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On DSGE Models

Lawrence J. Christiano, Martin S. Eichenbaum, and Mathias Trabandt

The outcome of any important macroeconomic policy change is the net effect of forces operating on different parts of the economy. A central challenge facing policymakers is how to assess the relative strength of those forces. Economists have a range of tools that can be used to make such assessments. Dynamic stochastic general equilibrium (DSGE) models are the leading tool for making such assessments in an open and transparent manner.

To be concrete, suppose we are interested in understanding the effects of a systematic change in policy, like switching from inflation targeting to price-level targeting. The most compelling strategy would be to do randomized control trials on actual economies, but that course of action is not available to us. So what are the alternatives? It is certainly useful to study historical episodes in which such a similar policy switch occurred or to use reduced-form time series methods, but these approaches also have obvious limitations. In the historical approach, the fact that no two episodes are exactly the same always raises questions about the relevance of a past episode for the current situation. In the case of reduced-form methods, it is not always clear which parameters should be changed and which should be kept constant across policy options. Inevitably, assessing the effects of a systematic policy change has to involve the use of a model.

■ *Lawrence J. Christiano is the Alfred W. Chase Professor of Economics and Martin S. Eichenbaum is the Charles Moskos Professor of Economics, both at Northwestern University, Evanston, Illinois. Mathias Trabandt is Professor of Macroeconomics at the School of Business and Economics, Freie Universität Berlin, Berlin, Germany and Research Fellow at the Halle Institute for Economic Research, Halle, Germany. Their email addresses are l-christiano@northwestern.edu, eich@northwestern.edu, and mathias.trabandt@gmail.com.*

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To be useful for policy analysis, dynamic stochastic general equilibrium models must be data-based. As a practical matter, macroeconomic data are not sufficient for discriminating between many alternative models that offer different answers to policy questions. Put differently, many DSGE models are observationally equivalent with respect to macro data. But modern DSGE models are based on microeconomic foundations. So microeconomic data and institutional facts can be brought to bear on their design, construction, and evaluation. Micro data break the observational equivalence that was the bane of macroeconomists.

The openness and transparency of dynamic stochastic general equilibrium models is a virtue—but it also makes them easy to criticize. Suspicious assumptions can be highlighted. Inconsistencies with the evidence can easily be spotted. Forces that are missing from the model can be identified. The process of responding to informed criticisms is a critical part of the process of building better DSGE models. Indeed, the transparent nature of DSGE models is exactly what makes it possible for diverse groups of researchers—including those who don't work on DSGE models—to be part of the DSGE project.

Some analysts object to working with dynamic stochastic general equilibrium models and prefer instead to think about policy by working with small equilibrium models that emphasize different subsets of the economy, labor, or financial markets. This approach has a vital contribution to make, because small models help build intuition about the mechanisms at work in DSGE models. But this approach cannot be a substitute for DSGE models themselves, because quantitative conclusions about the overall economic impact of a policy requires informal judgment as one integrates across individual small-scale models. The small-model approach to policy thus involves implicit assumptions and lacks the transparency of the DSGE approach.

To be clear, policy decisions are made by real people using their best judgment. Used wisely, dynamic stochastic general equilibrium models can improve and sharpen that judgment. In an ideal world, we will have both wise policymakers and empirically plausible models. But to rephrase Fischer's (2017) quoting of Samuelson on Solow: "We'd rather have Stanley Fischer than a DSGE model, but we'd rather have Stanley Fischer with a DSGE model than without one."

In the next section, we review the state of mainstream dynamic stochastic general equilibrium models before the financial crisis and the Great Recession. We then describe how DSGE models are estimated and evaluated. We address the question of why DSGE modelers—like most other economists and policymakers—failed to predict the financial crisis and the Great Recession, and how DSGE modelers responded to the financial crisis and its aftermath. We discuss how current DSGE models are actually used by policymakers. We then provide a brief response to some criticisms of DSGE models, with special emphasis on Stiglitz (2017), and offer some concluding remarks.

Before the Storm

In this section, we describe early dynamic stochastic general equilibrium models and how they evolved prior to the crisis.

Early Dynamic Stochastic General Equilibrium Models

As a practical matter, people often use the term "dynamic stochastic general equilibrium model" to refer to quantitative models of growth or business cycle fluctuations. A classic example of a quantitative DSGE model is the real business cycle model associated with Kydland and Prescott (1982) and Long and Plosser (1983). These early real business cycle models imagined an economy populated by households who participate in perfectly competitive goods, factor, and asset markets. These models took the position that fluctuations in aggregate economic activity are an efficient response of the economy to the one source of uncertainty in agents' environment, exogenous technology shocks. The associated policy implications are clear: there is no need for any form of government intervention. In fact, government policies aimed at stabilizing the business cycle are welfare reducing.

Excitement about real business cycle models crumbled under the impact of three forces. First, micro data cast doubt on some of the key assumptions of the model. These assumptions include, for example, perfect credit and insurance markets, as well as perfectly frictionless labor markets in which fluctuations in hours worked reflect movements along a given labor supply curve or optimal movements of agents in and out of the labor force (Chetty, Guren, Manoli, and Weber 2011).

Second, the models had difficulty in accounting for some key properties of the aggregate data, such as the observed volatility in hours worked, the equity premium, the low co-movement of real wages and hours worked (Christiano and Eichenbaum 1992; King and Rebelo 1999). Open-economy versions of these models also failed to account for key observations such as the cyclical co-movement of consumption and output across countries (Backus, Kehoe, and Kydland 1992) and the extremely high correlation between nominal and real exchange rates (Mussa 1986).

Third, because money plays no role in real business cycle models, those models seem inconsistent with mainstream interpretations of various historical episodes. An example is Hume's (1742) description of how money from the New World affected the European economy. A different example is the view that the earlier a country abandoned the gold standard during the Great Depression, the sooner its recovery began (Bernanke 1995). A final example is the view that the severity of the US recession in the early 1980s was in large part caused by monetary policy.

Finally, the simple real business cycle model is effectively mute on a host of policy-related questions of vital importance to macroeconomists and policymakers. Examples include: what are the consequences of different monetary policy rules for aggregate economic activity, what are the effects of alternative exchange rate regimes, and what regulations should we impose on the financial sector?

New Keynesian Models

Prototypical pre-crisis dynamic stochastic general equilibrium models built upon the chassis of the real business cycle model to allow for nominal frictions, both in labor and goods markets. These models are often described as New Keynesian DSGE models, but it would be just as appropriate to refer to them as Friedmanite DSGE models. The reason is that they embody the fundamental worldview articulated in Friedman's (1968) seminal Presidential Address to the American Economic

Association. According to this view, hyperinflations aside, monetary policy has essentially no impact on real variables like output and the real interest rate in the long run. However, due to sticky prices and wages, monetary policy matters in the short run.[1] Specifically, a policy-induced transitory fall in the nominal interest rate is associated with a decline in the real interest rate, an expansion in economic activity, and a moderate rise in inflation.

Models in which *permanent* changes in monetary policy induce roughly one-to-one changes in inflation and the nominal rate of interest are said to satisfy the Fisherian property. Models in which *transitory* changes in monetary policy induce movements in nominal interest rates and inflation of the opposite sign are said to satisfy the anti-Fisherian property. The canonical New Keynesian models of Yun (1996), Clarida, Galí, and Gertler (1999), and Woodford (2003) satisfy both properties.

The basic intuition behind the anti-Fisherian property of the New Keynesian model is as follows. Firms set their prices on the basis of current and future marginal costs. The future state of the economy is relatively unaffected by a transitory monetary policy shock, so actual inflation responds relatively little to a policy-induced transitory fall in the nominal interest rate. As a result, the real interest rate declines. Intertemporal substitution by households then induces a rise in current consumption, leading to a rise in labor income. That increase reinforces the contemporaneous rise in consumption and employment. The expansion in employment drives wages and marginal costs up. The latter effect drives inflation up. Because inflation and the nominal interest rate move in opposite directions, the model has the anti-Fisherian property. Less surprisingly, standard New Keynesian models satisfy the Fisherian property because their long-run properties are roughly the same as the underlying real business cycle chassis.

