

Robert Lucas, Recipient of the 1995 Nobel Memorial Prize in Economics

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I. Introduction

Over the last thirty years, the theory and practice of economic dynamics have undergone an extraordinary transformation. Robert Lucas has been and continues to be the leader of this transformation. He has provided economists with new tools and new ways of thinking about dynamic problems. Moreover, in the process, he has provided new answers to many of the problems of greatest concern to macroeconomists. From investment to unemployment, economic growth to monetary policy, monetary theories of the business cycle to income distribution, one can find a seminal and path-breaking analysis from Lucas.

In my review I will focus first on Lucas's vital contributions to economists' general approach to the subject. Then I will discuss some of his specific substantive applications of the approach. Each application alone represents a contribution that would have established Lucas as a major figure within the world economics profession.

II. Framework

A generation or so ago most dynamic economic analysis was conducted in static models modified to accommodate dynamic effects in an assortment of arbitrary and *ad hoc* ways. By contrast, today, dynamic issues are routinely and rigorously analyzed in the context of stochastic models whose equilibria are derived from well formulated dynamic decision problems of the participants. The way in which economists in general, and macroeconomists in particular, conceive of dynamic, stochastic economies and conduct policy evaluation has been fundamentally altered by this methodological shift. We have learned to be precise in our treatment of the microeconomic decision-making problems that underpin macroeconomic phenomena and to be consistent in our derivation of policy conclusions from them.

* I am grateful to Patrick Kennedy, Peter Klenow, and Christopher Sleet for major contributions to this paper.

Robert Lucas's contribution to all this has been enormous. His work has pioneered the development of the framework¹ described above and its application to macroeconomics. He is the first to study macroeconomic phenomena as the equilibria of dynamic, general equilibrium models, to be consistent and rigorous in his derivation of aggregate relationships from microeconomic foundations, and to take seriously the econometric and policy evaluation consequences of these principles. Though some of his conclusions remain controversial, many aspects of his framework have become standard.

The starting point of a typical Lucas paper is a precise statement of an economy and of the decision-making problems of the agents who inhabit the economy. Such a statement requires a description of the preferences and technologies of the agents, the institutional arrangements that constrain behavior, the information structure that determines what each agent knows in each state and at each date, and an equilibrium concept.

In a general dynamic setting, it is natural to think of an individual agent's strategy as a mapping from the space of agent information sets to the space of (probability distributions over) feasible actions. Roughly speaking, an agent will select a particular strategy in order to maximize its objective function given its beliefs about other agents' strategies. This last statement is made precise, in the context of a particular model, by the adoption of an equilibrium concept.

In much of his work, Lucas has relied upon competitive, Markovian models to analyze the macroeconomy. In Markovian models, an agent's knowledge of history is completely summarized by a vector of state variables. Agents' payoffs are typically assumed to be time separable and their current payoffs are taken to depend upon the relevant state variables and upon current actions. Moreover, the agents are assumed to condition their strategies upon the appropriate state variables. Finally, by assumption or construction, the state variables are assumed to follow Markov processes and, in solving for their strategies, individual agents are assumed to know, or to be able to compute, their laws of motion. Competitive, Markovian models have rather more structure. In these models, each agent is assumed to be of measure zero so that an individual's actions do not appear directly in another individual's payoff function. Variables that are the outcome of aggregate behavior, such as prices, appear as state variables in individual decision problems. The evolution of these state variables is exogenous to the agent, but endogenous to the whole economy. Moreover, the require-

¹His monograph *Models of Business Cycles* [1987a] provides a clear statement of the framework, while the text *Recursive Methods of Economic Dynamics* [1989] fills in the technical details. In this article, dates in brackets refer to publications by Robert Lucas (see Bibliography) and dates in parentheses to references listed at the end of this article.

ment that agents know the law of motion of all state variables entering their decision-making usually obliges the interpretation that each agent is capable of solving for the competitive equilibrium. Such an equilibrium is usually referred to as a *rational expectations equilibrium*, and is the most important of Lucas's trademarks in economics.

