# Quantitative Aggregate Economics[†]

*By* FINN E. KYDLAND*

I am delighted to be able to present this lecture before so many people. I'm also very happy when I get to work with *models* inhabited by many people. That is the key to the framework for which Ed Prescott and I were cited by the Nobel Committee: Individuals are introduced explicitly in the models. Their decision problems are fully dynamic—they are forward looking. That is one of the prerequisites for what we ultimately seek, which is a framework we can use to evaluate economic policy.

The eminent researcher and 1995 Nobel laureate in economics, Bob Lucas, from whom I have learned a great deal, wrote: "One of the functions of theoretical economics is to provide fully articulated, artificial economic systems that can serve as laboratories in which policies that would be prohibitively expensive to experiment with in actual economies can be tested out at much lower cost ... (Lucas, 1980, p. 696). Our task, as I see it ... is to write a FORTRAN 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" (pp. 709–10). The desired environments to which Lucas refers would make use of information on "*individual* responses [that] can be documented relatively cheaply ... by means of ... censuses, panels [and] other surveys ..." (p. 710). Lucas seems to suggest that economic researchers place people in desired model environments and record how they behave under alternative policy rules.

In practice, that is easier said than done. The key tool macroeconomists use is the *computational experiment.* With its help, the researcher performs exactly what I just described—places the model's people in the desired environment and records their behavior. But the purpose of the computational experiment is broader than only to evaluate policy rules. The computational experiment is useful for answering a host of quantitative questions, that is, those for which we seek numerical answers. When evaluating government policy, the policy is stated in the form of a rule that specifies how the government will behave—what action to take under various contingencies—today and in the indefinite future. That is one reason it would be so difficult and prohibitively expensive to perform the alternative Lucas mentions, namely, to test the policies in actual economies.

## I. The Computational Experiment

These models are inhabited by millions of people. My tiny laptop contains several such models. People are characterized by their preferences over goods and leisure into the indefinite future. Their budget constraints are explicit. They receive income from working and from owning capital, and their choices must remain within their budget constraints, given the prices they face—wage rates and interest rates, for example. In other words, these models are explicit about people's dynamic decision problems.

The models also contain thousands of businesses. Implied is a description of aggregate production possibilities—say, in the form of an aggregate production function. It describes the technology for converting inputs of capital and labor into output of goods and services, which can be used for consumption or to add to future productive capital—investment.

[†] This article is a slightly revised version of the lecture Finn E. Kydland delivered in Stockholm, Sweden, on December 8, 2004, when he received the Bank of Sweden Prize in Economic Sciences in Memory of Alfred Nobel. 

* Department of Economics, University of California, Santa Barbara, North Hall 2014, Santa Barbara, CA 93106. This written version is little changed from my lecture of December 8, 2004, and I have retained some of the oral "style." Exceptions are removing personal references, for example a tribute to my sometime coauthor Scott Freeman, who passed away after a long struggle with Lou Gehrig's disease.

A key aspect of the production function is its description of the technology level and its change over time. It is a broad concept at this level of abstraction. Technological change encompasses anything that affects the transformation, given by the aggregate production function, of aggregate inputs of capital and labor into goods and services. It includes, of course, the usual outcomes of innovative activity, but also could include, again at this level of abstraction, such factors as oil shocks, new environmental regulations, changes in the legal constraints affecting the nature of contracting between workers and firms, government provision of infrastructure, and the loss in financial intermediation associated with banking panics—all elements one might want to study in more detail, depending on the question. But, for many questions, it makes perfect sense to include them implicitly as part of the technology level.

I have described two elements of typical models used for computational experiments: the multitudes of model inhabitants and businesses. An essential aspect, however, is the calibration of the model environment. In a sense, models are measuring devices. They need to be calibrated; otherwise we would have little faith in the answers they provide. In this sense, they are like thermometers. We know what a thermometer is supposed to register if we dip it into water with chunks of ice, or into a pot of boiling water. In the same sense, the model should give approximately correct answers to questions whose answers we already know. Usually, there are many such questions. In the context of business-cycle analysis, we know a great deal about the long run of the economy, and we may also use the Panel Study of Income Dynamics, say, or similar panel studies from other nations to collect the data to calibrate the model. Thus, the calibration is part of the action of making the quantitative answer as reliable as possible.

