Monetary Policy under Uncertainty and Learning: An Overview

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Uncertainty is not just an important feature of the monetary policy landscape: it is the defining characteristic of that landscape.

—Alan Greenspan

Central bank economists and academic economists conducting research on the design of monetary policy have made significant advances in recent years. This work has led to a clearer understanding of the desirable properties of interest rate rules, the role of announcements and communication, and the consequences of inflation targeting for both inflation and the real economy. Dynamic stochastic general equilibrium (DSGE) models have been extended from the small-scale, often calibrated versions initially employed to address policy issues to much larger models that are estimated using Bayesian techniques. Many central banks now use these models for policy evaluation.[1] Much of this work neglects one of the key issues that policymaker face, however: the pervasive role of uncertainty. The recent global financial crisis and recession serve as the latest example of the policy challenges posed by unexpected and unforeseen events.

At the time of the conference, Klaus Schmidt-Hebbel was affiliated with the Central Bank of Chile.

1. See Galí (2008) for an excellent treatment of the basic New-Keynesian model that has become standard in monetary policy analysis. Examples of estimated DSGE models include Christiano, Eichenbaum, and Evans (2005), Levin and others (2006), Smets and Wouters (2003), Adolfson and others (2008), and Christiano, Motto, and Rostagno (2007).

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The huge swings in oil, food, and other commodity prices in recent years and the dramatic global financial crisis have dominated discussions of monetary policy in the past year. These events provide vivid reminders of how uncertainty, imperfect knowledge of the economy, and the need to learn about new developments in world goods and financial markets affect the macroeconomy and influence the conduct of monetary policy. In this book, leading international scholars address many of the key issues relevant for central banks who must by necessity operate in environments of uncertainty and in which policymakers and the public are continually learning about the economy.

1. Uncertainty and Learning

In this section, we selectively review the literature on uncertainty and learning, focusing specifically on the insights that are important for the conduct of monetary policy. The next section then surveys the new research contained in this volume.

1.1 Types of Uncertainty and their Implications for Monetary Policy

Limitations of economic theory and data, structural changes in the economy, the inherent unobservability of important macroeconomic variables such as potential output and the neutral interest rate, and disagreements over the correct model of the economy and the transmission process of policy are just some of the reasons why central bankers operate in an environment of uncertainty. Research into the effects of uncertainty and the design of optimal policy in the face of uncertainty has broadly focused on three types of uncertainty: additive uncertainty, model uncertainty, and imperfect information.

To illustrate these different forms of uncertainty, suppose that the "true" model of the economy takes the form

$$\mathbf{y}(t+1) = \mathbf{A}\mathbf{y}(t) + \mathbf{B}\mathbf{y}(t \mid t) + \mathbf{C}i(t) + \mathbf{D}\mathbf{u}(t+1), \tag{1}$$

where $\mathbf{y}(t)$ is a vector of macroeconomic variables at time t, $\mathbf{y}(t \mid t)$ is the policymaker's current estimate of $\mathbf{y}(t)$, $i(t)$ is the central bank's instrument, $\mathbf{u}(t)$ is a vector of random, exogenous disturbances, and $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, and $\mathbf{D}$ are matrices containing the parameters of the model. Most models used for monetary policy analysis can be represented by this linear structure.

Additive uncertainty is represented by the disturbances $\mathbf{u}(t + 1)$: when setting its instrument at time t, the central bank does not know what future shocks $\mathbf{u}(t + 1)$ will hit the economy. Model uncertainty arises because the central bank does not know the true parameters that characterize the model (that is, the values of **A**, **B**, **C**, and **D**); parameter estimates are subject to error, and the policymaker may believe some parameters are zero when they are in fact nonzero. Finally, imperfect information arises because the actual value of $\mathbf{y}(t)$ may be unobserved or only observed with error as a result of measurement error or data lags; as a consequence, the policymaker's best estimate of $\mathbf{y}(t)$, $\mathbf{y}(t \mid t)$, may be wrong. Following Walsh (2003), we discuss each of these sources of uncertainty in turn.

1.1.1 Additive uncertainty

The most extensively studied form of uncertainty is that arising from additive errors to the model's structural equations. In terms of the notation in equation (1), additive uncertainty is represented by $\mathbf{Du}(t + 1)$. At the time the central bank must make its policy choice, the value of this term is unknown. Uncertainty about the realized values that $\mathbf{Du}(t + 1)$ will take is the only form of uncertainty that typically is included in most models. Modern DSGE models often include random disturbances that enter the equilibrium conditions in nonlinear ways, but these models are then linearized, so that disturbances appear as additive error terms.

