

## Evolution and Intelligent Design<sup>†</sup>

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*The introduction of the precious metals for the purposes of money may with truth be considered as one of the most important steps towards the improvement of commerce, and the arts of civilised life; but it is no less true that, with the advancement of knowledge and science, we discover that it would be another improvement to banish them again from the employment to which, during a less enlightened period, they had been so advantageously applied.*

— David Ricardo (1816)

This essay is about some ideas and experiences that shaped Ricardo's proposal to banish precious metals as money, and other ideas that emerged from the struggles of academic economists and policymakers to implement and refine what they had learned from Ricardo. I focus on two sources of prevailing ideas in macroeconomics. One is a collection of powerful theoretical results and empirical methods described in Sections I, II, and III, which apply the rational expectations equilibrium concept to estimate models and design optimal macroeconomic policies intelligently. The other is an adaptive evolutionary process, modelled in Section IV and illustrated both in Section V, about ideas and events that influenced Ricardo, and in Section VI, about struggles of the US monetary authorities in the 1970s to realize the promise for improvement held out by Ricardo.

The rational expectations equilibrium concept equates all subjective distributions with an objective distribution. By equating subjective distributions for endogenous variables to an equilibrium distribution implied by a model, the rational expectations hypothesis makes agents' beliefs disappear as extra components of a theory, and sets up the powerful theoretical results and intelligent policy design exercises described in Section I. Section II describes theoretical and practical reasons for equating subjective distributions to an objective one and how it facilitates the rational expectations econometrics described in Section III.

The assumption that agents share common beliefs underpins influential doctrines about whether inflation-unemployment dynamics can be exploited by policymakers, the time inconsistency of benevolent government policy, the capacity of reputation to substitute for commitment, the incentives for one type of policymaker to emulate another, and the wisdom of making information public. The common beliefs assumption is especially stressed in those modern theories of optimal macroeconomic policy that focus on how a benevolent government shapes expectations optimally. This intelligent design approach to macroeconomic policy perfects an older econometric policy evaluation method that Robert E. Lucas, Jr. (1976) criticized because it imputed

<sup>†</sup> Presidential Address delivered at the one-hundred twentieth meeting of the American Economic Association, January 5, 2008, New Orleans, LA.

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different beliefs to the government and other agents. Intelligent design is normative (“what should be”) economics, but when it influences policymakers, it becomes positive (“what is”) economics. Some researchers in the intelligent design tradition ignore the distinction between positive and normative economics. Thus, Robert J. Barro (1979), Lucas and Nancy L. Stokey (1983), and S. Rao Aiyagari et al. (2002) use normative theories to understand observed time series properties of government debt and taxes. It is also true that some policy advisors have enough faith that evolution produces good outcomes to recommend copying best practices (for example, see John Maynard Keynes 1913). If only good things survive the tests of time and practice, evolution produces intelligent design.

Theories of out-of-equilibrium learning tell us not always to expect that. An observational equivalence possibility that emerges from the rational expectations econometrics of Section III sets the stage for Section IV, which describes how a system of adaptive agents converges to a self-confirming equilibrium in which all agents have correct forecasting distributions for events observed often along an equilibrium path, but possibly incorrect views about events that are rarely observed. This matters because intelligent design of rational expectations equilibria hinges on the government’s expectations about events that will not be observed. Self-confirming equilibria allow wrong models that match historical data to survive and to influence policy. Section V mentions examples from a millennium of monetary history that culminated in the ideas expressed by Ricardo. To tell stories about the emergence of US inflation in the 1970s and its conquest under Volcker and Greenspan, Section VI uses adaptive models in which the government solves intelligent design problems with probability models that are misspecified, either permanently or temporarily. While these stories differ in many interesting details, they all suggest that choices of the monetary authorities were affected by misunderstandings that do not occur within a rational expectations equilibrium.<sup>1</sup> These “misspecification stories” also provide a backhanded defense for inflation targeting.

### I. Intelligent Design with Common Beliefs

What I call intelligent design is to solve a Pareto problem for a model in which every agent inside the model optimizes in light of information and incentive constraints and a common probability model. Intelligent design is a coherent response to Lucas’s (1976) indictment of pre-rational expectations macroeconomic policy design procedures. Lucas rejected those procedures because they incorporated private agents’ decision rules that were not best responses to government policy under the equilibrium probability measure. The cross-equation restrictions imposed by a common belief assumption fix that problem.

Let  $f$  denote a probability density and  $\mathbf{x}'$  a history  $\mathbf{x}_t, \mathbf{x}_{t-1}, \dots, \mathbf{x}_0$ . Partition  $\mathbf{x}_t = [\mathbf{y}_t, \mathbf{v}_t]'$ , where  $\mathbf{v}_t$  is a vector of decisions taken by a government and  $\mathbf{y}_t$  is a vector of all other variables. Let  $f(\mathbf{y}^\infty, \mathbf{v}^\infty | \boldsymbol{\rho})$  be a joint density conditional on a parameter vector  $\boldsymbol{\rho} \in \Omega_\rho$ . Government chooses a sequence  $h$  of functions

$$(1) \quad \mathbf{v}_t = h_t(\mathbf{x}^t | \boldsymbol{\rho}), \quad t \geq 0,$$

to maximize a Pareto criterion that can be expressed as expected utility under density  $f(\mathbf{x}^\infty | \boldsymbol{\rho})$ :

$$(2) \quad \int U(\mathbf{y}^\infty, \mathbf{v}^\infty | \boldsymbol{\rho}) f(\mathbf{y}^\infty, \mathbf{v}^\infty | \boldsymbol{\rho}) d(\mathbf{y}^\infty, \mathbf{v}^\infty).$$

<sup>1</sup> These adaptive models make room for a “law of unintended consequences” cited by Milton Friedman (1992) that is excluded from rational expectations equilibria.

Intelligent design in macroeconomics solves government programming problems (item b below) with models  $f$  that impute common beliefs and best responses to all of the agents who inhabit the model. The common beliefs assumption makes parameters describing agents' beliefs about endogenous variables disappear from  $\rho$ .

The common beliefs assumption underlies a long list of useful results in modern macroeconomics. The following four have especially influenced thinking within central banks.

- a) *Expected versus unexpected government actions.* Lucas (1972b) drew a sharp distinction between the effects of foreseen and unforeseen monetary and fiscal policy actions when the government and the public share a probability model. That idea defines the terms in which central bankers now think about shocks and systematic policies.
- b) *Optimal fiscal and monetary policy cast as Ramsey and mechanism design problems.* A literature summarized and extended by Robert G. King and Alexander L. Wolman (1996), Richard Clarida, Jordi Galí, and Mark Gertler (1999), and Michael D. Woodford (2003) uses dynamic macroeconomic models with sticky prices to design monetary policy rules by finding practical ways to represent and implement solutions of Ramsey plans like equation (2). New dynamic models of public finance refine Ramsey plans by focusing on a trade-off between efficiency and incentives that emerges from the assumption that each individual privately observes his own skills and effort, a feature that imposes constraints on the allocations that a planner can implement relative to ones he could achieve if he had more information.<sup>2</sup>
- c) *Time inconsistency.* The availability of the rational expectations equilibrium concept enabled Finn E. Kydland and Edward C. Prescott (1977) and Guillermo A. Calvo (1978) to explain how alternative timing protocols affect a benevolent government's capacity to manipulate and its incentives to confirm prior expectations about its actions.<sup>3</sup> The time inconsistency "problem" is the observation that equilibrium outcomes in a representative-agent economy depend on the timing protocol for decision making that nature or the modeler imposes. Better outcomes emerge if a government chooses a history-contingent plan once and for all at time 0 than if it were allowed to choose sequentially. By choosing future actions at time 0, the government can take into account how expectations about its actions at times  $t > 0$  influence private agents' actions at all dates between 0 and  $t$ . A government must ignore those beneficial expectations effects if it is forced to choose sequentially.
- d) *Reputation can substitute for commitment.* Under rational expectations, a government strategy plays two roles, first, as a *decision rule*, and, second, as a *system of private sector*

<sup>2</sup> See for example Mikhail Golosov, Narayana Kocherlakota, and Aleh Tsyvinski (2003), Kocherlakota (2005), and Golosov, Tsyvinski, and Ivan Werning (2007).

<sup>3</sup> While technical treatments of the time inconsistency problem rely heavily on the rational expectations equilibrium concept, all that is needed to spot the problem is that private agents care about future government actions. In a discussion on August 16, 1787, at the US Constitutional Convention about whether the federal government should be prohibited from issuing fiduciary currency, Gouverneur Morris, Oliver Ellsworth, and James Madison recognized a time inconsistency problem, while Edmund Randolph and George Mason raised doubts about tying the hands of the government by arguing that no one can foresee all contingencies. See Madison (1987, 470–71).

*expectations* about government actions.<sup>4,5</sup> A system of expectations is a history-dependent strategy like equation (1). A credible government policy gives a government incentives to confirm prior expectations about its future actions, actions it cannot commit to because it chooses sequentially.<sup>6</sup> There are multiple equilibrium systems of expectations that a government would want to confirm, with incentive constraints linking good and bad ones.

These theoretical rational expectations results have determined the way monetary policy is now discussed within central banks. Because central banks want to implement solutions of Ramsey problems like (b) in contexts like (a) in which the distinction between foreseen and unforeseen policy actions is important, a time inconsistency problem like (c) arises, prompting them to focus on ways like (d) to sustain good expectations.<sup>7</sup>

## II. Justifications for Equating Objective and Subjective Distributions

These and many other theoretical results hinge on the part of the rational expectations equilibrium concept that equates subjective distributions for endogenous variables to an equilibrium distribution. To gain empirical content, rational expectations models also take the logically distinct step of equating an equilibrium distribution to the data generating distribution. I shall use asset pricing theory to illustrate two justifications for that step, one based on a survival argument that says that agents with beliefs closest to the truth will eventually determine market prices, another on empirical convenience.

Many researchers have used consumer  $i$ 's Euler equation,

$$(3) \quad 1 = \beta \int \frac{u'_i(c_{i,t+1}(\mathbf{x}^{t+1}))}{u'_i(c_{i,t}(\mathbf{x}^t))} R_{j,t+1}(\mathbf{x}_{t+1}) f_i(\mathbf{x}_{t+1} | \mathbf{x}^t) d\mathbf{x}_{t+1},$$

to generate restrictions on the covariation of consumption and a one-period return  $R_{j,t+1}(\mathbf{x}_{t+1})$  on asset  $j$ . Here,  $f_i(\mathbf{x}_{t+1} | \mathbf{x}^t) \equiv f(\mathbf{x}_{t+1} | \mathbf{x}^t, \boldsymbol{\theta}_i)$  is consumer  $i$ 's subjective one-step-ahead transition density for a state vector  $\mathbf{x}_{t+1}$  that determines both returns and time  $t + 1$  consumption,  $c_{i,t+1}$ ,  $\beta$  is a discount factor common across  $i$ , and  $u'_i(c_{i,t+1}(\mathbf{x}^{t+1}))$  is consumer  $i$ 's marginal utility of consumption. Here,  $\boldsymbol{\theta}_i$  is a parameter vector indexing consumer  $i$ 's subjective density.

<sup>4</sup> The theory is silent about who chooses an equilibrium system of beliefs, the government (after all, it is the *government's* decision rule) or the public (but then again, they *are* the private sector's expectations). This ambiguity and the multiplicity of equilibria make it difficult to use this theory to formulate advice about actions that can help a government earn a good reputation. Instead, the theory is about how a government comes into a period confronting the private sector's expectations about its actions, which it chooses to confirm. Alan S. Blinder (1998, 60–62) struggles with this issue when he describes pressures on the Fed not to disappoint the market. While Blinder's discussion is phrased almost entirely within the rational expectations paradigm, the account by Ben S. Bernanke (2007) of the problems the Fed experiences in anchoring private sector expectations is not. Bernanke argues in terms of objects outside a rational expectations equilibrium.

