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> "Our task as I see it ... is to write a FORTAN program that will accept specific economic policy rules as 'input' and will generate as 'output' statistics describing the operating characteristics of time series we care about, which are predicted to result from these policies."
>
> Lucas (1980, pp.709-710.)

1. Introduction

In 1982 one of the most important papers in macroeconomics was published. By taking a version of the stochastic growth model to the computer, Kydland and Prescott (1982) demonstrated how it could mimic the pattern of U.S. business

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cycles surprisingly well. The course of macroeconomics has been profoundly influenced ever since. It was technological innovation in the state of macroeconomic science along two dimensions:

1. By employing techniques used to simulate dynamic stochastic models from operations research and engineering, it showed how truly feasible it was to start economic modelling at the level of specifying agents' tastes, technologies, endowments and the stochastic structure of the environment in which they reside. Theorists, since the work of Arrow and Debreu, had long started at such an elemental level. Concrete predictions about complicated mathematical models, more often than not, are hard to come by using pencil-and-paper techniques alone. This had limited the spread of models used by theorists to the general population of economists. The suggestion that complicated dynamic stochastic general equilibrium models could be solved on a computer, using modern numerical techniques, opened up exciting new possibilities.

2. The analysis suggested a new methodology for taking economic models to the data. This involved three steps. First, casting the question being addressed in operational terms by developing a set of stylized facts or obser-

vations. Second, assigning functional forms and parameter values to the model. Third, evaluating the model in terms of its ability to replicate the stylized facts formed from the data.

2. Business Cycle Modelling in the 1970's

Business cycle analysis in the 1970's stressed the role that monetary shocks played in causing economic fluctuations. There were two competing paradigms: the Lucas-Barro island model and the Gray-Fischer-Taylor labor contracting model. The first model emphasized agents' *misperceptions* about the aggregate price level as a major factor underlying the cycle. Here an unobserved monetary impulse affected output only to the extent that agents erroneously inferred a shift in the real return to work as the general level of prices changed in response to monetary shocks. The second framework stressed nominal wage rigidity resulting from labor contracting as a prime ingredient in the propagation mechanism governing economic fluctuations. Money induced movements in the price level, that were *unanticipated* at the time labor contracting took place, caused changes in the real wage that resulted in associated output movements, given the fixed nominal wage. It is interesting to note that, unlike the seminal Lucas (1972) paper, almost all of the work on 'misperceived' or 'unanticipated' money was based on descriptive

characterization of aggregate supply and demand that lacked a rigorous foundation in microeconomic theory. Macroeconomics was apart from the way the rest of economics was done.

Both paradigms fell out of grace largely due to questions regarding their empirical relevance. How much of the money stock can be misperceived? Barro and Hercowitz (1980) found that there was little relationship between measures of misperceived money and output. The Gray-Fischer-Taylor contracting model predicted that real wages should move countercyclically — at last if unanticipated money was a prime ingredient in the cycle. Bils (1985) found that real wages were in fact procyclical. Ahmed (1987) found that there was little relationship between the degree of indexation in an industry's wages and fluctuations in its output, something one would expect from the theory. Perhaps as a consequence of the perceived failure of the monetary shock models to provide a convincing explanation of economic fluctuations, the real business cycle models developed by Kydland and Prescott (1982) and Long and Plosser (1983) caught on.

3. Precursors to Real Business Cycle Theory

The 1970's was also a time when theorists were busy developing the language of stochastic dynamic competitive analysis. It is clear that the real business cycles

models of Kydland and Prescott (1982) and Long and Plosser (1983) grew out of this literature. The stochastic growth model developed by Brock and Mirmon (1972) had previously modelled economic fluctuations as the result of aggregate shocks.