The problem of characterizing optimal policy in the face of additive uncertainty is well understood when the policymaker's objectives can be expressed as a quadratic function of various target variables. The standard assumption that central banks desire to minimize the volatility of inflation around its target and real output around potential output lends itself naturally to a representation in terms of a quadratic loss function in which squared deviations of inflation from the target and real output from potential output are penalized. The combination of linear, additive disturbances and quadratic objectives satisfies the well-known principle of certainty equivalence—all that matters for optimal policy are the expected values of the unknowns. Simply replace unknown disturbances with one's best forecast of their values and then treat these forecasts as if they were known with certainty. Thus, again in terms of equation (1), the central bank would replace $\mathbf{Du}(t + 1)$ with its expected value,

$\mathbf{D}E\mathbf{u}(t + 1)$ and then choose policy as if the true model were known with certainty to be

$$\mathbf{y}(t + 1) = \mathbf{A}\mathbf{y}(t) + \mathbf{B}\mathbf{y}(t \mid t) + \mathbf{C}i(t) + \mathbf{D}E\mathbf{u}(t + 1). \tag{2}$$

In this case, optimal policy does not require knowledge of the variances of the disturbances or the covariances among the different disturbances. This does not mean that *only* the expected value of the disturbance is relevant. Policymakers will usually need to forecast future values of these exogenous disturbances, and this will require some knowledge of, or at least assumptions about, the persistence of shocks. For example, a forecast that the price of oil will rise is generally not sufficient; the policymaker will need to forecast whether the rise is temporary or whether it is likely to be persistent.

To deal with additive uncertainty, Giannoni and Woodford (2002) propose optimal policies, which they call robustly optimal policies. Robustly optimal policy rules describe how the policy instrument should be set solely in terms of the macroeconomic variables that define the central bank's objective. If the central bank is concerned about maintaining low and stable inflation, stabilizing a measure of output relative to potential (the output gap), and stabilizing interest rate volatility, then the robustly optimal policy rule would show how the policy interest rate should be set as a function of inflation, the output gap, and lagged interest rates. Thus, implementing such a policy does not require information about the time series properties of the exogenous disturbances. Such a property is desirable, as it may be difficult to accurately forecast the degree of persistence in exogenous economic disturbances.

When the central bank is concerned with inflation and output gap stability, the optimal rule can be defined solely in terms of inflation and the output gap. In fact, the optimal policy can be characterized simply, as follows: keep a specific linear combination of inflation (relative to target) and the output equal to zero; if inflation is above target, then the output gap should be negative. The Bank of Norway, for example, describes the desirable properties of an interest rate path as one that ensures that the output gap is negative if the inflation gap (that is, inflation relative to the target) is positive. Adjusting the policy interest rate to maintain this sort of relationship between inflation and the output gap is often called a targeting rule, as it only involves the variables that are directly part of the central bank's objectives.

Unfortunately, robustly optimal policy rules generally require the central bank to make forecasts of inflation and the output gap.

Because monetary policy affects the economy with significant lags, policy must be forward looking, and this forces the central bank to rely on forecasts. To form forecasts of future inflation or real economic activity, however, the policymaker will need to decide whether a shock such as an oil price increase is temporary and will be reversed or is permanent. Thus, robustly optimal rules do not actually eliminate the need to forecast future disturbances.

In contrast to a robustly optimal rule, central bank behavior is often represented by simple instrument rules such as a Taylor rule. These rules typically assume that monetary policy is adjusted systematically in response to current movements in inflation and measures of the output gap. Other variables, such as the exchange rate, are sometimes also included. Given a specification of the central bank's objective, the coefficients in the rule can be chosen optimally. In contrast to fully optimal rules such as Giannoni and Woodford's robustly optimal rules, the best response coefficients in simple Taylor-type rules will depend on the relative variances of the basic disturbances that affect the economy. Designing the optimal "simple" rule thus requires a great deal of information about the additive shocks that hit the economy.

1.1.2 Model uncertainty

Model uncertainty encompasses a wide range of potential sources of error. Model misspecification, parameter uncertainty, and estimation error can all be grouped under this heading. Uncertainty about the values of the coefficient matrices **A**, **B**, **C**, and **D** is one reflection of model uncertainty. This uncertainty may arise because the central bank does not know the true values of the parameters in the model and must estimate them, or it could stem from the fact that the central bank's model incorporates incorrect assumptions about how the macroeconomic variables are related. Moreover, the true model may be evolving over time in unknown ways as a result of technological changes and innovations.

To illustrate how model uncertain affects the policy problem, suppose that we can ignore imperfect information, so that $\mathbf{y}(t) = \mathbf{y}(t \mid t)$. Let $\mathbf{A} + \mathbf{B} = \mathbf{H}$, and to keep the example simple, assume only elements of **A** and **B** are not known with certainty. The model then becomes

$$\mathbf{y}(t+1) = \hat{\mathbf{H}}\mathbf{y}(t) + \mathbf{C}i(t) + \mathbf{v}(t+1), \tag{3}$$

where $\mathbf{v}(t+1) = \mathbf{Du}(t+1) + (\mathbf{H} - \hat{\mathbf{H}})\mathbf{y}(t)$ and $\hat{\mathbf{H}}$ is the central bank's estimate of $\mathbf{H}$. Errors in estimating $\mathbf{H}$ now become part of the equation's error term, but the key difference from the case of additive uncertainty is that the errors represented by $\mathbf{v}(t+1)$ are now correlated with the endogenous variables $\mathbf{y}(t)$. The disturbance terms are no longer exogenous; misspecification is correlated with macroeconomic outcomes. This has important implications for policy choice, as first pointed out by Brainard (1967).

The type of uncertainty represented in equation (3) is called multiplicative uncertainty, since the uncertainty associated with the parameters in $\mathbf{H}$ multiply the endogenous variables. In the example he considered, Brainard (1967) showed that multiplicative uncertainty would make optimal policy less activist. Alan Blinder famously characterized the first step in a preemptive policy for controlling inflation as requiring the central bank to "estimate how much you need to tighten or loosen policy to 'get it right,' then do less" (Blinder, 1998, p. 17). This statement accurately reflected the caution that Brainard found to be appropriate in the face of multiplicative uncertainty.