Many researchers found New Keynesian models attractive because they seemed sensible and they allowed researchers to engage in the types of policy debates about which real business cycle models had been silent. A critical question was: What properties should quantitative versions of these models have? To address this question, the empirical literature focused on quantifying the dynamic effects of a shock to monetary policy. This type of shock has long been of interest to macroeconomists. For example, Friedman and Schwartz (1963) attributed the major portion of business cycle variations to exogenous shocks in the money supply. The recent literature finds these shocks interesting because they provide a potentially powerful diagnostic for discriminating between models. Perhaps the most extreme example is that a real business cycle model implies nothing happens to real variables after a monetary policy shock. In contrast, simple New Keynesian models imply that real variables do respond to a monetary policy shock.

A monetary policy shock can reflect a variety of factors, including measurement error in the real-time data on which policymakers condition their actions and

[1] For example, Friedman (1968, p. 10) writes that after the monetary authority increases money growth, "much or most of the rise in income will take the form of an increase in output and employment rather than in prices. People have been expecting prices to be stable, and prices and wages have been set for some time in the future on that basis. It takes time for people to adjust to a new state of demand. Producers will tend to react to the initial expansion in aggregate demand by increasing output, employees by working longer hours, and the unemployed, by taking jobs now offered at former nominal wages."

the basic randomness that is inherent in group decisions. In a seminal paper, Sims (1986) argued that one should identify monetary policy shocks with disturbances to a monetary policy reaction function in which the policy instrument is a short-term interest rate. Bernanke and Blinder (1992) and Christiano, Eichenbaum, and Evans (1996, 1999) identify monetary policy shocks using the assumption that they have no contemporaneous impact on inflation and output.[2] This set of identifying restrictions, like the entire New Keynesian enterprise, falls squarely in the Friedman worldview. In testimony before Congress, Friedman (1959) said: "Monetary and fiscal policy is rather like a water tap that you turn on now and that then only starts to run 6, 9, 12, 16 months from now."

In practice, this Friedman-style identifying strategy is implemented using a vector autoregression representation with a large set of variables. Figure 1, taken from Christiano, Trabandt, and Walentin (2010), displays the effects of identified monetary policy shocks estimated using data covering the period 1951:Q1 to 2008:Q4. For convenience, we only show the response functions for a subset of the variables in the vector autoregression. The dashed lines correspond to 95 percent confidence intervals about the point estimates, shown by the thick solid line.

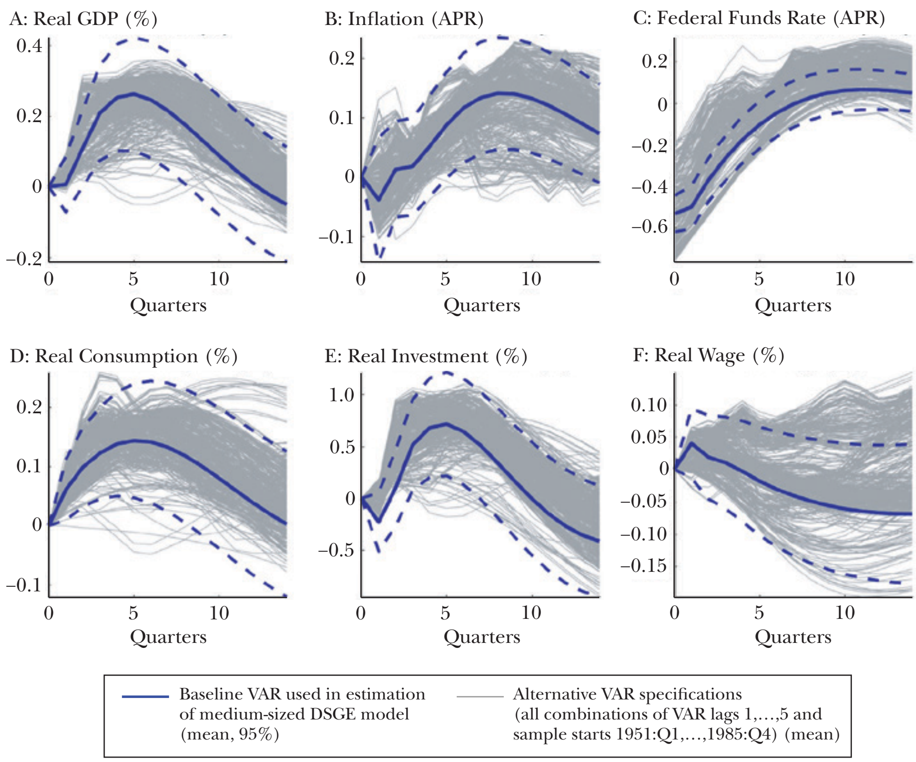
Overall, the results are consistent with the view that an expansionary monetary policy shock has the effects that Friedman (1968) asserted in his Presidential Address. Specifically, an expansionary monetary policy shock corresponding to a decline in the US federal funds rate leads to hump-shaped expansions in consumption, investment, and output, as well as relatively small rises in real wages and inflation. Since the inflation rate moves very little in response to a monetary policy shock, the responses in the real interest rate and the federal funds rate are roughly the same.

A natural question is how robust the results in Figure 1 are to the various technical assumptions underlying the statistical analysis. Here, we focus on sensitivity to the number of lags in the vector autoregression and to the start of the sample period. A vector autoregression represents each variable as a function of the lagged values of all the variables in the system. Denote the number of lags by n. The baseline specification in Figure 1 assumes $n = 2$. Figure 1 reports the results of redoing the analysis for $n = 1, \dots, 5$. For each value of n, Figure 1 reports the results based on starting the sample period in each of the quarters from 1951:Q1 up through 1985:Q4. In this way, we generate 700 sets of results, each of which is displayed by a thin grey line in Figure 1. Note that the basic qualitative properties of the benchmark analysis are remarkably robust, although there are of course specifications of n and the sample period that yield different implications. It is interesting how similar the shape of the confidence and sensitivity intervals are.

In recent years, researchers have developed alternative procedures for identifying monetary policy shocks. These procedures focus on movements in the federal funds futures rate in a tight window of time around announcements made by monetary policymakers: for example, see Gertler and Karadi (2015) who build

[2] Christiano, Eichenbaum, and Evans (1999) show that the results from imposing this assumption on monthly or quarterly data are qualitatively similar. The assumption is obviously more compelling for monthly data.

Figure 1
Vector Autoregression (VAR) Impulse Responses to a Monetary Policy Shock



Source: Christiano, Trabandt, and Walentin (2010).
Note: The figure displays the effects of identified monetary policy shocks estimated using data covering the period 1951:Q1 to 2008:Q4. All data are expressed in deviations from what would have happened in the absence of the shock. The units are given in the titles of the subplots. Percent means percent deviation from unshocked path. APR means annualized percentage rate deviation from the unshocked path. The dashed lines correspond to 95 percent confidence intervals about the point estimates, shown with a thick solid line. The baseline specification of the vector autoregression assumes the number of lags $n = 2$. The figure also reports the results of redoing the analysis for $n = 1, \dots, 5$. For each value of n, the figure reports the results based on starting the sample period in each of the quarters from 1951:Q1 up through 1985:Q4. In this way, we generate 700 sets of results, each of which is displayed by a thin grey line (for details, see Christiano, Trabandt, and Walentin 2010).

on the work of Kuttner (2001) and Gürkaynak, Sack, and Swanson (2005). Broadly speaking, this literature reaches the same conclusions about the effects of monetary policy shocks displayed in Figure 1. In our view, these conclusions summarize the conventional view about the effects of a monetary policy shock.

