# Yes we can! Teaching DSGE models to undergraduate students

Solis-Garcia, Mario

Macalester College

21 September 2017

# Yes we can! Teaching DSGE models to undergraduate students*

Mario Solis-Garcia†
Macalester College

October 2, 2017

**Abstract**

Dynamic stochastic general equilibrium (DSGE) models have become the workhorse of modern macroeconomics and the standard way to communicate ideas among applied macroeconomists. Undergraduate students, however, often remain unaware of their existence. The lack of specialized knowledge can hurt them if they decide to attend graduate school. Indeed, many first-year PhD students discover that the material they are currently learning differs significantly from what they mastered in college. But this can change. In this essay, I describe how to teach a full-fledged macroeconomics course where DSGE models take center stage. I discuss how to arrange such a course within a one-semester time frame, detail the main components of instruction, and finish with some thoughts based on my teaching experience at Macalester College.

**JEL codes**: A22, B41, E30, E60.
**Keywords**: DSGE models, Bayesian estimation, undergraduate education, advanced macroeconomics.

* I thank Pete Ferderer and Gary Krueger for encouraging me to write this essay and for detailed comments and suggestions on early drafts. I also appreciate the feedback and comments of former ECON 420 students at Macalester College and ECON 4741H students at the University of Minnesota, where this course was first offered while I worked on my PhD degree. Finally, special thanks go to Stefan Faridani, Noah Nieting, Cory Stern, Rachel Toor, and Yingtong Xie.

† Contact: Department of Economics, Macalester College, 1600 Grand Avenue, St. Paul, MN 55105. E-mail correspondence to msolisga@macalester.edu.

# 1 Introduction

Dynamic stochastic general equilibrium (DSGE) models have become the workhorse of modern macroeconomics and the standard way to communicate ideas among applied macroeconomists. Designed to rival structural macroeconometric models—by satisfying the Lucas critique (Lucas 1976)—DSGE models have proliferated in the profession, even serving as an input for policy (e.g., Del Negro, Eusepi, Giannoni, Sbordone, Tambalotti, Cocci, Hasegawa, and Linder 2013) and as a tool for forecasting the business cycle (e.g., Del Negro and Schorfheide 2013).

And now some bad news: Fernández-Villaverde, Rubio-Ramírez, and Schorfheide (2016, p. 530) argue that "Unfortunately for PhD students and fortunately for those who have worked with DSGE models for a long time, the barriers to entry into the DSGE literature are quite high." If these heartbreaking words apply to PhD students, common sense suggests the barriers to entry are gigantic for undergraduates and that the divergence between graduate and undergraduate macroeconomics will prevail—and perhaps increase—for the indefinite future.[1]

But common sense doesn't always work as advertised. I believe that the gap between PhD and college-level macroeconomics can be closed—and significantly so.[2] In this essay, I share my experience in teaching an *applied and DSGE-based* macroeconomics course. Colleagues

[1] The remarks by Fernández-Villaverde et al. (2016) are not a recent feature of the DSGE literature. Indeed, the pioneering work in the field (e.g., Kydland and Prescott 1982) was thought to be extremely complicated; since the analysis required knowledge of dynamic programming and computational techniques, these pieces remained impenetrable to outsiders. Almost a decade later, Campbell (1994) showed how an *approximation* to the solution of the stochastic growth model—via a linearization of the first-order conditions—could simplify the analysis. To this day, several papers have built upon Campbell's idea and elaborated on solution techniques for DSGE models (e.g., Uhlig 1999, Christiano 2002, and Sims 2002).

[2] And as the song says, "[B]ut I'm not the only one." I looked at the economics course offerings in the top 10 national universities and liberal arts colleges (according to US News) and found 6 courses that appear to walk along the same path as this course. See the Appendix for details.

find it surprising that it's possible to teach these exacting tools to undergraduate students. Though requiring a considerable effort, we can get undergraduate students close to the research frontier.

Just as not every undergraduate student is a candidate for an economics major—something we learn after teaching our fair share of introductory courses—not every economics major is a candidate for this course: motivated and mathematically mature students are its main market. I encourage students to enroll in the course if one or more of the following are satisfied: (a) they will embark in graduate studies in economics—even if they don't want to specialize in macroeconomics, (b) they enjoyed their intermediate macroeconomics course and want to dig deeper into the field, or (c) they are interested in learning tools and techniques at the intersection of mathematics and economics or programming tools like Matlab. (I expand on these ideas in Section 3.1 below.)

Why offer my experiences in writing? The answer is simple. I want to encourage faculty who aspire to teach these methods to do so—by offering a detailed path that can guide them in their efforts. Recent PhD graduates may be especially interested in this essay, as they are often told that the undergraduate macroeconomics curriculum consists mostly of IS-LM-AS models or their recent variants (e.g., Weerapana 2003) and, consequently, feel that the knowledge they gained in graduate school is only useful when doing their own research.