A computational experiment yields time series of the aggregate decisions of the model economy's people. Through the model formulation and its calibration, we have determined the desired nature of the economic environment. Then, the millions of people and the thousands of businesses in the economy make their decisions over time, and the computer records the corresponding aggregate outcomes. We obtain time series as if we were confronted with an actual economy. These time series may be described statistically and compared with analogous statistics from the data for the nation under study. In a business-cycle study, these statistics may include standard deviations of detrended aggregates describing the amplitudes of their business-cycle movements, as well as correlation coefficients as measures of their comovements.

## II. A Simple Example

Now I should like to walk you through a simple model—substantially simpler than that in Kydland and Edward C. Prescott (1982), for example. It contains household and business sectors. To make it as straightforward as possible, I'll abstract from the government and from the rest of the world. Moreover, for simplicity, steady-state growth is zero. I have two main goals: to discuss the sense in which the model contains a household and a business sector; and to give examples of what is involved in calibrating the parameters (see Thomas F. Cooley and Prescott, 1995, for a detailed description of the practice of calibration, and Kydland, 1995, for an elaborate example in which the calibration steps have been worked out).

First, we have a description of the typical household's preferences in the form of a utility function to be maximized:

$$E\sum_{t=0}^{\infty}\beta^t\frac{(C_t^{\alpha}L_t^{1-\alpha})^{1-\sigma}-1}{1-\sigma}.$$

Business cycles involve uncertainty about the future, so what one aims to maximize is *expected* (denoted by $E$) utility as a function of consumption, $C$, and leisure, $L$, over the indefinite future. The parameter $\beta$ is a number slightly less than one and can be calibrated from knowledge of the long-run real interest rate. It simply describes the degree of people's impatience. Additional parameters are $\alpha$ and $\sigma$, also to be calibrated. I'll return to $\alpha$ in a moment. One may call $\sigma$ a risk-aversion parameter, a quantity about which finance people know a great deal. I could have picked a more general functional form in the class of so-called constant-elasticity-of-substitution functions. This particular one is consistent with the empirical observation that, as the U.S. real wage has doubled over the past decades, long-run hours worked per household have changed little.

The model formulation I present is the statement of a planner's problem whose solution can be shown to be the equilibrium of an economy inhabited by millions of people with preferences such as this utility function. It contains a resource constraint,

$$C_t + I_t = z_t K_t^{\theta} N_t^{1-\theta} = r_t K_t + w_t N_t,$$

which states that the sum of consumption and investment cannot exceed what the economy produces. The right-hand side of the first equality states that the economy produces output using capital—factories, machines, office buildings—along with the labor input of workers, and the technology level is denoted by $z$. In other words, this is total output—gross domestic product—as given by the production function, the specification of which is essential to all of macroeconomics. Moreover, GDP must equal gross domestic income: the sum of capital income, capital earning a rental rate $r$, and labor income, where labor is compensated with the real wage rate $w$.

In addition to this resource constraint, we have a constraint on time, which here can be devoted either to leisure or to labor input:

$$L_t + N_t = 1.$$

The right-hand side equals one; that is, without loss of generality I have chosen units so that if we add all the discretionary time—total time net of sleep and personal care—across people, it equals one.

Then we have two relations representing key aspects of what makes an economy dynamic:

$$K_{t+1} = (1 - \delta)K_t + I_t$$

and

$$z_{t+1} = \rho z_t + \varepsilon_{t+1}.$$

The first, where $K_t$ denotes the capital stock at the beginning of period $t$, describes how the capital stock at any time depends on past investment decisions, subject to depreciating at the rate $\delta$. Finally, the technology level is all-important because it is what gives rise to uncertainty, in this simple model. If, as is borne out by the data, the parameter $\rho$ is close to one, the relation says that new technological innovations, given by $\varepsilon$, are long-lasting. One usually specifies this random variable $\varepsilon$ as drawn from a normal probability distribution, whose variance can be estimated from the data.