Lucas has incorporated a number of structures within the general competitive-Markovian framework. For example, he has assumed a number of different trading regimes from complete markets to island economies. He has also modified the basic framework to permit an analysis of government policy by incorporating a government as a dominant player. Such modifications often introduce, in one form or another, the time-consistency problem.² Lucas and Stokey [1983] address one aspect of this. In his most recent work, Lucas has dropped the assumption of symmetrically informed consumers and has analyzed the problem of a government designing optimal dynamic mechanisms for social and unemployment insurance.

To be concrete about some of these issues, consider the following abstract model. Suppose at time 0 the state of an environment is completely described by the pair (s_0, z_0) and that an agent in this environment picks a sequence of future value of s . The evolution of the state variable s is then endogenous to the agent's decision problem. By contrast, suppose that z , evolves according to a Markov process described by a function $Q: Z \times Z \rightarrow [0,1]$. Finally, suppose that the sequence s is picked so as to solve a problem of the form

$$\max_{\{s_t\}_{t=0}^{\infty}} E \sum_{t=0}^{\infty} \beta^t F(s_t, s_{t+1}) \quad \exists s_{t+1} \in A(s_t, z_t) \quad \forall t$$

Call this Program 1. Here, A describes the agent's set of permissible state choices at $t+1$ conditional on its choice at t and the realization of z . $F(\cdot)$ is a per period payoff function and the agent maximizes the expected discounted sum of these. F is taken to depend on the current choice of s and yesterday's choice. This setup is Markovian in the sense described earlier. It has proven to be a useful framework for analyzing dynamic decision-making problems in a wide variety of contexts. For example, if F is a profit function, s a capital stock sequence and z an output price sequence, then it is a framework for analyzing investment under uncertainty (as in Lucas and Prescott [1971a]).

For the expectations operator in Program 1 to be well defined, it is necessary to be explicit about the information known by the agent at time

²Roughly speaking, the time-consistency problem arises in many government policy games, where subgame perfect outcomes are inferior to those that could be achieved by commitment.

0. In addition to the initial values of the states A and F , the agents are assumed to know Q . The expectations that they form are then described as rational expectations.

There is more than one way to solve Program 1. Lucas has relied heavily on dynamic programming techniques. Under certain assumptions, these techniques provide powerful methods for analyzing recursive problems, such as Program 1, and for qualitatively characterizing agents' policy rules and thus their behavior. In the early 1970s, when Lucas first began employing these methods, dynamic programming was a relatively new technique³ and its application to economics, let alone macroeconomics, unusual. Now its use is widespread and likely to become even more so following the exposition of Stokey, Lucas and Prescott [1989].

The next step is to use these to construct equilibrium solutions of the economy in which the agents live. As has already been mentioned, in competitive, Markovian models state variables determined endogenously at the level of the macroeconomy, for example prices, often enter the agent's decision-making problems. The variable z in Program 1 could be such an aggregate state variable. Q is exogenous to the agent's problem but endogenous to the economy as a whole. Agents are required to form a belief about Q in order to solve for their optimal s sequence. Since these beliefs influence their behavior they induce a Q . Thus, an equilibrium may be interpreted as a fixed point in the mapping from beliefs to laws of motion for such state variables. This is the motivation for the label rational expectations equilibrium. This use of rational expectations contrasts markedly with the *ad hoc* mechanisms used to explain agent's beliefs about the future in the earlier macroeconomic literature. Lucas's application of rational expectations equilibrium to a variety of macroeconomic problems excited a good deal of comment and criticism⁴ during the 1970s, sufficiently such that he was often labeled as the founder of the rational expectations school of macroeconomics. Because rational expectations equilibria models of the macroeconomy rigorously derived from microeconomic foundations have not been supplanted, as yet, by any other approach of comparable rigor, it is not surprising that, as time has passed, the use of this equilibrium concept has become quite standard.

There are a number of ways to derive and characterize a rational expectations equilibrium. Sometimes this derivation can be made relatively straightforward by an application of the Welfare Theorems of the competi-

³ Only in 1965 had Blackwell provided his demonstration that the dynamic programming operator was, under certain circumstances, a contraction.