## 2 Why should we teach this course?

There are at least three reasons. First, to help students work as close as possible to the macroeconomics research frontier—students should be able to access the top journals and papers in the field—which is far from trivial. Second, to increase their human capital and improve their prospects after graduation. And finally, because deep inside our hearts we hope that students, when introduced to the frontier of modern macroeconomics, decide that a life of research is a life worth living and move on to the exciting process of obtaining a PhD in Economics. We can only dream.[3]

## 2.1 The research frontier (and the secret handshake)

Teaching this course to undergraduates gets them fairly close to the frontier of macroeconomics; indeed, most of the applied work generated in the last 30 years involves DSGE models. However, as the quote from Fernández-Villaverde et al. (2016) suggests, there is a "secret handshake" that makes reading (and *understanding*) papers at the research frontier rather hard for an uninitiated undergraduate, perhaps so much that skimming through the abstract and the introduction is the only choice he or she has.

Allow me to elaborate on this claim. Around their third year in college, undergraduates in rigorous programs are already familiar with applied microeconomics papers and their structure: (a) a question is raised, (b) a bit of theory or a partial equilibrium, reduced-form model is shown, (c) the data are described, and (d) a lot of regression tables are presented. Conversely, a typical journal article using a DSGE framework will (a) present an idea or mechanism, (b) lay out the model and equilibrium conditions, and (c) open the floodgates so that tables and graphs (that *apparently* present the results) start to flow.

Yet this atypical structure—different enough from the coziness of applied micro papers—

[3] . . . nevertheless, it appears that dreams can come true after all: out of the 53 students who have taken the course, 4 are currently enrolled in a graduate program in Economics and 9 of them will very likely follow this route within the next three years. See more in Section 2.2.

baffles students: "Wait, is this a theory paper? (It does look like micro!)" "Estimated parameters? Where's the regression equation? (Can anyone tell me what the $R^2$ is?)" "They're simulating *WHAT*?" As it turns out, this confusion arises because students lack the secret handshake, and they won't learn the ritual until they go to graduate school... if they go to graduate school.

Maybe you think I'm overstating the case. Perhaps we can get students close to the research frontier if we only focus on the main ideas from the papers (e.g., "if consumers cannot save, then the multiplier is bigger"). Or better yet, if we're lucky enough to have a group of very motivated students, we can teach them to read the model equations (e.g., "this is what the intratemporal condition means") and move on. But even after considering these two solutions, I think we still fall short. The DSGE literature contains many ideas that go beyond talking points drilled during class or a set of equilibrium conditions that can now be read: these ideas are important *because of the underlying economic mechanism,* and it is hard to appreciate this mechanism without a clear understanding of DSGE models.[4]

Once students understand how these models work, they can start thinking about their own research ideas with a DSGE toolkit at their side. Capstone papers and honors theses can now go beyond the classic econometrics archetype—and that's a good thing.

"We want more examples!"—we often hear from students. Taking their word for it, I share two examples that show what student papers look like. First, a capstone paper (Faridani 2017) that links the housing *rental* market to the jobless recovery that followed the Great Recession:

[4] Here's the same argument translated to econometrics lingo: I want students to understand how the OLS regression coefficients can be derived with linear algebra and why $\hat{\beta} = (X'X)^{-1}X'Y$ makes sense. I don't want them to just know that the OLS coefficients characterize the "best fit" line and can be obtained by typing "`regress y x`."

> I hypothesize that weakness in the housing market—particularly rentals—disincentivized job search by taking the pressure of rising rents off of unemployed workers. In this paper, I calibrated a search model with no market failures. The purpose of the model is to understand the consequences of a simultaneous shock to housing prices and productivity. If housing prices take a long time to recover, the model predicts movements of and along the Beveridge Curve that are very similar to those observed during and after the Great Recession. If, in a counterfactual scenario, housing prices recover quickly, then employment also recovers and the simulated Beveridge curve looks nothing like the observed one. I conclude that persistent weakness in the housing market may have contributed to the joblessness of the recovery that followed the Great Recession.

Second, an honors thesis I supervised (Stern 2016) that quantifies the effects of the Affordable Care Act (ACA) on the labor market and asks whether (as some pundits argued) the ACA is a "certified job-killer" (he concludes it's not—also, recent research agrees with this conclusion; e.g., Duggan, Goda, and Jackson 2017):

> This paper develops a three-agent search model to test the effects of the ACA's individual mandate on the lagged labor market recovery from the Great Recession. There are several important results from the simulated model. First, I find that positive shocks to mandatory health care costs lead to increases in aggregate employment and output, which opposes recent conclusions in the literature. Second, I observe that there is a trade-off between consumption and mandatory health care expenditure, which, in conjunction with the higher cost of unemployment, provides a general equilibrium explanation for the positive correlation between equilibrium levels of health care costs and aggregate employment. Third, I simulate shocks to the labor market separation rate, and determine that these shocks have positive effects on vacancies, matches, and search effort, while having minimal effects external to the labor market. Fourth, I demonstrate the robustness of the model using shocks to TFP. The simulated variables comove appropriately and the artificial time series associated with these shocks sufficiently portray U.S. economic data.

The most exciting feature from these examples is seeing how students can tackle the "big questions" in the profession. Indeed, jobless recoveries have been on our radar since the early 1990s, and the effects of the ACA are relevant not only in terms of the underlying economics but also in terms of the macroeconomic outcome of this policy. Moreover, both papers use labor search models—the standard approach to address questions concerning the labor market—and reach conclusions that go beyond what the classic econometrics route offers.

### 2.2 Human capital and job search

Students place a high premium in job security after graduation. While the DSGE toolkit taught in class is valuable and without doubt increases their human capital, what sort of additional (and *marketable*) skills can students get from the course? Asked in a slightly different way, what outcomes can they look forward to after graduation, conditional on the human capital they've accumulated?