As we have seen, this simple economy already has a number of parameters we need to calibrate. One reason for presenting this model is so I can discuss two typical examples of calibration. I'll choose the parameters $\alpha$ in the utility functions and $\theta$ in the production function. Suppose we obtain a panel of thousands of people and calculate the average time they devote to market activity. That figure pins down, via a steady-state first-order condition, the value of $\alpha$ that makes this average identical in the model economy to that in the data. Similarly, with regard to the parameter $\theta$, a property of the model is that if we look up National Income and Product Accounts data and find that, say, an average 36 percent of total gross domestic income is compensation for capital input, and 64 percent represents labor income, then this calibrates the parameter $\theta$ to 0.36.

I have used this model as a vehicle for discussing the two key sectors of the economy. The household sector contains many people characterized by the utility function—a description of the preferences over consumption and leisure into the indefinite future. The business sector is described by the technology for producing goods and services from capital and labor inputs. I have discussed the features that make this model dynamic, and one key source of uncertainty. One could include many other such features. Ed Prescott mentioned in his lecture the so-called time-to-build assumption, which would make the model more detailed, as in the 1982 paper to which the Nobel Committee refers. That model also contains inventories, as well as both permanent and temporary shocks. What to include depends on the question the model is designed to address. The question for which this framework was first put to use by Ed Prescott and me can be stated as follows: if technology shocks were the only source of impulse, what portion of business-cycle fluctuations would still have remained? The model produced a preliminary answer to

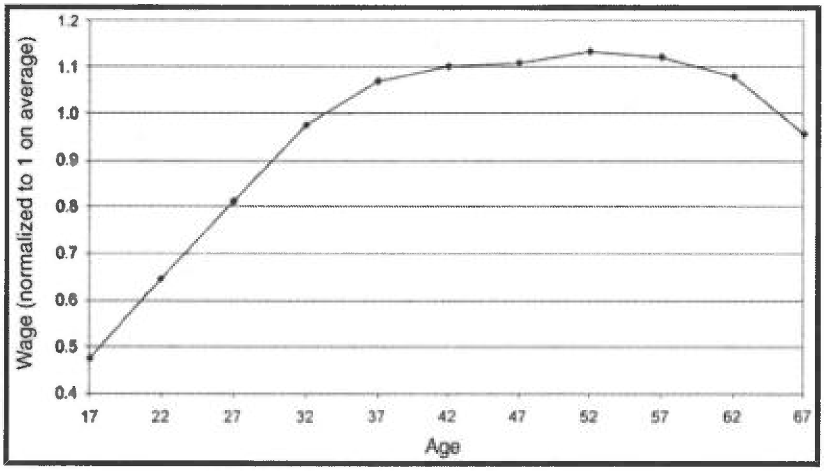


FIGURE 1. UNITED STATES: LIFE-CYCLE WAGE PROFILES

*Source:* Cross-sectional data based on 1990 U.S. Census, as reported in Kjetil Storesletten (1995).

that question: well over one-half, and that answer has pretty much been confirmed to be somewhere around 70 percent. The model provided measurement.

### III. Does Being Different Matter?

Returning to the utility function, I assume in my prototype model above that preferences are given by some function that covers the entire future—goes to infinity. In other words, we have great power in setting up this economy: we can decide that people are immortal! That assumption turns out to be surprisingly innocuous for many questions. Of course, it makes sense to check if it makes a difference and, as economists often conclude in many contexts, it depends. For many business-cycle questions, the answer is no. That is rather surprising. If you think about the life-cycle behavior of individuals, typically they earn relatively little labor income early in their lives, then experience a substantial increase in yearly income when they enter the middle stage, and, finally, for those who live long enough, enter a period in which they will have retired from market work. In other words, the labor-earnings profile is decidedly hump-shaped. But we also know that people prefer a consumption stream that is much more even over time. So there will be a period in which they spend more than their income, then spend less for two or three decades, and finally revert to spending more than their labor income toward the end of their lives. Moreover, the behavior in various other ways typically is quite interesting at the beginning and end of one's working life.