The Christiano, Eichenbaum, and Evans Model

A key challenge was to develop an empirically plausible version of the New Keynesian model that could account quantitatively for the type of impulse response functions displayed in Figure 1. Christiano, Eichenbaum, and Evans (2005) developed a version of the New Keynesian model that met this challenge. We go into some detail describing the basic features of that model because they form the core of leading pre-crisis dynamic stochastic general equilibrium models, such as Smets and Wouters (2003, 2007).

Consumption and Investment Decisions by the Representative Household. Consistent with a long tradition in macroeconomics, the model economy in Christiano, Eichenbaum, and Evans (2005) is populated by a representative household. At each date, the household allocates money to purchases of financial assets, as well as consumption and investment goods. The household receives income from wages, from renting capital to firms, and from financial assets, all net of taxes.

As in the simple New Keynesian model, Christiano, Eichenbaum, and Evans (2005) make assumptions that imply the household's borrowing constraints are not binding, so the interest rate determines the intertemporal time pattern of consumption. Of course, the present value of income determines the level of consumption. Holding interest rates constant, the solution to the household problem is consistent with a key prediction of Friedman's permanent income hypothesis: persistent changes in income have a much bigger impact on household consumption than transitory changes.

To be consistent with the response of consumption and the interest rate to a monetary policy shock observed in Figure 1, Christiano, Eichenbaum, and Evans (2005) depart from the standard assumption that utility is time-separable in consumption. Generally speaking, that assumption implies that after a policy-induced decline in the interest rate, consumption jumps immediately and then falls. But this pattern is very different from the hump-shape response that we see in Figure 1. To remedy this problem, Christiano, Eichenbaum, and Evans (2005) follow Fuhrer (2000) by adopting the assumption of habit-formation in consumption. Under this specification, the marginal utility of current consumption depends positively on the level of the household's past consumption. Households then choose to raise consumption slowly over time, generating a hump-shape response-pattern as in Figure 1. As it turns out, there is substantial support for habit persistence in the finance, growth, and psychology literatures.[3]

To be consistent with the hump-shaped response of investment to a monetary policy shock, Christiano, Eichenbaum, and Evans (2005) had to assume that households face costs of changing the rate of investment. To see why, note that absent uncertainty, arbitrage implies that the one-period return on capital is equal to the real rate of interest on bonds. Absent any adjustment costs, the one-period return on capital is the sum of the marginal product of capital plus one minus the depreciation rate. Suppose that there is an expansionary monetary policy shock that drives down the real interest rate, with the maximal impact occurring

[3] For example, in the finance literature, see Eichenbaum and Hansen (1990), Constantinides (1990), and Boldrin, Christiano, and Fisher (2001). In the growth literature, see Carroll, Overland, and Weil (1997, 2000). In the psychology literature, see Gremel et al. (2016).

contemporaneously, as in the data. Absent adjustment costs, arbitrage then requires that the marginal product of capital follow a pattern identical to the real interest rate. For that to happen, both the capital stock and investment must have exactly the opposite pattern to the marginal product of capital. With the biggest surge in investment occurring in the period of the monetary policy shock, the simple model cannot reproduce the hump-shape pattern in Figure 1. When it is costly to adjust the rate of investment, households choose to raise investment slowly over time, generating a hump-shape response pattern as in Figure 1.

Lucca (2006) and Matsuyama (1984) provide interesting theoretical foundations for the investment adjustment cost in Christiano, Eichenbaum, and Evans (2005). In addition, there is substantial empirical evidence in support of the specification (Eberly, Rebelo, and Vincent 2012; Matsuyama 1984).

An important alternative specification of adjustment costs penalizes changes in the capital stock. This specification has a long history in macroeconomics, going back at least to Lucas and Prescott (1971). Christiano, Eichenbaum, and Evans (2005) show that with this type of adjustment cost, investment jumps after an expansionary monetary policy shock and then converges monotonically back to its pre-shock level from above. This response pattern is inconsistent with the vector autoregression evidence.

Nominal Rigidities. In contrast to real business cycle models, goods and labor markets in Christiano, Eichenbaum, and Evans (2005) are not perfectly competitive. This departure is necessary to allow for sticky prices and sticky nominal wages—if a price or wage is sticky, someone has to set it. In this model, nominal rigidities arise from Calvo (1983)-style frictions. In particular, firms and households can change prices or wages with some exogenous probability. In addition, they must satisfy whatever demand materializes at those prices and wages.

Calvo-style frictions make sense only in environments where inflation is moderate. Even in moderate inflation environments, Calvo-style frictions have implications that are inconsistent with aspects of micro data (for example, Nakamura and Steinsson 2008; Eichenbaum, Jaimovich, and Rebelo 2011). Still, the continued use of this assumption reflects two factors. First, Calvo-style frictions allow models to capture, in an elegant and tractable manner, what many researchers believe is an essential feature of business cycles; for moderate inflation economies, firms and labor suppliers typically respond to variations in demand by varying quantities rather than prices. Second, authors like Eichenbaum, Jaimovich, and Rebelo (2011) argue that, for moderate inflation economies, the Calvo model provides a good approximation to more plausible models in which firms face costs of changing their pricing strategies.

Acyclical Marginal Costs. Christiano, Eichenbaum, and Evans (2005) build features into the model which ensure that firms' marginal costs are nearly acyclical. They do so for three reasons. First, there is substantial empirical evidence in favor of this view (for example, Anderson, Rebelo, and Wong 2018). Second, the more acyclical is marginal cost, the more plausible is the assumption that firms satisfy demand. Third, as in standard New Keynesian models, inflation is an increasing function of current and expected future marginal costs. Thus, relatively acyclical marginal costs are critical for dampening movements in the inflation rate.

The model in Christiano, Eichenbaum, and Evans (2005) incorporates two mechanisms to ensure that marginal costs are relatively acyclical: the sticky nominal wage assumption mentioned above; and the rate at which capital is utilized can be varied in response to shocks.

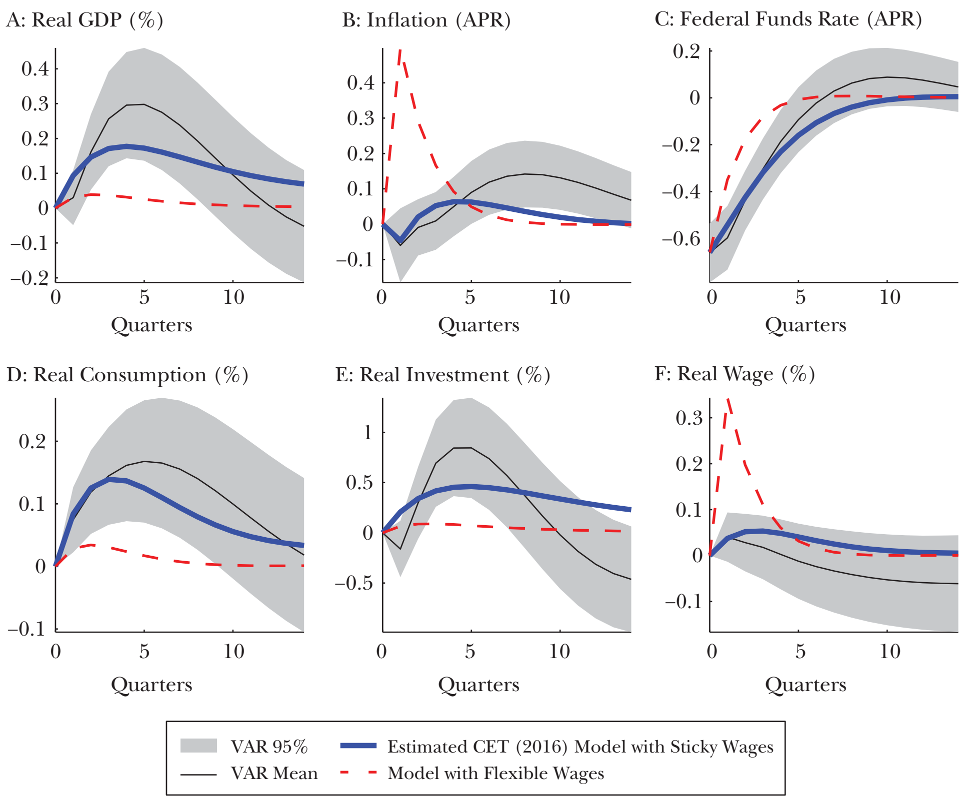
Quantitative Properties. To illustrate the model's quantitative properties, we work with the variant of the model of Christiano, Eichenbaum, and Evans (2005) estimated in Christiano, Eichenbaum, and Trabandt (2016). We re-estimated the model using a Bayesian procedure that treats the impulse responses to a monetary policy shock based on vector autoregressions as data. The online Appendix to this paper provides details about the prior and posterior distributions of model parameters. Here we highlight some of the key estimated parameters. The posterior mode estimates imply that firms change prices on average once every 2.3 quarters; the household changes nominal wages about once a year; past consumption enters with a coefficient of 0.75 in the household's utility function; and the elasticity of investment with respect to a one percent temporary increase in the current price of installed capital is equal to 0.16.