To shed some light in this question, I asked former students to share their post-graduation outcomes via an informal survey: 33 out of 53 students replied. From the 33 students, 10 accepted private-sector jobs and 10 went to the academic world—nine enrolled in graduate school and one accepted a research assistant position. Two students are still deciding which path to take and the rest are rising seniors so they don't have a job yet.

At the time of writing, 11 of the 53 students are studying in a graduate program—four of them an economics PhD—and 14 plan to apply to graduate school within the next three years—nine in economics.

## 3 How should we teach this course?

Professors at other institutions ask: "Well, so how do you make it work?" This section contains my answer. Because it's always important to align expectations, everything related to the teaching experience refers to a 14-week, 4-credit course with 3 hours of lecture and 1.5 hours of laboratory per week.

## 3.1 Organization

**Prerequisites: mathematics** A second question that is often asked is: "What are the students like? Math majors only?" Surprisingly, there is a large degree of mathematical heterogeneity in students—they only need to know how to set up a Lagrange multiplier problem (and not be afraid to use it).

If you're skeptical about the last sentence—perhaps your prior is that mathematical maturity matters—I can confirm that there are no large differences in performance between math-inclined and regular economics majors. Indeed, many of the students who have successfully taken the class are economics majors only (or dual majors with other disciplines outside of mathematics and statistics) and have not received mathematical training beyond the requirements set by the Economics Department (one semester of multivariable calculus and one semester of statistics).

**Prerequisites: macroeconomics** The course is suitable for juniors and seniors who have completed their intermediate macroeconomics course. Personally, I teach intermediate macroeconomics sticking to an equilibrium-based approach (Williamson 2017), but this is neither necessary nor sufficient to succeed in the next course as some students take their macroeconomics from faculty who follow a more traditional route (e.g., Mankiw 2016). The first day of class I tell students—half joking, half not—that those who used the Williamson book will enjoy an advantage... but only for the first week of class. Knowing the equilibrium-based approach gives students a head start, but once we get to the detailed analysis of DSGE models the advantage vanishes. Suffice to say, both kinds of students have done well in the class.

**Prerequisites: computation** I don't assume that students will know a programming language before enrolling in the course. Instead, I provide a self-contained experience using Matlab. Why Matlab? Three reasons. First, the language has a large user base and this allows students to seek (and find) help in external sources quite easily. Second, Matlab coding is a marketable skill that commands a premium in the job market. Finally, the price is right: the student edition packs every tool needed in the course and pricing is competitive—at least compared to the average price of an intermediate-level economics book.[5]

**Textbook** I do not assign a textbook for the course. I tell students they should expect to know macroeconomics at the level of Williamson (2017) or Mankiw (2016) and that good references that overlap with the material we cover in class are McCandless (2008) and DeJong and Dave (2011). For day-to-day lecturing needs I have prepared a set of class notes—alas, a never-ending work-in-progress—that cover each of the topics from class.[6]

**Journal articles** "You don't read papers in the first year. You're here to learn tools"—say most first-year PhD macroeconomics professors. I adhere to this philosophy for the first half of the course, as I center my efforts into teaching students the details of competitive equilibrium, Matlab coding, dynamic programming, and log-linearization. At least for the

[5] Some schools may even allow students to download the software for free as a result of a campus-wide license.

[6] I keep samples of these lecture notes on my website (`www.macalester.edu/~msolisga`).

first weeks, most of the exposition follows the class notes. Once these concepts have been mastered, a number of journal articles come into play (more details in sections 3.6 and 3.8 below).

## 3.2 Starting the course: competitive equilibrium (weeks 1-2)

The notion of a competitive equilibrium is used over and over (and over and over) throughout the course. It is so paramount to the course's goals that by the end of the first day we're already defining a competitive equilibrium. Why? Because if students don't have this nailed down they won't be able to do anything else.

In more detail, the first item in the agenda requires that we deal with a one-period economy with a representative consumer and a representative firm. I carefully define the equilibrium, derive the first-order conditions and explain the consumption-labor supply tradeoff, and show how to combine everything into a $2 \times 2$ system of nonlinear equations that can be solved by hand.

Next, I move on to a two-period economy and follow the same steps as in the one-period economy. Comparing the two sets of equilibrium conditions, it's easy to argue that a two-period model is almost identical to its one-period counterpart except for the intertemporal condition, which defines another clear tradeoff in economics: consumption today in exchange for consumption tomorrow. By now students are starting to get the pattern, so it's easy to jump to a $T$-period economy (where $T$ is finite); the main argument is that a $T$-period economy is virtually identical to a two-period one, except for the fact that we now need to solve a larger system of equations.[7]

[7] If we assume an elastic labor supply, the system size is $(3T+2) \times (3T+2)$. Students are often surprised

## 3.3 Solving systems of equations in Matlab (weeks 2-3)

At the same time we're learning the theory behind $T$-period economies, I'm getting everyone acquainted with Matlab. Lab sessions (coordinated with some well-designed handouts) are the natural place to achieve this goal; once students become fluent in Matlab I teach them the basics of solving nonlinear systems of equations—namely Newton's method. I share Matlab scripts that teach students how to combine pieces of code to solve for the equilibrium values of the economies we talked about in class ("learning by reverse-engineering"). I also make them work some of the large systems of equations they derived in the competitive equilibrium part and show them various tricks to economize on notation.