⁴ For example, it was often argued that it was unreasonable to expect agents to know the true structure of the economy.

tive general equilibrium model. In these cases the planner's problem can be formulated directly as a model of agent behavior. This is precisely the method adopted in Lucas and Prescott's seminal investment paper and in Lucas's work on asset pricing. Subsequently, it has been widely used by those investigating stochastic intertemporal competitive equilibrium models of macroeconomics, in what has become known as the real business cycle model.

Often, however, distortions of one sort or another will prevent the application of the Welfare Theorems and the system as a whole does not solve an optimization problem. There is no general method for obtaining solutions in such cases, and, typically, a good deal of ingenuity is required to make progress. It is no surprise that Lucas was the pioneer in this area. His celebrated monetary model of the business cycle (Lucas [1972b]) or his more recent model of the growth process (Lucas [1988a]) are examples of his work along this line.

Lucas's work has also had startling implications for macroeconometrics and policy evaluation, as he himself has made clear (Lucas [1975a]). Arguably, it is these implications that have provided the strongest rationale for adopting Lucas's general approach.

As I noted earlier, Lucas's framework implies that the state variables, and in particular the aggregate state variables, follow Markov processes. Moreover, in many models these processes are found to have unique invariant limiting distributions. Asymptotic theory can then be invoked to show that the sample moments converge to the population moments and thus one can recover estimates of structural parameters describing preferences and technologies from the sample moments. It was Lucas and Prescott who suggested how this might be done — they took a decisive step towards integrating theory and econometrics. It is a step that has been followed up by many macroeconometricians.

By augmenting models, such as that described by Program 1 above, with a government policy rule, one can analyze policy both at a theoretical level and an empirical one. Lucas forcefully argued that in many situations this was the only way to do policy analysis. He was especially critical of policy analysis within large-scale macroeconomic forecasting models. Dynamic economic theory, of the sort illustrated by Program 1 and used by Lucas throughout his work, implies that agents' policy rules will *not* be invariant to changes in the government's policy rule, as these changes alter the agents' constraint sets and their objective functions. Yet such invariance was precisely what the prevailing style of economic policy analysis assumed.

Lucas drove home his attack by way of three examples: the consumption function, the investment function and the function relating expected output to unexpected inflation. Specifically, Lucas argued that a temporary

income tax surcharge changes the relation between consumption and past and present income, that the investment response to the introduction of an investment tax credit depends on whether the credit is temporary or permanent, and that the output-inflation tradeoff deteriorates as inflation becomes more volatile.

The *Lucas critique*, the name now given universally to this argument, has revolutionized the evaluation of policy, down to the most practical level in central banks and finance ministries. Policy evaluation procedures now routinely respect the dependence of private decision rules on the government's policy rule. The vast consumption literature, though uncovering paradoxes and adopting a more general formulation than Lucas's, has studiously avoided trespassing the Lucas critique. Work on the Phillips Curve has been virtually abandoned, devastated by the theoretical and empirical force of the critique. Time consistency and policy commitment issues have moved to the forefront of theoretical work on the taxation of labor and capital, on debt financing and on monetary policy. Builders of large-scale models for the U.S. Federal Reserve and the IMF strive to address the Lucas critique.

Succeeding generations of economists are being trained to derive macroeconomic models rigorously from fully articulated micro-foundations and to evaluate policy and build empirical models in a manner consistent with the Lucas critique. In sum, Lucas's methodology has had profound ramifications for theoretical and applied work in dynamic economics. We cannot, Lucas maintained, posit purposive and intelligent individuals when examining microeconomic phenomena, and then turn around and assume for aggregate analysis that individuals behave mechanistically.

