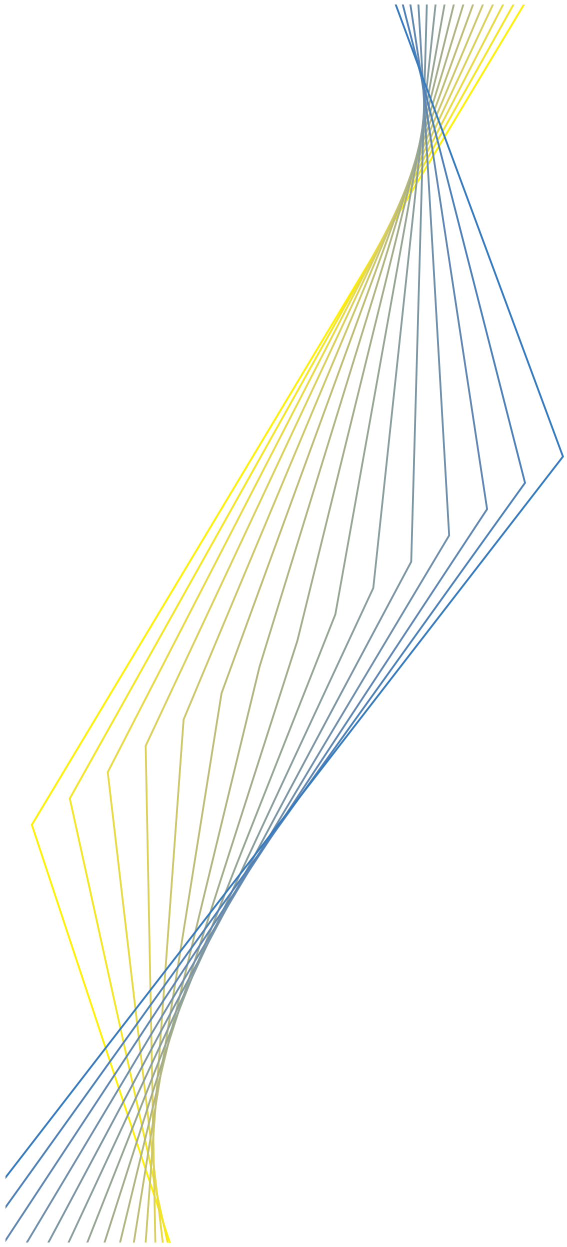

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ON THE INDETERMINACY OF DETERMINACY AND INDETERMINACY[1]

ANDREAS BEYER[2],
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SEPTEMBER 2003

1 This note has benefitted from conversations with Harold Cole, Thomas Lubik, Lee Ohanian and Frank Schorfheide. The authors wish to thank two anonymous referees for the ECB working paper series for helpful suggestions. This note was completed in the summer of 2003 while Farmer was visiting the Directorate General Research as part of the European Central Bank's Visitor Programme. He wishes to thank members of DG-Research for their hospitality. The views expressed in this note are those of the authors and do not necessarily represent those of the ECB. This paper can be downloaded without charge from http://www.ecb.int or from the Social Science Research Network electronic library at http://ssrn.com/abstract_id=487417.
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ISSN 1561-0810 (print)

ISSN 1725-2806 (online)

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Abstract

A number of authors have attempted to test whether the U.S. economy is in a determinate or an indeterminate equilibrium. We argue that to answer this question, one must impose a priori restrictions on lag length that cannot be tested. We provide examples of two economic models. Model 1 displays an indeterminate equilibrium, driven by sunspots. Model 2 displays a determinate equilibrium driven by fundamentals. Given assumptions about the shock distribution of model 2, it is possible to find a distribution of sunspot shocks that drive model 1 such that the two models are observationally equivalent.

JEL-Classification: C39, C62, D51

Key-words: Identification, indeterminacy.