Thus, it would seem that life-cycle behavior could matter substantially. José-Víctor Ríos-Rull (1996), however, finds, for a typical business-cycle question such as the one I mentioned above, that if we employ an economy with mortal consumers in which realistic life-cycle behavior is included, then as we aggregate the time series across all of these people in the computational experiments, we obtain approximately the same answer as in the immortal-consumer economy. Of course, there are many questions for which life-cycle behavior does make a large difference. Among those are the economic impact on savings, interest rates, and tax rates of immigration, Social Security reform, and baby boomers' retirement, to mention a few.

To give you a sense of how different people are and to emphasize the need for including them when addressing *some* questions, I will show you some numbers. Figure 1 displays the average life-cycle profile of the efficiency of working in the market sector, as indicated by individuals' real wage rates.

The graph shows a major reason for the hump-shaped profile of people's labor earnings

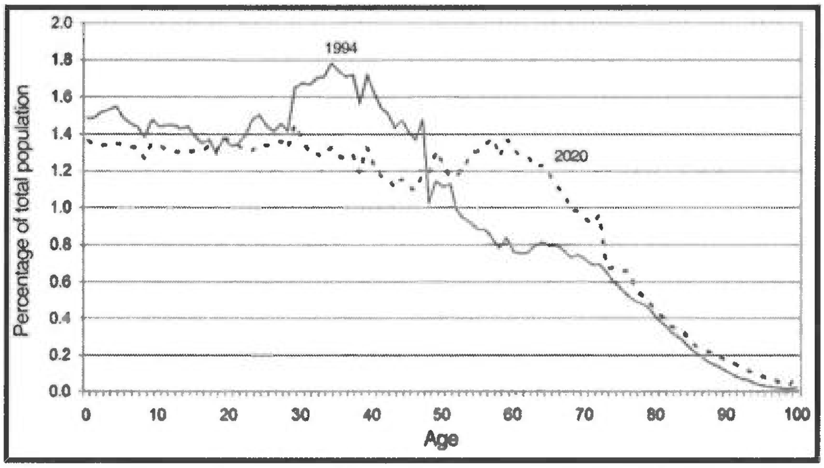


FIGURE 2. UNITED STATES: AGE DISTRIBUTION OF POPULATION, 1994 AND 2020

*Source:* U.S. Census Bureau.

depending on age. The curve is normalized so that it averages one. It starts at around 0.5 and rises rapidly so that for a long time span later in people's working lives their efficiency is more than twice what it is when they enter the workforce. In addition to these life-cycle differences in workers' skills comes the fact that workers are quite different in their abilities as they enter the work force, depending on education and other factors. An interesting study of the aggregate implications of the interaction between, on the one hand, the labor input divided into low- and high-skilled workers and, on the other hand, the capital input divided into structures and equipment is in Per Krusell et al. (2000). Their focus is on real-wage movements in particular. For a more elaborate discussion of cyclical implications, especially as they pertain to measured labor-input fluctuations, see Kydland and D'Ann M. Petersen (1997), on which some parts of this lecture are based.

Figure 2 displays the age distribution of the U.S. population in 1994 and the projected population to 2020. The vertical axis shows the percentage of people of different ages. One can see the noticeable hump in 1994 roughly in the 30- to 40-year age range. Predictably, there will be a corresponding hump in 2020. Of course, a reason to worry about this empirical pattern is that by 2020 many, if not most, of these baby boomers will have retired, putting a major strain on the government budget constraint in general and the Social Security system in particular. A beautiful study of the effects the baby boomers in Spain (where immigration represents much less of a complication for the population dynamics than for the United States) may have on future savings and real interest rates is in Ríos-Rull (2001).