In research subsequent to the work of Brainard, it was found that caution is not necessarily the best response to model uncertainty (Craine, 1979; Giannoni, 2002; Söderström, 2002). In fact, some forms of multiplicative uncertainty call for a more robust response than otherwise. For example, this may be the case when the uncertainty involves the dynamic response of the economy to shocks. If the central bank is uncertain about the degree to which current inflation may influence future inflation, it may be best to respond strongly to ensure that current inflation remains stable. Thus, an aggressive policy rather than a cautious one may be the best policy. In general, economists have found that there are no clear guidelines about how best to react when faced with this type of uncertainty.

Multiplicative uncertainty is certainly not the only, or even the most important, form of model uncertainty. More commonly, there are competing models for how the economy operates and how monetary policy affects macroeconomic activity and inflation. Within current macroeconomic circles, there are economists who employ models in which monetary policy can have important short-run real effects because of sticky prices and wages and other economists who use models in which monetary policy is impotent in affecting the real economy because all wages and prices are flexible. Faced with these competing models in an environment in which no one knows the true model of the economy, how should policymakers behave?

Clearly, policy is unlikely to contribute to macroeconomic stability if policymakers hold beliefs about the economy that are wrong. Romer and Romer (2002) attribute policy mistakes in the United States in the late 1960s and the 1970s to the use of a wrong model. Specifically, they argue that policymakers in the 1960s believed there was a permanent tradeoff between average unemployment and average inflation, and this led to the onset of the Great Inflation in the United States. Romer and Romer then argue that once inflation had reached high levels, policymakers came to believe that inflation was insensitive to recessions, implying that the cost of reducing inflation would be extremely high. Inflation was therefore allowed to rise, and policymakers delayed reducing it because they based their decisions on models that we now view as incorrect.

The example of model uncertainty provided by equation (3) shows how errors in the central bank's estimate of the parameters in $\mathbf{H}$ would interact with the endogenous variables represented by $\mathbf{y}(t)$. However, if $\mathbf{H} - \hat{\mathbf{H}}$ reflects estimation error or purely random fluctuations in the elements of $\mathbf{H}$, it might not be systematically related to economic developments. Hansen and Sargent (2003, 2004) study optimal policy in environments where the model uncertainty faced by the policymaker is not exogenous, but is designed to be particularly troublesome. They consider the case in which the policymaker fears that model misspecification will yield what, from the policymaker's perspective, is the worst possible outcome. In this environment, the policymaker seeks policies that are robust in the sense that they lead to reasonable outcomes even in the worst-case scenario. In the context of a simple monetary policy problem, Walsh (2004) shows that the worst-case scenario for the central bank involves the occurrence of a positive inflation shock when the economy is already in a recession. Such a scenario pushes the economy further away from the objectives of both low inflation and full employment.

Optimal policy in the face of this malicious misspecification turns out to require the central bank to employ a model of the economy that is deliberately distorted, in the sense that the central bank should assume that inflation shocks will be much more persistent than they are actually expected to be. Thus, in contrast to Gianonni and Woodford (2002), who designed policy rules that do not require the central bank to actually know (or even estimate) the true persistence of inflation shocks, Hansen and Sargent's approach has the central bank behave as if inflation shocks were always very persistent, even if they generally are not.

Worst-case scenarios are, almost by definition, events that occur with low probability, and the Hansen-Sargent approach has been criticized for putting too much weight on the worst-case scenario in policy decisions. However, the idea that a policymaker might want to use a distorted model when designing policy is supported by other lines of research. For example, Levin and Williams (2003) consider what happens when a policy is designed to be optimal for a particular model, but that model turns out to be wrong. They find that policy rules designed to be optimal in models that display high levels of inertia also perform well if the "true" model of the economy is very forward looking. Unfortunately, they find the converse not to be true. Policies designed to do well if forward-looking behavior is important often perform disastrously if the actual economy displays high degrees of inertia. Hence, even if the central bank believes that inflation and real economic activity are heavily influenced by expectations of future inflation and growth, it might still want to act as if the economy were much more backward looking.

In practice, central banks often deal with model uncertainty by employing several models of the economy, using the different models to cross-check forecasts and to ensure that policies are not excessively sensitive to assuming that a particular model is correct. Given competing models of the economy, a sensible approach might be to evaluate alternative polices in several models and to weight the different models based on an assessment of their likelihood. However, Cogley, Colacito, and Sargent (2007) illustrate how model uncertainty can lead to bad policies even when the policymaker is carefully trying to account for the uncertainty by using multiple models to evaluate policies. They consider two simple models. One model, labeled the Samuelson-Solow model, implies that the central bank faces a tradeoff between average unemployment and average inflation. The other incorporates the natural rate hypothesis, implying no tradeoff between average inflation and unemployment. This second model also implies that a credible disinflation would reduce inflation costlessly. The policymaker assigns probabilities to each model, reflecting the likelihood the data assign to each model being the true model. Cogley, Colacito, and Sargent show that by the early 1970s, U.S. data implied that almost all weight should be placed on the natural rate model. This meant that the optimal policy would be to immediately bring down inflation. However, the data still assigned a small but positive probability that the Samuelson-Solow model might be correct, and if that model turned out to be true, the output costs of an immediate disinflation would be enormous. So even though the central bank is almost certain the natural rate model is correct, it fails to reduce inflation out of fear that the Samuelson-Solow model might be correct. Thus, even a model that the data suggest is unlikely to be true can affect policy choices when the policymaker employs several models as a means of seeking robust policies.