Non Technical Summary

The equilibrium of a rational expectations model is determinate if it is locally unique; it is indeterminate if many other equilibria are arbitrarily close to the first. If equilibria are indeterminate, non-fundamental shocks may contribute to the variance of economic fluctuations and, if agents are risk averse, these fluctuations will reduce welfare. In the recent literature researchers have attempted to test empirically whether the U.S. economy is in a determinate or an indeterminate equilibrium. We argue that to answer this question, one must impose a priori restrictions on lag length that cannot be tested. In this note we point out, by means of a simple example, that it is not possible to decide whether real world data is generated by a determinate or an indeterminate process. We construct two models that generate the same likelihood function and hence are observationally equivalent. One model displays an indeterminate equilibrium driven purely by non-fundamental (sunspot) shocks. The other model displays a determinate equilibrium driven purely by fundamental shocks. Our result is discouraging for the possibility of distinguishing between good and bad economic policies since it implies that, at a very fundamental level, determinate and indeterminate models cannot be disentangled.

1 Introduction

The equilibrium of a rational expectations model is determinate if it is locally unique; it is indeterminate if many other equilibria are arbitrarily close to the first. If equilibria are indeterminate, non-fundamental shocks may contribute to the variance of economic fluctuations and, if agents are risk averse, these fluctuations will reduce welfare. Hence, it is of some importance to a policy maker to ensure that his actions do not induce indeterminacy.

In an influential article, Clarida Gali and Gertler [5] have argued that U.S. monetary policy led to an indeterminate equilibrium in the period from 1950 through 1979 and to a determinate equilibrium in the period since 1980. Their work has been criticized by Lubik and Schorfheide [9] who point out that determinacy is a property of a system that cannot be established using single equation methods. Lubik and Schorfheide write down a fully specified rational expectations model based on a representative agent economy. Using a Bayesian approach, they specify a prior probability distribution over parameters that places equal weight on determinate and indeterminate regions of the parameter space. Using data for the U.S. economy on the output gap, the interest rate and the inflation rate, they compute posterior odds ratios for these regions and are able to strongly confirm Clarida-Gali-Gertler's findings.

In this note we point out, by means of a simple example, that it is not possible to decide whether real world data is generated by a determinate or an indeterminate process. We construct two models that generate the same likelihood function and hence are observationally equivalent. Model 1 displays an indeterminate equilibrium driven purely by non-fundamental (sunspot) shocks. Model 2 displays a determinate equilibrium driven purely by fundamental shocks.

2 Placing our Work in Context

The possibility that the equilibria of infinite horizon monetary economies may be indeterminate has been recognized at least since the 1970's. More recently, attention has been drawn to indeterminacy in real economies: Benhabib and Farmer [1] provide a simple version of a real business cycle model with increasing returns-to-scale that displays indeterminate equilibria and Farmer and Guo [3] calibrate this model and simulate data that mimics the properties of a real business cycle model. Two papers by Kamihigashi [8] and Cole and Ohanian [6] point to an observational equivalence between sunspot and non-sunspot models but there has been very little work, that we are aware of, on the econometrics of this issue. Farmer and Guo [4] is the first paper we know of that attempts to test for indeterminacy in a fully specified econometric model. Pesaran [10] points out in his 1987 book that restrictions on lag-length will play an important role in deciding the issue of indeterminacy in linear rational expectations models although the consequences of this point for policy analysis do not seem to have been widely recognized. Both Farmer and Guo [4] and Lubik and Schorfheide [9] rely on a priori restrictions of this kind.

3 Two Equivalent Models

This section constructs an example to illustrate our main point. We write down two single equation models that govern the behavior of a scalar variable, p_t. In Model 1, p_t depends only on its own future expectation and we choose parameters such that the model has an indeterminate equilibrium that is driven by non-fundamental noise. For simplicity, we assume that there is no fundamental uncertainty in this economy, although the example could easily be complicated to allow for this possibility. In Model 2 p_t depends on its own expected future values and it also depends on p_{t-1}: we choose parameters to ensure that there is a unique rational expectations equilibrium.