Finally, Figure 3 tells us about the age distribution of immigrants to the United States. The curve for U.S. natives is the same as that for 1994 in Figure 2, except now each age group is five years wide and so the curve is smoother. The key message of the figure is that immigrants to the United States are relatively quite young.

These features of the data all correspond to elements that one may wish to add to a model of heterogeneous individuals—something we, as economists, have become adept at doing. When Víctor Ríos-Rull was my colleague at Carnegie Mellon University in the early 1990s, computers were not nearly as powerful as they are today. Víctor did early pioneering research with such models. Back then, some could take a long time—maybe a day or two—for the computer to calculate the model time series to analyze.

All these features to which I have alluded—the age-dependent work efficiency, population dynamics, and so on—can and have been added to models such as those used by Ríos-Rull and others in the past decade. A student of Víctor's and mine at Carnegie Mellon, Kjetil Storesletten, now at the University of Oslo, made an interesting study of the interaction of immigration with government

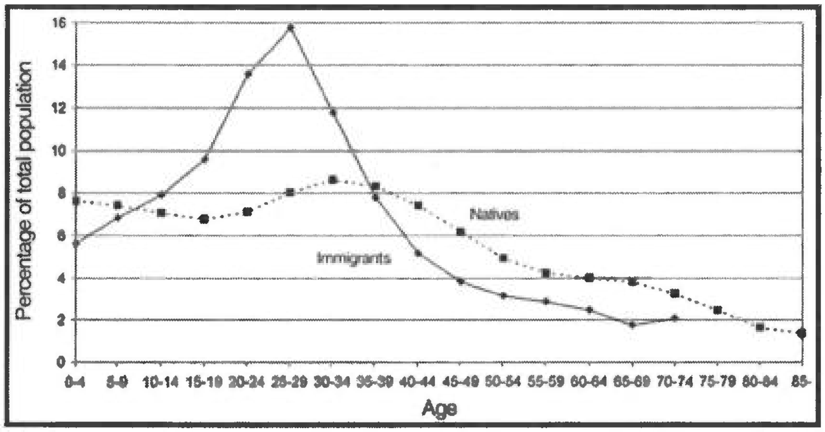


FIGURE 3. UNITED STATES: AGE DISTRIBUTION OF NATIVES AND NEW IMMIGRANTS

*Source:* Immigration and Naturalization Services Yearbook (years 1983–1989), as reported in Kjetil Storesletten (1995).

fiscal policy. Stark predictions have been made by researchers who do intergenerational accounting, suggesting that tax rates will have to rise substantially in the not-so-distant future in order for the government budget constraint to be satisfied. The interesting question Storesletten (2000) asks is: To what extent can one avoid that tax increase by raising the rate of immigration, especially if one could be selective in the immigrants to admit?

Our ability to compute equilibriums for economies with very different people has expanded dramatically in recent years, with many studies heavily influenced by the pioneering paper by Krusell and Tony Smith (1998). Today, we see interesting research with the implication, for example, that income and wealth distributions vary and evolve over time, for example Storesletten et al. (2004). This exciting work is made possible through advances in our understanding of dynamic methodology, but also because of the power of today's computers.

## IV. No Money?

A belief sometimes expressed is that this framework is used for analyzing real phenomena only. That is a huge misunderstanding. The same framework is also used to study monetary phenomena. For example, one could use it to ask the perennial question: Do monetary shocks cause business cycles?

Here is one way to introduce money into a framework such as the one I have described to you. Suppose people purchase a whole variety of sizes of goods. We might as well say there is a continuum, from tiny to large. People make small purchases and large. Because of the cost of carrying out transactions using means of exchange (checks, for example) backed by interest-earning assets, it has to be optimal to make the small purchases using currency and the large purchases using these other means of exchange. The extent to which you want to use either becomes an economic decision whose incentives change over the cycle. They change for the choice of the proportion of the two means of exchange one wishes to hold, as well as for the frequency with which one replenishes one's liquid balances. The finding from this study with Scott Freeman (2000) is that money fluctuates procyclically even when the central bank does nothing. In other words, if one finds, as was the case over extended periods of U.S. history, that money moves up and down with output, that fact by itself says nothing about money causing output.