<sup>5</sup> The theory of credible public policy seems to explain why some policymakers who surely knew about better decision rules chose to administer ones supporting bad outcomes. V. V. Chari, Lawrence J. Christiano, and Martin Eichenbaum (1998) and Stefania Albanesi, Chari, and Christinao (2002) interpret the big inflation of the 1970s and its stabilization in the 1980s in terms of the actions of benevolent and knowledgeable policymakers who were trapped by the public's expectations about what it would do.

<sup>6</sup> See the credible public policy models of Stokey (1989, 1991) and Chari and Patrick J. Kehoe (1993b, a). By making an intrinsically "forward-looking" variable, a promised discounted value for the representative household, also be a "backward-looking" state variable that encodes history, Dilip Abreu, David Pearce, and Ennio Stacchetti (1986, 1990) tie past and future together in a subtle way that exploits the common beliefs equilibrium concept. For some applications, see Roberto Chang (1998), Christopher Phelan and Stacchetti (2001), and Lars Ljungqvist and Sargent (2004, ch. 22).

<sup>7</sup> See Blinder (1998) and Bernanke et al. (2001).

### A. Complete Markets and Survival

In a finite-horizon setting, J. Michael Harrison and David M. Kreps (1979) showed that when there are complete markets, the *stochastic discount factor*

$$(4) \quad m_{t+1} = \beta \frac{u'_i(c_{i,t+1}(\mathbf{x}^{t+1}))}{u'_i(c_{i,t}(\mathbf{x}^t))} \frac{f_i(\mathbf{x}_{t+1}|\mathbf{x}^t)}{f(\mathbf{x}_{t+1}|\mathbf{x}^t)}$$

is unique. Here,  $f(\mathbf{x}_{t+1}|\mathbf{x}^t) \equiv f(\mathbf{x}_{t+1}|\mathbf{x}^t, \boldsymbol{\rho})$  is a common physical conditional density parameterized by the vector  $\boldsymbol{\rho}$ .<sup>8</sup> Because offsetting differences in marginal utility functions and probabilities can leave the left side of (4) unaltered, the uniqueness of the stochastic discount factor allows for different densities  $f_i$ . Suppose that density  $f$  actually governs outcomes. Lawrence Blume and David Easley (2006) showed that in complete markets economies with Pareto optimal allocations and an *infinite* horizon, the  $f_i(\mathbf{x}^\infty)$ 's of agents who have positive wealth in the limit merge to the density that is closest to the truth  $f(\mathbf{x}^\infty)$ .<sup>9</sup> Merging means that the densities agree about tail events.<sup>10</sup> If  $f_i(\mathbf{x}^\infty) = f(\mathbf{x}^\infty)$  for some  $i$ , then for an infinite horizon complete markets economy with a Pareto optimal allocation, this survival result implies the rational expectations assumption, provided that agents have access to an infinite history of observations at time 0.

### B. Incomplete Markets

Sanford J. Grossman and Robert J. Shiller (1981), Lars Peter Hansen and Kenneth J. Singleton (1983), and Hansen and Scott F. Richard (1987) wanted an econometric framework to apply to incomplete markets where Blume and Easley's complete markets survival argument doesn't hold true.<sup>11</sup> Hansen and Singleton (1983) and Hansen and Richard (1987) simply imposed rational expectations and made enough stationarity assumptions to validate a Law of Large Numbers that gives GMM or maximum likelihood estimators good asymptotic properties. Under the rational expectations assumption, (3) imposes testable restrictions on the empirical joint distribution of returns and either individual or aggregate consumption.

### C. An Empirical Reason to Allow for Belief Heterogeneity

Many have followed Hansen and Singleton (1983) and Hansen and Richard (1987) by imposing rational expectations, letting  $u(c) = c^{1-\gamma}/(1-\gamma)$ , and defining the stochastic discount factor as the intertemporal marginal rate of substitution

$$(5) \quad m_{t+1} = \frac{\beta \mu'(c_{t+1})}{u'(c_t)}.$$

<sup>8</sup> I allow  $f_i(\mathbf{x}^t|\boldsymbol{\theta}_i)$  and  $f(\mathbf{x}^t|\boldsymbol{\rho})$  to have different parameterizations partly to set the stage for Section IIIA and Section IV.

<sup>9</sup> Closest as measured by Kullback and Leibler's relative entropy.

<sup>10</sup> In the context of a complete markets economy with a Lucas tree, Alvaro Sandroni (2000) argued that a disagreement about tail events would present some consumers with arbitrage opportunities that cannot exist in equilibrium.

<sup>11</sup> It is empirically difficult to distinguish a diversity of beliefs that is inspired by differences among models  $f_i(\mathbf{x}^t)$  from one that is generated by different information under a common probability model. Under a common probability model but differing information sets, Grossman and Shiller (1982) obtain an aggregation of beliefs under incomplete markets in a continuous time setting with a single consumption good. When the value of a continuously and costlessly traded asset  $i$  and all individuals' consumption flows are diffusions, Grossman and Shiller show that the excess return on asset  $i$  is explained by its covariance with aggregate consumption, conditioned on any information set that is common to all investors. To get this result, Grossman and Shiller apply a law of iterated expectations with respect to a probability model that is common to all investors.

The aggregate consumption data have mistreated (5) and the Euler equation

$$(6) \quad 1 = \int m_{t+1}(\mathbf{x}^{t+1}) R_{j,t+1}(\mathbf{x}_{t+1}) f(\mathbf{x}_{t+1} | \mathbf{x}^t) d\mathbf{x}_{t+1}.$$

One reaction has been to retain the rational expectations assumption but to add backward-looking (see John Y. Campbell and John H. Cochrane 1999) or forward-looking (see Larry G. Epstein and Stanley E. Zin 1989) contributions to time  $t$  felicity. Another reaction has been to let disparate beliefs contribute to the stochastic discount factor. Hansen and Ravi Jagannathan (1991) treated the stochastic discount factor  $m_{t+1}$  as an unknown nonnegative random variable and deduced what observed returns  $R_{j,t+1}$  and restriction (6) imply about the first and second moments of admissible stochastic discount factors (with incomplete markets, there exist multiple stochastic discount factors). Their idea was that prior to specifying a particular theory about the utility function linking  $m$  to real variables like consumption, it is useful to characterize the mean and standard deviation that an empirically successful  $m$  must have. This approach leaves open the possibility that a successful theory of a stochastic discount factor will assign a role to a fluctuating probability ratio  $f_i(\mathbf{x}_{t+1} | \mathbf{x}^t) / f(\mathbf{x}_{t+1} | \mathbf{x}^t) \neq 1$ , even for an economy in which agent  $i$  is a single representative agent. The likelihood ratio  $f_i(\mathbf{x}_{t+1} | \mathbf{x}^t) / f(\mathbf{x}_{t+1} | \mathbf{x}^t)$  creates a wedge relative to the Euler equation that has usually been fit in the rational expectations macroeconomic tradition originating in Hansen and Singleton (1983) and Rajnish Mehra and Prescott (1985). Likelihood ratio wedge approaches have been investigated by Peter Bossaerts (2002, 2004), Hansen (2007), Hansen and Sargent (2007), and Timothy Cogley and Sargent (2007), among others. The art in Hansen (2007) is to extend rational expectations enough to understand the data better while retaining the econometric discipline that rational expectations models acquire by economizing on free parameters that characterize agents' beliefs.<sup>12</sup>

#### D. Another Empirical Reason to Allow for Belief Heterogeneity

Applied macroeconomists study data that can be weakly informative about parameters and model features. Ultimately, this is why differences of opinion about how an economy works can persist. The philosophy of Evan W. Anderson, Hansen, and Sargent (2003), Hansen (2007), and Hansen and Sargent (2007) is to let agents inside a model have views that can diverge from the truth in ways about which the data speak quietly and slowly.

### III. Rational Expectations Econometrics

Ideas from rational expectations econometrics motivate stories and models that feature gaps between an objective distribution and the temporary subjective distributions used by a government that solves a sequence of intelligent design problems. I review econometric methods that allow an outsider to learn about a rational expectations equilibrium and introduce some objects and possibilities that are in play in models containing agents who are learning an equilibrium.

A rational expectations equilibrium is a joint probability density  $f(\mathbf{x}^t | \boldsymbol{\theta}_o)$  over histories  $\mathbf{x}^t$  indexed by free parameters  $\boldsymbol{\theta}_o \in \Theta$  that describe preferences, technologies, endowments, and information. For reasons that will become clear, I have called the parameter vector  $\boldsymbol{\theta}$  rather than  $\boldsymbol{\rho}$  as in Section I. Rational expectations econometrics tells an econometrician who is outside the model how to learn  $\boldsymbol{\theta}$ . The econometrician knows only a parametric form for the model and therefore initially knows less about the equilibrium joint probability distribution than nature and

<sup>12</sup> Hansen (2007) brings only one new free parameter that governs how much a representative agent's beliefs are exponentially twisted vis-à-vis the data-generating mechanism.

the agents inside the model. The econometrician's tools for learning  $\theta$  are (i) a likelihood function, (ii) a time series or panel of observations drawn from the equilibrium distribution, and (iii) a Law of Large Numbers, a Central Limit Theorem, and some large deviations theorems that characterize limits, rates of convergence, and tail behaviors of estimators. With enough data and a correct likelihood function, an econometrician can learn  $\theta_o$ .

A rational expectations equilibrium evaluated at a particular history is a *likelihood function*:

$$(7) \quad L(\mathbf{x}^t | \theta) = f(\mathbf{x}^t | \theta) = f(\mathbf{x}_t | \mathbf{x}^{t-1}; \theta) f(\mathbf{x}_{t-1} | \mathbf{x}^{t-2}; \theta) \cdots f(\mathbf{x}_1 | \mathbf{x}_0; \theta) f(\mathbf{x}_0 | \theta).$$

The most confident and ambitious branch of rational expectations econometrics recommends maximizing a likelihood function or combining it with a Bayesian prior  $p(\theta)$  to construct a posterior  $p(\theta | \mathbf{x}^t)$ .<sup>13</sup> In choosing  $\theta$  to maximize a likelihood function, a rational expectations econometrician in effect searches simultaneously for a stochastic process of exogenous variables and a system of expectations that prompts forward-looking artificial agents inside a model to make decisions that best fit the data.<sup>14</sup> Taking logs in (7) gives

$$(8) \quad \log L(\theta | \mathbf{x}^t) = \ell(\mathbf{x}_t | \mathbf{x}^{t-1}; \theta) + \ell(\mathbf{x}_{t-1} | \mathbf{x}^{t-2}; \theta) + \cdots + \ell(\mathbf{x}_1 | \mathbf{x}_0; \theta) + \ell(\mathbf{x}_0 | \theta),$$

where  $\ell(\mathbf{x}_t | \mathbf{x}^{t-1}; \theta) = \log f(\mathbf{x}_t | \mathbf{x}^{t-1}; \theta)$ . Define the score function as  $s_t(\mathbf{x}^t, \theta) = \partial \ell(\mathbf{x}_t | \mathbf{x}^{t-1}, \theta) / \partial \theta$ . The first-order conditions for maximum likelihood estimation are

$$(9) \quad \frac{1}{t+1} \sum_{\tau=0}^t s_\tau(\mathbf{x}^\tau, \hat{\theta}_t) = 0.$$

By solving these equations, an econometrician finds a  $\hat{\theta}_t$  that allows him to approximate the equilibrium density very well as  $t \rightarrow +\infty$ .

#### A. Using a Misspecified Model to Estimate a Better One

Lucas (1976) convinced us that nonstructural models are bad vehicles for policy analysis. But the first-order conditions for estimating a good fitting nonstructural model *can* help to make good inferences about parameters of a structural economic model.