3.1 Model 1

This model has a single structural equation that takes the form;

$$p_t = aE_t[p_{t+1}], \tag{1}$$

and we impose the parameter restriction, $|a| > 0$. We write the system as a first order matrix difference equation in the two endogenous variables p_t and $E_t[p_{t+1}]$

$$\overset{A}{\begin{bmatrix} 1 & -a \\ 1 & 0 \end{bmatrix}} \overset{Y_t}{\begin{bmatrix} p_t \\ E_t\left[p_{t+1}\right] \end{bmatrix}} = \overset{B}{\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}} \overset{Y_{t-1}}{\begin{bmatrix} p_{t-1} \\ E_{t-1}\left[p_t\right] \end{bmatrix}} + \overset{\Psi_w}{\begin{bmatrix} 0 \\ 1 \end{bmatrix}} w_t. \tag{2}$$

We call Equation (2) the *companion form* of the system. It contains a non-fundamental error, w_t which is defined in the second row of Equation (2) to be the difference between p_t and its date $t-1$ expectation. In a determinate rational expectations model this non-fundamental shock would be endogenously determined as a function of the fundamental shocks to the system in a way that removes the influence of any explosive root. In the case of indeterminate equilibria there are not enough explosive roots to uniquely determine the endogenous variables of the model. This is the case in our example, since we make the assumption $|a| > 0$. In our example there are no fundamental shocks and w_t represents an independent non-fundamental shock.

In general, the *reduced form* of the system is found by solving the companion form explicitly and eliminating the influence of the unstable roots. In our example the matrix A is invertible and one can compute the roots of

$A^{-1}B$ by hand:[1] They are equal to 0 and λ where $\lambda \equiv a^{-1}$. The reduced form is given by the expression

$$\begin{bmatrix} p_t \\ E_t[p_{t+1}] \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & \lambda \end{bmatrix} \begin{bmatrix} p_{t-1} \\ E_{t-1}[p_t] \end{bmatrix} + \begin{bmatrix} 1 \\ \lambda \end{bmatrix} w_t. \tag{3}$$

Rewriting this equation we obtain the following expressions for p_t and $E_t[p_{t+1}]$ as functions of the observable variable p_{t-1} and the sunspot shock w_t

$$p_t = \lambda p_{t-1} + w_t, \tag{4}$$

$$E_t[p_{t+1}] = \lambda^2 p_{t-1} + \lambda w_t. \tag{5}$$

3.2 Model 2

For the case of Model 2 we assume again that there is a single structural equation given by the expression

$$p_t = aE_t[p_{t+1}] + bp_{t-1} + v_t. \tag{6}$$

Equation (6) differs from (1) in three respects. First, the lagged state variable p_{t-1} enters the equation, second, there is a fundamental shock, v_t and third, we choose a and b such that the equilibrium of the model is determinate.

The companion form of Equation (6) is represented below,

$$\overbrace{\begin{bmatrix} 1 & -a \\ 1 & 0 \end{bmatrix}}^{A} \overbrace{\begin{bmatrix} p_t \\ E_t[p_{t+1}] \end{bmatrix}}^{Y_t} = \overbrace{\begin{bmatrix} b & 0 \\ 0 & 1 \end{bmatrix}}^{B} \overbrace{\begin{bmatrix} p_{t-1} \\ E_{t-1}[p_t] \end{bmatrix}}^{Y_{t-1}} + \overbrace{\begin{bmatrix} 1 \\ 0 \end{bmatrix}}^{\Psi_v} v_t + \overbrace{\begin{bmatrix} 0 \\ 1 \end{bmatrix}}^{\Psi_w} w_t. \tag{7}$$

Model 2 has two shocks; v_t is a fundamental shock and w_t is a non-fundamental shock. w_t is defined in the second row of Equation (7) to be the difference

[1] Chris Sims [7] provides code in matlab to compute the reduced form of a linear model of this kind in which the dimension of the system is arbitrary and the matrices A and B may be singular.

between p_t and its date $t-1$ expectation. Since we choose parameters such that there is a unique equilibrium, the non-fundamental shock w_t will be determined endogenously as a function of v_t.