1.1.3 Imperfect information

A final type of uncertainty arises from imperfect information. Just about any form of uncertainty could be labeled as being due to imperfect information (about the realizations of the additive disturbances, about the true model, and so on). However, we use the term to refer to a specific aspect of uncertainty—namely, that stemming from the inability to perfectly observe the current state of the economy or macroeconomic variables that are critical for policy design.

Policy decisions are made based on noisy and imperfect data about the economy. A number of authors investigate how data uncertainty affects optimal policy. Intuitively, one would expect that the presence of noise in macroeconomic data would call for responding less strongly to new data. Responding too strongly might simply introduce volatility if the signal-to-noise ratio is small, that is, if much of the variation in the data is simply noise. Rudebusch (2001) explores how data noise would reduce the optimal responses to inflation and the output gap in a standard Taylor rule. Earlier work that ignored data uncertainty found that the optimal response to the output gap was much larger than Taylor found for the Federal Reserve under Alan Greenspan. Rudebusch attributed part of the weaker response found in the data to the presence of noise in measures of the output gap.

Besides the issue of pure measurement error in real time data on observable variables, a further difficulty arises from the fact that many of the variables that play critical roles in theoretical models are not directly observed. The output gap is the best example of this problem. New-Keynesian models define the output gap as the percentage difference between actual output and the output the economy would produce if all wages and prices were flexible, the so-called flexible-price output level. While data on actual output is subject to measurement error and data revisions, it is at least directly measurable. The same cannot be said of the flexible-price output level. Any estimate of the latter will be dependent on a particular theoretical model of how the economy would behave with flexible prices. Older definitions of the output gap that measured output relative to potential output suffered from similar problems. Potential output is not observed but must be estimated, and standard techniques typically relied on simple statistical methods to equate potential output with trend output. This left open the issue of how best to estimate the trend growth rate of real output.

Measures of trend output are inevitably backward looking. They use historical data to estimate trends, so they are likely to have difficulty picking up shifts in underlying growth trends. A case in point was the 1970s, when many countries experienced a decline in trend growth. Orphanides (2003) argues that bad macroeconomic policies in the 1970s in the United States resulted from the failure to recognize this decline in the trend rate of growth. Because it based its estimate of trend growth on historical data, the Federal Reserve was slow to pick up the decline in the growth rate, and it thus overestimated the path of trend output in the 1970s. As a consequence of overestimating trend output, the Federal Reserve believed a negative output gap was opening up. It therefore adopted policies that, in retrospect, were too expansionary. This data-uncertainty hypothesis represents an alternative explanation for the Great Inflation of the 1970s to the interpretation based on the model-uncertainty hypothesis.

Given the difficulties involved in measuring the output gap, McCallum (2001) argues that central banks should not react to it strongly. Alternatively, Orphanides and Williams (2002) find that policy rules that respond to the change in the estimated output gap often perform well and avoid some of the measurement problems that make it difficult to estimate the level of potential output.

Problems with estimating the output gap are only one example of how key variables that modern economic theory suggests should be central to monetary policy are difficult to estimate and may even be unobservable. Another example is the neutral real interest rate, defined as the real interest rate consistent with a zero output gap and a zero deviation of inflation from target. Some modern models imply that the actual real interest rate should move in parallel with this neutral real rate, but the neutral real rate is ultimately unobservable. Several authors attempt to estimate the neutral real rate and the output gap (see Kuttner, 1994; Laubach and Williams, 2003; Garnier and Wilhelmsen, 2005; Benati and Vitale, 2007), but such estimates generally rely on restrictions implied by a particular model of the economy. If policymakers are uncertain about the correct model, they will also be uncertain about how best to measure the neutral real rate and the output gap. Imperfect information is thus a major problem facing policymakers.

1.2 Learning

The uncertainty faced by central banks largely reflects our imperfect understanding of macroeconomics. Economists and policymakers are constantly engaged in a process of learning about the economy. Similarly, members of the public are forming expectations based on their evolving understanding of the economy and the policymaker's behavior. Consequently, learning is pervasive—models are constantly refined and reestimated, new models are developed to reflect the latest progress in economic research, and previously ignored factors suddenly become important and must be incorporated into policy models. At the same time, the public must assess policy decisions and attempt to learn about the central banks' objectives and the way policy is being carried out. In recent years, a large literature has developed that investigates the effects of learning on macroeconomic outcomes and its implications for monetary policy.