Indirect estimation assumes that a researcher wants to estimate a parameter vector  $\rho$  of a structural rational expectations model for which (1) analytical difficulties prevent evaluating a likelihood function  $f(\mathbf{x}^t | \rho)$  directly, and (2) computational methods allow simulating time series from  $f(\mathbf{x}^t | \rho)$  at a given vector  $\rho$ . See Christian Gourieroux, Alain Monfort, and Eric Renault (1993), A. A. Smith, Jr. (1993), and A. Ronald Gallant and George Tauchen (1996). Indirect estimation carries along two models, a model of economic interest with an intractable likelihood function, and an auxiliary purely statistical model with a tractable likelihood function that fits the historical data well. The parameters of the economist's model  $\rho$  are interpretable in terms of preferences, technologies, and information sets, while the parameters  $\theta$  of the auxiliary model  $f(\mathbf{x}^t | \theta)$  are data fitting devices. The idea of Gallant and Tauchen (1996) is, first, to estimate the auxiliary model by maximum likelihood, then to use the score functions for the auxiliary model and the first-order conditions (9) to construct a GMM estimator that can be used in conjunction

<sup>13</sup> For early applications of this empirical approach, see Sargent (1977), Sargent (1979), Hansen and Sargent (1980), John B. Taylor (1980), and Ates C. Dagi and Taylor (1984).

<sup>14</sup> As the econometrician searches over probability measures indexed by  $\theta$ , he imputes to the agents the system of expectations implied by the  $\theta$  under consideration.

with simulations of the economic model to estimate the parameters  $\rho$ . Thus, let the auxiliary model have a log likelihood function given by equation (8) and, for the data sample in hand, compute the maximum likelihood estimate  $\hat{\theta}$ . For different  $\rho$ 's, simulate paths  $x_\tau(\rho)$  for  $\tau = 0, \dots, t$  from the economic model. Think of using these artificial data to evaluate the score function for the *auxiliary* model  $s_\tau(x^\tau(\rho), \hat{\theta})$  for each  $\tau$ . Gallant and Tauchen estimate  $\rho$  by setting the average score for the auxiliary model<sup>15</sup>

$$(10) \quad \frac{1}{t+1} \sum_{\tau=0}^t s_\tau(x^\tau(\rho), \hat{\theta})$$

as close to zero as possible when measured by a quadratic form of the type used in GMM. If the auxiliary model fits well, this method gives good estimates of the parameters  $\rho$  of the economic model. In particular, the indirect estimator is as efficient as maximum likelihood in the ideal case where the economic and auxiliary models are observationally equivalent.

### B. A Troublesome Possibility

This ideal case raises the following question: what happens when macroeconomic policymakers incorrectly use what, from nature's point of view, is actually an auxiliary model? Data give the government no indication that it should abandon its model. Nevertheless, the government can make major policy design mistakes because it misunderstands the consequences of policies that it has not chosen.<sup>16</sup> The possibility that the government uses what, unbeknownst to it, is an auxiliary model, not a structural one, sets the stage for the self-confirming equilibria that play an important role in the adaptive learning models of the following section and in the stories to be told in Sections V and VI.

## IV. Adaptive Learning Models and Their Limiting Outcomes

Section II described how a survival argument for equating objective and subjective distributions falls short in many economies. This section takes up where that discussion left off by describing transient and limiting outcomes in models in which agents make decisions by using statistical models that at least temporarily are misspecified. I summarize findings from a literature that studies systems of agents who use forward-looking decision algorithms based on temporary models that they update using recursive least squares algorithms (see Albert Marcet and Sargent 1989a; George W. Evans and Seppo Honkapohja 1999, 2001; Woodford 1990; and Drew Fudenberg and David K. Levine 1998).<sup>17</sup> These adaptive systems can have limiting outcomes in which objective and subjective distributions are identical over frequently observed events, but not over rarely observed events. That causes problems for intelligent macroeconomic policy design. I shall use such adaptive systems to tell some stories in Section VI. I begin by defining population objects that suppose that agents have finished learning.

### A. Self-Confirming Equilibrium

A true data-generating process and an approximating model, respectively, are

$$(11) \quad f(y^\infty, v^\infty | \rho) \quad \text{and} \quad f(y^\infty, v^\infty | \theta).$$

<sup>15</sup> This description fits what they call Case 2.

<sup>16</sup> See Lucas (1976), Sargent (1999, ch. 7), and Fudenberg and Levine (2007).

<sup>17</sup> Appendix A describes a related literature on learning in games.



A decision maker has preferences ordered by

$$(12) \quad \int U(\mathbf{y}^\infty, \mathbf{v}^\infty) f(\mathbf{y}^\infty, \mathbf{v}^\infty | \boldsymbol{\theta}) d(\mathbf{y}^\infty, \mathbf{v}^\infty)$$

and chooses a history-dependent plan

$$(13) \quad \mathbf{v}_t = h_t(\mathbf{x}^t | \boldsymbol{\theta}), \quad t \geq 0$$

that maximizes (12). This gives rise to the sequence of decisions  $\mathbf{v}(h | \boldsymbol{\theta})^\infty$ . The difference between this choice problem and the canonical intelligent design problem in Section I is the presence of the approximating model  $f(\mathbf{y}^\infty, \mathbf{v}^\infty | \boldsymbol{\theta})$  in (12) rather than the true model that appeared in (2). I call maximizing (12) a ‘‘Phelps problem’’ in honor of a policy design problem of Edmund S. Phelps (1967) that will play an important role in Section VI.

**DEFINITION 1:** *A self-confirming equilibrium (SCE) is a parameter vector  $\boldsymbol{\theta}_o$  for the approximating model that satisfies the data-matching conditions*

$$(14) \quad f(\mathbf{y}^\infty, \mathbf{v}(h | \boldsymbol{\theta}_o)^\infty | \boldsymbol{\theta}_o) = f(\mathbf{y}^\infty, \mathbf{v}(h | \boldsymbol{\theta}_o)^\infty | \boldsymbol{\rho}).$$

An SCE builds in, first, optimization of (12) given beliefs indexed by  $\boldsymbol{\theta}_o$ , and, second, a  $\boldsymbol{\theta} = \boldsymbol{\theta}_o$  that satisfies the data matching conditions (14). Data matching prevails for events that occur under the equilibrium policy  $\mathbf{v}(h | \boldsymbol{\theta}_o)^\infty$ , but it is possible that

$$(15) \quad f(\mathbf{y}^\infty, \mathbf{v}^\infty | \boldsymbol{\theta}_o) \neq f(\mathbf{y}^\infty, \mathbf{v}^\infty | \boldsymbol{\rho})$$

for  $\mathbf{v}^\infty \neq \mathbf{v}(h | \boldsymbol{\theta}_o)^\infty$ . In an SCE, the approximating model is observationally equivalent with the true model for events that occur under the SCE government policy, but not necessarily under alternative government policies.

### B. Learning Converges to an SCE

An SCE is a possible limit point of an adaptive learning process. Margaret M. Bray and Kreps (1987) distinguish between learning *about* an equilibrium and learning *within* an equilibrium.<sup>18</sup> By saying *about* and not *within*, Bray and Kreps emphasize that the challenge is to analyze how a system of agents can come to learn an endogenous objective distribution by using adaptive algorithms that do not simply apply Bayes’s law to a correct probability model.<sup>19</sup> We cannot appeal to the same econometrics that lets a rational expectations econometrician learn an equilibrium because an econometrician is *outside* the model and his learning is a sideshow that does not

<sup>18</sup> A difficult challenge in the machine learning literature is to construct an adaptive algorithm that learns dynamic programming. For a recent significant advance based on the application of the adjoint of a resolvent operator and a Law of Large Numbers, see Sean Meyn (2007, ch. 11).

<sup>19</sup> Bray and Kreps’s ‘‘about’’ versus ‘‘within’’ tension also pertains to Bayesian theories of convergence to Nash equilibria. Marimon (1997) said that a Bayesian knows the truth from the beginning. Young (2004) pointed out that the absolute continuity assumption underlying the beautiful convergence result of Kalai and Lehrer (1993, 1994) requires that players have substantial prior knowledge about their opponents’ strategies. Young doubts that Kalai and Lehrer have answered the question ‘‘... can one identify priors [over opponents’ strategies] whose support is wide enough to capture the strategies that one’s (rational) opponents are actually using, without assuming away the uncertainty inherent in the situation?’’ Young (2004, 95).

affect the data generating mechanism. It is different when people learning about an equilibrium are inside the model. Their learning affects decisions and alters the distribution of endogenous variables over time, making them aim at moving targets.

Suppose that an adaptive learner begins with an initial estimate  $\hat{\theta}_0$  at time 0 and uses a recursive least squares learning algorithm

$$(16) \quad \hat{\theta}_{t+1} - \hat{\theta}_t = e_t(\hat{\theta}_t, y^t, v^t, t).$$

As in the models of learning in games of Dean P. Foster and H. Peyton Young (2003) and Young (2004, ch. 8), we assume that decision makers mistakenly regard their time  $t$  model indexed by  $\hat{\theta}_t$  as permanent and form the sequence of decisions<sup>20</sup>

$$(17) \quad \hat{v}(h)_t = h_t(x^t | \hat{\theta}_t),$$

where  $h_t(x^t | \theta)$  is the same function (13) that solves the original Phelps problem (12) under the model  $f(y^\infty, v^\infty | \theta)$ . The joint density of  $(y^\infty, v^\infty, \hat{\theta}^\infty)$  becomes

$$(18) \quad f(y^\infty, \hat{v}(h)^\infty, \hat{\theta}^\infty | \rho).$$

The learning literature states restrictions on the estimator  $e$  and the densities  $f(\cdot | \theta)$  and  $f(\cdot | \rho)$  that imply that

$$(19) \quad \hat{\theta}_t \rightarrow \theta_o,$$

where convergence can be either almost surely or in distribution, depending on details of the estimator  $e$  in (16).<sup>21</sup>

### C. Applications of Adaptive Learning Models in Macroeconomics

One important application of adaptive models in macroeconomics has been to select among multiple rational expectations equilibria (see Evans and Honkapohja (2001) for many useful examples). Another has been to choose among alternative representations of policy rules from Ramsey problems, a subset of which are stable under adaptive learning (Evans and Honkapohja 2003). Yet another has been to improve the fit of models of asset pricing and big inflations by positing small gaps between an objective density and asset holders' subjective densities (e.g., Klaus Adam, Albert Marcet, and Juan Pablo Nicolini 2006; Marcet and Nicolini 2003). In the

<sup>20</sup> In-Koo Cho and Kenneth Kasa (2006) create a model structure closer to the vision of Foster and Young (2003). In particular, Cho and Kasa's model has the following structure: (1) one or more decision makers take actions at time  $t$  by solving a dynamic programming problem based on a possibly misspecified time  $t$  model; (2) the actions of some of those decision makers influence the data-generating process; (3) a decision maker shows that he is aware of possible misspecifications of his model by trying to detect them with an econometric specification test; (4) if the specification test rejects the model, the decision maker selects an improved model; while (5) if the current model is not rejected, the decision maker formulates policy using the model under the assumption (used to formulate the dynamic programming problem) that he will retain this model forever. Cho and Kasa show that the same stochastic approximation and large deviations results that pertain to a least-squares learning setup also describe the outcomes of their model-validation setup.

<sup>21</sup> For example, so-called "constant gain" algorithms give rise to convergence in distribution, while estimators whose gains diminish at proper rates converge almost surely. See Noah Williams (2004), Marcet and Sargent (1995) study rates of convergence and provide some examples in which convergence occurs at a  $\sqrt{T}$  rate and others in which convergence occurs markedly more slowly.

remainder of this paper, I focus on yet another application, namely, to situations in which a government solves an intelligent design problem using a misspecified model.