Throughout his distinguished career, Lucas has had a clear view of how research should proceed. The relation of the theorist to the facts is never an easy one — theory must oversimplify to make progress. In 1981, Lucas replied to the criticisms offered by James Tobin along these lines (Lucas [1981c], pp. 561–2):

Much of [Tobin's] criticism is directed at the level of abstraction of these models. (By "abstract" I do not mean "rigorous", of course, but "leaving a lot of important things out".) "The new classical macroeconomics [is] an intellectually ingenious construct that does not describe the societies in which we happen to live." Mine, in particular, uses "...very questionable *ad hoc* assumptions for which no empirical evidence is offered." "The Lucas model explains the same gross observations as Keynesian theory and the Phelps–Friedman hypothesis" but "...it leaves many other facts unexplained."

The reader should be aware that my description of the model under discussion begins, "Each period, N identical individuals are born, each of whom lives for two periods (the current one and the next)." And so on. If this sort of thing appeals to you, read the article. If it does not, you are right in guessing that it does not get any better as it proceeds. Now it does not seem to be a critical or an economic insight to observe that one can detect differences between the world described in this paper and the United States, or that it utilizes "questionable *ad hoc* assumptions", or that it leaves facts unexplained. If ever there was a model rigged, frankly and unapologetically, to fit a limited set of facts, it is this one. *Ad hoc?*

If you only knew how hard it was. Insofar as theoretical models of this type have an influence that it is worth trying to counteract (as Tobin wishes to do), it must be because people perceive useful analogies between the patently artificial world of the model and the world we live in.

That paper with N identical individuals each living two periods has had an enormous influence not just on the economics profession, but on central bankers and other policymakers around the world. Lucas has been supremely successful in capturing the essence of important economic issues in his abstract and rigorous models.

III. Applications

The macroeconomics community has become used to path-breaking papers from Robert Lucas at regular intervals. These papers, on business cycles, asset pricing, or growth, have set the agenda of modern macroeconomics. I now proceed to survey some of them. Each is couched in the approach described in Section II above. Each is a classic.

1. "Investment under Uncertainty" with Edward Prescott [1971a]

I have already referred to this paper in several places during my discussion of Lucas's methodology above. It is a carefully constructed partial equilibrium analysis of a competitive industry. The industry is composed of identical firms who maximize the sum of discounted profits. The only input to production is capital. Adjustment costs in physical investment make it optimal for firms to save resources by slowly adjusting their actual capital stock to their desired capital stock. In the model, capital has a constant price, and demand for the firm's output follows a Markov process known to firms. In this environment there are clear benefits from forecasting future output prices. The price of the industry's output is determined by demand

and industry supply, which is determined by the capital stock. In equilibrium, each firm's chosen path of the industry capital stock, conditioned on a forecast for prices, must be such that the path of the industry capital stock is indeed consistent with those forecasted prices. Thus, the equilibrium is a rational expectations equilibrium in the sense previously described.

Lucas and Prescott then rely on the Welfare Theorems and consider the associated planner's problem. They find conditions under which the Markov process for the industry capital stock, implied by the solution of the planner's problem, converges to a unique invariant probability measure and thus indicate how the model might be implemented econometrically.

2. "Expectations and the Neutrality of Money" [1972b]

In this paper, arguably the most significant paper in theoretical macroeconomics since Keynes, Lucas develops a general equilibrium model of a fully elaborated economy, with production, labor supply, consumption and the price level endogenously determined.⁵ Economic actors trade in two physically separated markets. An important restriction on the flow of information, discussed below, results from the assumption of physical isolation of the two markets. Individuals live for two periods in an overlapping generations setting similar to that of Samuelson (1958). In the second period of life, individuals spend currency earned in their youth. The aged purchase output from the currently working young generation; the young will spend the cash next period when they are old. Retirement in the second period of life is mandatory. There are two sources of uncertainty in the model. One is real — the number of individuals differs randomly across markets. The new generation of traders is unequally divided between the two markets. Thus, the price of labor, and hence output, depends upon the proportion of young that were placed in the market.