Much of the work on learning in macroeconomics is based on the seminal work of Evans and Honkapohja (2001). Evans and Honkapohja (in this volume) provide an excellent overview of this research and its implications for monetary policy. The literature they survey drops the extreme informational assumptions implicit in the rational expectations approach. Instead, individuals (and policymakers) are viewed essentially as econometricians, using the latest data to reestimate and update their models and then using these models to make forecasts of future inflation and other macroeconomic variables. Evans and Honkapohja argue that this view of learning reflects the principle of cognitive consistency, in that it assumes private "agents should be about as smart as (good) economists" (in this volume, page 67). Explicitly incorporating learning allows the authors to study two general issues of relevance for policy. First, will the economy under learning converge to the equilibrium consistent with rational expectations? And second, how are macroeconomic dynamics affected by learning? If rational expectations equilibria are not stable under learning—a property called E-stability or learnability—then the properties of the rational expectations equilibrium becomes irrelevant for describing the economy's behavior once the economy's structure is understood. The standard practice in policy analysis is to study the properties of alternative policies under the assumption that the private sector fully understands how the central bank is behaving. This may be an appropriate assumption in terms of the eventual behavior of the economy, but only if the public eventually learns the true structure of the economy. If the public gradually learns about the different policies the central bank might follow, then the economy may not converge to the rational expectations equilibrium.

As Evans and Honkapohja (in this volume) discuss in their overview chapter, some policy rules for the central bank that appear to be quite reasonable rules under rational expectations can lead to instability under quite reasonable models of learning. However, Bullard and Mitra (2002) show that when the central bank follows a simple Taylor rule for setting the nominal interest rate, the same condition that ensures a unique equilibrium under rational expectations also ensures that the equilibrium is stable under learning. This condition, called the Taylor Principle, requires the central bank to adjust the nominal rate more than one-to-one with inflation.[2] Bullard and Mitra also show that if the central bank responds to expected future inflation rather than current inflation, some policy rules that lead to indeterminacy (multiple equilibria) under rational expectations have equilibria that are stable under learning. In general, Evans and Honkapohja argue that expectations-based policy rules—that is, rules in which the central bank responds to the private sector's inflation expectations and the output gap—have desirable properties. These rules implicitly incorporate the public's learning into the policy rule.

The second broad arena in which the learning literature has contributed to our understanding is macroeconomic dynamics. The manner in which the economy evolves will depend on the way the public learns, and the economy's response to disturbances can differ significantly under learning versus under rational expectations. Incorporating the effects of learning can be particularly important if the central bank is considering changing its policy behavior. The private sector's attempts to learn the new policy can affect the economy's adjustment if the central bank is not explicit or transparent about its policy. For example, Erceg and Levin (2003) study the role of learning in accounting for the steep recessions in the United States associated with the Volcker disinflation of the early 1980s. Under rational expectations, an announced reduction

2. This condition is weakened slightly if the central bank also responds to the output gap.

in the Fed's inflation target should have lowered inflation with little loss in real output. Erceg and Levin show that they can best match the historical experience of a gradual disinflation accompanied by recession when they assume that the Fed's anti-inflation stance lacked credibility and the public engaged in a process of learning about the Fed's target.

The learning literature has also developed new insights that are relevant for the debate over the optimal degree of central bank transparency. In general, greater transparency helps speed learning by providing useful information to the public. In that way, transparency can reduce the volatility that can occur when the public is trying to learn the central bank's objectives. Transparency can also ensure that the economy converges more quickly to the rational expectations equilibrium (Rudebusch and Williams, 2008). Incorporating learning is also relevant for ensuring that policies are robust when private agents and the policymaker may have evolving beliefs about the economy, as in Orphanides and Williams (in this volume).

Perhaps the most important lesson from the learning literature is that in a world of uncertainty and change, both private economic agents and the central bank engage in learning, and this process of learning cannot be ignored when designing policies to ensure determinacy, stability, and robustness.

1.3 Summary

Central banks must make policy decisions in the face of uncertainty based on imperfect and evolving knowledge about the economy. While few general results have emerged from the research on monetary policy in the face of uncertainty and learning, a key lesson is that neither uncertainty nor learning can be ignored. Policymakers must recognize that situations in which the uncertainty associated with forecasts can be ignored—that is, when certainty equivalence holds—are unlikely to hold in practice. Accounting for the role of multiple models and seeking policies that are robust across a range of plausible models is important. Seeking robustness may require using models that are distorted in ways that capture if not the worst-case scenarios, at least the more threatening ones. It is critical to recognize the role of data uncertainty, measurement error, and unobservability of key macroeconomic variables in designing and implementing monetary policy. Finally, policymakers must also account for the way policy actions affect the ability of the private sector to learn and the fact that the process of learning itself will influence the impact policy has on inflation and the real economy.

2. Overview of the Book

The essays in this volume offer both theoretical insight and practical guidance to evaluating monetary policy in the presence of uncertainty and the need to learn. The papers address a number of general questions. Are there practical means for calculating optimal policies in the face of very general specifications of model uncertainty? Does model uncertainty limit the usefulness of optimal control techniques? What types of monetary policy rules ensure stability when private agents employ constant-gain learning strategies? How do alternative notions of learning affect the stability of forward-looking models? How are the costs of disinflations affected by the credibility of the central bank's inflation target and the need for the public to engage in learning? How might disinflations affect the structure of the inflation process as private firms update their beliefs about the behavior of inflation, and do these effects alter the relative costs and benefits of announcing a gradual reduction in inflation targets? Are there general rules for formulating models and policy rules that ensure stability when private agents only have lagged data available? Can alternative models, useful for policy analysis, be developed if the effects of monetary policy arise from sticky information rather than sticky wages and prices? Is it possible to estimate unobservable variables that are key for monetary policy decisions using a simple model applied to different countries—and what does it reveal about international comovement and convergence of the unobservables and their observable counterparts?