#### D. REE or SCE?

Some builders of adaptive models have specified an approximating model to equal a true one, meaning that there exists a value  $\theta_o$  for which  $f(y^\infty, v^\infty | \rho) = f(y^\infty, v^\infty | \theta_o)$  for all plans  $v^\infty$ , not just equilibrium ones. This specification prevails in adaptive models in which least squares learning schemes converge to rational expectations equilibria (see Woodford 1990; Marcet and Sargent 1989b). When  $f(y^\infty, v^\infty | \rho) \neq f(y^\infty, v^\infty | \theta_o)$  for some choices of  $v$ , the most that can be hoped for is convergence to an SCE.<sup>22</sup>

#### E. SCE-REE Gaps and Policy Design

Why is a gap between a rational expectations equilibrium and a self-confirming equilibrium important for a macroeconomist? Macroeconomists build models with many small agents and some large agents called governments. It doesn't matter to a small agent that his views may be incorrect views off an equilibrium path. But it can matter very much when a large agent like a government has incorrect views off an equilibrium path because in solving a Ramsey problem, a government contemplates the consequences of off-equilibrium path experiments. Wrong views about off-equilibrium path events shape government policy and the equilibrium path.

To illustrate these ideas, I sample some historical events that central bankers have learned from. Section V summarizes hundreds of years of monetary theories and experiments that took us to the threshold of the twentieth century experiment with fiat currency. Section VI jumps ahead to the 1960s and 1970s and uses statistical models to describe how the US monetary authorities struggled to understand inflation-unemployment dynamics as they sought to meet their dual mandate of promoting high output growth and low inflation.

#### V. Learning Monetary Policy before and after Ricardo

Central bankers are preoccupied with nominal anchors. For centuries, commodity monies built in redundant nominal anchors. When Ricardo wrote, new technologies of coin production and expert opinion had established the confidence to dispense with redundant nominal anchors and to rely on a unique anchor taking the form of melt-mint points for a single standard commodity coin. In the twentieth century, monetary authorities implemented Ricardo's recommendation to banish precious metals from the monetary system and sought an alternative monetary anchor based on a theory of fiat money and the public's faith in the wisdom and good intentions of the monetary authorities.

<sup>22</sup> Sargent (1999, ch. 6) works with a weaker notion of an SCE that William A. Branch and Evans (2005, 2006) call a misspecification equilibrium. Branch and Evans construct misspecification equilibria in which agents  $i$  and  $j$  have different models parameterized, say, by  $\theta_i$  and  $\theta_j$ , and in which  $f(x^t | \theta_i) \neq f(x^t | \theta_j) \neq f(x^t | \rho)$ , where again  $\rho$  parameterizes the data-generating mechanism. A misspecification equilibrium imposes moment conditions on agents' approximating models that imply parameters  $\theta_i$  that give equal minimum mean square error forecast errors  $E_{\theta_i}[(x_{t+1} - E_{\theta_j}(x_{t+1} | x^t))(x_{t+1} - E_{\theta_j}(x_{t+1} | x^t))']$  for all surviving models. Branch and Evans model equilibria in which beliefs and forecasts are heterogeneous across agents, though they have equal mean squared errors. They provide conditions under which recursive least squares learning algorithms converge to a subset of the possible misspecification equilibria. The models of William A. Brock and Cars H. Hommes (1997) and Brock and de Patrick de Fontnouvelle (2000) are early versions of misspecification equilibria.

### A. From Commodity to Token to Fiat Money

Appendix B describes a 700-year process of theorizing and experimenting that transformed a European commodity money system with *many* nominal anchors—mint-melt price pairs (i.e., gold or silver points) for full-bodied coins of all denominations—to a *one* nominal anchor system that retained gold points for only one standard full-bodied coin and used government-issued convertible token coins and notes for other denominations.<sup>23</sup> After another 100 years, governments abolished the gold points for the standard coin, too, leaving the nominal anchor to be the monetary authorities' knowledge of the quantity theory of money and their good intentions. Appendix B notes how commodity money concealed the quantity theory of money by making the price level be a low variance exogenous variable and the money supply be a low variance endogenous variable. I see a self-confirming equilibrium working here. Eventually, some atypical policy experiments generated data with sufficient variance in price levels and money supplies to reveal the quantity theory to empiricists, a theory that led to Ricardo's proposal and ultimately induced monetary experts like Keynes to advocate a well-managed fiat system.

### B. Two Threats to a Well-Managed Fiat Money System

Friedman (1992, 249–52) claimed that our fiat money system is historically unprecedented and repeated the warning of Irving Fisher (1926, 131) that “Irredeemable paper money has almost invariably proved a curse to the country employing it” because two obstacles obstruct the path to managing a fiat currency well: (i) political pressures to use fiat money to finance government expenditures, and (ii) temptations to exploit a Phillips curve (Friedman 1992, 207). Learning models have been used to interpret monetary authorities' struggles to understand and avoid these obstacles. Marcet and Nicolini (2003) and Sargent, Williams, and Tao Zha (2006a) constructed adaptive models that focus on Friedman's obstacle (i) and feature private agents' learning. Those papers both select among rational equilibria and modify their outcomes enough to fit data from big inflations in Latin America. In the remainder of this paper, I focus on statistical models that feature monetary authorities' struggles with Friedman's obstacle (ii).

## VI. Learning Inflation-Unemployment Dynamics

This section describes three stories about how the US monetary authorities learned about inflation-unemployment dynamics after World War II. These stories assume that a monetary authority can control inflation if it wants.<sup>24</sup> Then why did the US monetary authority allow inflation to rise in the late 1960s and 1970s, and why did it bring inflation down in the 1980s and 1990s? If we assume that its purposes did not change, and that it always disliked inflation and unemployment, then it is natural to focus on changes over time in the monetary authority's understanding of inflation-unemployment dynamics. I describe three stories associated with empirical models that feature either temporary or permanent discrepancies between a government's model and a true data-generating mechanism.<sup>25</sup>

<sup>23</sup> Frank Whitson Fetter (1978, 16) and Friedman (1992, 150–51) discuss how concerns about small denomination coins shaped the gold standard.

<sup>24</sup> Appendix C discusses a monetary policy rules literature that focuses on the gap between the monetary authorities' instruments and inflation outcomes.

<sup>25</sup> For testimony that policy authorities in the United States are concerned about related issues, see Bernanke (2007) and Frederic S. Mishkin (2007). See Evans and Honkapohja (2003), Athanasios Orphanides and John C. Williams (2005, 2007), and James Bullard and Kaushik Mitra (2007) for applications of models of this type to evaluate the

It is natural to impute popular contemporary models to the government. The “revisionist history” of the US Phillips curve by Robert G. King and Mark W. Watson (1994) provides a good source for these. King and Watson studied how econometric directions of fit (i.e., should one regress inflation on unemployment or unemployment on inflation?) affect government decisions. To make contact with studies from the 1970s, King and Watson call regressions of inflation on unemployment the Keynesian direction of fit and unemployment on inflation the classical direction.<sup>26</sup> I impute simplified versions of more completely articulated models to the government.<sup>27</sup> These simple models capture the substantially different operating characteristics that drive our stories.

The three stories have monetary authorities solve adaptive intelligent design problems that induce them to make decisions that are influenced by their erroneous views about the consequences of actions not taken. The stories differ in the nature of those misunderstandings. In the first story, the monetary authority’s misspecified model misses a chain of causation linking its decisions first to the private sector’s expectations of inflation and then to the position of an unemployment-inflation trade-off. In the second story, there exists a parameter vector  $\theta_o = \rho$  that aligns the monetary authority’s model with the data-generating mechanism on *and* off the chosen stochastic monetary policy path, but except in the limit as  $t \rightarrow \infty$ , the government’s temporary misestimates  $\hat{\theta}_t$  of  $\theta_o$  induce it to misunderstand the consequences of policies that it chooses not to implement. In the third story, the government mixes across submodels with operating characteristics that give very different readings about the consequences of following a no-feedback low-inflation policy.

#### A. The (Temporary) Conquest of US Inflation

This story is about generating sufficient variation in the data to allow a government’s misspecified model to detect that there is no exploitable trade-off between inflation and unemployment. The only way the government’s model lets it discover that there truly is no *exploitable* trade-off is for it falsely to infer that there is no trade-off *whatsoever*. That imperfection dooms stabilizations of inflation to be temporary.

This story uses specifications  $f(y^\infty, v^\infty | \rho) \neq f(y^\infty, v^\infty | \theta)$  to capture the idea that a monetary authority misunderstands how its decisions affect private agents’ expectations about inflation and, therefore, the joint distribution of unemployment and inflation. I illustrate the forces at work with the following simplified version of a model that Christopher A. Sims (1988), Cho, Williams, and Sargent (2002), and Sargent and Williams (2005) studied and that Heetaik Chung (1990), Sargent (1999), and Sargent, Williams, and Zha (2006b) fit to US data. The true model is

$$(20) \quad U = \rho_0 - \rho_1 \rho_3 w_2 + \rho_2 w_1;$$

$$(21) \quad \pi = v + \rho_3 w_2,$$

where  $U$  is the unemployment rate,  $\pi$  is the rate of inflation,  $v$  is the systematic part of the inflation rate chosen by the monetary authority,  $w$  is a  $2 \times 1$  Gaussian random vector with mean zero

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stability and performance of alternative monetary policy rules. See Timothy Cogley (2005) and Monika Piazzesi and Martin Schneider (2007) for applications to the yield curve.

<sup>26</sup> Sargent (1999, ch. 7) described how those specification decisions can affect self-confirming equilibrium outcomes.

<sup>27</sup> Some economists today use the slang “reduced form” to refer to incompletely articulated models. I prefer to reserve the term “reduced form” for its original meaning in Cowles commission econometrics, namely, a particular statistical representation associated with a well-articulated structural model.

and identity covariance, and  $\rho_0 > 0$ ,  $\rho_1 > 0$ , where  $\rho_0$  is the natural rate of unemployment and  $\rho_1$  is the slope of the Phillips curve. The parameters  $\rho_2$  and  $\rho_3$  set the volatility of the shocks. Through equation (20), which is the aggregate supply curve proposed by Lucas (1973), the model captures a rational expectations version of the natural unemployment rate hypothesis that asserts that the systematic component of inflation  $v$  does not affect the distribution of the unemployment rate conditional on  $v$ . The government's one-period loss function is  $E(U^2 + \pi^2)$ .

The government's approximating model denies the natural rate hypothesis by asserting that  $v$  affects the probability distribution of  $U$  according to

$$(22) \quad U = \theta_0 + \theta_1(v + \theta_3\tilde{w}_2) + \theta_2\tilde{w}_1;$$

$$(23) \quad \pi = v + \theta_3\tilde{w}_2,$$

where the random vector  $\tilde{w}$  has the same distribution as  $w$ . Under the true model and the protocol that the government chooses target inflation before the private sector sets its expectation of inflation, the government's best policy is  $v = 0$ . However, under the approximating model (22)–(23), the government's best policy is

$$(24) \quad v = h(\theta) = \frac{-\theta_1\theta_0}{1 + \theta_1^2}.$$

There exists a unique self-confirming equilibrium in which

$$(25) \quad (\theta_0)_o = \rho_0 + \rho_1 h(\theta_o),$$

$$(26) \quad (\theta_1)_o = -\rho_1,$$

and  $(\theta_2)_o = \rho_2, (\theta_3)_o = \rho_3$ . The self-confirming equilibrium equals the time-consistent equilibrium of Kydland and Prescott (1977).<sup>28</sup> An adaptive government's estimates  $\hat{\theta}_t$  converge to the self-confirming equilibrium vector  $\theta_o$ , and the systematic part of inflation converges to  $v = h(\theta_o)$ .