This literature started at the level of describing agents' tastes, technologies and the stochastic nature of the environment they resided in. To complete the analysis, some important steps had to be taken. First, the decision problems facing economic agents had to be cast and solved. Lucas and Prescott (1971) handled this by giving agents' decision problems dynamic programming formulations. After that the notion of a competitive equilibrium had to be formulated. Some key details needed to be filled in here. Agents solved their decision problems taken as given some perceived probabilistic law of motion for prices, etc. The solution to this programming problem determined the agents' optimal actions. Aggregating over individual actions and imposing equilibrium determined the actual stochastic process governing prices. Lucas and Prescott (1971) imposed the assumption that the actual and perceived probabilistic law of motion for prices coincide; i.e., that price expectations are rational. Solving for a stochastic dynamic competitive equilibrium amounted to a complicated fixed point problem. This way of casting stochastic dynamic competitive equilibria, so elegantly layed out by Lucas and

Prescott (1971) well over twenty years ago, is now standard operating procedure in modern macroeconomics.

Another important observation made in the Lucas and Prescott (1971) work was the connection between dynamic competitive equilibrium and planning problems (Pareto optima). As Lucas and Prescott (1971) noted we are only usually interested in latter because tell us something about the properties of the former. For the environment they were studying, Lucas and Prescott (1971) showed how the competitive equilibrium could be solved out as the solution to a planning problem, and conversely how the solution to their planning problem was a competitive equilibria. It should be noted that the stochastic growth models of Brock and Mirmon (1972), Kydland and Prescott (1982), and Long and Plosser (1983) are all formulated in terms of planning problems. The legitimacy of this short-cut device for solving dynamic stochastic competitive equilibrium was made clear by Lucas and Prescott (1971), and in subsequent work by Prescott and Mehra (1980). Finally, another step in extending the Arrow and Debreu paradigm to dynamic stochastic economies was undertaken in Prescott and Lucas (1972). Here the question of proving the existence of a supporting price system, with a standard inner product representation, for a dynamic stochastic competitive equilibrium was handled.

In sum, the roots for the real business models of the 1980's were grown in the fertile soil provided by 1970's stochastic dynamic competitive analysis.

4. Quantitative Theory

As with many ideas that change the course of a science, the work of Kydland and Prescott (1982) met with a firestorm of resistance. As the smoke has cleared, it has become apparent that main contribution of the work was methodological in nature.[1] First, it suggested using small-scale dynamic computable general equilibrium models to address economic questions. Second, it developed a strategy for taking these models to economic data. This involved a systematic characterization of the question being addressed in terms of a set of facts, the assignment of parameter values and functional forms to the model, and the evaluation of the model in terms of its ability to cast light on the question being addressed. This methodology can be used irregardless of: (a) whether real shocks cause the business cycles, (b) whether or not the world is Pareto optimal and consequently whether there is or isn't a role for government policy, and (c) with or without econometric meth-

[1]This highlights a key difference between the work of Kydland and Prescott (1982) and Long and Plosser (1983). Both works argued that business cycles can be realistically modeled as the consequence of real phenomena occurring in Pareto-optimal environments. But it was the first paper that suggested a new research methodology as well.

ods. As a consequence of the general nature of the methodological approach, it has now become known as 'quantitative theory'.

4.1. Business Cycle Modelling

Kydland and Prescott (1982) defined the business cycle as a set of stylized facts characterizing the pattern of fluctuation, comovements, and persistence in key macroeconomic variables, such as output, investment, consumption and hours worked.[2] Since then there has been a flood of work seeking to explain additional business cycle facts by using a variation on the prototypical real business cycle model, or exploring how well alternative paradigms fare in explaining economic fluctuations.

In the U.S. data hours worked fluctuate about as much as productivity. In the prototypical real business cycle model productivity is twice as volatile as hours worked. In one of the first extensions of the basic paradigm, Hansen (1985) attacked this problem by modelling variations in employment as occurring along the extensive, rather than the intensive, margin. He did this by assuming that the employed must work a fixed number of hours per week. Christiano and Eichenbaum (1992) have noted that another shortcoming of the basic paradigm is that

[2]The catalogue for business cycle facts is Kydland and Prescott (1990).

it generates a near perfect correlation between hours worked and productivity. In the data this correlation is weak. Christiano and Eichenbaum (1992) address this problem by introducing shocks to government spending. In a similar vein, Benhabib, Rogerson and Wright (1991), Braun (1994), and Finn (1994) have illustrated how shocks to household production, income tax rates, or the price of oil all help resolve the hours-productivity puzzle. Summers (1986) criticized the original Kydland and Prescott (1982) model because it "does not resolve — or even mention — the empirical reality ... that consumption and leisure move in opposite directions over the business cycle with no apparent procyclicality of real wages. It is finessed by ignoring wage data". Gomme and Greenwood (1994) introduce optimal labor contracting into the prototypical real business to allow it to reproduce the acyclical fluctuations in real wages, and the countercyclical movement of labor's share of income, that are observed in the data. Last, Mendoza (1991) and Backus, Kehoe and Kydland (1992) have extended the basic real business framework to study open economy business cycles.