Premultiplying equation (7) by A^{-1} leads to the expression,

$$\left[\begin{array}{c} p_t \\ E_t\left[p_{t+1}\right] \end{array}\right]=\left[\begin{array}{cc} 0 & 1 \\ -\frac{b}{a} & \frac{1}{a} \end{array}\right]\left[\begin{array}{c} p_{t-1} \\ E_{t-1}\left[p_t\right] \end{array}\right]+\left[\begin{array}{c} 0 \\ -\frac{1}{a} \end{array}\right] v_t+\left[\begin{array}{c} 1 \\ \frac{1}{a} \end{array}\right] w_t. \quad (8)$$

It is convenient for the following analysis to reparameterize the model in terms of the two roots of

$$A^{-1}B=\left[\begin{array}{cc} 0 & 1 \\ -\frac{b}{a} & \frac{1}{a} \end{array}\right]$$

which we call θ and λ. The parameters a and b are given by the expressions, $a=1/\left(\theta+\lambda\right)$ and $b=\lambda\theta/\left(\theta+\lambda\right)$. If the equilibrium is unique, there must be one unstable root that allows one to pin down the non-predetermined variable $E_t\left[p_{t+1}\right]$ as a function of the lagged state variable p_{t-1} and the fundamental shock v_t. Without loss of generality we assume that θ is the unstable root such that

$$|\theta|>1, \quad |\lambda|<1.$$

In Appendix A we show how to solve explicitly for the reduced form, which can be written as follows:

$$\begin{aligned} p_t &= \lambda p_{t-1}+\frac{\left(\lambda+\theta\right)}{\theta} v_t, && (9) \\ E_t\left[p_{t+1}\right] &= \lambda^2 p_{t-1}+\frac{\lambda\left(\lambda+\theta\right)}{\theta} v_t. && (10) \end{aligned}$$

4 Models 1 and 2 Compared

The reduced form of Model 2 is given by Equations (9) and (10). Recall that the reduced form for Model 1 is given by Equations (4) and (5) which we repeat below;

$$p_t = \lambda p_{t-1} + w_t, \tag{11}$$

$$E_t[p_{t+1}] = \lambda^2 p_{t-1} + \lambda w_t. \tag{12}$$

An econometrician who observes p_t can consistently estimate λ and the variance of the error term; but in the absence of independent information on the true variance of w_t or v_t there is no way to distinguish w_t from $((\lambda + \theta)/\theta) v_t$. Suppose that Model 2 is the data-generating process and that v_t has distribution D_v with mean 0 and standard deviation σ_v. Then there exists a sunspot error with distribution D_w and standard deviation σ_w, where

$$\sigma_w = \frac{(\lambda + \theta)}{\theta}\sigma_v$$

such that the likelihood functions of models 1 and 2 are identical. If D_v is normal (as is often assumed) then D_w is also normal. We have provided an example of a determinate model and an indeterminate model that are observationally equivalent.

5 Conclusion

There is no reason to think that our example is special and in current research [2] we are exploring more general examples with multiple equations that are derived from structural models that are widely used in the literature. Our result is discouraging for the possibility of distinguishing between good and bad economic policies since it implies that, at a very fundamental level, determinate and indeterminate models cannot be disentangled.

If our result is correct then how are Lubik and Schorfheide able to distinguish determinate and indeterminate regions of the parameter space in U.S. data? We think that their result hinges on prior restrictions over lag length that exclude certain models from consideration. To see how this might work, suppose that a Bayesian were to be confronted with data generated by Model 2 in which the equilibrium was determinate. Let the Bayesian choose a prior probability distribution over parameters that places zero weight on the possibility that $b \neq 0$, hence, no amount of evidence will allow him to revise this prior in favor of a model with $b \neq 0$. This individual would conclude, incorrectly, that the data was generated by Model 1 with an indeterminate equilibrium. As Pesaran pointed out in his 1987 book, [10], prior restrictions on lag length are likely to be extremely important in deciding between determinate and indeterminate models.