The data-matching restriction (25) pinpoints how the government mistakenly ignores the effect of its policy choice  $v$ , which also equals the public's expected rate of inflation, on the position of the Phillips curve. The population regression coefficient of  $U$  on  $\pi$  is  $\theta_1 = -\rho_1\rho_3^2/[\text{var}(v) + \rho_3^2]$ . If historically  $v$  had been randomly generated with enough variance, then even though it fits the wrong model, the government would estimate a Phillips curve slope  $\theta_1$  of approximately zero, and according to (24) would set  $v$  approximately to its optimal value of 0 under the true model.<sup>29</sup> But within an SCE,  $v$  doesn't vary enough for the government to estimate a  $\theta_1$  close enough to zero for that to happen. Furthermore, the outcome that  $\hat{\theta}_t \rightarrow \theta_o$  means that the variation of  $v_t$  that occurs along transient paths converging to an SCE is insufficient to allow the government's model to approximate the data in a way that tells it to implement the optimal policy under the true model.

<sup>28</sup> The same suboptimal outcome occurs, but for a different reason than the inferior timing protocol isolated by Kydland and Prescott (1977). Here the source of suboptimality is the government's ignorance. The timing protocol is such that if the government knew the correct model, it would attain what Stokey (1989) calls a Ramsey outcome of  $v = 0$ .

<sup>29</sup> Before adopting such a randomized policy for inflation, a monetary authority should consider the forces isolated by Larry E. Jones and Rodolfo E. Manuelli (2001).

That is not the end of the story, however, because the adaptive model's endogenous stochastic dynamics occasionally make  $v$  vary enough for the government to discover a version of the natural rate hypothesis that is too strong because it mistakenly asserts that there is almost no trade-off whatsoever between  $\pi$  and  $U$ . The adaptive system is destined to experience recurrent episodes in which "a most likely unlikely" sequence of  $w$ 's lowers the unconditional correlation between  $U$  and  $\pi$ , which alters  $\hat{\theta}_t$  in ways that induce the government to push  $v_t$  below its self-confirming value.<sup>30</sup> That generates data that further weaken the unconditional correlation between inflation and unemployment and moves  $\hat{\theta}_t$  in a direction that drives  $v$  even lower. The ultimate destination of this "escape" from a self-confirming equilibrium is that the government estimates that  $\theta_1$  is close to 0, prompting it to set  $v_t$  close to the optimal value 0. These escapes are more likely when the government's estimator (16) discounts past data more heavily, for example, by implementing a so-called constant gain algorithm. An escape is temporary because the mean dynamics that drive the system toward the SCE vector  $\theta_o$  are bound to reassert themselves and push inflation back toward the suboptimal SCE value of  $h(\theta_o)$ . If this is a good parable for the Volcker-Greenspan stabilization, we should be worried.

*Details.*—Simulations of Sims (1988) generated sample paths that seemed promising for explaining a Volcker-like stabilization prompted by the government's ability to learn a good enough version of the natural rate hypothesis. However, formal econometric attempts to implement the model by Chung (1990) and Sargent (1999) failed to fit the US data well, mainly because the government's adaptive algorithm caught on to the adverse shifts in the Phillips curve quickly in the early 1970s. Sargent, Williams, and Zha (2006b) replaced the constant gain algorithm used in the earlier models with a Bayesian updating procedure implied by a drifting coefficients model with covariance matrix  $V$  for the innovations in the drifts to the coefficients. By estimating  $V$  along with the parameters of nature's model by maximum likelihood, they reverse engineered a drifting set of government beliefs that, when put into the Phelps problem each period, produce a sequence of first-period Phelps policy recommendations that do a good job of matching the actual inflation data. The estimated  $V$  implies that the intercept in the Fed's model is quite volatile and thus makes contact with Arthur Burns's Fed, which according to Robert Hetzel (1998), attributed much of the inflation of the 1970s to special factors akin to dummy variables that capture intercept drift in regressions. More generally, the large estimated  $V$  conveys the image of a government that expects coefficients to drift so much that it discounts past data heavily. The statistical model's conjuring up a Fed that overfits its models to recent data is food for thought for Fed watchers. The synthesized government beliefs succeed in rationalizing inflation ex post as a response to these government beliefs, and the beliefs themselves do a good job of forecasting inflation, thus capturing what seems to have been a remarkably good record of inflation forecasting by the Fed (see Bernanke 2007).<sup>31</sup>

*The Best of All Possible Worlds?*—In the preceding story, government policy actions recurrently take values that are optimal under the correct model, but only temporarily because the mean dynamics push the government's beliefs back to the SCE. Thus, this story, at best, only temporarily supports the optimism expressed by Sims (1988) that the government's misspecified

<sup>30</sup> That unlikely events occur in the most likely way is a key aspect of large deviation theory. See Cho, Williams, and Sargent (2002) for an elaboration of "most likely unlikely" sequences of shocks.

<sup>31</sup> But relative to available alternatives, the imputed beliefs do a poor job of forecasting unemployment, a deficiency of the model that hints that the reverse-engineering exercise may be imputing unrealistic views about *joint* inflation-unemployment dynamics to the Phelps problem in order to rationalize observed inflation outcomes. By conditioning estimates on greenbook forecasts, Giacomo Carboni and Martin Ellison (2007) repair this deficiency and also reduce the estimated  $V$  while leaving the basic story intact.

model can approximate the lack of an exploitable  $U - \pi$  trade-off well enough to induce the government to do what would be the right thing if it actually knew the true model. For the misspecified model to reveal the lack of an exploitable trade-off, the government has to induce adequate variation in inflation, which it does not do within an SCE. So the first story stops short of being one in which evolution converges to “the best of all possible worlds.” A more optimistic outcome prevails in our next story, which endows the government with a model that allows its misunderstandings of off-equilibrium-path choices eventually to vanish.

### B. A Keynesian Account

The previous story is about how the troublesome possibility raised in Section IIIB plays out. The model of Giorgio Primiceri (2006) envisions a world in which that possibility is off the table because  $f(y^\infty, v^\infty | \rho) = f(y^\infty, v^\infty | \theta_0)$  for all  $v^\infty$  and an SCE equals an REE. All of the action in Primiceri’s model comes from calibrating an initial  $\hat{\theta}_0 \neq \theta_0$  which leads to a transient stochastic path that converges to an SCE presided over by Greenspan and whose transient dynamics mimic the post-WWII United States.

Primiceri’s definition of an SCE is special in that, while it sets the government’s model  $f(x^t | \theta)$  equal to the true model  $f(x^t | \rho)$ , it assumes that private agents make forecasts of inflation that do not equal those implied by  $f(x^t | \rho)$ . There is implicitly a third density  $f(x^t)$  inside the model that equals neither the government’s  $f(x^t | \theta)$  nor nature’s  $f(x^t | \rho)$ . In particular, Primiceri assumes that  $f(x^t | \theta) = f(x^t | \rho)$  is a version of a Solow-Tobin model that itself imputes irrational expectations about inflation to the private sector.<sup>32</sup>

Primiceri has a time invariant true data-generating model featuring (i) an expectations augmented Phillips curve; (ii) a Phillip Cagan (1956)-Friedman (1957) adaptive expectations scheme that describes how the public forms expectations of inflation that appear in (i)<sup>33</sup>; (iii) an aggregate demand equation that describes how the time  $t$  value of an uninterpreted government policy instrument  $v_t$  affects current and future gaps between the unemployment rate  $u_t$  and a natural rate of unemployment  $u_t^N$ ,<sup>34</sup> and (iv) a one-period government loss function  $(\pi_t - \pi^*)^2 + \lambda(u_t - \hat{u}_t^N)^2$  where  $\pi^*$  is a target rate of inflation and  $\hat{u}_t^N$  is the government’s estimate of natural unemployment rate. The model allows the government’s misperception of the natural rate to influence policy, as advocated by Orphanides (2002, 2003). It also allows two other aspects of government perceptions to influence policy in important ways, namely, perceptions about the persistence of inflation and about the contemporaneous trade-off between inflation and unemployment.

Primiceri’s maximum likelihood estimates succeed in accounting for the acceleration of inflation in the 1960s and 1970s, then the fall in the 1980s in terms of the government’s initial underestimates of the natural unemployment rate, and a temporal pattern of underestimates of the persistence of inflation and overestimates of the costs of disinflation coming from its estimated inflation-unemployment trade-off.<sup>35</sup> Figure 1 reproduces Primiceri’s figure II, which shows his

<sup>32</sup> See Robert M. Solow (1968), James Tobin (1968), Lucas (1972a), and Sargent (1971).

<sup>33</sup> Primiceri assumes that a fraction of agents forms expectations this way and the rest have rational expectations. Primiceri’s specification imposes that the sum of weights on lagged inflation equals unity. Lucas (1972a) and Sargent (1971) argued that, except in a special case, the sum of the weights on lagged inflation being one is not a valid implication of rational expectations. Also see Robert G. King and Mark W. Watson (1994) and Sargent (1999). John F. Muth (1960) deduced a density  $f(x^t)$  that rationalizes Friedman’s adaptive expectations scheme.

<sup>34</sup> Feature (ii) of Primiceri’s model embraces a Keynesian spirit of assuming that the authority influences output directly through the aggregate demand function, then inflation indirectly through the expectations-augmented Phillips curve. Contrast this with the classical specification adopted by Sims (1988), Chung (1990), Sargent (1999), Cho, Williams, and Sargent (2002), and Sargent, Williams, and Zha (2006b).

<sup>35</sup> Primiceri calibrates initial government beliefs by using data between 1948 and 1960 to estimate the model’s parameters. These calibrated beliefs feature a level of persistence of inflation in the Phillips curve that is much lower



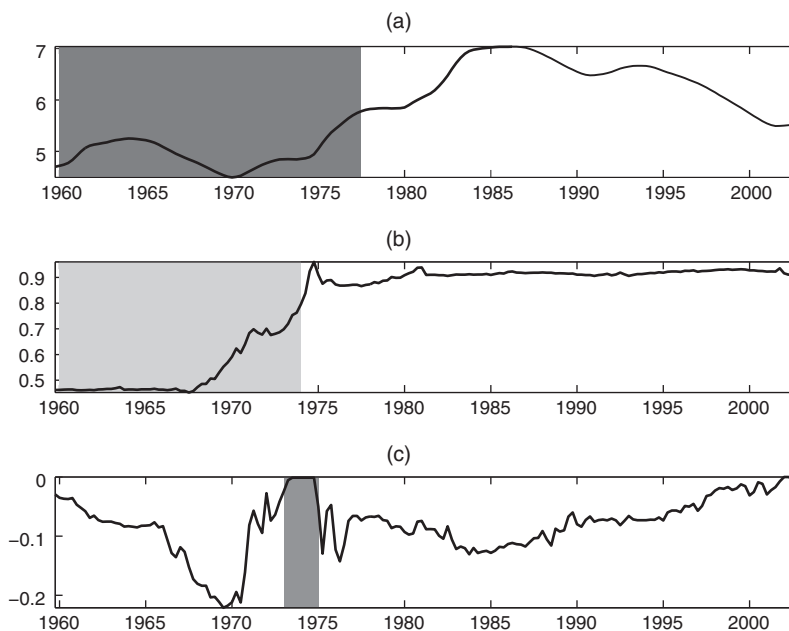


FIGURE 1

*Notes:* Evolution of policy-maker's beliefs about: (a) the natural rate of unemployment; (b) the persistence of inflation in the Phillips curve; and (c) the slope of the Phillips curve in King and Watson's Keynesian direction. Shaded areas are where the government (a) underestimates the natural rate of unemployment, (b) underestimates the persistence of inflation, and (c) thinks that the sacrifice ratio is very large.