The thin solid line in the panels of Figure 2 is the impulse response function estimate reproduced from Figure 1. The grey area depicts the 95 percent confidence intervals associated with that estimate. The thicker solid line depicts the impulse response function of the estimated DSGE model to a monetary policy shock, calculated using the mode of the posterior distribution of the model's parameters.

Four key features of the results are worth noting. First, the model succeeds in accounting for the hump-shape rise in consumption, investment, and real GDP after a policy-induced fall in the federal funds rate. Second, the model succeeds in accounting for the small rise in inflation after the shock. Third, the model has the property that real wages are essentially unaffected by the policy shock. Finally, the model has the anti-Fisherian property that the nominal interest rate and inflation move in the opposite direction after a transitory monetary policy shock.

We emphasize that the model's properties depend critically on sticky wages. The dashed line in Figure 2 depicts the model's implications if we recalculate the impulse responses assuming that nominal wages are fully flexible (holding other model parameters fixed at the mode of the posterior distribution). Note that the model's performance deteriorates drastically. In Christiano, Eichenbaum, and Evans (2005), sticky wages are sticky by assumption. In Christiano, Eichenbaum, and Trabandt (2016), we show that wage stickiness arises endogenously in a version of the Christiano, Eichenbaum, and Evans (2005) model that has labor market search and matching frictions. The key feature of the model is that workers and firms bargain in a way that reduces the sensitivity of the wage to macroeconomic aggregates. One advantage of endogenously generating sticky wages in this way is we can analyze the aggregate effects of various policies like unemployment insurance. Finally, we note that habit formation and investment adjustment costs are critical to the model's success. Absent those features, it would be very difficult to generate hump-shaped responses with reasonable degrees of nominal rigidities.

Figure 2
Impulse Responses to a Monetary Policy Shock: Vector Autoregression (VAR) versus Model



Source: Authors.
Note: The thin solid lines in Figure 2 are the impulse response function estimates reproduced from Figure 1. All data are expressed in deviations from what would have happened in the absence of the shock. The units are given in the titles of the subplots. Percent means percent deviation from unshocked path. The grey area depicts the 95 percent confidence intervals associated with those estimates. The thicker solid line depicts the impulse response function of the dynamic stochastic general equilibrium model to a monetary policy shock, calculated using the mode of the posterior distribution of the model's parameters. The dashed line depicts the model's implications if we recalculate the impulse responses assuming that nominal wages are fully flexible (holding other model parameters fixed at the mode of the posterior distribution).

How Dynamic Stochastic General Equilibrium Models Are Estimated and Evaluated

Prior to the financial crisis, researchers generally worked with log-linear approximations to the equilibria of dynamic stochastic general equilibrium models. There were three reasons for this choice. First, for the models being considered and for the size of shocks that seemed relevant for the postwar US data, linear approximations are very accurate (for discussion, see the papers in Taylor and Uhlig 1990). Second, linear approximations allow researchers to exploit the large array of tools for forecasting, filtering, and estimation provided in the literature on linear time series analysis. Third, it was simply not computationally feasible to solve and estimate large, nonlinear DSGE models. The technological constraints were real and binding.

Researchers choose values for the key parameters of their models using a variety of strategies. In some cases, researchers choose parameter values to match unconditional model and data moments, or they reference findings in the empirical micro literature. This procedure is called calibration and does not use formal sampling theory. Calibration was the default procedure in the early real business cycle literature, and it is also sometimes used in the dynamic stochastic general equilibrium literature. Most of the modern DSGE literature conducts inference about parameter values and model fit using one of two strategies that make use of formal econometric sampling theory: limited information and full information.

The limited information strategy does not exploit all of the model's implications for moments of the data. One variant of this strategy minimizes the distance between a subset of model-implied second moments and their analogs in the data. A more influential variant of this first strategy estimates parameters by minimizing the distance between model and data impulse responses to economic shocks. Examples of this impulse response matching approach include Christiano, Eichenbaum, and Evans (2005), Altig, Christiano, Eichenbaum, and Linde (2011), Iacoviello (2005), and Rotemberg and Woodford (1991).

One way to estimate the data impulse response functions is based on partially identified vector autoregressions. Another variant of this strategy, sometimes referred to as the method of external instruments, involves using historical or narrative methods to obtain instruments for the underlying shocks (Mertens and Ravn 2013). Finally, researchers have exploited movements in asset prices immediately after central bank policy announcements to identify monetary policy shocks and their consequences. This approach is referred to as high frequency identification (for example, early contributions include Kuttner 2001; Gürkaynak, Sack, and Swanson 2005).

The initial limited information applications in the DSGE literature used generalized method of moments estimators and classical sampling theory (Hansen 1982). Building on the work of Chernozhukov and Hong (2003), Christiano, Trabandt, and Walentin (2010) showed how the Bayesian approach can be applied in limited information contexts. A critical advantage of the Bayesian approach is that one can formally and transparently bring to bear information from a variety of sources on what constitutes "reasonable" values for model parameters. Suppose, for example, that one could only match the dynamic response to a monetary policy shock for model parameter values that firms change their prices on average every two years. This implication is strongly at variance with evidence from micro data. In the Bayesian approach, the analyst would impose priors that sharply penalize such parameter values, so that those parameter values would be assigned low probabilities in the analyst's posterior distribution. Best practice compares priors and posteriors for model parameters. This comparison allows the analyst to make clear the role of priors and the data in generating the results.

At a deeper level, micro data influences, in a critical but slow-moving manner, the class of models with which we work. Our discussion of the demise of the pure real business cycle model is one illustration of this process. The models of financial frictions and heterogeneous agents discussed below are an additional illustration of how DSGE models evolve over time in response to micro data.

The other strategy for estimating dynamic stochastic general equilibrium models involves full-information methods. In many applications, the data used for estimation is relatively uninformative about the value of some of the parameters in DSGE models (Canova and Sala 2009). A natural way to deal with this fact is to bring other information to bear on the analysis. Bayesian priors are a vehicle for doing exactly that, which is an important reason why the Bayesian approach has been very influential in full-information applications. Starting from Smets and Wouters (2003), a large econometric literature has expanded the Bayesian toolkit to include better ways to conduct inference about model parameters and to analyze model fit. For a recent survey, see Fernández-Villaverde, Rubio-Ramierez, and Schorfheide (2016).

Why Didn't DSGE Models Predict the Financial Crisis?

Pre-crisis dynamic stochastic general equilibrium models did not predict the increasing vulnerability of the US economy to a financial crisis. They have also been criticized for not placing more emphasis on financial frictions. Here, we give our perspective on these failures.

The debate about the causes of the financial crisis is ongoing. Our view, shared by Bernanke (2009) and many others, is that the financial crisis was precipitated by a rollover crisis in a very large and highly levered shadow-banking sector that relied on short-term debt to fund long-term assets. By shadow banks, we mean financial institutions not covered by the protective umbrella of the Federal Reserve and Federal Deposit Insurance Corporation (for further discussion, see Bernanke 2010).