## 3.4 Dynamic programming (weeks 3-5)

Once students are comfortable with the notion of competitive equilibrium and Matlab, I ask them to ponder the following: the economies we see in the real world go on forever, so how can we incorporate infinity into our models? I point out that what we know so far can help us define and characterize an equilibrium in an infinite-horizon world, but gives us no useful information on how to actually *solve it.*

Hence, it's time to bring in some tools from the field of dynamic programming. While a full treatment of dynamic programming is unfeasible in a one-semester course—and much less in a couple of weeks—I am convinced that giving students a taste of it can help a lot.

At its core, dynamic programming is nothing more than dynamic optimization. I thus start with a finite-horizon environment and describe how the notions they already know

when they calculate the system size for a relatively large $T$. ("So if $T = 100$ then... Wait, what?")

(Lagrange multiplier problems and first-order conditions) are related to the new concepts from the dynamic programming world (value functions and envelope conditions). Once this mapping is set, we begin to explore the canonical example for learning dynamic programming in macroeconomics: an infinite-horizon real business cycle (RBC) model with inelastic labor supply, logarithmic utility, full depreciation, and Cobb-Douglas technology.

After defining an equilibrium and characterizing the solution, I present (without proof) the main theorems that prove existence and characterize the solution (see Stokey, Lucas, and Prescott 1989, chap. 4) and emphasize the value function iteration (VFI) theorem. Keeping with the tradition of first-year PhD macroeconomics, I ask them to (manually) work the VFI algorithm and demonstrate that their answers converge to the model's true policy function. I also solve for the policy functions using the undetermined coefficients algorithm, which seems to help them connect the dots between what they already know and what they are currently learning.

Next, I put forward some notes on *stochastic* dynamic programming. I keep the discussion at a fairly basic level to avoid getting lost in a sea of technical details involving measure theory and convergence of stochastic processes. I let them work a couple of additional examples in Matlab—simple additions to the canonical model such as labor supply or TFP shocks. I argue that once we know how to solve our model economies using dynamic programming, then all other cases can be solved in a sort of similar way after invoking the VFI algorithm and making sure that the curse of dimensionality doesn't bite too much.[8] Having said this, I introduce the concept of (log-)linearization.

[8] Purists may disagree with this statement as setting up a dynamic programming problem is more an art than a science, but that's exactly the idea I want to convey here.

### 3.5 Log-linearization (weeks 5-7)

By now the students know that the problems we are interested in have a solution and that we want to obtain a policy function where model variables are a function of the states. But we don't really know how to do this.[9] We want a procedure that allows us to obtain the policy functions for the model economy of our choice, and this is where the log-linearization procedure comes in.

I start by laying out Taylor's theorem for function approximations. I present the smallest amount of mathematics needed to understand it and, once they are comfortable with the graphical intuition behind the procedure, I introduce log-linearization. I use the mechanized approach pioneered by Uhlig (1999)—consistent with a first-order approximation of the log transformation of the original function—and provide a lot of hands-on practice by working through many of the examples we've used so far.

Finally, I bring Matlab back into the picture; while I don't delve too deep into the theory of linear dynamical systems, I explain how the undetermined coefficients algorithm works and why we need a computer to obtain the policy functions. I share a sample script that students can use as a blueprint for their computational work.

### 3.6 Applications part 1 (weeks 8-10)

I bring in plenty of applications from the literature—think of refinements to the canonical model—and make students solve for the policy functions of the associated models. The goal of this part of the course is simple: I want to convince them that *any* DSGE model starts

[9] Strictly speaking, dynamic programming works, but remember that I just told them we wouldn't pursue this route.

from the basic RBC prototype (i.e., an infinite horizon model with logarithmic utility and inelastic labor supply, full depreciation, etc.) they already know. They just need to build on top of it.

**Labor supply** I drop the inelastic labor supply assumption and allow consumers to derive utility from leisure. I set up the full model economy, derive first-order conditions, log-linearize, and map to the system of matrix equations suggested by Uhlig (1999). Once the students know how this model behaves I present the work of Hansen (1985), who introduced the concept of indivisible labor supply.[10,11] I ask students to replicate Hansen's paper using the log-linearization tools they just learned. Why? Because if students are able to reproduce the results of this model economy, then they should be able to tackle most everything I throw their way. Not surprisingly, students struggle a lot in this part. Typically, more than half of the class is (severely) sleep-deprived by the time this assignment is turned in. However, nearly all students agree that replicating the paper is not only a key activity in the semester but also one of the coolest things they've done in their major.

**Fiscal policy** I explain how to add fiscal policy (taxes and expenditure) to the model; here I follow Braun (1994) and McGrattan (1994). This discussion—besides being interesting on its own and adding a ton of realism—allows me to explain how including additional state

[10] Early DSGE models (e.g., Kydland and Prescott 1982) only looked at the *intensive* margin—the variation in hours worked for a particular household. Thus, by construction, there was no room for unemployment and, consequently, these models couldn't account for (most of) the properties of the labor market. In Hansen's model the *extensive* margin matters, as agents either work some positive number of hours or none at all (consistent with the fact that in the real world, a lot of people work full time or opt out of the labor market). Thus, the model allows us to answer: What is more important when accounting for aggregate hours? Agents moving in or out of the labor force (the extensive margin), or agents adjusting the number of hours to work in a day?