*Source:* I have modified a figure of Primiceri (2006, p. 882).

estimates of the evolution of the Fed's estimates of the natural rate of unemployment, the persistence of inflation, and the slope of the Phillips curve. Primiceri's Phelps problem attributes the acceleration of inflation to the monetary authority's initial underestimates of both the natural rate and the persistence of inflation. A low estimated persistence of inflation indicates to the government that mean reverting inflation will evaporate soon enough on its own, making a less anti-inflationary policy emerge from the Phelps problem. After inflation had risen, the Phelps problem attributes the monetary authority's reluctance to deflate to its overestimate of the costs of disinflation, as captured by the slope of the Phillips curve. We will return to this point in Section VIC, where we link it to the conceptual issues about direction of fit raised by King and Watson (1994).<sup>36</sup>

than what prevails in the estimated model's self-confirming equilibrium. In addition to these initial conditions, Primiceri sets two constant gain parameters, one for the natural rate, another for all other coefficients in the government's beliefs. These calibrated objects, the data, and the parameters of the structural relations pin down the government's beliefs. Primiceri uses maximum likelihood to estimate parameters appearing in the government's objective function and the time-invariant structural equations.

<sup>36</sup> Among many interesting features of Primiceri's results are his estimate of  $k$ , the parameter in the government's one-period loss function that allows Primiceri to evaluate the government's temptation to deviate from the natural rate (he finds that the temptation is small) and the time series that he extracts for  $v_t$ , which tracks a real interest rate very well after 1980.

Underestimates of the natural unemployment rate and overestimates of the sacrifice ratio are connected. When the Fed underestimates the natural rate and overestimates the unemployment gap, it overpredicts the amount of disinflation. That causes it to revise its estimate of the slope of the Phillips curve toward zero. Thus, Orphanides's story about the consequences of misestimating the natural rate of unemployment complements Primiceri's story about sacrifice ratio pessimism.

### C. An Eclectic Account

The stories in the previous two sections take stands on both the true and the government's approximating models. Cogley and Sargent (2005) perform an exercise that does not require specifying a true data-generating mechanism, the empirical distribution being enough. But the government's views about the consequences of choosing alternative feasible policies continue to play the leading role. The government's model  $f(y^\infty, v^\infty | \theta)$  mixes three submodels according to Bayesian posterior probabilities that are included in the vector  $\hat{\theta}_t$ .

A government entertains three models that Cogley and Sargent use to capture prominent specifications from the literature about US unemployment-inflation dynamics described by King and Watson (1994). The models are (1) a Samuelson-Solow Phillips curve with King and Watson's Keynesian direction of fit, a model that implies a long-run exploitable trade-off between inflation and unemployment; (2) a Solow-Tobin model with a Keynesian direction of fit that features a short-run but no long-run trade-off between inflation and unemployment (albeit according to what Lucas (1972a) and Sargent (1971) claimed was an unsound notion of long-run); and (3) a Lucas specification with a classical direction of fit that implies no exploitable trade-off between inflation and unemployment. If the Lucas model has probability one, the Phelps problem gives the trivial solution that the government should set the systematic part of inflation equal to zero. If either of the other models has probability one, the systematic part of inflation is a linear function of the state variables appearing in those exploitable dynamic Phillips curves. The government attaches positive probability to all three models, so the Phelps problem brokers a compromise among the recommendations of the three models. But what kind of compromise? It depends on submodel probabilities multiplied by value functions.

The government starts with a prior that has non-zero weights on all three models in 1960, then each period uses Bayes's law to update parameters of each of the three submodels and also its prior over the submodels.<sup>37</sup> In each period, the government solves a Phelps problem that penalizes inflation and unemployment and that uses its time  $t$  submodel probabilities to average over its time  $t$  estimates of its three submodels. Cogley and Sargent put prior probabilities in 1960 of 0.98 on the Samuelson-Solow model and 0.01 each on the Solow-Tobin and the Lucas model. We set those low prior probabilities on the Lucas and Solow-Tobin models because only the Samuelson-Solow model existed in 1960.<sup>38</sup> Applying this machine to US inflation-unemployment data, Cogley and Sargent computed time series of both the posterior model weights  $\alpha_{i,t}$  and the systematic part of the inflation rate set by the government in the Phelps problem.

<sup>37</sup> See Cogley, Ricardo Colacito, and Sargent (2007) for a related setup that has only two submodels, each of which has known coefficients, and in which the government designs purposeful experiments because it includes the submodel probabilities in the state vector. By way of contrast, the model being discussed in the text has the government making decisions as if its temporary mixture of models would prevail forever and therefore excludes purposeful experimentation. Cogley et al. (2008) study purposeful experimentation when a government trusts neither its submodels nor its Bayesian posterior over submodels.

<sup>38</sup> We have to put positive probabilities on the yet-to-be invented models in 1960 in order to launch our story. Foster and Young (2003) introduce new models randomly while having only one model being used to guide decisions at any moment.

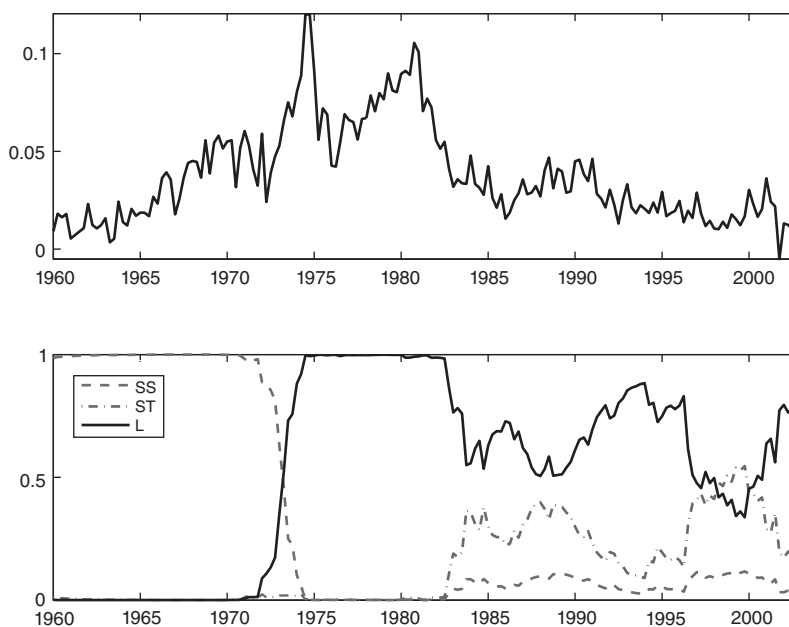


FIGURE 2

Notes: Top panel: CPI inflation. Bottom panel: Bayesian posterior model weights on the Samuelson-Solow (SS), Solow-Tobin (ST), and Lucas (L) models.

Figures 2 and 3 taken from Cogley and Sargent (2005) frame the following puzzles. By the early 1970s, the data had moved the government's prior to put probability approaching one on the Lucas model that recommends zero inflation (see Figure 2). Why, nevertheless, was actual inflation so high and variable in the 1970s? And why was the systematic part of inflation that emerges from the Phelps problem (see Figure 3) even higher and more variable? Why did the Phelps planner discount the recommendations of the Lucas model despite its high posterior probability?

The answer is to be found in what the Samuelson-Solow and Solow-Tobin models say would happen if the Lucas zero-target-inflation policy were to be adopted (see Figure 4). The Phelps problem weighs the submodel posterior probabilities against losses associated with various off-taken-path recommendations. In the early 1970s, their Keynesian direction of fit moved the coefficients in those submodels in ways that pointed to very high sacrifice ratios. Despite their low posterior probabilities, those models implied very high expected discounted losses if the Lucas policy recommendation were to be implemented immediately. In contrast, the high-probability Lucas model implied less adverse consequences if the recommendations of the Samuelson-Solow or Solow-Tobin models were allowed to prevail. So the Cogley and Sargent story is that the Lucas model's policy recommendation did not prevail in the 1970s because there remained a low probability that it would be disastrous. In order for a low-inflation recommendation to emerge from the Phelps problem, the estimated coefficients in the Samuelson-Solow and Solow-Tobin models had to adjust in ways that would moderate the consequences of a low-inflation policy. That happened by the mid-1980s.<sup>39</sup>

<sup>39</sup> The data also indicate that Bayes's law sponsors comebacks for the Samuelson-Solow and Solow-Tobin models in the 1980s and 1990s. One reaction that a true believer in the Lucas model might have is that Bayes's law is just too

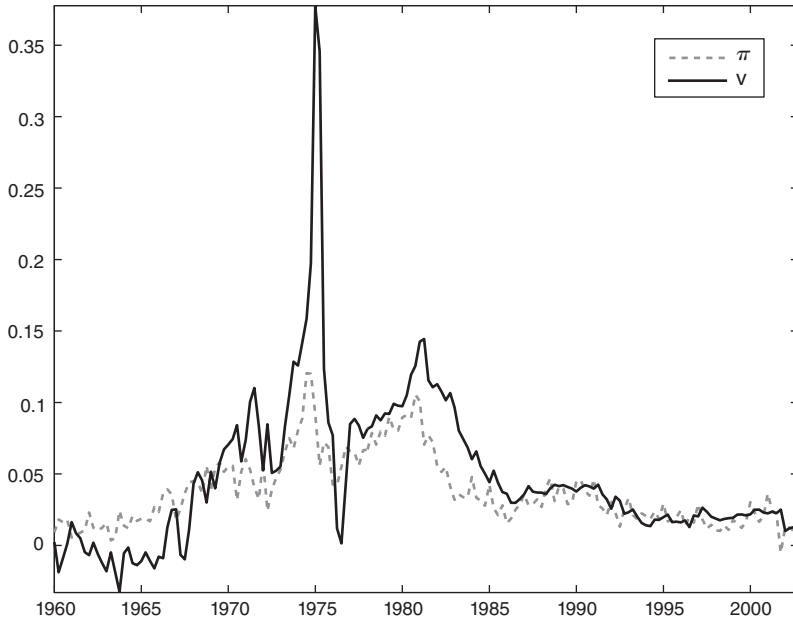


FIGURE 3

Note: CPI inflation and recommendation from Phelps problem.

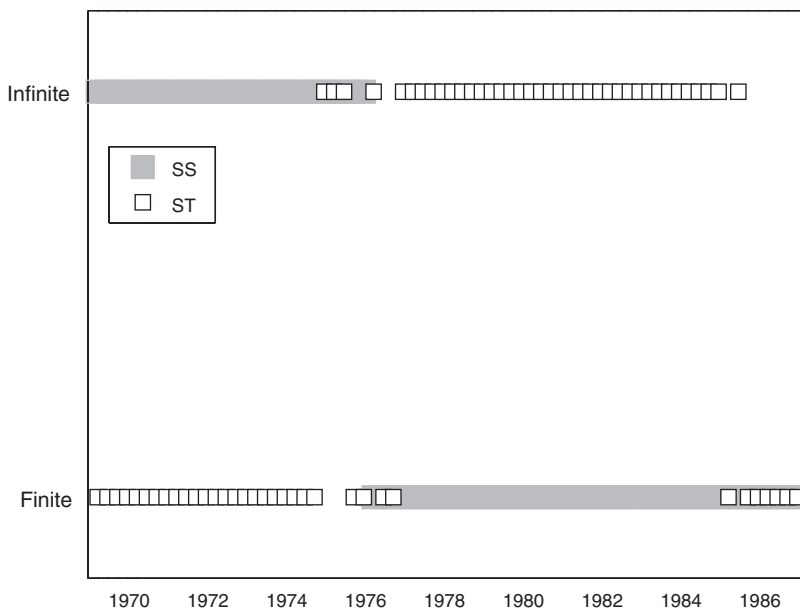


FIGURE 4

Notes: Losses under no-inflation policies for Samuelson-Solow (SS) model and Solow-Tobin (ST) models.