This rollover crisis was triggered by a set of developments in the housing sector. US housing prices began to rise rapidly in the 1990s. The S&P/Case-Shiller U.S. National Home Price Index rose by a factor of roughly 2.5 between 1991 and 2006. The precise role played by expectations, the subprime market, declining lending standards in mortgage markets, and overly loose monetary policy is not critical for our purposes. What is critical is that housing prices began to decline in mid-2006, causing a fall in the value of the assets of shadow banks that had heavily invested in mortgage-backed securities. The Fed's willingness to provide a safety net for the shadow banking system was at best implicit, creating the conditions under which a rollover crisis was possible. In fact, a rollover crisis did occur and shadow banks had to sell their asset-backed securities at fire-sale prices, precipitating the financial crisis and the Great Recession.

Against this background, we turn to the two criticisms of dynamic stochastic general equilibrium models mentioned above. The first criticism, namely the failure to signal the increasing vulnerability of the US economy to a financial crisis, is correct. The failure reflected a broader failure of the economics community.

The overwhelming majority of academics, regulators, and practitioners did not realize that a small shadow-banking system had metastasized into a massive, poorly regulated, Wild-West-like sector that was not protected by deposit insurance or lender-of-last-resort backstops.

The second criticism of dynamic stochastic general equilibrium models was that they did not sufficiently emphasize financial frictions. In practice, modelers have to make choices about which frictions to emphasize. One reason why modelers did not emphasize financial frictions in DSGE models is that until the Great Recession, postwar recessions in the United States and western Europe did not seem closely tied to disturbances in financial markets. The savings and loans crisis in the US economy in the late 1980s and early 1990s was a localized affair that did not grow into anything like the Great Recession. Similarly, the stock market meltdown in 1987 and the bursting of the tech bubble in 2001 only had minor effects on aggregate economic activity.

At the same time, the financial frictions that were included in dynamic stochastic general equilibrium models did not seem to have very big effects. Consider, for example, Bernanke, Gertler, and Gilchrist's (1999) model, which is arguably the most influential pre-crisis DSGE model with financial frictions. The financial accelerator in that model has only a modest quantitative effect on the way the model economy responds to shocks (see for example, Lindé, Smets, and Wouters 2016). In the same spirit, Kocherlakota (2000) argues that models with credit constraints (of the type in Kiyotaki and Moore 1997) have only negligible effects on dynamic responses to shocks. Finally, Brzoza-Brzezina and Kolasa (2013) compare the empirical performance of the standard New Keynesian DSGE model with variants that incorporate Kiyotaki and Moore (1997) and Bernanke, Gertler, and Gilchrist (1999)-type constraints. Their key finding is that neither model substantially improves on the performance of the benchmark model, either in terms of marginal likelihoods or impulse response functions. Thus, guided by the postwar data from the United States and western Europe and experience with existing models of financial frictions, DSGE modelers emphasized other frictions.

After the Storm

Given the data-driven nature of the dynamic stochastic general equilibrium enterprise, it is not surprising that the financial crisis and its aftermath had an enormous impact on dynamic stochastic general equilibrium models. In this section, we discuss the major strands of work in post–financial crisis DSGE models.

Financial Frictions

The literature on financial frictions can loosely be divided between papers that focus on frictions originating inside financial institutions and those that arise from the characteristics of the people who borrow from financial institutions. Theories of bank runs and rollover crisis focus on the first class of frictions. Theories of collateral constrained borrowers focus on the second class of frictions. This is not the place for a systematic review, but here we discuss some examples of each.

Frictions that Originate Inside Financial Institutions. Motivated by events associated with the financial crisis, Gertler and Kiyotaki (2015) and Gertler, Kiyotaki, and Prestipino (2016) develop a dynamic stochastic general equilibrium model of a rollover crisis in the shadow banking sector, which triggers fire sales. The resulting decline in asset values tightens balance sheet constraints in the rest of the financial sector and throughout the economy.[4]

In the Gertler and Kiyotaki (2015) model, shadow banks finance the purchase of long-term assets by issuing short-term (one-period) debt. Banks have two ways to deal with short-term debt that is coming due. The first is to issue new short-term debt (that is, "rolling over the debt"). The second is to sell assets. The creditor's only decision is whether to buy new short-term debt. There is nothing the creditor can do to affect payments received on past short-term debt.[5]

There is always an equilibrium in the Gertler and Kiyotaki (2015) model in which shadow banks can roll over the short-term debt without incident. But, there can also be an equilibrium in which each creditor chooses not to roll over the debt. Suppose that an individual creditor believes that other creditors won't extend new credit to banks. In that case, there will be a system-wide failure of the banks, as attempts to pay off bank debt lead to fire sales of assets that wipe out bank equity. The individual creditor would prefer to buy assets at fire sale prices rather than extend credit to a bank that has zero net worth. With every potential creditor thinking this way, it is a Nash equilibrium for each creditor not to purchase new liabilities from banks. Such an equilibrium is referred to as a rollover crisis.

A rollover crisis leads to fire sales because, with all banks selling, the only potential buyers are other agents who have little experience evaluating the banks' assets. In this state of the world, agency problems associated with asymmetric information become important.[6]

As part of the specification of the model, Gertler and Kiyotaki (2015) assume that the probability of a rollover crisis is proportional to the losses that depositors would experience in the event that a rollover crisis occurs. Thus, if bank creditors think that banks' net worth would be positive in a crisis, then a rollover crisis is impossible. However, if banks' net worth is negative in this scenario, then a rollover crisis can occur.

We use this model to illustrate how a relatively small shock can trigger a system-wide rollover crisis in the shadow banking system. To this end, consider the following illustrative example, which captures in a highly stylized way the key features of the shadow-banking system before (left-side table below) and after (right- side table below) the crisis.

[4] The key theoretical antecedent is the bank run model of Diamond and Dybvig (1983) and the sovereign debt rollover crisis model of Cole and Kehoe (2000).

[5] Unlike in the classic bank run model of Diamond and Dybvig (1983), there is no reason to impose a sequential debt service constraint.

[6] Gertler and Kiyotaki (2015) capture these agency problems by assuming that the buyers of long-term assets during a rollover crisis are relatively inefficient at managing the assets.

Pre-housing market correction

Assets	Liabilities
120 (105)	Deposits: 100
	Banker net worth 20 (5)

Post-housing market correction

Assets	Liabilities
110 (95)	Deposits: 100
	Banker net worth 10 (–5)

In the left-side table, the shadow banks' assets and liabilities are 120 and 100, respectively—so their net worth is positive. The numbers in parentheses show the value of the assets and net worth of the shadow banks if there were to be a rollover crisis and fire-sale of assets. Since net worth remains positive, the Gertler and Kiyotaki (2015) analysis implies that a rollover crisis cannot occur.

Now imagine that the assets of the shadow banks decline because of a small shift in fundamentals. Here, we have in mind the events associated with the decline in housing prices that began in the summer of 2006. The right-side table is the analog of the left side, taking into account the lower value of the shadow banks' assets. In the example, the market value of assets has fallen by 10, from 120 to 110. In the absence of a rollover crisis, the system is solvent. However, the value of the assets in the case of a rollover crisis is 95 and the net worth of the bank is negative in that scenario. Thus, a relatively small change in asset values could lead to a severe financial crisis.

The example illustrates two important potential uses of DSGE models. First, an estimated DSGE model can be used to calculate the probability of a rollover crisis, conditional on the state of the economy. In principle, one could estimate this probability function using reduced form methods. However, because financial crises are rare events, estimates emerging from reduced form methods would have enormous sampling uncertainty. Because of its general equilibrium structure, an empirically plausible DSGE model would address the sampling uncertainty problem by making use of a wider array of information drawn from non-crisis times to assess the probability of a financial crisis.