Appendix

This Appendix shows how to solve Model 2 in terms of the roots λ and θ. The reduced form of this model is given by the expression

$$\begin{aligned}\begin{bmatrix} p_t \\ E_t\left[p_{t+1}\right] \end{bmatrix} &= \overset{A^{-1}}{\begin{bmatrix} 1 & -a \\ 1 & 0 \end{bmatrix}^{-1}} \overset{B}{\begin{bmatrix} b & 0 \\ 0 & 1 \end{bmatrix}} \begin{bmatrix} p_{t-1} \\ E_{t-1}\left[p_t\right] \end{bmatrix} \\ &+ \overset{A^{-1}}{\begin{bmatrix} 1 & -a \\ 1 & 0 \end{bmatrix}^{-1}} \begin{bmatrix} 1 \\ 0 \end{bmatrix} v_t \\ &+ \overset{A^{-1}}{\begin{bmatrix} 1 & -a \\ 1 & 0 \end{bmatrix}^{-1}} \begin{bmatrix} 0 \\ 1 \end{bmatrix} w_t \end{aligned} \tag{A1}$$

where

$$\overset{A^{-1}}{\begin{bmatrix} 1 & -a \\ 1 & 0 \end{bmatrix}} \overset{B}{\begin{bmatrix} b & 0 \\ 0 & 1 \end{bmatrix}} = \begin{bmatrix} 0 & 1 \\ -\frac{1}{a} & \frac{1}{a} \end{bmatrix} \begin{bmatrix} b & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{b}{a} & \frac{1}{a} \end{bmatrix}.$$

Since this is a two-parameter model we can completely characterize the system in terms of the two roots, λ and θ. The characteristic polynomial of $A^{-1}B$ is given by

$$F^2 - \frac{1}{a}F + \frac{b}{a} = 0, \tag{A2}$$

and the roots λ and θ are related to the parameters a and b by the equations,

$$\begin{aligned} \theta + \lambda &= \frac{1}{a}, \\ \theta\lambda &= \frac{b}{a}, \end{aligned}$$

from which it follows that

$$a = \frac{1}{\lambda + \theta} \text{ and } b = \frac{\lambda\theta}{\lambda + \theta}.$$

We can rewrite the matrix $A^{-1}B$ in terms of λ and θ as;

$$A^{-1}B = \begin{bmatrix} 0 & 1 \\ -(\lambda+\theta) & \lambda+\theta \end{bmatrix} \begin{bmatrix} \frac{\lambda\theta}{\lambda+\theta} & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\theta\lambda & \lambda+\theta \end{bmatrix}.$$

The eigenvectors of $A^{-1}B$ associated with the roots λ and θ are given by the expressions

$$\theta \longrightarrow \begin{bmatrix} 1 \\ \theta \end{bmatrix} \quad \text{and} \quad \lambda \to \begin{bmatrix} 1 \\ \lambda \end{bmatrix},$$

and hence $A^{-1}B$ can be diagonalized as

$$A^{-1}B = Q\Lambda Q^{-1} = \overset{Q}{\begin{bmatrix} 1 & 1 \\ \theta & \lambda \end{bmatrix}} \overset{\Lambda}{\begin{bmatrix} \theta & 0 \\ 0 & \lambda \end{bmatrix}} \overset{Q^{-1}}{\begin{bmatrix} \frac{\lambda}{\lambda-\theta} & \frac{-1}{\lambda-\theta} \\ \frac{-\theta}{\lambda-\theta} & \frac{1}{\lambda-\theta} \end{bmatrix}},$$

where the columns of Q are eigenvectors.

We now write the system as a pair of scalar equations by introducing the following definitions:

$$Z_t = \begin{bmatrix} z_{1t} \\ z_{2t} \end{bmatrix} = Q^{-1} \begin{bmatrix} p_t \\ E_t\left[p_{t+1}\right] \end{bmatrix},$$

$$\xi_t = \begin{bmatrix} \xi_{1t} \\ \xi_{2t} \end{bmatrix} = Q^{-1}A^{-1} \begin{bmatrix} 1 \\ 0 \end{bmatrix} v_t,$$

$$\eta_t = \begin{bmatrix} \eta_{1t} \\ \eta_{2t} \end{bmatrix} = Q^{-1}A^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} w_t.$$