Because these models are inhabited by people, we can evaluate the welfare cost of inflation. In a project with Freeman and Espen Henriksen, a Carnegie Mellon Ph.D. student (forthcoming), we did exactly that. We are now pushing that project further, asking, for example, what will happen if transaction costs drop over time, which already has happened and likely will continue to do so.

## V. International Business Cycles

I have presented to you a closed-economy model. In the past 10 or 15 years, however,

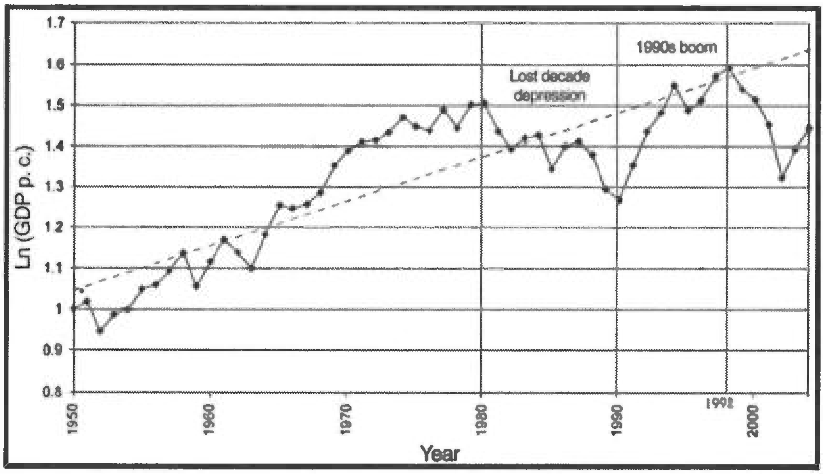


FIGURE 4. ARGENTINA: GDP PER WORKING-AGE PERSON (INDEX)

economists have put this framework to use to study the interaction of many nations. This is a particularly interesting field because anomalies abound for bright young (and even old) researchers to account for. Here's an example which, on the face of it, may seem like an anomaly. For many nations, cyclically the trade balance is the worst when one's goods are the cheapest. It turns out that once one writes down a model in which nations trade, as, for example, David K. Backus et al. (1994) did, capital accumulation is important for the answer. Another factor is that there is "nonsynchronized" technological change in the different nations, which over time spills over from one nation to the next. The conclusion is that the empirical regularity to which I just referred is not an anomaly at all. It is what the model suggests would happen.

Here's a cute application. I loved to use it in my undergraduate course. I came across an article in the *Wall Street Journal* in April 1998 reporting that the International Monetary Fund dispatched representatives to Argentina, supposedly to convince the Argentine government to cool the economy. The reasons stated were threefold: (a) high growth rates, 6.5 to 7 percent annually, coming on top of strong growth that started in 1990, interrupted only by the Tequila crisis around 1995; (b) export prices falling dramatically; and (c) the trade deficit returning. Sound bad? As it turns out, these comovements are what a standard model would tell us to expect in an economy that's doing well. Our framework dictates that these three features, in combination, ought to be favorable. I should say that I have no way of knowing if the *Wall Street Journal* misstated, to some extent, the IMF's basis for going to Argentina. For example, the IMF may have been worried also about fiscal "overstimulation," as one might call it.

## VI. The Case of Argentina

Recently, a number of studies of great depressions have been carried out. Many were put together for a conference at the Federal Reserve Bank of Minneapolis and will be collected in a volume edited by Tim Kehoe and Ed Prescott. The reasons I mention the great depression studies are twofold. First, people used to think great depressions are events of such a character and magnitude that we need a separate framework to study them. I think this conference showed that any such suggestion is nonsense. The second reason is that this conference gave Carlos Zarazaga and me (2002) the impetus to study the case of Argentina, which had a great depression in the 1980s.