[11] McCandless (2008, chap. 6) also provides a detailed exposition of the model.

variables in the system (beyond TFP) doesn't complicate things (from a computational point of view).

**Other topics** Once labor supply and fiscal policy are set I move on to other applications, which change from semester to semester. One possibility is to explain the methodology that allows us to include (deterministic and stochastic) growth in the standard model or talk about the stylized model found in King and Rebelo (1999), which includes indivisible labor supply and capacity utilization. Other applications I have covered in the past include business cycle accounting (Chari, Kehoe, and McGrattan 2007; Rodríguez-López and Solis-Garcia 2016), New Keynesian macroeconomics (Galí 2015; Christiano, Eichenbaum, and Evans 2005; Clarida, Galí, and Gertler 1999), search models (Andolfatto 1996; Merz 1995), and financial frictions (Carlstrom and Fuerst 1997; Bernanke and Gertler 1989).

## 3.7 Bayesian econometrics (weeks 11-13)

Just as a bold red wine pairs goes with an aged steak and Miles Davis's *Blue in Green* is heaven-sent in a rainy afternoon, Bayesian estimation pairs really well with DSGE models.[12]

Leaving the poetry aside, we start running into some problems. Typically, the paper by An and Schorfheide (2007) is regarded as the groundbreaking contribution that brought Bayesian econometrics into the DSGE arena. Sadly, any undergraduate student who goes in for a read will be quickly lost in the details (though to be fair, graduate students often go astray as well). While we can successfully teach undergraduates about this tool, special care

[12] There are other alternatives that can help us to parametrize a model. Calibration was the tool of choice—rather, the only tool available—in the 1980s and early 1990s, followed by a short-lived transition to maximum likelihood estimation and the generalized method of moments. Out of these three methodologies, it's safe to say that calibration remains the most used.

must be had when covering this topic.

**Approaching the theory** I start with calibration. Notwithstanding its abysmal reputation in some circles, calibration is a natural way to approach the parametrization exercise: students have been looking at parameters all along but haven't really thought about *why* they take the values they take. I motivate the discussion by linking calibration to the need to avoid free parameters and the theory we've covered before. For example, it's easy to illustrate how the value of the discount factor $\beta$ is connected to the risk-free rate via the steady-state conditions of a model that includes government bonds.

Unfortunately, attempting to cover a full course in Bayesian theory requires a great deal of work. Yet this is not my purpose. Even though students won't understand the statistical theory behind Markov chain Monte Carlo (MCMC), they can certainly understand the *logic* behind it. And this is exactly what I try to do: I spend a couple of sessions explaining accept-reject algorithms and how they work in a broad sense, which leaves us ready to understand what MCMC does.

In more detail, I start with the simple concept of random variable generation (I follow Robert and Casella 2010). I introduce the generalized inverse of a function and prove by example how we can generate random numbers from a uniform distribution using Matlab and how we can use this to obtain draws from other distributions with the help of statistical theory. I present the fundamental theorem of simulation and stop at accept-reject algorithms, which in a sense are the core of MCMC.

I link these ideas with Bayes's rule and explain how likelihoods—which are nothing more than probabilities—can be obtained via the Kalman filter in a linearized setting and how the computer and an accept-reject algorithm can take care of the rest. I walk through this material emphasizing the intuition and paying little attention to the formal details. In the end, students "get the big picture" and the estimation procedure doesn't seem like a black box to them. Next, I use Dynare to get things rolling.

**Dynare** Dynare (http://www.dynare.org) is a *free add-on* program installed on top of Matlab that solves and estimates DSGE models and is extremely easy to use.[13] Is it overkill to first teach students how to solve models in Matlab and then make them relearn everything in Dynare? No. Quite the opposite, I have found that this sequencing generates a reinforcement of concepts that proves to be very valuable. I teach by example: we take an RBC model with elastic labor supply and map it to a Dynare script. I spell out how the scripts are built (I offer some sample scripts and discuss the various blocks that the code needs to have) and then we all stand in awe before the beauty of Dynare's wysiwyg.[14] I also offer tips that help them identify the red flags that show up when the estimation goes awry.

In my experience, students take a bit of time to adjust to Dynare, though the fact that they're still working within the Matlab environment seems to help in the transition process. While the quirks of a structured language make them trip up frequently (e.g., a missed semicolon, forgetting to end a Dynare block, and so on), after a bit of help and feedback they become fluent in Dynare in no time. Of course, extensive cooperation in the lab session

[13] The primary source of documentation for Dynare is found in its reference manual (Adjemian, Bastani, Juillard, Mihoubi, Perendia, Ratto, and Villemot 2011); in addition, the files found in Johannes Pfeifer's Dynare webpage (https://sites.google.com/site/pfeiferecon/dynare) are extremely useful to have around when performing an estimation exercise.

[14] "What you see is what you get," (wysiwyg) is one of Dynare's most attractive features. The program's inputs are the equilibrium conditions of a model, and adding these to the code is straightforward. For example, an intertemporal condition like $1/C_t = \beta E_t(r_{t+1} + 1 - \delta)/C_{t+1}$ can be typed as `1/C = beta*(r(+1)+1-delta)/C(+1)`, minimizing the errors and easing up the mapping between model and code.

helps as well.