The volume also addresses a number of issues specific to Chile's monetary policy. Did Chile's gradual disinflation experience based on annual targets in 1991–2000 contribute to lower costs of disinflation? How empirically important are additive, model, and information uncertainty? How sensitive is monetary policy to the laws of motion of exogenous shocks and to model misspecification? Finally, how sensitive are boom-bust cycles in Chile to alternative monetary policy rules?

The rest of this section briefly summarizes the chapters in the book, exploring how they answer the above set of questions. The second chapter in the volume, by George Evans and Seppo Honkapohja, provides an overview of the lessons for monetary policy derived from the growing literature on learning. Evans and Honkapohja have been the leading figures in developing and applying the notions of adaptive learning to macroeconomic issues. Their work is partly motivated by the idea that economic agents have neither the information nor the information-processing capabilities implicitly assumed by rational expectations approaches. Instead, economists should recognize that individuals are boundedly rational. One means of operationalizing this notion of bounded rationality is to assume that individuals learn adaptively. As the authors note, adaptive learning reflects the way economists typically learn about the empirical structure of the economy—they use new data to update their estimates of the economy's structural relationships or their forecasting equations. Applying this notion of learning to the private sector provides a tractable means of investigating a number of policy-relevant issues without imposing the extreme informational assumptions common to rational expectations models. Using the basic forward-looking New-Keynesian model that has become standard in the literature on monetary policy, the authors discuss a number of policy-related issues such as determinacy and E-stability under alternative policy rules, imperfect information on current variables, imperfect knowledge of structural parameters, and alternative models of adaptive learning. They also study the implications of learning for understanding hyperinflations and liquidity trap environments.

In their chapter, Lars E.O. Svensson and Noah Williams use a benchmark New-Keynesian model to show how policy is affected by the model uncertainty policymakers face. The authors have developed a new methodology for designing optimal monetary policies in the face of model uncertainty. This approach models uncertainty as reflected in shifts in the structural equations that characterize the economy. They represent the economy as jumping randomly between various states. Conditional on each state, the structure of the economy can be described in terms of linear equations and quadratic preferences. The approach is thus called a Markov jump-linear-quadratic model. As the authors argue, this approach can be used to model many types of uncertainty. They also discuss the role of learning, since they assume that the current state of the economy is not observable. The fully optimal policy in their framework will involve some experimentation—that is, deliberate policy actions designed to help the central bank better understand the behavior of the economy. Such policies are difficult to calculate, so Svensson and Williams focus on what they label adaptive optimal policies (AOP). Under these policies, the central bank does not consciously experiment. Svensson and Williams find that the gains from experimentation are typically small, a finding consistent with the reluctance of central banks to experiment with the macroeconomy. To illustrate the applicability of their approach to uncertainty, they employ a small, New-Keynesian model that was originally estimated using U.S. data by Lindé (2005). Using this model, the authors compare the AOP policy with optimal policy without learning, that is, when the central bank does not use the new data it receives to update its knowledge about the economy. Besides illustrating the algorithms they have developed to calculate AOP policies, the paper draws a very important policy conclusion: while learning is important for improving the design of policy in the face of uncertainty, the gains from experimentation are small.

Athanasios Orphanides and John Williams study the implications of alternative policies in the face of uncertainty and learning. They employ a small model estimated using U.S. data, but in evaluating monetary policies, they assume that the central bank must estimate key macroeconomic variables such as the natural rate of unemployment and the equilibrium real interest rate. Private agents are also uncertain about the structure of the model and employ least squares learning to update their beliefs about the economy. The authors show that ignoring uncertainty and learning can be costly in this environment: policies that are optimal when uncertainty is ignored lead to poor macroeconomic outcomes when knowledge is imperfect. Policies that are more robust to imperfect knowledge can be obtained if the central bank acts more conservatively, in the sense of placing greater weight on inflation objectives relative to stabilizing real economic activity. Interestingly, Orphanides and Williams show that simple policy rules that respond to expected future inflation and either lagged unemployment or the change in the unemployment rate perform well in the face of imperfect knowledge.

George Evans and Seppo Honkapohja examine the behavior of monetary policy rules when the private sector is engaged in learning. A huge literature examines the implications of simple policy rules, but this work generally assumes that private agents are fully aware of the rule the central bank is following. If, instead, members of the private sector must learn about the central bank's behavior, some important new issues arise. One issue relates to the stability of policy rules under different assumptions about the way private agents learn. The standard assumption in the literature on adaptive learning is that as agents obtain more observations, they place less weight on each one, a learning process known as decreasing gain. An alternative assumption is that agents use constant-gain least-squares learning, in which the weight on new information does not decrease as more observations are accumulated. Constant-gain learning may be appropriate when structural shifts might occur, making observations from the distant past less informative. Evans and Honkapohja show that some rules that perform well under decreasing-gain learning lead to expectational instability under constant-gain learning. Thus, not only is the fact that the private sector is learning important, but how they learn is also relevant. Finally, the authors show that what they describe as expectations-based optimal policy rules, in which the central bank responds to private sector expectations, have desirable properties.