Second, DSGE models can potentially be used to design policies that address financial crises. While we think that existing DSGE models of financial crisis such as Gertler and Kiyotaki (2015) yield valuable insights, these models are clearly still in their infancy. For example, the model assumes that people know what can happen in a crisis, together with the associated probabilities. This seems implausible, given the fact that a full-blown crisis happens two or three times per century in developed economy like the United States. It seems safe to conjecture that factors such as aversion to "Knightian uncertainty" play an important role in driving fire sales in a crisis (see for example, Caballero and Krishnamurthy 2008). Still, research on various types of crises is proceeding at a rapid pace, and we expect to see substantial improvements in DSGE models on the subject (for examples, see Bianchi, Hatchondo, and Martinez 2016 and the references therein).

Frictions Associated with the People that Borrow from Financial Institutions. We now turn to the second set of financial frictions. One of the themes of this paper is that data analysis lies at the heart of the DSGE project. Elsewhere, we have stressed the importance of microeconomic data. Here, we also stress the role of financial data as a source of information about the sources of economic fluctuations. Using an estimated DSGE model, Christiano, Motto, and Rostagno (2014) argue that the dominant source of US business cycle fluctuations are disturbances in the riskiness of individual firms (what they call "risk shocks"). A motivation for their analysis is that in recessions, firms pay a premium to borrow money, above the rate at which a risk-free entity like the US government borrows. They interpret this premium as, in effect, reflecting the view of lenders that firms represent a riskier bet. Christiano, Motto, and Rostagno (2014) estimate their DSGE model using a large number of macroeconomic and financial variables and conclude that fluctuations in risk can account for the bulk of GDP fluctuations.

To understand the intuition behind the model, consider a recession that is triggered by an increase in the riskiness of firms.[7] As the cost of borrowing rises, firms borrow less and demand less capital. This decline induces a fall in both the quantity and price of capital. In the presence of nominal rigidities and a Taylor rule for monetary policy, the decline in investment leads to an economy-wide recession, including a fall in consumption and a rise in firm bankruptcies. With the decline in aggregate demand, inflation falls. Significantly, the risk shock leads to an increase in the cross-sectional dispersion of the rate of return on firm equity. Moreover, the recession is also associated with a fall in the stock market, driven primarily by capital losses associated with the fall in the price of capital. All these effects are observed in a typical recession.[8] This is why Christiano, Motto, and Rostagno's (2014) estimation procedure attributes 60 percent of the variance of US business cycles to risk shocks.

The dynamic effects of risk shocks in the Christiano, Motto, and Rostagno (2014) model resemble business cycles so well that many of the standard shocks that appear in previous business cycle models are rendered unimportant in the empirical analysis. For example, Christiano et al. (2014) find that aggregate shocks to the technology for producing new capital account for only 13 percent of the business cycle variation in GDP. This contrasts sharply with the results in Justiniano, Primiceri, and Tambalotti (2010), who argue that this shock accounts for roughly 50 percent of business cycle variation of GDP. The critical difference is that Christiano, Motto, and Rostagno (2014) include financial data like the stock market in their analysis. Shocks to the supply of capital give rise to countercyclical movements in the stock market, so they cannot be the prime source of business cycles.

Financial frictions have also been incorporated into a growing literature that introduces the housing market into DSGE models. One part of this literature focuses on the implications of housing prices for households' capacity to borrow (see for example, Iacoviello and Neri 2010; Berger, Guerrieri, Lorenzoni, and Vavra forthcoming). Another part focuses on the implications of land and housing prices on firms' capacity to borrow (Liu, Wang, and Zha 2013).

[7] In Christiano, Motto, and Rostagno (2014), a rise in risk corresponds to an increase in the variance of a firm-specific shock to technology. Absent financial frictions, such a shock would have no impact on aggregate output. A rise in the variance would lead to bigger-sized shocks at the firm level but the average across firms is only a function of the mean (law of large numbers).

[8] To our knowledge, the first paper to articulate the idea that a positive shock to idiosyncratic risk could produce effects that resemble a recession is Williamson (1987).

Zero Lower Bound and Other Nonlinearities

The financial crisis and its aftermath was associated with two important nonlinear phenomena. The first phenomenon was the rollover crisis in the shadow-banking sector discussed above. The Gertler and Kiyotaki (2015) model illustrates the type of nonlinear model required to analyze this type of crisis. The second phenomenon was that the nominal interest rate hit the zero-lower bound in December 2008. An earlier theoretical literature associated with Krugman (1998), Benhabib, Schmitt-Grohé, and Uribe (2001), and Eggertsson and Woodford (2003) had analyzed the implications of the zero-lower bound for the macroeconomy. Building on this literature, DSGE modelers quickly incorporated the zero-lower bound into their models and analyzed its implications.

In what follows, we discuss how nonlinear DSGE models have been used to assess which shocks triggered the financial crisis and what propagated their effects over time. We focus on three papers to give the reader a flavor of this literature. We then review some of the policy advice relating to fiscal policy and forward guidance that emerges from recent DSGE models that incorporate a zero lower bound.

The Causes of the Crisis and Slow Recovery. Several DSGE models provide a quantitatively plausible description of the behavior of major economic aggregates during the Great Recession when the zero lower bound was a binding constraint. In Christiano, Eichenbaum, and Trabandt (2015), we analyze the post-crisis period taking into account that the zero lower bound was binding. In addition, we take into account the forward guidance of the Federal Reserve Open Market Committee about future monetary policy. This guidance was highly nonlinear in nature: it involved a regime switch depending on the realization of endogenous variables (like the unemployment rate). We argue that the bulk of movements in aggregate real economic activity during the Great Recession was due to financial frictions interacting with the zero lower bound. Our analysis also indicates that the observed fall in total factor productivity and the rise in the cost of working capital played important roles in accounting for the surprisingly small drop in inflation after the financial crisis.

Lindé and Trabandt (2018) argue that nonlinearities in price and wage-setting are an alternative reason for the small decline in inflation during the Great Recession. In particular, they assume that the elasticity of demand of a goods-producing firm is increasing in its relative price along the lines proposed in Kimball (1995). So, during a recession when marginal costs are falling, firms that can change their prices have less of an incentive to do so relative to the case in which the elasticity of demand is constant. They show that this effect is quantitatively important in the standard nonlinear New Keynesian DSGE model.

Gust, Herbst, López-Salido, and Smith (2017) estimate a fully nonlinear DSGE model with an occasionally binding zero lower bound. Nonlinearities in the model play an important role for inference about the source and propagation of shocks. According to their analysis, shocks to the demand for risk-free bonds and, to a lesser extent, the marginal efficiency of investment proxying for financial frictions, played a critical role in the crisis and its aftermath.

Critically, the above papers include both financial frictions and nominal rigidities. A model of the crisis and its aftermath that didn't have financial frictions would not be plausible. At the same time, a model that included financial frictions but didn't allow for nominal rigidities would have difficulty accounting for the broad-based decline across all sectors of the economy. For example, such a model would predict a boom in sectors of the economy that are less dependent on the financial sector.

The fact that DSGE models with nominal rigidities and financial frictions can provide quantitatively plausible accounts of the financial crisis and the Great Recession makes them obvious frameworks within which to analyze alternative policies. We begin with a discussion of fiscal policy.

Fiscal Policy. In standard DSGE models, an increase in government spending triggers a rise in output and inflation. When monetary policy is conducted according to a standard Taylor rule, a rise in inflation triggers a rise in the real interest rate. Other things equal, the policy-induced rise in the real interest rate lowers investment and consumption demand. As a result, the government spending multiplier is typically less than one in these models. But when the zero lower bound binds, the rise in inflation associated with an increase in government spending does not trigger a rise in the real interest rate. With the nominal interest rate stuck at zero, a rise in inflation lowers the real interest rate, crowding consumption and investment in, rather than out. This raises the quantitative question: how does a binding zero lower bound constraint on the nominal interest rate affect the size of the government spending multiplier?