The direction-of-fit issue discussed by King and Watson (1994) helps explain how some of Primiceri's results relate to Cogley and Sargent's. Both models emphasize how monetary policy changed as the authorities updated their estimates, and Primiceri also attributes the inflation of the 1970s to the high perceived sacrifice ratio that Keynesian Phillips curve models presented to policymakers. But Primiceri assumes that the Fed relied exclusively on a version of the Solow-Tobin model and is silent about why the Fed disregarded the recommendations of the Lucas model. The central element of his story—the high perceived cost of disinflation or sacrifice ratio—is not a robust feature across the three submodels used by Cogley and Sargent, because it depends critically on the direction of fit, as documented by Cogley and Sargent (2005, 546–47). The sacrifice ratios differ so much across submodels because of how the submodels interpret the diminished, near-zero contemporaneous covariance between inflation and unemployment that had emerged by the mid-1970s. In a Keynesian Phillips curve, this diminished covariance flattens the short-term trade-off, making the authorities believe that a long spell of high unemployment would be needed to bring inflation down, prompting Keynesian modelers to be less inclined to disinflate. But for a classical Phillips curve, the shift toward a zero covariance steepens the short-term tradeoff, making the authorities believe that inflation could be reduced at less cost in terms of unemployment. Thus, a classically oriented policymaker was more inclined to disinflate.

#### D. *Lessons about Inflation Targeting*

Each of our stories about post-WWII US inflation features a government loss function that weighs both unemployment and inflation, thereby taking seriously the “dual mandate” that the Full Employment Act of 1946 and the Full Employment and Balanced Growth Act of 1978 (Humphrey-Hawkins) convey to the Fed. If they had assumed that the government one-period loss function is  $\pi^2$  instead of  $(U^2 + \pi^2)$ ,<sup>40</sup> then none of our stories could get off the ground. Despite the different imperfections in the approximating models they attribute to the monetary authority, all of the models would have the monetary authority always set target inflation to zero and be indifferent to the accompanying unemployment outcome. Each of our three stories thus contains a justification for inflation targeting as a device that compensates for model misspecification.<sup>41</sup>

Inflation-unemployment outcomes after WWII have caused many countries to adjust what they expect from monetary policy by mandating inflation targeting. That partly reflects extensive cross-country copying and partly a widespread belief that monetary authorities do not have good enough models to do more. When we asked for more, we usually got less.

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for giving in still putting positive probability on those other models after the early 1970s data had come in, and that the inflation problem of the 1970s would have been solved by driving a stake through those other models. But no one has the authority to drive stakes through models, and models with operating characteristics much like those two survive today. The dispute between the fallacious (according to Friedman and Anna J. Schwartz (1963, 191)) real bills doctrine and the quantity theory of money is mottled with repeated episodes having one of these doctrines being disposed of in favor of the other, then the other making a comeback. The real bills doctrine rides high in times like these when the Fed pegs a short term interest rate.

<sup>40</sup> Or Primiceri's loss function  $(\pi_t - \pi^*)^2 + \lambda(u_t - k\hat{u}_t^N)^2$ .

<sup>41</sup> Here, the reason for assigning an inflation target to the monetary authority is to prevent it from doing what it might want to do because it has a misspecified model, in contrast to the reasoning of Kenneth Rogoff (1985), in which the justification for strategic delegation is to prevent a monetary authority from doing what it is tempted to do when it has a correct model, but a timing protocol that presents temptations to deviate from superior policies that could be attained under a timing protocol that enables it to precommit.

## VII. Concluding Remarks

It is easy to agree with a warning by Sims (1980) that leaving the rational expectations equilibrium concept sends us into a “wilderness” because there is such a bewildering variety of ways to imagine discrepancies between objective and subjective distributions.<sup>42</sup> For this reason, relative to some models of learning in games (see Appendix A), the adaptive models described in this paper are cautious modifications of rational expectations theories and rational expectations econometrics by virtue of the ways that we allow our adaptive agents to use economic theory, statistics, and dynamic programming. The timidity of my departure from rational expectations reflects a desire to retain the discipline of rational expectations econometrics. I have focused on some of the things that can happen when a government solves an intelligent design problem with a misspecified model. I view the very simple statistical models in Section VI as parables that capture the situation that we are always in, namely, that our probability models are misspecified.<sup>43</sup> By stressing the possibility that learning has propelled us to a self-confirming equilibrium in which the government chooses an optimal policy based on a wrong model, the learning literature changes how we should think about generating the novel datasets and policies that will allow misguided governments to break out of the lack-of-experimentation traps to which self-confirming equilibria confine them.

It is also easy to admire the spirit of the quote from Ricardo. It conveys respect for the struggles of our predecessors and the monetary institutions that they created, and confidence that, armed with new models and technologies, we can do better.

### APPENDIXES

#### A. *Learning in Games*

In a game, a Nash equilibrium is the natural counterpart of a rational expectations equilibrium or a recursive competitive equilibrium. An extensive literature studies whether a system of adaptive players converges to a Nash equilibrium. A range of plausible adaptive algorithms has been proposed that are differentiated by how much foresight and theorizing they attribute to the players.<sup>44</sup> At one extreme are adaptive models that have naïve players who ignore strategic interactions and either play against histograms of their opponents’ past actions (fictitious play) or alter their moves in directions that ex post reduce their *regret* from not having taken other actions in the past, given their opponents’ histories of actions. At the other extreme are models in which players construct statistical theories about their opponents’ behavior, use them for a while to make forward-looking decisions, occasionally subject their theories to hypothesis tests, discard rejected ones, and choose new specifications.

This literature has sought plausible and robust algorithms that converge to a Nash equilibrium. Sergiu Hart and Andreu Mas-Colell say that this is a tall order:

*It is notoriously difficult to formulate sensible adaptive dynamics that guarantee convergence to Nash equilibrium. In fact, short of variants of exhaustive search (deterministic or stochastic), there are no general results.*

— Hart and Mas-Colell (2003)

<sup>42</sup> There is an infinite number of ways to be wrong, but only one way to be correct.

<sup>43</sup> This is the starting point of calibration in macroeconomics, i.e., the refusal to use maximum likelihood because the model builder views it as an approximation.

<sup>44</sup> For a critical survey of this literature, see H. Peyton Young (2004).

Hart and Mas-Colell and Foster and Rakesh Vohra (1999) show that the source of the difficulty is that most adaptive schemes specify that adjustments in a player's strategy do not depend on other players' payoff functions, an uncoupling of the dynamics that in general prevents the system from converging to a Nash equilibrium. Many examples of the adaptive schemes in the literature are uncoupled. Because many game theorists find uncoupled schemes desirable, parts of the literature have lowered the bar by looking for convergence to something weaker than Nash equilibria, namely, correlated equilibria or coarse correlated equilibria. Hart and Mas-Colell (2003, 1834) observed that "It is thus interesting that Nash equilibrium, a notion that does not predicate coordinated behavior, cannot be guaranteed to be reached in an uncoupled way, while correlated equilibrium, a notion based on coordination, can."<sup>45</sup>

Hart and Mas-Colell (2000, 2001, 2003) study adaptive schemes that are backward looking. For example, some of the most interesting ones have a player construct counterfactual historical payoffs that he would have received had he played other strategies, then compute a measure of regret, then adjust future play in directions that would have minimized regret. These schemes impute little or no theorizing and foresight to the players.

For my present purposes, one of the most interesting contributions comes from part of the literature that attributes more sophistication to players, in particular, the work of Foster and Young (2003), which is also summarized in Young (2004, ch. 8).<sup>46</sup> Their model has the following components: (1) each player has a large set of potential models that describe his opponents' strategies; (2) players use a random device to select a particular model; (3) after that model is selected, there is an "act-and-collect-data" period during which a player (incorrectly) assumes that he will believe his current model forever; during this period, each player chooses his actions via a smoothed best response to what his model tells him about opponents' actions (e.g., a quantal response function); (4) after a data-collection period, a player compares the empirical pattern of his opponents' play with that predicted by his model. He performs a hypothesis test that compares the theoretical and empirical distributions. If he rejects his current model, he randomly draws a new model from his set of models, then returns to step 2. If he accepts the model, he returns to step 3, waits a random number of periods, and then begins another data-collection period.

With suitable assumptions about the lengths of testing periods and the tolerances of the hypothesis tests, Foster and Young (2003) show that behaviors eventually emerge that are often close to Nash equilibria. Their notion of hypothesis tests is sufficiently broad to include many plausible procedures. Their convergence result seems to be an uncoupled multi-agent learning scheme that actually approaches Nash equilibria, not something weaker like the coarse correlated equilibrium that the entirely backward-looking schemes mentioned above can approach. They avoid the conundrum of Hart and Mas-Colell partly by weakening the notion of convergence.

### B. *From Commodity to Fiat Money*

A long process led to the ideas in the opening quote from David Ricardo, which in time led Keynes and others to propose a fiat currency.

<sup>45</sup> Experimental economics has supplied datasets designed to check ideas from the literature on adaptive learning in games. Laboratory experiments using macroeconomics are rarer than those using microeconomics. See Duffy (2006) for an account of the existing experiments. I suspect that the main reason for fewer experiments in macro than in micro is that the choices confronting artificial agents within even one of the simpler recursive competitive equilibria used in macroeconomics are very complicated relative to the settings with which experimentalists usually confront subjects.

<sup>46</sup> For a distinct but related approach, see Philippe Jehiel (1995, 1998). The Foster and Young (2003) model seems to me to capture some of the flavor of the anticipated utility framework advocated by Kreps (1998). The classifier models in Ramon Marimon, Ellen McGrattan, and Sargent (1990) have a similar flavor.

*Learning to Supplement a Commodity Currency with Tokens.*—Angela Redish (1990, 2000) and Sargent and François Velde (2002) described how it took 800 years to understand and cope with two imperfections that marred an ideal self-regulating commodity money system in which coins of all denominations were meant to exchange at values proportional to their silver (or gold) content. In the ideal system, a government instructed a mint to offer to sell coins of different denominations for precious metal at prices proportional to their weights in precious metal. The mint did not buy coins for metal, but citizens were free to melt precious metal coins to recover precious metal. If minting and melting were costless, this self-regulating system would automatically adjust the denomination structure of coins to suit coin holders' preferences by letting them melt coins of a denomination they wanted less of, then take the metal to the mint to buy coins of the denomination they wanted.<sup>47</sup> In the ideal system, a metal melt point equaled a metal mint point, denomination by denomination.

In practice, two imperfections hampered this system: (1) it was costly to produce coins; and (2) coins depreciated through wear and tear and sweating and clipping. The first imperfection gave rise to nonempty intervals between melt and mint points for gold or silver coins of each denomination—an upper point that indicated a melting point for that coin and a lower one that prompted minting. The proportionate spreads between minting and melting points differed because as a fraction of the value of the coin, it was cheaper to produce a large denomination coin than a small denomination coin. Unless the government were to subsidize the mint for producing low denomination coins, the spread between minting and melting points would be proportionately wider for low denomination coins. The second imperfection allowed underweight coins to circulate alongside full weight coins.

A nonempty interval between melting and minting points allowed coins to circulate by *tale* (i.e., by what is written on the coin rather than by weight) at an exchange value that exceeded their value by weight. Indeed, in the presence of costs of producing coins, the money supply mechanism provided incentives for people to purchase new coins from the mint only when their value in exchange exceeded their value by weight by enough to cover the mint's brassage and seigniorage fees (Adam Smith 1789, book I, ch. 5).