The second source of uncertainty is nominal — the government changes the quantity of currency held by the old in both markets. Furthermore, the magnitude of the introduction of new currency is not known to the young until they are old. The choice problem confronted by the young generation is as follows: unsure if the current wage (the market rate of exchange between currency and labor) is due to the quantity of money or the relative scarcity of labor in the individual's own market, the young must choose how much labor to supply. The analytical complexity of the problem emerges immediately. The young generation must solve the problem according to their perceptions of the random process through which the

⁵ A conference devoted solely to the progeny of this paper was recently held to commemorate the 25th anniversary of its writing.

government introduces new currency and the random process that determines the division of the working young between the two markets. Prices convey information on these variables, but the physical separation of the markets limits the information which can be inferred by the prices observed in a trader's own market. The process by which expectations are formed is essential to the determination of equilibrium allocations in this economy. Prices impact the traders' decision rules, but their decision rules impact the prices that prevail in each market. Here again, the essence of the rational expectations equilibrium is that each trader's perception of the processes underlying the random distribution of prices must match the actual distribution of price outcomes which his behavior determines.

Lucas's 1972 paper was, in part, an extension and formalization of the "islands" parable spelled out in Phelps (1970). Lucas adopted this island analogy to introduce an explicit notion of imperfect information — individuals on different islands cannot distinguish between relative price shifts and aggregate price shifts. The problem with Phelps's version was that expectations about the aggregate price level were slow to adjust to new information, leaving individuals with unexploited opportunities to improve their welfare. Lucas not only provided an explicit characterization of the islands model based on first principles, but he also resolved the problem of the formation of expectations. Lucas's rigorous mathematical representation of a rational expectations equilibrium was an essential contribution to macroeconomics.

In a 1973 paper in the *American Economic Review*, Lucas incorporated some of the ideas of his 1972 paper, but in a more accessible representation. One implication of the paper was that monetary policy affects output only if changes in policy are unanticipated. To the extent that monetary surprises are transmitted through the price level, a Phillips curve relationship between output and (unexpected) price movements emerges. The paper received a great deal of professional attention and led to a large literature testing the policy ineffectiveness proposition. Although professional interest in the Phillips curve has faded, Lucas's work in this area had profound impact on the development of macroeconomics. Lucas stimulated a body of work which ultimately changed macroeconomists' perceptions about the relevance of a Phillips curve relationship.

3. "Asset Prices in an Exchange Economy" [1978a]

Here, Lucas built the theoretical foundation for the determination of asset prices under uncertainty. He integrated ideas from economics and finance into a unified general equilibrium model of asset pricing. In addition, Lucas demonstrated the compelling and rigorous nature of a rational expectations equilibrium originally set forth in his 1972 *JET* paper and in his 1971 paper with Prescott.

Before Lucas, the finance literature developed important partial equilibrium models of asset prices. The Capital Asset Pricing Model (CAPM) of Sharpe (1964) and Lintner (1965) derived a relationship between the return on a risky asset and the covariance of the asset's return with the return on the market portfolio. The basic CAPM was limited in that it was only a two-period model, and individual preferences were defined only over the mean and variance of asset returns. Merton (1973) extended the CAPM to a more general intertemporal setting and examined the relation of asset prices to the economic environment as described by a finite vector of state variables. In an extension of Merton and of related work by Rubinstein (1976), Breeden (1979) used a simple form for the individual's utility function to reduce asset prices to a function of a single state variable — aggregate consumption. This version of the CAPM is known as the consumption CAPM, or consumption beta model. It is based on the first order conditions from the individual's intertemporal problem of optimal consumption demand. The simple version of the consumption CAPM has been used by a number of authors.

Lucas's 1978 paper elegantly formalized the relationship between real activity, preferences for consumption goods, and asset prices within a general equilibrium model built up from first principles. Lucas gave structural content to the relationships alluded to in the finance literature. The model consists of a single consumer, a representative "stand in" for a large number of consumers who are identical with respect to preferences and endowments. A random amount of the nonstorable consumption good is produced costlessly by a number of identical productive units. Output is exogenous and follows a Markov process with a time invariant transition function. An asset is a claim to the stochastic stream of output (dividends) from a productive unit. Consumption of the good and ownership of assets are determined each period in competitive spot markets. The model is constructed so that the equilibrium allocations are obvious — each consumer holds one unit of each asset and consumes all dividends each period.