### 3.8 Applications part 2 (weeks 13-14)

I ask students to skim through the paper by Smets and Wouters (2007), which has become a classic in the macro literature. Trying to estimate part of a full-blown New Keynesian model may be too much, so I ask students to parametrize the Hansen (1985) model using Bayesian econometrics—Hansen used calibration—and to compare their estimated parameter values to the ones in the original paper.

Conditional on the material I have covered in the semester (e.g., search models), I offer additional examples if time permits. At this point in the course, however, the applications mostly revolve around their research projects, as discussed in Section 4.1 below.

## 4 Some thoughts on the course's outcomes

Here I offer some thoughts on the course that reflect upon the experience of several semesters. I focus on how the course integrates with the college's capstone requirement and on the topics I exclude from the course's contents.

### 4.1 The capstone experience

Generally, capstone courses force students to work individually, but I allow for groups since the learning curve is steep as opposed to, say, a development economics course where the main toolkit—econometrics—is already mastered by the time they take it. (An exception to the group-forming rule concerns junior students who are planning to use their capstone paper as the starting point of their Honors project.)

The capstone experience has been positive overall but there is still room for improvement; the key concept is "research experience." Students who have written a formal research paper before (more precisely, students who have taken econometrics *prior* to enrolling in the course) are already trained in the basics of research and their job throughout the semester centers around learning course content and tools. My recent experience with a number of students lacking the econometrics course (or taking it concurrently) shows that they have a hard time finding a research idea and writing about it, *while at the same time* learning course content and tools. Coincidentally, all these students were juniors.[15]

Ex post, I think it is better to frame the writing requirement based on seniority. At Macalester, nearly all of the upper-level courses offered by the Economics Department (geared mainly towards seniors but open to juniors) count for the students' capstone requirement, *but only if taken in their senior year.* Hence, a junior enrolled in an upper-level capstone course will get credit for the course, but not for the capstone component. A solution may be opening a menu where juniors can choose between two options: (a) writing a paper (as senior students do) or (b) writing a research proposal (considerably shorter and with lower requirements than a capstone paper) and taking a final exam.

## 4.2 What I leave out

It's sad, but perhaps expected, that not all aspects of DSGE theory are included. As mentioned above, I do a superficial treatment of dynamic programming—just enough to get

[15] In prior iterations of the course I had juniors who did very well, though all of them had previously honed their research skills in the econometrics course.

the main theorems in—but I don't spend a lot of time working through different examples beyond the simple RBC model with labor supply and TFP shocks.

I also don't talk about heterogeneous agent macroeconomics, other than mentioning that these models are way above the level of the course. I soothe their disappointment by pointing out that these models are useful for discussing inequality and welfare, but they are less connected to business cycle theory (although this may change soon—see Kaplan, Moll, and Violante 2016).

Finally, I mostly stay within the realm of linearized DSGE models. Global solution methods have been gaining ground (especially in this day and age when the zero lower bound has made a comeback) and higher-order expansions (see Schmitt-Grohé and Uribe 2004) are becoming more popular, yet I think that these tools require a considerable amount of extra material in order to be properly used. While Dynare is able to manage higher-order expansions, the underlying theory is still too much for an undergraduate to absorb in the space of 14 weeks.

# 5 Concluding remarks

I hope this essay has convinced you that the following statements are true. Yes, *we can* teach DSGE models to undergraduate students. *We can* get them closer to the research frontier. *We can* help them improve their post-graduation job outcomes. And *we can* have a profound impact on some students, so far-reaching that they end up becoming a PhD economist (and a younger, first-rate colleague as well).

Being able to understand DSGE models and the concepts involved (even if not to the full extent) is a great advantage for students heading to PhD programs in economics and others who want a deeper understanding of macroeconomics. Yet this is not the main point. At the most basic level, the problem we have as teachers of undergraduate students is that we're not preparing them as we should for the difficulties they'll face in graduate school. Far too many undergraduates have felt intimidated—some of them might use "stupid" instead—by the sheer amount of material and new ideas found in first-year PhD macroeconomics. Taking this course allows them to feel less overwhelmed. If we can increase student confidence while in a PhD program (or at the very least, secure them a couple of extra hours of sleep) then it's all worth it.

Teaching undergraduates the ins and outs of DSGE-based macroeconomics has been a great experience that should keep on getting better over time. I can only look forward to what the next cohort of students from Macalester (and other schools!) will produce…once they know the secret handshake.

# References

Stéphane Adjemian, Houtan Bastani, Michel Juillard, Ferhat Mihoubi, George Perendia, Marco Ratto, and Sébastien Villemot. Dynare: Reference Manual, Version 4. Dynare Working Papers 1, CEPREMAP, 2011.

Sungbae An and Frank Schorfheide. Bayesian analysis of DSGE models. *Econometric Reviews*, 26(2-4):113–72, 2007.

David Andolfatto. Business cycles and labor-market search. *American Economic Review*, 86 (1):112–32, 1996.

Ben Bernanke and Mark Gertler. Agency costs, net worth, and business fluctuations. *American Economic Review*, 79(1):14–31, 1989.

Anton Braun. Tax disturbances and real economic activity in the postwar United States. *Journal of Monetary Economics*, 33(3):441–62, 1994.