Roger Guesnerie considers an approach to learning that differs from the adaptive learning models that have become common in monetary policy analysis. Under adaptive learning, individuals behave much like econometricians, using new observations on macroeconomic conditions to update their estimates of key economic relationships. In contrast to this approach, Guesnerie develops the concept of eductive stability. Intuitively, an eductively stable system has the property that if it is common knowledge that the economy is within some neighborhood of the equilibrium, then individuals behave in such a way that the actual equilibrium is within this neighborhood, regardless of their specific beliefs. Eductive stability can then be thought of as a property of an equilibrium such that, if the economic agents' beliefs are in some region, they will remain within that region under a broad set of updating rules. Eductive stability can thus be viewed as a necessary condition for any adaptive learning procedure to be stable. Applying the notion of eductive stability to a simple, cashless forward-looking model, Guesnerie finds that Taylor rules that react too strongly to inflation may not be eductively stable.

Bennett T. McCallum argues that the requirement of stability under least-squares learning is a "compelling necessary condition for a rational expectations equilibrium to be considered plausible." While previous work by McCallum and others demonstrates that monetary policy rules that ensure a unique rational expectations equilibrium (that is, that ensure determinacy) are least-squares learnable, this result is based on the assumption that individuals are able to observe the current equilibrium for the economy. More realistically, individuals may only observe lagged data on the economy, and in this case, the close connection between determinacy and learnability no longer holds. In fact, learnability is ensured only under additional, special assumptions. McCallum also explores the requirement that models be well formulated, where this is interpreted to mean that certain discontinuities in the models' steady state are ruled out. He shows that even when individuals observe current endogenous variables, a well-formulated model does not imply learnability (and vice versa).

Most modern models used for monetary policy analysis assume that nominal prices and wages are sticky, adjusting only slowly over time. In a series of previous papers, Ricardo Reis develops the idea that the economy may be characterized not by sticky prices, but by sticky information. Agents are inattentive to news because they incur costs of acquiring, absorbing, and processing information. In this volume, Reis presents a DSGE model of business cycles and monetary policy, where the only rigidity is pervasive inattention in all markets and where different agents update their information at different dates. The model is estimated on data for the post-1986 United States and the post-1993 euro area and then applied to conduct several counterfactual policy experiments for both regions. Monetary policy shocks have exhibited little persistence, implying a quick response of most macroeconomic variables to monetary shocks. Announcing a policy change in advance increases the response of inflation in comparison with unannounced changes. A gradual policy change has a stronger impact than an expected nongradual change, but only if the gradualist policy is announced and credible. Taylor's (1993) aggressively anti-inflation policy rule would yield higher welfare levels than what is attained by using the actual policy rules estimated for both regions. Finally, compared with flexible inflation targeting under a conventional Taylor rule, welfare would be reduced in both regions if their central banks were to adopt either strict or flexible price-level targeting.

Klaus Schmidt-Hebbel and Carl E. Walsh apply a parsimonious monetary policy model to estimate three key unobservable variables—specifically, the neutral real interest rate, the output gap, and the natural rate of unemployment—for three large non-inflation-targeting economies (namely, the United States, the euro area, and Japan) and seven inflation-targeting countries (namely, Australia, Canada, Chile, New Zealand, Norway, Sweden, and the United Kingdom), using quarterly data for 1970–2006 (at most). Country-by-country estimation closely follows the sequential-step procedure developed by Laubach and Williams (2003) for estimating two unobservables for the United States. The country results reported in this chapter, while mixed, show that trend output growth and the neutral real interest rate vary over time in most countries, and the natural rate of unemployment is found to vary over time in Chile and the United States. As discussed above, policymakers must consider that key unobservables may vary over time if they are to conduct monetary policy efficiently. Regarding common time trends, Schmidt-Hebbel and Walsh show that the volatilities of inflation, output growth, and the real interest rate have declined in their country sample over the last decades, which is consistent with the great moderation observed worldwide since the early 1990s. The three big economies exhibit neither large nor rising comovements of key variables over time. Most smaller inflation-targeting economies, however, exhibit rising comovements of key observables and unobservables with the United States. Finally, on convergence of variable levels observed across countries in the sample period, the authors reject convergence of unobservables in inflation-targeting countries to the levels estimated for the United States and the euro area, but they report convergence of actual growth and interest rates in most inflation-targeting countries to the growth and interest rate levels observed in the United States and the euro area.

In their chapter, Martin Melecký, Diego Rodríquez-Palenzuela, and Ulf Söderström use a model estimated on euro area data to assess the effects of monetary policy transparency and credibility on inflation and output volatility. The key uncertainty faced by private agents in the model arises from shifts in the central bank's policy rule. These shifts might reflect transitory interest rate movements, or they might reflect persistent changes in the central bank's inflation target. The authors employ a forward-looking DSGE model that incorporates sticky prices and sticky wages. They find that the gains from credibly announcing changes in the target inflation rate are relatively small. However, they show that this result depends on the assumption that the private sector fully understands the stochastic process that governs persistence in the target rate. When this aspect of the target rate behavior is not known, the inference problem private agents face is more complicated, and the gains from announcing the target can be much larger, particularly if private agents overestimate the volatility of the target.