Lucas then conducts the following exercise: what asset prices support the competitive equilibrium? To determine equilibrium asset prices, Lucas characterizes the dynamic optimal consumption rule of consumers. Imposing both the known equilibrium allocation and the consumer's optimal rule uniquely determines asset prices that must hold in equilibrium. He exploits the consumer's Euler equation which, in basic terms, relates the marginal rate of substitution of current for future consumption to the market determined transformation of current consumption into future consumption. This relationship implies that the price of the asset today is equal to the discounted expected value of next period's asset price plus next period's dividend, where the discount factor is a function of the consumer's

impatience and the intertemporal marginal rate of substitution of consumption. The model derives, from first principles, an explicit characterization of the interest rate at which expected future dividends should be discounted. Asset prices are expressed as a fixed function of the state of the economy. Knowledge of the price function and the transition function for output determine the stochastic process for asset prices. The individual's decision rules for goods consumption and for portfolio allocation are based on expected future price behavior, which is determined by the price function. However, the price function is itself determined by the decision rules for consumption and portfolio allocation. Hence consumer behavior determines the price function, but the price function determines consumer behavior.

This is where the notion of a rational expectations equilibrium is important. Rational expectations equate the perceived pricing function to the actual pricing function. A rational expectations equilibrium is a fixed point of this mapping. Using dynamic programming techniques Lucas shows that there exists a unique pricing function which represents the rational expectations equilibrium. Lucas's paper is a formal and rigorous treatment of the relation between asset prices and real activity. It bridged a gap between the treatment of optimal consumption behavior in economics and the asset pricing models used in finance. Lucas's model provided a powerful method for analyzing equilibrium asset prices. One specifies a dynamic model with fully elaborated preferences, endowments, and technology, then solves it for the optimal intertemporal allocation of consumption. The optimal consumption is used in conjunction with the individual's Euler equations to determine the asset prices which support this equilibrium. Lucas's model extended to include production as an endogenous variable, as in Brock (1982), set the standard for analyzing theoretical issues of asset pricing. Few papers today address issues in equilibrium asset pricing without referring to Lucas's seminal work. A large number of papers have examined the empirical implications of the model, and can be nested within Lucas's general framework. For example, Hansen and Singleton (1983) characterize the joint restriction on asset prices and consumption implied by a particular general equilibrium model. Mehra and Prescott (1985) use a discrete state-space version to analyze the premium on stock returns over riskless bonds. Campbell (1986) examines implications for the term structure of interest rates.

4. "Optimal Fiscal and Monetary Policy in an Economy without Capital" with Nancy Stokey [1983]

Lucas and Stokey define a dynamic exchange economy with fully elaborated microeconomic specification. They show that with debt instruments of a rich maturity structure, optimal taxes are time consistent. However in

a similar economy with nominal assets (fiat currency), they show that time consistency fails for optimal monetary policy. The paper brings together ideas from optimal tax theory, as in Ramsey (1927), Pigou (1947), Kydland and Prescott (1977), Barro (1979) and Turnovsky and Brock (1980), and optimal monetary theory, as in Bailey (1956), Calvo (1978), Clower (1967), Friedman (1969) and Phelps (1973), to demonstrate how time consistency holds for optimal taxes but fails for optimal monetary policy in a particular economy.

The paper builds on the optimal tax policy analysis of Ramsey (1927). In that work, government finances an exogenously given level of expenditure through flat-rate tax levies on different goods. Ramsey characterized tax policies that maximized the utility of a representative consumer who solved the individual choice problem taking prices and taxes as given. Lucas and Stokey, along with some of the authors above, interpret the many goods of the Ramsey set-up as a single consumption good dated over many periods in time. However the analogy between the original Ramsey problem and the dynamic problem is not complete: in the Ramsey problem taxes are levied simultaneously, so there is no sense in which a government pursuing an optimal policy might renege. In the dynamic problem, the optimal tax levies of the initial period are not implemented until later dates. If at any of these subsequent dates the government can do better by altering its original policy, it will surely deviate. Hence, absent some commitment mechanism or rule, announcements of optimal tax policies at time zero ought not be believed by individuals if they will not be optimal for the government to carry out in the future. That is what is meant by the time-inconsistency of optimal policy.