John Campbell. Inspecting the mechanism: An analytical approach to the stochastic growth model. *Journal of Monetary Economics*, 33(3):463–506, 1994.

Charles Carlstrom and Timothy Fuerst. Agency costs, net worth, and business fluctuations: A computable general equilibrium analysis. *American Economic Review*, 87(5):893–910, 1997.

V. V. Chari, Patrick Kehoe, and Ellen McGrattan. Business cycle accounting. *Econometrica*, 75(3):781–836, 2007.

Lawrence Christiano. Solving dynamic equilibrium models by a method of undetermined coefficients. *Computational Economics*, 20(1-2):21–55, 2002.

Lawrence Christiano, Martin Eichenbaum, and Charles Evans. Nominal rigidities and the dynamic effects of a shock to monetary policy. *Journal of Political Economy*, 113(1):1–45, 2005.

Richard Clarida, Jordi Galí, and Mark Gertler. The science of monetary policy: a New Keynesian perspective. *Journal of Economic Literature*, 37(4):1661–707, 1999.

David DeJong and Chetan Dave. *Structural Macroeconometrics*. Princeton University Press, Princeton NJ, 2nd edition, 2011.

Marco Del Negro and Frank Schorfheide. DSGE model-based forecasting. In Graham Elliot and Allan Timmermann, editors, *Handbook of Economic Forecasting*, volume 2A, pages 57–140. Elsevier, Amsterdam, 2013.

Marco Del Negro, Stefano Eusepi, Marc Giannoni, Argia Sbordone, Andrea Tambalotti, Matthew Cocci, Raiden Hasegawa, and Henry Linder. The FRBNY DSGE model. Staff Report 647, Federal Reserve Bank of New York, 2013.

Mark Duggan, Gopi Goda, and Emilie Jackson. The effects of the Affordable Care Act on health insurance coverage and labor market outcomes. Working Paper 23607, National Bureau of Economic Research, 2017.

Stefan Faridani. Was persistent weakness in the housing market responsible for the jobless recovery? Unpublished manuscript, 2017.

Jesús Fernández-Villaverde, Juan Rubio-Ramírez, and Frank Schorfheide. Solution and estimation methods for DSGE models. In John Taylor and Harald Uhlig, editors, *Handbook of Macroeconomics*, volume 2A, pages 527–724. Elsevier, Amsterdam, 2016.

Jordi Galí. *Monetary Policy, Inflation, and the Business Cycle: An Introduction to the New Keynesian Framework and its Applications.* Princeton University Press, Princeton NJ, 2nd edition, 2015.

Gary Hansen. Indivisible labor and the business cycle. *Journal of Monetary Economics*, 16 (3):309–28, 1985.

Greg Kaplan, Benjamin Moll, and Giovanni Violante. Monetary policy according to HANK. Working Paper 21897, National Bureau of Economic Research, 2016.

Robert King and Sergio Rebelo. Resuscitating Real Business Cycles. In John Taylor and Michael Woodford, editors, *Handbook of Macroeconomics*, volume 1B, pages 927–1007. Elsevier, Amsterdam, 1999.

Finn Kydland and Edward Prescott. Time to build and aggregate fluctuations. *Econometrica*, 50(6):1345–70, 1982.

Robert Lucas. Econometric policy evaluation: A critique. *Carnegie-Rochester Conference Series on Public Policy*, 1(1):19–46, 1976.

Gregory Mankiw. *Macroeconomics.* Worth Publishers, New York NY, 9th edition, 2016.

George McCandless. *The ABCs of RBCs.* Harvard University Press, Cambridge MA, 2008.

Ellen McGrattan. The macroeconomic effects of distortionary taxation. *Journal of Monetary Economics*, 33(3):573–601, 1994.

Monika Merz. Search in the labor market and the real business cycle. *Journal of Monetary Economics*, 36(2):269–300, 1995.

Christian Robert and George Casella. *Monte Carlo Statistical Methods*. Springer, New York NY, 2nd edition, 2010.

Jesús Rodríguez-López and Mario Solis-Garcia. Accounting for Spanish business cycles. *Macroeconomic Dynamics*, 20(3):685–714, 2016.

Stephanie Schmitt-Grohé and Martín Uribe. Solving dynamic general equilibrium models using a second-order approximation to the policy function. *Journal of Economic Dynamics and Control*, 28(4):755–75, 2004.

Christopher Sims. Solving linear rational expectation models. *Computational Economics*, 20 (1-2):1–20, 2002.

Frank Smets and Raf Wouters. Shocks and frictions in U.S. business cycles: A Bayesian DSGE approach. *American Economic Review*, 97(3):586–606, 2007.

Cory Stern. Is the Affordable Care Act's individual mandate a "certified job-killer"? Unpublished manuscript, 2016.

Nancy Stokey, Robert Lucas, and Edward Prescott. *Recursive Methods in Macroeconomic Dynamics*. Harvard University Press, Cambridge MA, 1989.

Harald Uhlig. A toolkit for analyzing nonlinear dynamic stochastic models easily. In Ramon Marimon and Andrew Scott, editors, *Computational Methods for the Study of Dynamic Economies*, pages 30–61. Oxford University Press, New York NY, 1999.

Akila Weerapana. Intermediate macroeconomics without the IS-LM model. *Journal of Economic Education*, 34(3):241–62, 2003.

Stephen Williamson. *Macroeconomics*. Prentice Hall, Boston MA, 6th edition, 2017.