To give you a sense of what has happened in Argentina in the last 50 years, Figure 4 displays the log of its real GDP per person of working age. You see the dramatic decline in the 1980s—over 20 percent—during Argentina's "lost decade," qualifying it as a great depression. An even larger and much faster decline took place after 1998.

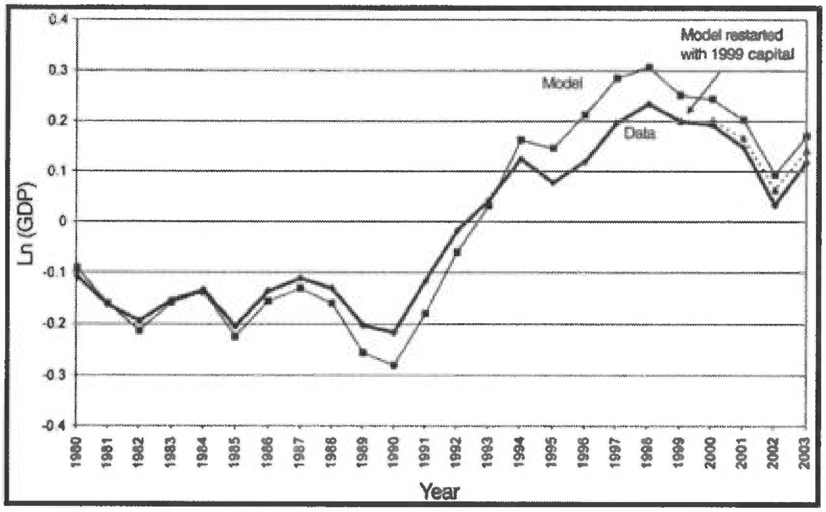


Figure 5. Argentina: GDP

As already mentioned, Argentina's economy experienced an upturn in the 1990s. That episode, to Carlos and me (forthcoming), was even more interesting than the depression. Clearly, Argentina grew fast by most standards. The surprising thing was—and only the model could tell us this—when one puts the numbers for total factor productivity growth into a standard model and calibrates it, the model says that investment should have been much greater in the 1990s. Of course, for that very reason, the capital stock should have been much larger by the end of the decade.

Figure 5 contains a picture of real GDP for Argentina, again in log scale. One can see the growth in the 1990s. Suppose we put into the model the actual numbers for total factor productivity measured by the method Robert Solow (1957) proposed for measuring them in a growth context. We use the period up to 1980 to estimate statistically the process for the technology level. The model accounts well for the great depression of the 1980s, and also for the downturn after 1999. The large discrepancy is for the 1990s where the model says that growth in the 1990s should have been much higher. The third curve is included to indicate what happens if we assume that the capital stock in 1999 is taken from the actual data for that year, and then we start the model up again in 1999. The model accounts well for the remaining years.

What if we look more closely at the capital input? I mentioned it as representing the key anomaly. That is borne out in Figure 6, which displays an even greater discrepancy between model prediction and data for the 1990s than in the case of GDP. The difference in 1999 is almost 20 percent. As in Figure 5, the third curve displays the model prediction if we start with the 1999 capital stock so as to account for the remaining five years.

For Argentina, the data in Figure 7 must be extremely depressing because they show the fall in capital stock per working-age person (which would look more or less the same in per capita terms). This represents the quantity of productive capacity in Argentina, given by the best measurements available. The capital stock in 2003, per person, was much lower than in 1982. The neoclassical growth model then would imply, as the data show, wage rates that were much lower than those that would have prevailed in Argentina if the economy had grown the way other nations' economies did. This is bad news for the future of Argentina's poor (and it certainly has been so far). Clearly, Argentina needs to grow at a rapid rate—not just 3 or 4 percent a year—to catch up. If it doesn't, then the poor will stay poor for a long time. People with relatively high human capital are likely to do reasonably well, but the wealth and income disparities will keep getting wider.