Lucas and Stokey develop a dynamic economy of identical, infinitely lived individuals in an exchange economy. Government is modeled as a dominant player whose object is to finance an exogenously given, stochastic path of expenditures in a way that maximizes the utility of agents. There are two parts to the paper. In the first, which focuses on fiscal policy, the government is restricted to using distortionary flat-tax levies on consumption in each period and state contingent debt of a full range of maturities to finance expenditures. Agents behave competitively. The government maximizes aggregate welfare subject to a resource constraint. The solution to the problem boils down to smoothing taxes over time through a state-contingent plan. For nearly all cases where government spending is stationary, this means that the tax rate is close to a martingale.

The proof that such plans are time consistent is highly dependent upon the existence of state-contingent government debt contracts with a rich maturity structure. The proof proceeds by showing that at time zero, there exists a particular issue of debt with a maturity structure such that for all realizations of initial government spending, the government next period

will find that the original tax sequence maximizes their problem at time 1. The reason is that the new government takes as binding the obligation to honor and refinance last period's government's debt at market prices. The government at time 1 in turn has at its disposal a particular (and feasible) re-issue of debt that lets the government in period 2 find the original (time zero) sequence of taxes optimal, given that it must honor past debt.

The second half of the paper focuses on monetary policy by observing that the Ramsey framework applies to optimal monetary expansion, where the inflation tax on cash balances is viewed as an excise tax. The introduction of currency is managed by introducing a second consumption good that must be purchased with cash holdings (a cash-in-advance constraint for one of the goods). Cash holdings amount to a stock of wealth, like a capital stock. In the absence of lump-sum taxes, the optimal levy from today's perspective is to tax existing stocks, but not to tax stocks accumulated in the future. However the structure of debt commitments is not sufficiently binding to make an earlier promise not to tax currency credible in the present. The result is that though there is an optimal monetary rule, it is not time consistent. The paper has led to a number of efforts in dynamic optimal tax and monetary theory. These include a vast and growing number of papers on the random walk (martingale) property of optimal taxes, and optimal taxes in economies with capital.

5. "On the Mechanics of Economic Development" [1988a]

Lucas exposes the empirical defects of the basic neoclassical growth model and then proposes two endogenous growth models, one driven by human capital accumulation with an externality in human capital and the other driven by learning by doing in purely external form. In the model with unbounded human capital accumulation, the growth rate of human capital is a linear function of the fraction of (non-leisure) time spent away from work. With human capital investment requiring direct investment of time, the model captures schooling as opposed to on-the-job training. Lucas observes that if this applies to each finitely lived individual, it will apply to the infinitely lived family if each new member's initial human capital is proportional to the level already attained by older members of the family. Because of the externality the optimal growth rate of human capital exceeds the equilibrium growth rate. Sustained growth occurs with or without the human capital externality, though physical capital grows faster than human capital in the presence of an externality in human capital.

That Lucas's model produces growth even in the absence of the human capital externality is itself important, as it substitutes purposive investment in human capital for exogenous productivity change as the engine of growth. The human capital externality model is consistent with permanent

income differentials but not with growth differentials, though the latter would arise if certain preference parameters differed across countries. From the version with externalities emerges the following key result: Workers of each skill level earn higher wages in a country with higher average human capital. With no externality in human capital, the ratio of physical to human capital in each country will converge to a specific value, one independent of initial conditions. Some countries will be wealthier because of higher initial stocks of physical and human capital. Yet a typical worker from a less developed country, with 1/10th the per capita income of the U.S., will, when transported to the U.S., still earn 1/10th of the average U.S. worker. Thus the human capital externality is crucial for explaining the premium that immigrants to developed countries earn above the wages they earned in their country of origin. The model with learning by doing contains two goods and two countries, so trade arises. The learning is entirely external to the firm and entirely internal to the country of production. One good experiences faster productivity growth than the other. A country's specialization depends solely on initial conditions. Depending on whether the two goods are good substitutes, consumption of the faster growing productivity good rises over time relative to the other good. Producing high-learning goods leads to higher growth only if the two goods are good substitutes. Opening a country up to trade can lead to specialization in the industry with a slow rate of learning, leading to a lower (suboptimally lower given the external nature of learning) rate of growth.