It soon became clear that the modelling strategy advanced by Kydland and Prescott (1982) could also be used to analyze the impact that monetary shocks have on the economy. Cooley and Hansen (1989) introduced money via a cash-in-advance constraint into an otherwise standard real business cycle model. They

found that there was little role for money in the business cycle. Subsequent work by Cho and Cooley (1994) has examined the effect that nominal wage contracting has in such an environment. A larger role for money in the business cycle emerges.

Work has also been undertaken, using the Kydland and Prescott (1982) methodology, exploring the potential that alternative paradigms have for explaining economic fluctuations. An early example is the work by Greenwood, Hercowitz and Huffman (1988) who took the view that shocks to the marginal efficiency of investment are important for business cycles. This was embedded into a model where the utilization rate of capital was variable and governed by Keynes's concept of user cost. More recently, Rotemberg and Woodford (1992) have built dynamic stochastic models of imperfectly competitive product markets. These models are capable of explaining many types of Keynesian phenomena. For instance, Farmer and Guo (1993) have shown that in such environments sunspot equilibria can emerge that generate plausible business cycle behavior. The resulting cycles are reminiscent of Keynes's notion of animal spirits.

A notable shortcoming of the prototypical real business cycle model lies in its inability to match certain facts from financial markets. In an important paper Mehra and Prescott (1985) used the Kydland and Prescott (1982) methodology to see if the standard model could mimic the high differential return paid on equity

relative to bonds. They found that it couldn't. This has lead to a mountain of work in finance aimed at resolving this puzzle. Work is proceeding on extending the basic model to environments with heterogeneous agents, incomplete markets, and various types of trading costs. An example of such work is Aiyagari and Gertler (1991).

To conclude, business cycle analysis a la Kydland and Prescott (1982) has now traveled from far from its birthplace, the neoclassical growth model.

4.2. Policy Analysis

It quickly became apparent that the Kydland and Prescott (1982) methodology could be adopted for policy analysis. Since the modelling strategy started at the level of specifying agents' tastes, technologies, and the stochastic structure of the environment, it should be immune to the Lucas critique. The first step in such an analysis is to calibrate the structure of computational general equilibrium model being used to the actual economy under study. After doing this various policy rules could be fed in as 'input' and the time series behavior for various economic series of interest could be generated as 'output'. In fact, the seeds of such an analysis were present in Kydland and Prescott's (1978) classic illustration of how the discretionary use of an investment tax credit aimed at stabilizing business

cycle could actually amplify economic fluctuations.

The first full fledged use of the Kydland and Prescott (1982) methodology to study macroeconomic policy was for tax analysis. Greenwood and Huffman (1991) and McGratten (1994) examined the impact that the U.S. tax system has on economic fluctuations and economic welfare.[3] Greenwood and Huffman (1991) also illustrated how taxes could be used to stabilize economic fluctuations. They found that the welfare gains from such a policy to be negative. Recent work by Chari, Christiano and Kehoe (1993) has studied Ramsey taxation within the context of the stochastic growth model. [Lucas's (1990) work on supply side economics adopts the Kydland and Prescott (1982) calibration methodology]. It should be noted that the discussion of optimal taxation policy (or economic policy more generally) has been heavily influenced by Kydland and Prescott's (1978) well-known work on the time inconsistency of government plans. This paper has spawned a literature on the sustainability of optimal taxation plans; for example, the work of Lucas and Stokey(1983), Persson, Persson and Svensson (1987), Chari and Kehoe (1990).

The use of the Kydland and Prescott (1982) modelling methodology for policy analysis has now sprung up in pastures far beyond the stochastic growth model.