Christiano, Eichenbaum, and Rebelo (2011) address this question in a DSGE model, assuming all taxes are lump sum. A basic principle that emerges from their analysis is that the multiplier is larger the more binding is the zero lower bound. They measure how binding the zero lower bound is by how much a policymaker would like to lower the nominal interest rate below zero if it were possible to do so. For their preferred specification, the multiplier is much larger than one. When the zero lower bound is not binding, then the multiplier would be substantially below one.

Erceg and Lindé (2014) examine (among other things) the impact of distortionary taxation on the magnitude of the government spending multiplier in the zero lower bound. They find that the results based on lump-sum taxation are robust relative to the situation in which distortionary taxes are raised gradually to pay for the increase in government spending.

At this point, a large literature now studies the fiscal multiplier when the zero lower bound can bind using DSGE models that allow for financial frictions, open-economy considerations and liquidity constrained consumers. Such models are playing an important role in the debate among academics and policymakers about whether and how fiscal policy should be used to fight recessions. We offer two examples. First, Coenen et al. (2012) analyze the impact of different fiscal stimulus shocks in several DSGE models that are used by policy-making institutions. Second, Blanchard, Erceg, and Lindé (2017) analyze the effects of a fiscal expansion by the core euro area economies on the periphery euro area economies. Finally, we note that the early papers on the size of the government spending multiplier use log-linearized versions of DSGE models. For example, Christiano, Eichenbaum, and Rebelo (2011) work with a linearized version of their model, while in Christiano, Eichenbaum, and Trabandt (2015), we work with a nonlinear version of the model. Significantly, there is now a literature that assesses the sensitivity of multiplier calculations to linear versus nonlinear solutions (for example, Christiano and Eichenbaum 2012; Boneva, Braun, and Waki 2016; Christiano, Eichenbaum, and Johannsen 2017; Lindé and Trabandt forthcoming).

Forward Guidance. When the zero lower bound constraint on the nominal interest rate became binding, conventional monetary policy (that is, lowering short-term interest rates) was no longer possible. Monetary policymakers considered a variety of alternatives. Here, we focus on forward guidance as a policy option analyzed by Eggertsson and Woodford (2003) and Woodford (2012) in New Keynesian models. By forward guidance, we mean that the monetary policymaker promises to keep the policy interest rate lower for longer than the monetary rule would otherwise suggest.

As documented in Carlstrom, Fuerst, and Paustian (2015), forward guidance is implausibly powerful in standard DSGE models like Christiano, Eichenbaum, and Evans (2005). Del Negro, Giannoni, and Patterson (2012) refer to this phenomenon as the "forward guidance puzzle." This puzzle has fueled an active debate. Carlstrom, Fuerst, and Paustian (2015) and Kiley (2016) show that the magnitude of the forward guidance puzzle is substantially reduced in a sticky information (as opposed to a sticky price) model. Other responses to the forward guidance puzzle involve more fundamental changes, such as abandoning the representative agent framework, which is discussed in the next subsection. More radical responses involve abandoning strong forms of rational expectations (see for example Gabaix 2016; Woodford 2018; Angeletos and Lian forthcoming).

Heterogeneous Agent Models

In the standard New Keynesian model, the primary channel by which monetary-policy-induced interest rate changes affect consumption is by causing the representative household to reallocate consumption over time. However, there is a great deal of empirical micro evidence against the importance of this reallocation channel, in part because many households face binding borrowing constraints.

Motivated by these observations, macroeconomists are exploring DSGE models where heterogeneous consumers face idiosyncratic shocks and binding borrowing constraints.[9] Kaplan, Moll, and Violante (2018) and McKay, Nakamura, and Steinsson (2016) are useful starting points that convey the flavor of the literature. Both of these papers present DSGE models in which households have uninsurable, idiosyncratic income risk, and in which many households face borrowing constraints.[10]

The literature on DSGE models with heterogeneous agents is still young, but it has already yielded important insights into important policy issues like the impact of forward guidance (McKay, Nakamura, and Steinsson 2016; Farhi and Werning 2017). The literature has also led to a richer understanding of how monetary policy actions affect the economy. In Kaplan, Moll, and Violante (2018), for example, a monetary policy action initially affects the small set of households who

[9] There is also important work allowing for firm heterogeneity in DSGE models (for examples, see Gilchrist, Schoenle, Sim, and Zakrajšek 2017; Ottonello and Winberry 2017).

[10] Important earlier papers in this literature include Oh and Reis (2012), Guerrieri and Lorenzoni (2017), McKay and Reis (2016), Gornemann, Kuester, and Nakajima (2016), and Auclert (2017).

actively intertemporally adjust spending in response to an interest rate change. However, most of the impact occurs through a multiplier-type process that occurs as other firms and households adjust their spending in response to the change in demand by the "intertemporal adjusters." This area of research typifies the cutting edge of DSGE models: the key features are motivated by micro data, and the implications (say, for the multiplier-type process) are assessed using both micro and macro data.

How Are DSGE Models Used in Policy Institutions?

As a case study of how DSGE models are used in policy institutions, we focus on the Board of Governors of the Federal Reserve System. We are guided in our discussion by Stanley Fischer's (2017) description of the policy-making process at the Federal Reserve Board.

Before the Federal Open Market Committee meets to make policy decisions, all participants are given copies of the so-called Tealbook, which includes parts A and B.[11] Tealbook A contains a summary and analysis of recent economic and financial developments in the United States and foreign economies, as well as the staff's economic forecast. The staff also provides model-based simulations of a number of alternative scenarios highlighting upside and downside risks. Examples of such scenarios include a decline in the price of oil, a rise in the value of the dollar or wage growth that is stronger than the one built into the baseline forecast. These scenarios are generated using one or more of the Board's macroeconomic models, including the DSGE models, SIGMA, and EDO.[12] Tealbook A also contains estimates of future outcomes in which the Federal Reserve Board uses alternative monetary policy rules as well model-based estimates of optimal monetary policy. According to Fischer (2017), DSGE models play a central, though not exclusive, role in this process.

Tealbook B provides an analysis of specific policy options. According to Fischer (2017), "Typically, there are three policy alternatives—A, B, and C—ranging from dovish to hawkish, with a centrist one in between." DSGE models, along with other approaches, are used to generate the quantitative implications of the specific policy alternatives considered.

The Federal Reserve System is not the only policy institution that uses DSGE models. For example, the European Central Bank, the International Monetary Fund, the Bank of Israel, the Czech National Bank, the Sveriges Riksbank, the Bank of Canada, and the Swiss National Bank all use such models in their policy process.[13]

[11] The Tealbooks are available with a five-year lag at https://www.federalreserve.gov/monetarypolicy/fomc_historical.htm.

[12] For a discussion of the SIGMA and EDO models, see Erceg, Guerrieri, and Gust (2006) and, at the Federal Reserve website, https://www.federalreserve.gov/econres/edo-models-about.htm.

[13] For a review of the dynamic stochastic general equilibrium models used in the policy process at the European Central Bank, see Smets, Christoffel, Coenen, Motto, and Rostagno (2010). Carabenciov et al. (2013) and Freedman, Kumhof, Laxton, Muir, and Mursual (2009) describe global DSGE models used for policy analysis at the International Monetary Fund (IMF), while Benes, Kumhof, and Laxton (2014) describe

We just argued that DSGE models are used to run policy simulations in various policy institutions. The results of those simulations are useful to the extent that the models are empirically plausible. One important way to assess the plausibility of a model is to consider its real time forecasting performance. Cai, Del Negro, Giannoni, Gupta, Li, and Moszkowski (2018) compare real-time forecasts of the New York Fed DSGE model with those of various private forecasters and with the median forecasts of the Federal Open Market Committee members. The DSGE model that they consider is a variant of Christiano, Motto, and Rostagno (2014) that allows for shocks to the demand for government bonds. Cai et al. find that the model-based real time forecasts of inflation and output growth are comparable to those of private forecasters. Strikingly, the New York Fed DSGE model does a better job at forecasting the slow recovery than the Federal Open Market Committee, at least as judged by the root mean square errors of their median forecasts. Cai et al. argue that financial frictions play a critical role in allowing the model to anticipate the slow growth in output after the financial crisis.