Lucas's 1985 Marshall lectures [1988a], along with the 1982 dissertation of his University of Chicago student, Paul Romer (1986), caused a thousand flowers to bloom in the then-dormant growth literature. Lucas began by noting that the neoclassical growth model predicts that incomes, growth rates, and returns to capital will be equalized across countries. He starkly contrasts this prediction with the huge and persistent differentials in international growth rates and real wages and the small magnitude of capital flowing on balance from rich to poor countries. Both Romer (1986) and this paper by Lucas use increasing returns to overturn the convergence of cross-country income levels and growth rates implicit in a convex model. Under convex production technology and bounded human capital, the marginal product of additional investment will be highest in the country that is least advanced. Here capital should flow from the advanced to the less developed countries to take advantage of the high returns to capital, generating higher growth among poorer countries and convergence of income levels. By allowing constant or increasing returns in a broad notion of capital that incorporates disembodied knowledge, Romer's externality model makes it possible for rates of return and growth to be highest in that country which is most advanced. Lucas sharpens Romer's analysis by decomposing the broad measure of capital into physical and human

capital, allowing unbounded accumulation of human capital, and confining the external effects to human capital. The latter implies that a worker is more productive the more clever are the people who surround the worker, a notion economists in academic departments naturally find compelling.

Lucas makes the crucial assumption that human capital, unlike physical capital, is not internationally mobile. Whereas rates of return to physical capital must be equalized across countries (or else arbitrageurs will ship it to the machine-starved countries), the returns to human capital need not be. Thus Lucas's human capital externality model can explain the strong incentive for individuals of all skill levels to migrate from less developed to developed countries. Lucas's model also rationalizes extreme concentration of resources in specific locations. In a convex model, within a country where both physical and human capital are mobile, physical and human capital will spread evenly over the available land. As Lucas emphasizes, both physical and human capital are in fact highly concentrated in cities.

Lucas's second model places less emphasis on the details of growth and more on the interaction of growth with trade. Here he stresses that increasing returns can dramatically overturn the usual presumptions about the positive welfare effects of trade. If some industries/goods have higher intrinsic rates of learning, and the learning is purely external to the firm (but, importantly, not the country of production), then a given country may have an initial comparative advantage in a slow-learning potential industry. The country will initially specialize in the slow-learning industry, after which the localized learning reinforces the initial comparative advantage. Here a given country may be worse off after trade liberalization! This provocative model has helped spawn a whole school of papers on the interaction between growth and trade in models with increasing returns and externalities. As noted at the outset, Lucas and Romer have inspired a burgeoning literature on endogenous sources of growth. It is difficult to understate the impact the papers have had on the research efforts of the profession: Growth conferences are held with great frequency, weekly growth seminars meet at universities around the world, and scores of graduate students are writing their dissertations on refinements of the Lucas and Romer models.

Lucas's and Romer's renaissance of growth theory seem destined to have a permanent influence on the profession's thinking about aggregate economics. First, the inability of the basic growth model to explain the tremendous diversity of growth rates and income levels across countries will simply not go away. Second, we desperately want and need to understand why some countries enjoy higher standards of living and growth rates than others. In Lucas's own words, "The consequences for human welfare ... are simply staggering: Once one starts to think about them, it is hard to think about anything else." Finally, though real progress has been made,

the endogenous growth literature has only scratched the surface of understanding the variety of observations we have on country growth patterns. Lucas has paved the way to such an understanding, but much research, especially linking structural models more formally with the data, must be carried out for us to advance further down his path.

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