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ON THE INDETERMINACY OF DETERMINACY AND INDETERMINACY

ANDREAS BEYER2,
ROGER E. A. FARMER3
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2 European Central Bank, Postfach 16 03 19, D-60066, Frankfurt am Main, Andreas.Beyer@ecb.int

3 UCLA, Dept. of Economics, 8283 Bunche Hall, Box 951477, Los Angeles, CA 90095-1477, rfarmer@econ.ucla.edu
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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.

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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:

$$p_t = aE_t[p_{t+1}], \quad (1)$$

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 $E_t[p_{t+1}]$

$$
\begin{bmatrix}
A \\
B
\end{bmatrix}
\begin{bmatrix}
Y_t \\
E_t[p_{t+1}]
\end{bmatrix} = 
\begin{bmatrix}
B \\
A
\end{bmatrix}
\begin{bmatrix}
Y_{t-1} \\
E_{t-1}[p_t]
\end{bmatrix} + \begin{bmatrix}
\psi_w \\
0
\end{bmatrix} w_t. \quad (2)
$$

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 \( \lambda \) 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

\[
p_t = a E_t[p_{t+1}] + b p_{t-1} + v_t. \tag{6}
\]

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,

\[
\begin{bmatrix}
    1 & -a \\
    1 & 0
\end{bmatrix} \begin{bmatrix}
    Y_t \\
    p_t
\end{bmatrix} = \begin{bmatrix}
    B \\
    0
\end{bmatrix} \begin{bmatrix}
    Y_{t-1} \\
    p_{t-1}
\end{bmatrix} + \begin{bmatrix}
    1 \\
    0
\end{bmatrix} v_t + \begin{bmatrix}
    0 \\
    1
\end{bmatrix} w_t. \tag{7}
\]

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,

$$
\begin{bmatrix}
  p_t \\
  E_t [p_{t+1}]
\end{bmatrix} =
\begin{bmatrix}
  0 & 1 \\
  -\frac{b}{a} & \frac{1}{a}
\end{bmatrix}
\begin{bmatrix}
  p_{t-1} \\
  E_{t-1} [p_t]
\end{bmatrix} +
\begin{bmatrix}
  0 \\
  -\frac{1}{a}
\end{bmatrix} v_t +
\begin{bmatrix}
  1
\end{bmatrix} w_t.
\tag{8}
$$

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

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

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

$$
p_t = \lambda p_{t-1} + \frac{\lambda + \theta}{\theta} v_t,
\tag{9}
$$

$$
E_t [p_{t+1}] = \lambda^2 p_{t-1} + \frac{\lambda (\lambda + \theta)}{\theta} v_t.
\tag{10}
$$
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;

\[ p_t = \lambda p_{t-1} + w_t, \]  
\[ E_t[p_{t+1}] = \lambda^2 p_{t-1} + \lambda w_t. \]  

An econometrician who observes \( p_t \) can consistently estimate \( \lambda \) 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 \( \sigma_v \). Then there exists a sunspot error with distribution \( D_w \) and standard deviation \( \sigma_w \), 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 $\lambda$ and $\theta$. The reduced form of this model is given by the expression

$$
\begin{bmatrix}
    p_t \\
    E_t[p_{t+1}]
\end{bmatrix}
= 
A^{-1}
\begin{bmatrix}
    1 & -a \\
    1 & 0
\end{bmatrix}
B
\begin{bmatrix}
    p_{t-1} \\
    E_{t-1}[p_t]
\end{bmatrix}
+ 
A^{-1}
\begin{bmatrix}
    1 & -a \\
    1 & 0
\end{bmatrix}
^{-1}
\begin{bmatrix}
    1 \\
    0
\end{bmatrix} v_t
+ 
A^{-1}
\begin{bmatrix}
    1 & -a \\
    1 & 0
\end{bmatrix}
^{-1}
\begin{bmatrix}
    0 \\
    1
\end{bmatrix} w_t
$$

(A1)

where

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

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

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

(A2)

and the roots $\lambda$ and $\theta$ are related to the parameters $a$ and $b$ by the equations,

$$
\theta + \lambda = \frac{1}{a},
$$

$$
\theta \lambda = \frac{b}{a},
$$

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 $\lambda$ and $\theta$ as:

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

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

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

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

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

where the columns of $Q$ are eigenvectors.

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

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

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

$$\eta_t = \begin{bmatrix} \eta_{1t} \\ \eta_{2t} \end{bmatrix} = Q^{-1} A^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} w_t.$$
Using the definitions of $Q^{-1}$, $A^{-1}$ and $Q^{-1}A^{-1}$,

\[
Q^{-1} = \begin{bmatrix}
\frac{\lambda}{\lambda - \theta} & -\frac{1}{\lambda - \theta} \\
\frac{-\theta}{\lambda - \theta} & \frac{1}{\lambda - \theta}
\end{bmatrix},
\]

\[
A^{-1} = \begin{bmatrix}
0 & 1 \\
-(\lambda + \theta) & (\lambda + \theta)
\end{bmatrix},
\]

\[
Q^{-1}A^{-1} = \begin{bmatrix}
\frac{\lambda+\theta}{\lambda - \theta} & -\frac{\theta}{\lambda - \theta} \\
\frac{-\lambda+\theta}{\lambda - \theta} & \frac{\lambda}{\lambda - \theta}
\end{bmatrix},
\]

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

\[
\begin{aligned}
z_{1t} &= \frac{\lambda}{\lambda - \theta} \nu_t - \frac{1}{\lambda - \theta} \mathbb{E}_t [p_{t+1}], \\
z_{2t} &= \frac{-\theta}{\lambda - \theta} \nu_t + \frac{1}{\lambda - \theta} \mathbb{E}_t [p_{t+1}], \\
\xi_{1t} &= \frac{\lambda+\theta}{\lambda - \theta} \nu_t, \\
\xi_{2t} &= -\frac{\lambda+\theta}{\lambda - \theta} \nu_t, \\
\eta_{1t} &= \frac{-\theta}{\lambda - \theta} \nu_t, \\
\eta_{2t} &= \frac{\lambda}{\lambda - \theta} \nu_t.
\end{aligned}
\]  \hspace{1cm} (A3)

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

\[
\begin{aligned}
z_{1t} &= \theta z_{1t-1} + \xi_{1t} + \eta_{1t}, \\
z_{2t} &= \lambda z_{2t-1} + \xi_{2t} + \eta_{2t}.
\end{aligned}
\]  \hspace{1cm} (A4) (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

\[
\xi_{1t} + \eta_{1t} = 0, \hspace{1cm} (A6)
\]
i.e. the sum of fundamental and non-fundamental errors must add up to zero. From (A3) it also follows that

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

and hence

\[ E_t [p_{t+1}] = \lambda p_t. \]  \hspace{1cm} (A7)

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

\[ z_{2t} = p_t, \]  \hspace{1cm} (A8)

and using the expression (A6) and the definitions of \( \eta_{1t} \) and \( \xi_{1t} \) from (A3) it follows that

\[ w_t = \frac{\theta + \lambda}{\theta} v_t. \]  \hspace{1cm} (A9)

Finally, substituting (A8) in (A5) and eliminating \( \xi_{2t} \) and \( \eta_{2t} \) 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),

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