# Appendix

Do other academic institutions offer courses similar to the one I describe in the text? To answer this question, I looked at the economics undergraduate course offerings in the top 10 national universities and liberal arts colleges (according to US News) and found 6 courses that appear to walk along the same path as this course. To keep things manageable I filtered results: I looked at the school/department course catalog where possible, and I excluded topics or seminar courses—as their contents can vary over time.

**Top national universities** According to US News, the top 10 national universities are Princeton [1], Harvard [2], Chicago [3], Yale [3], Columbia [5], Stanford [5], MIT [7], Duke [8], Pennsylvania [8], and Johns Hopkins [10]. (University ranking in bracket.) From these, only four institutions offer courses that are along these lines, as presented in Table 1 below.

**Top liberal arts colleges** From the same source, the top 10 liberal arts colleges are Williams [1], Amherst [2], Wellesley [3], Middlebury [4], Swarthmore [4], Bowdoin [6], Carleton [7], Pomona [7], Claremont-McKenna [9], and Davidson [9]. Only one institution offers a related course, as the top panel of Table 2 shows. (If we're willing to move past the top 10, we can find three institutions that offer similar courses: the United States Naval Academy [12], Bates [27], and the University of Richmond [27].)

Table 1: DSGE-based macroeconomics courses, national universities.

| **Institution** | **Course name and description** |
|---|---|
| Chicago | ECON 23200. Topics in Macroeconomics. This course focuses on the use of dynamic general equilibrium models to study questions in macroeconomics. Topics include long-run growth and dynamic fiscal policy (Ricardian equivalence, tax smoothing, capital taxation), labor market search, industry investment, and asset pricing. On the technical side, we cover basic optimal control (Hamiltonians) and dynamic programming (Bellman equations). |
| | ECON 23330. Introduction to Dynamic Economic Modeling. This course provides an introduction to dynamic economic models, with applications to macroeconomics, labor economics, financial economics, and other subfields of economics. The core methodology will be consistent over time, but the applications will vary from year to year. The course will analyze decentralized equilibrium and social planner's problems in dynamic environments. It will focus on developing techniques for analyzing such models graphically, analytically, and computationally. Students should be familiar with constrained optimization (e.g. Lagrangians), linear algebra, and difference equations, as well as microeconomics, macroeconomics, and econometrics at an intermediate level. |
| Yale | Econ 417b. Computational Methods in Economics. Many of the models used in modern quantitative research in economics do not have analytical (or closed-form) solutions. For this reason, the computer has become an indispensable tool for conducting research in economics. The purpose of this course is twofold: first, to introduce students to numerical methods for analyzing economic models; second, to illustrate how economists use these methods to study models in a variety of subdisciplines, with special emphasis on macroeconomics, labor economics, industrial organization, public finance, financial economics, and environmental economics. The course will also teach the basics of scientific programming so students need not have any prior experience with programming languages. |
| Columbia | Economics GU4213. Advanced Macroeconomics. An introduction to the dynamic models used in the study of modern macroeconomics. Applications of the models will include theoretical issues such as optimal lifetime consumption decisions and policy issues such as inflation targeting. This course is strongly recommended for students considering graduate work in economics. |
| MIT | 14.06. Advanced Macroeconomics. Blends a thorough study of the theoretical foundations of modern macroeconomics with a review of useful mathematical tools, such as dynamic programming, optimal control, and dynamic systems. Develops comfort with formal macroeconomic reasoning and deepens understanding of key macroeconomic phenomena, such as business cycles. Goes on to study more specific topics, such as unemployment, financial crises, and the role of fiscal and monetary policy. Special attention to reviewing relevant facts and disentangling them from their popular interpretations. Uses insights and tools from game theory. Includes applications to recent and historical events. |

Table 2: DSGE-based macroeconomics courses, liberal arts colleges.

| **Institution** | **Course name and description** |
|---|---|
| Swarthmore | ECON 102. Advanced Macroeconomics. Subjects covered include microfoundations of macroeconomics, growth theory, rational expectations, and New Classical and New Keynesian macroeconomics. Extensive problem solving, with an emphasis on the qualitative analysis of dynamic systems. |
| U.S. Naval Academy | E405. Advanced Macroeconomic Theory. Advanced topics in modern macroeconomics, including new classical, new Keynesian and expectation formation models. Introduction to macro dynamics, business cycle and growth models. Emphasis on empirical macro models. |
| | E436. Business Cycles. An advanced treatment of the empirical and theoretical issues surrounding business cycles. Topics include empirical regularities of cycles. Models of inventory cycles, labor and credit markets, technology shocks, and the international transmission of cycles. Simulation-based methods of analyzing such models, the role of fiscal policy and monetary policy in economic stabilization, the international transmission of cycles. |
| Bates | EC 318. Advanced macroeconomics. Theories and empirical studies of business cycles: fixed-investment behavior, inventory activity, and monetary fluctuations. The course examines recent work on inflation, expectations, economic growth theory, and techniques in current use for forecasting general economic activity. |
| Richmond | ECON 372. Advanced macroeconomics. Examination of selected topics in macroeconomics beyond the basic theory level covered in Economics 272. Topics may include forecasting, time-series econometrics, growth theory, analysis of dynamic, stochastic general-equilibrium models, and open-economy macroeconomics. |