Volker Wieland develops a model designed to provide an understanding of the path of gradual disinflation in inflation targeting countries such as Chile. He introduces two new elements into a New-Keynesian model to capture disinflationary experiences. First, private firms engage in adaptive learning; in setting prices, they need to forecast future inflation and, to do so, they employ least squares methods to update estimates of a simple forecasting equation. Second, Wieland develops a model of price indexation in which the degree of indexation is endogenously determined. This approach contrasts with the many models that assume that some prices are partially indexed to past inflation but which treat the degree of indexation as exogenous. Specifically, whenever a firm has an opportunity to optimally reset its price, it also decides whether to index future price changes to past inflation or to the central bank's inflation target. As a consequence, an immediate disinflation via a reduction in the central bank's inflation target causes firms to quickly drop backward-looking indexation and base indexation on the inflation target. The initial impact of this rapid disinflation, however, is a large output decline. The decline in real economic activity can be muted if the central bank carries out a more gradual disinflation. As firms update their assessment of inflation persistence during a gradual disinflation, the real costs of the disinflation decline, but firms are less likely to shift their indexation to the central bank's target in the gradual disinflation scenario. Wieland then goes on to analyze the use of temporary inflation targets that gradually decline toward a low steady-state inflation rate. This situation captures the gradual disinflation strategy based on annual inflation targets adopted by Chile in 1990–2000, similar to several other inflation-targeting countries that adopted annual inflation targets when actual inflation was still high. Meeting short-term targets helps increase the rate at which firms alter their indexation strategies from being based on lagged inflation to being based on the new inflation targets. This helps achieve low inflation.

Felipe Morandé and Mauricio Tejada assess the empirical importance of the three classical sources of uncertainty for monetary policy in Chile. They analyze data uncertainty by comparing real-time estimates for the output gap with each other and with final-data measures; they conclude that the correlations between real-time data and final-data output gap estimates are relatively low. To evaluate the empirical importance of additive uncertainty (associated with the variance of shocks) and multiplicative uncertainty (associate with parameter uncertainty), Morandé and Tejada estimate a small open economy forward-looking New-Keynesian model for Chile, with time-varying parameters and state-dependent variances of disturbances. The results for all model equations show that additive uncertainty dominates multiplicative uncertainty. The estimations support the hypothesis of state-dependent variances linked to two states of either low or high shock volatility. Measures of total uncertainty of both the output gap and inflation have declined over time, and the period of greater stability coincides with full-fledged inflation targeting adopted since 2001.

In previous work, Marco del Negro and Frank Schorfheide (and others) develop the DSGE-VAR model, which relaxes cross-equation restrictions and can be regarded as a structural vector autorgression (VAR) model that retains many features of the underlying DSGE specification. In this volume, Del Negro and Schorfheide present estimation results for a small open economy DSGE-VAR model for Chile in 1999–2007. The authors find it helpful to tilt their VAR estimates toward the restriction generated by their DSGE model because the VAR without tight priors is unlikely to provide good forecasts or sharp policy advice. Observed inflation variability was mostly due to domestic shocks. Regarding monetary policy rules, one finding is that the Central Bank of Chile did not respond significantly to exchange rate and terms-of-trade shocks. A stronger Central Bank response to inflation shocks would have had little effect on inflation volatility, but a weaker response would have led to an inflation volatility spike. Del Negro and Schorfheide derive two more general lessons from their exercise. First, the outcomes of policy experiments are very sensitive to the parameters that reflect the law of motion of exogenous shocks. Second, the presence of misspecification—when the DSGE model is rejected relative to a more loosely parameterized model—does not necessarily imply that the answers to the policy exercises obtained from the DSGE model are not robust.

In the final chapter, Manuel Marfán, Juan Pablo Medina, and Claudio Soto specify and calibrate a DSGE model for Chile to analyze the macroeconomic effects of shocks when private agents suffer from misperceptions about future productivity levels that generate boom-bust cycles, such as those recurrently observed in both emerging market and industrial economies in the 1990s and the 2000s. The model, based on a three-sector small open economy forward-looking DSGE specification with several nominal and real rigidities and a Taylor rule, is used to conduct several simulations. The first simulation shows that a boom-bust cycle can be simulated by an unexpected decline and subsequent reversal in the foreign interest rate, which accounts well for the stylized facts observed in Chile in the 1990s. The second simulation focuses on the effects of overoptimistic expectations about future productivity levels and, alternatively, future productivity trends, which turn out to be wrong ex post.[3] Only overoptimism

3. Overoptimism based, for instance, on the expected outcome of recent economic reforms that is ex-ante hard to evaluate.

about productivity trends (not levels) is able to replicate Chile's cycle, similarly to the foreign-interest-rate-induced cycle. Finally, Marfán, Medina, and Soto contrast the macroeconomic effects of alternative monetary policy reactions in response to an increase in trend productivity. If the central bank follows a stricter inflation-targeting regime, the boom-bust cycle of most macroeconomic variables would be amplified. If the central bank includes the exchange rate as an argument in its policy rule, it may prevent the contraction of the traded sector that occurs under the baseline policy rule, but the volatility of other variables would be amplified. This suggests that the trade-offs faced in the conduct of monetary policy (and exchange rate policy) are not trivial in a boom-bust cycle triggered by misperception about future productivity.

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