In sum, dynamic stochastic general equilibrium models play an important role in the policymaking process. To be clear: they do not substitute for judgment, nor should they. But policymakers have voted with their collective feet on the usefulness of DSGE models. In this sense, DSGE models are meeting the market test.

A Brief Response to Some Critiques

Here, we briefly respond to some recent critiques of dynamic stochastic general equilibrium models. We focus on Stiglitz (2017) because his critique is both well known and representative of some common criticisms.

Econometric Methods

Stiglitz (2017, p. 1), citing what he refers to as Korinek (2017)'s "devastating critique" of DSGE practitioners, claims: "Standard statistical standards are shunted aside [by DSGE modelers]." As evidence, he writes: "[T]he time series employed are typically detrended using methods such as the HP [Hodrick–Prescott] filter to focus the analysis on stationary fluctuations at business cycle frequencies. Although this is useful in some applications, it risks throwing the baby out with the bathwater as many important macroeconomic phenomena are non-stationary or occur at lower frequencies" (p. 3). But this criticism is simply

MAPMOD, a DSGE model used at the IMF for the analysis of macroprudential policies. Clinton, Hlédik, Holub, Laxton, and Wang (2017) describe the role of DSGE models in policy analysis at the Czech National Bank, and Adolfson, Laséen, Christiano, Trabandt, and Walentin (2013) describe the RAMSES II DSGE model used for policy analysis at the Sveriges Riksbank. Argov et al. (2012) describe the DSGE model used for policy analysis at the Bank of Israel, Dorich, Johnston, Mendes, Murchison, and Zhang (2013) describe ToTEM, the DSGE model used at the Bank of Canada for policy analysis, and Alpanda, Cateau, and Meh (2014) describe MP2, the DSGE model used at the Bank of Canada to analyze macroprudential policies. Rudolf and Zurlinden (2014) and Gerdrup, Kravik, Paulsen, and Robstad (2017) describe the DSGE model used at the Swiss National Bank and the Norges bank, respectively, for policy analysis.

incorrect. The vast bulk of the modern DSGE literature does not estimate models using HP filtered data. Moreover, DSGE models of endogenous growth provide a particularly stark counterexample to the claim that this approach is limited to the analysis of stationary fluctuations at business cycle frequencies. Notably, neither Stiglitz nor Korinek offer any constructive advice on how to address the difficult problem of dealing with nonstationary data. In sharp contrast, the DSGE literature struggles mightily with this problem and adopts different strategies for modeling non-stationarity in the data. As one example, see Comin and Gertler (2006)'s analysis of medium-term business cycles.

Stiglitz (2017) then claims (pp. 3–4) "for given detrended time series, the set of moments chosen to evaluate the model and compare it to the data is largely arbitrary—there is no strong scientific basis for one particular set of moments over another … [F]or a given set of moments, there is no well-defined statistic to measure the goodness of fit of a DSGE model or to establish what constitutes an improvement in such a framework." This criticism might have been appropriate in the 1980s. But, it simply does not apply to modern analyses, which use full information maximimum likelihood or generalized method of moments.

Financial Frictions

Stiglitz (2017) asserts that pre-crisis DSGE models did not allow for financial frictions or liquidity-constrained consumers. This claim is incorrect. As one example, Galí, López-Salido, and Vallés (2007) investigate the implications of the assumption that some consumers are liquidity constrained. Specifically, they assume that a fraction of households cannot borrow at all. They then assess how this change affects the implications of DSGE models for the effects of a shock to government consumption. Not surprisingly, they find that liquidity constraints substantially magnify the impact of government spending on GDP. Looking back further, Carlstrom and Fuerst (1997) and Bernanke, Gertler, and Gilchrist (1999) develop DSGE models that incorporate credit market frictions that give rise to a "financial accelerator" in which credit markets work to amplify and propagate shocks to the macroeconomy.

In other examples, Christiano, Motto, and Rostagno (2003) add several features to the model of Christiano, Eichenbaum, and Evans (2005) to allow for richer financial markets. They incorporate the fractional reserve banking model developed by Chari, Christiano, and Eichenbaum (1995). They allow for financial frictions as modeled by Bernanke, Gertler, and Gilchrist (1999) and Williamson (1987). In addition they assume that agents can only borrow using nominal non-state-contingent debt, so that the model incorporates the Fisherian debt deflation channel. Finally, Iacoviello (2005) develops and estimates a DSGE model with nominal loans and collateral constraints tied to housing values. This paper is an important antecedent to the large post-crisis DSGE literature on the aggregate implications of housing market booms and busts.

Stiglitz (2017) also asserts that DSGE models abstract from interest rate spreads. He writes (p. 10): "... in standard [DSGE] models ... all that matters is that somehow the central bank is able to control the interest rate. But, the interest rate is not the interest rate confronting households and firms; the spread between the two is a critical endogenous variable." However, pre-crisis DSGE models like those in Williamson (1987), Carlstrom and Fuerst (1997), Chari, Christiano, and Eichenbaum (1995), and Christiano, Motto, and Rostagno (2003) and post-crisis DSGE models like Gertler and Karadi (2011), Jermann and Quadrini (2012), Curdia and Woodford (2010), and Christiano, Motto, and Rostagno (2014) offer counterexamples. In all those papers, which are only a subset of the relevant literature, credit and the endogenous spread between the interest rates confronting households and firms play central roles.

Nonlinearities and Lack of Policy Advice

Stiglitz (2017, p. 7) writes that "the large DSGE models that account for some of the more realistic features of the macroeconomy can only be 'solved' for linear approximations and small shocks—precluding the big shocks that take us far away from the domain over which the linear approximation has validity." He (p. 12) writes that "an adequate macro model has to explain how even a moderate shock has large macroeconomic consequences." He claims (p. 1): "[T]he inability of the DSGE model to ... provide policy guidance on how to deal with the consequences [of the crisis], precipitated current dissatisfaction with the model."

Many papers cited throughout this essay offer clear counterexamples to the criticism that dynamic stochastic general equilibrium models don't address nonlinearities and large shocks, or that such models cannot explain why moderate shocks can have large consequences. The claim that DSGE models are unable to provide policy guidance does not square with the simple fact that central banks all over the world actually use DSGE models as part of their policy process.

Heterogeneity

Stiglitz (2017, p. 5) writes that DSGE models do not include heterogeneous agents: "DSGE models seem to take it as a religious tenet that consumption should be explained by a model of a representative agent maximizing his utility over an infinite lifetime without borrowing constraints." This view is obviously at variance with the cutting-edge research in DSGE models discussed earlier.

Dynamic stochastic general equilibrium models will become better as modelers respond to informed criticism. Stiglitz's criticisms are not informed.

Conclusion

The enterprise of dynamic stochastic general equilibrium modeling is an organic process that involves the constant interaction of data and theory. Pre-crisis DSGE models had shortcomings that were highlighted by the financial crisis and its aftermath. Substantial progress has occurred since then. We have emphasized the incorporation of financial frictions and heterogeneity into DSGE models. However, we should also mention that other exciting work is being done in this area, like research on deviations from conventional rational expectations. These deviations include *k*-level thinking, robust control, social learning, adaptive learning, and relaxing the assumption of common knowledge. Frankly, we do not know which of these competing approaches will play a prominent role in the next generation of mainstream DSGE models.

Will the future generation of DSGE models predict the time and nature of the next crisis? Frankly, we doubt it. As far as we know, there is no sure, time-tested way of foreseeing the future. The proximate cause for the financial crisis was a failure across the economics profession, policymakers, regulators, and financial market professionals to recognize and to react appropriately to the growing size and leverage of the shadow-banking sector. DSGE models are evolving in response to that failure as well as to the treasure trove of micro data available to economists. We don't know where that process will lead. But we do know that DSGE models will remain central to how macroeconomists think about aggregate phenomena and policy. There is simply no credible alternative to policy analysis in a world of competing economic forces operating on different parts of the economy.

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