[3]The the welfare costs using inflation as a tax were examined in Cooley and Hansen (1989).

For instance, Hansen and Imorogohlu (1992) have examined the effects that unemployment insurance has in environments with heterogeneous agents, incomplete markets, and moral hazard problems (i.e., where the government can detect with certainty whether an unemployed agent has a job opportunity or not). Similarly, Hopenhayn and Rogerson (1993) study the effects that government employment policy, such as mandatory severance payments, have on firms' entry/exit and hiring decisions, and consequently the equilibrium level of employment in an industry.

4.3. Numerical Methods

The suggestion that complicated dynamic stochastic economies could be solved on a computer has sparked intense interest in computational techniques.[4] Kydland and Prescott (1982) obtained the solution to their model economy by computing a linear-quadratic dynamic programming problem.[5] This technique worked when the solution to the decentralized competitive equilibrium under study could be formulated as the outcome of a dynamic programming problem. This generally isn't true in economies where distortions are present — the typical case for those

[4]Long and Plosser's (1983) real business cycle model had a closed form solution that they found by 'dumb luck' (p. 47). Real business cycle analysis might have stalled in its tracks if the success of the research program depended upon such fortuitous findings.

[5]Simon (1956) was instrumental in introducing the use of the linear-quadratic regulator problem into economics.

interested in policy analysis. So the search began for numerical methods that could compute the solutions for nonoptimal dynamic stochastic economies.

Two approaches have been taken to this. The first approach extends the Kydland and Prescott (1982) method. These algorithms iterate on individuals' optimizations problems and aggregate laws of motion until a competitive equilibrium is found. Kydland (1987) is an example of such work. The second approach attacks the equilibrium conditions (usually in the form of a set of Euler equations) for the model directly. These equilibrium conditions are solved using either linearization techniques, as in King, Plosser and Rebelo (1988), or by nonlinear methods, as in Coleman (1990) and Den Haan and Marcet (1990). The hunt is now on for algorithms that can solve distorted economies with large numbers of heterogeneous agents that are subject to uncertainty at both the aggregate and idiosyncratic levels— an example of such an algorithm is in Krusell and Smith (1994).

4.4. Econometric Methods

The work of Kydland and Prescott (1982) suggested a new methodology for taking economic models to the data. This involved three steps. First, the parsimonious representation of the question being addressed in terms of some stylized facts,

often a set of second moments describing business cycle data.[6] Second, the assignment of functional forms and parameter values to the model. This is often done so that the model is consistent with long-run features of data.[7] Third, the evaluation of the model on its ability to replicate the stylized facts formed from the data. The virtue of this approach is that it is both simple and systematic, with the economics of the problem always remaining close at hand. But nothing in this procedure precludes the use of econometric methods. For example, parameter values for computational general equilibrium models can be picked using either maximum likelihood or generalized method of moments techniques, as McGratten (1994) and Christiano and Eichenbaum (1992) have demonstrated. Furthermore, simulated models can be readily evaluated on their ability to match up some set of stylized facts. Lundvik (1992) has used simulated moments estimation to do this.

[6]Before the work of Kydland and Prescott (1982) most macroeconomists would have had a hard time providing a list of empirical regularities that characterized the business cycle.

[7]These are Kaldor's growth facts, such as a constant real interest rate and a constant labor's share of income, etc.

5. Conclusion

The year 1982 saw one of the most important papers in modern macroeconomics published. That was Kydland and Prescott's "Time to Build and Aggregate Fluctuations". It ushered in the era of quantitative theory. This approach suggested using numerical methods in conjunction with computers as an extension of the mind to explore the properties of small, but complicated, dynamic stochastic general equilibrium models. The analysis could start at the level of specifying agents' tastes, technologies and the stochastic structure of the environment they reside in. The paper also presented an easy-to-use and systematic empirical methodology for bringing models closer to the data in a manner that highlights the economics of the problem at hand. This methodology is a powerful machine in the economist's workplace. It probably has changed the course of macroeconomics in much the same way as Keynes's "General Theory" and Lucas's "Expectations and the Neutrality of Money" have.

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