Using the definitions of Q^{-1}, A^{-1} and $Q^{-1}A^{-1}$,

$$
\begin{aligned}
Q^{-1} &= \begin{bmatrix} \frac{\lambda}{\lambda-\theta} & \frac{-1}{\lambda-\theta} \\ \frac{-\theta}{\lambda-\theta} & \frac{1}{\lambda-\theta} \end{bmatrix}, \\
A^{-1} &= \begin{bmatrix} 0 & 1 \\ -(\lambda+\theta) & (\lambda+\theta) \end{bmatrix}, \\
Q^{-1}A^{-1} &= \begin{bmatrix} \frac{\lambda+\theta}{\lambda-\theta} & \frac{-\theta}{\lambda-\theta} \\ -\frac{\lambda+\theta}{\lambda-\theta} & \frac{\lambda}{\lambda-\theta} \end{bmatrix},
\end{aligned}
$$

we can write the expressions for $z_{1t}, z_{2t}, \xi_{1t}, \xi_{2t}, \eta_{1t}$ and η_{2t} in terms of the parameters θ and λ:

$$
\left.
\begin{aligned}
z_{1t} &= \tfrac{\lambda}{\lambda-\theta}p_t - \tfrac{1}{\lambda-\theta}E_t\left[p_{t+1}\right], \\
z_{2t} &= \tfrac{-\theta}{\lambda-\theta}p_t + \tfrac{1}{\lambda-\theta}E_t\left[p_{t+1}\right], \\
\xi_{1t} &= \tfrac{\lambda+\theta}{\lambda-\theta}v_t, \\
\xi_{2t} &= -\tfrac{\lambda+\theta}{\lambda-\theta}v_t, \\
\eta_{1t} &= \tfrac{-\theta}{\lambda-\theta}w_t, \\
\eta_{2t} &= \tfrac{\lambda}{\lambda-\theta}w_t.
\end{aligned}
\right\} \tag{A3}
$$

Using these definitions, the system can be decomposed into the following pair of scalar difference equations:

$$z_{1t} = \theta z_{1t-1} + \xi_{1t} + \eta_{1t}, \tag{A4}$$

$$z_{2t} = \lambda z_{2t-1} + \xi_{2t} + \eta_{2t}. \tag{A5}$$

Since $\theta > 1$, we must set

$$z_{1t} = \theta z_{1t-1} = 0,$$

to eliminate the influence of the explosive root. It follows from (A4) that

$$\xi_{1t} + \eta_{1t} = 0, \tag{A6}$$

i.e. the sum of fundamental and non-fundamental errors must add up to zero. >From (A3) it also follows that

$$\frac{\lambda}{\lambda-\theta}p_t - \frac{1}{\lambda-\theta}E_t\left[p_{t+1}\right] = 0,$$

and hence

$$E_t\left[p_{t+1}\right] = \lambda p_t. \tag{A7}$$

Using (A7) and the definition of z_{2t} from (A3) yields

$$z_{2t} = p_t, \tag{A8}$$

and using the expression (A6) and the definitions of η_{1t} and ξ_{1t} from (A3) it follows that

$$w_t = \frac{\theta+\lambda}{\theta}v_t. \tag{A9}$$

Finally, substituting (A8) in (A5) and eliminating ξ_{2t} and η_{2t} using (A3) and (A9) yields the following reduced form expression for p_t

$$p_t = \lambda p_{t-1} - \left(\frac{\lambda+\theta}{\lambda-\theta}\right)v_t + \left(\frac{\lambda}{\lambda-\theta}\right)\left(\frac{\theta+\lambda}{\theta}\right)v_t,$$

which simplifies to give

$$p_t = \lambda p_{t-1} + \left(\frac{\theta+\lambda}{\theta}\right)v_t.$$

Finally, from (A7),

$$E_t\left[p_{t+1}\right] = \lambda^2 p_{t-1} + \lambda\left(\frac{\theta+\lambda}{\theta}\right)v_t.$$

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