Nonempty intervals with proportionately wider widths for lower denomination coins and a consequent exchange rate indeterminacy allowed the intervals to shift over time and eventually to become so misaligned that they recurrently provided incentives to melt small denomination coins. That created the recurring shortages of small coins documented by Carlo Cipolla (1956, 1982).<sup>48</sup>

Cipolla (1956) described a temporary practical remedy for these shortages. The authorities debased small denomination coins, thereby shifting their mint-melt intervals in a direction that motivated citizens to purchase new coins from the mint. Monetary authorities throughout Europe used this method for hundreds of years. There were repeated debasements in small denomination silver coins and secular declines in rates of exchange of small denomination for large denomination coins.

Many experiments, some inadvertent, others purposeful, were performed, and numerous theoretical tracts were written and disputed before what Cipolla (1956) called the "standard formula" for issuing token small denomination coins was put into practice in the mid-nineteenth century.<sup>49</sup>

<sup>47</sup> Sargent and Velde (2002, 95) cited Bernardo Davanzati, who in 1588 wrote that "metal should be worth as much in bullion as in coin, and be able to change from metal to money and money to metal without loss, like an amphibious animal."

<sup>48</sup> This multi-interval commodity money system in which coins circulate by *tale* is taken for granted by Smith (1789, book I, ch. 5).

<sup>49</sup> This process of shuttling through experiments, reformulations of theories, and further experiments reminds me of the hypothesis-testing learning models of Foster and Young (2003) and Cho and Kasa (2006).



It solved the problem of misaligned mint-melt intervals for coins of different denominations by, first, having only one large denomination full weight coin that the mint sold for a precious metal, and, second, having the government issue difficult-to-counterfeit small denomination token coins that it promised to convert on demand into the large denomination coin. This required a technology for manufacturing coins that were difficult to counterfeit.<sup>50</sup>

As examples of inadvertent experiments, token monies were occasionally issued inside besieged cities and sometimes they worked. A document that anticipated ideas of John Law, Adam Smith, and David Ricardo sparked a purposeful experiment. It advised King Ferdinand II of Spain that he could issue token copper coins that Spanish residents would voluntarily accept from the government in exchange for full-bodied silver coins. It described how this fiscal boon to the Spanish treasury could be attained in a noninflationary way.<sup>51</sup> Three successive Spanish kings tried this experiment, which had all of the ingredients of the nineteenth-century standard formula except convertibility. For 25 years, the experiment worked well, yielding the government substantial revenues without inflation. But eventually excessive issues of copper coins caused inflation, in the aftermath of which the Spanish monetary authorities pursued a fascinating sequence of experiments. They repeatedly restamped copper coins and manipulated the unit of account in order either to adjust the price level or raise revenues for the Spanish government.

The quantity theory can operate only in the limited interval between the mint and melt points for a precious metal, so a commodity money system conceals the quantity theory. When the Spanish broke through those restrictions, they gave the British statistician Sir William Petty data that he used to discover a quantity theory of money (see Charles Henry Hull 1899). Other episodes created more data that further substantiated the quantity theory of money, for example, the construction and collapse of John Law's system (see Velde 2007) and the overissuing of French assignats after the sales of the church lands that had initially backed them were suspended when war broke out in 1792 (see Sargent and Velde 1995). But the same episodes that lent vivid empirical support to a quantity theory also brought evidence that government monetary authorities could not be trusted to administer a pure fiat standard in ways that stabilized prices.<sup>52</sup>

In 1660, the master of the British mint, Henry Slingsby, added an element missing from the Spanish experiment, namely, convertibility of token coins, and recommended what in the nineteenth century became the standard formula.<sup>53</sup> But perhaps because the inflation accompanying the Spanish and similar experiments had given token coins a bad name, the British government ignored Slingsby's recommendations. Many experts, including John Locke (1691), continued to insist that token coins of any denomination were dangerous and that a good faith commodity money system required that coins of all denominations be full bodied. For a long time, that sentiment convinced national governments not to issue tokens, but other entities created them. In seventeenth- and eighteenth-century Britain, hundreds of private firms and municipalities issued small denomination tokens that formed a substantial part of the country's coinage. Between 1816 and 1836, the British government implemented the standard formula by nationalizing a token coin industry that had long existed.

*Ricardo's Proposal.*—It required 156 years to take the short logical step from Henry Slingsby's 1660 standard formula for issuing convertible token subsidiary coins to David Ricardo's 1816

<sup>50</sup> See Redish (1990, 2000) and George Selgin (2003).

<sup>51</sup> See the document cited in Sargent and Velde (2002, 231–32).

<sup>52</sup> I suspect that is why later advocates for replacing the gold standard with “more scientific” systems of managed currencies including Adam Smith and Ricardo to Keynes purposefully omitted references to some of the historical experiments that generated the data that were sources for the quantity theory of money. For example, Smith (1789) did not cite John Law's theoretical writings as among the sources for his monetary recommendations.

<sup>53</sup> See Sargent and Velde (2002, 268–69).

recommendation. Ricardo proposed that a country's domestic money supply should ideally consist of paper notes that the government promises to exchange at a pegged price for gold bullion bars, but that no gold coins should actually be minted. A variant of Ricardo's scheme in which a government promises to redeem domestic notes for gold, but only for foreign residents, came to be practiced around 1900. This arrangement, by which "a cheap local currency [is] artificially maintained at par with the international standard of value" (Keynes 1913, 25), was called the "gold exchange standard." Keynes described how by 1913 this system had come to prevail in India through a sequence of haphazard administrative decisions that eventually produced a coherent system that no one had planned, but that Keynes applauded. Keynes (1913, 25) predicted that Ricardo's scheme would be an essential part of "the ideal currency system of the future."<sup>54</sup>

The standard formula eliminates the gold or silver points for all but one standard coin, uses the mint and melt points for that coin to regulate the total quantity of money, and promises freely to convert tokens into that standard coin in order to produce the correct denomination composition. It was one more step from the standard formula or Ricardo's proposal to the recommendation of Fisher (1920), Keynes, and others that well-intentioned government officials, not the mint and melt points for a standard coin, should regulate the supply of money. Discovering the quantity theory of money was an essential step in learning the conditions under which a fiat money system could be managed to provide greater price level stability than could be achieved with a gold standard.

As Keynes wanted, in the twentieth century, governments throughout the world carried out the historically unprecedented experiment of managing currencies completely cut off from gold backing (see Friedman 1992, 245). Figure 5 documents that, at least until very recently, the monetary authorities in four hard-currency countries failed to deliver the kind of price stability that a commodity standard had achieved. There was much more inflation in many other countries.

### C. A Monetary Policy Rules Literature

The adaptive models described in Section VI explain the rise and fall of post-World War II US inflation in terms of monetary policy rules that drifted in response to drifts in the monetary authorities' models of the economy. All three models embed very crude descriptions of the monetary policy rules and sidestep many interesting questions about monetary policy transmission mechanisms. It is appropriate to say a few words about a related literature that uses time series data to infer the structure of postwar US monetary policy rules and how they have changed over time. The bottom line is that this literature has mixed evidence about whether monetary policy rules shifted enough to validate stories along the lines of our three adaptive models.<sup>55</sup>

Bernanke and Ilian Mihov (1998) developed an SVAR methodology for measuring innovations in monetary policy and their macroeconomic effects. They compared alternative ways of measuring monetary policy shocks and derived a new measure of policy innovations based on possibly time-varying estimates of the Fed's operating procedures. They presented a measure of the overall stance of policy (see Bernanke and Mihov 1998, fig. III, 899) that is striking in how the distribution of tight and loose policies seem not to have changed much in the periods before and after 1980.

<sup>54</sup> Speaking of how a change in Indians' preferences for holding gold could cause world-wide inflation in prices: "The time may not be far distant when Europe, having perfected her mechanism of exchange on the basis of a gold standard, will find it possible to regulate her standard of value on a more rational and stable basis. It is not likely that we shall leave permanently the most intimate adjustments of our economic organism at the mercy of a lucky prospector, a new chemical process, or a change of ideas [preferences for holding gold] in Asia" (Keynes 1913, 71).

<sup>55</sup> This mixed news partly reflects the fact that it is statistically difficult to detect drifts or shifts in the systematic part of a vector autoregression, and much easier to detect changes in volatilities.

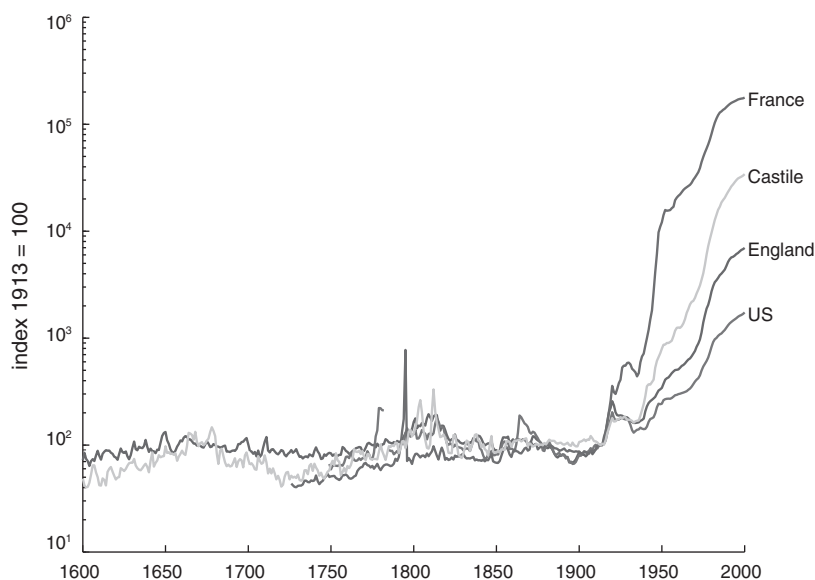


FIGURE 5

*Note:* Indices of prices in terms of unit of account in England, the United States, France, and Spain. Sargent and Velde (2002, 35).

But Clarida, Galí, and Gertler (2000) estimated a forward-looking monetary policy reaction function for the postwar United States economy before and after Volcker's appointment as Fed Chairman in 1979, and they found substantial differences across periods. They found that interest rate policy in the Volcker-Greenspan period has been much more sensitive to changes in expected inflation than in the pre-Volcker period. They then extracted implications of the estimated rules for the equilibrium properties of inflation and output in a new Keynesian DSGE model and showed that the Volcker-Greenspan rule is stabilizing, but that the earlier rule was not. Thomas A. Lubik and Frank Schorfheide (2004) estimated a new Keynesian model like Clarida et al.'s in which the equilibrium is undetermined if monetary policy is passive. They constructed posterior weights for the determinacy and indeterminacy region of the parameter space, as well as estimates for the propagation of fundamental and sunspot shocks. They found that US monetary policy after 1982 was consistent with determinacy, but that the pre-Volcker policy was not, and also that before 1979 indeterminacy substantially altered the propagation of shocks.

In contrast, working in terms of less completely interpreted models, Sims and Zha (2006) estimated a multivariate regime-switching model for monetary policy and found that the best fit allows time variation in disturbance variances only. When they permitted the systematic VAR coefficients to change, the best fit was with change only in the monetary policy rule. They estimated three regimes that correspond to periods across which the folk-wisdom states that monetary policy differed. But they found that those differences among regimes were not large enough to account for the rise and decline of inflation of the 1970s and 1980s. Likewise, by estimating a time-varying VAR with stochastic volatility, Primiceri (2005) found that both the systematic and nonsystematic components of monetary policy had changed. In particular, he found that the systematic responses of the interest rate to inflation and unemployment exhibited a trend toward more aggressive behavior, while also having sizeable high frequency oscillations. But Primiceri concluded that those had small effects on the rest of the economy and that exogenous

nonpolicy shocks were more important than interest rate policy in explaining the US inflation and unemployment episodes of the 1970s, thus coming down more on the “bad luck” than the “bad policies” side of the argument. I hope that conclusion is too pessimistic, because we have learned to do better.

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