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From Solow to Romer: Teaching endogenous technological change in undergraduate economics

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ABSTRACT

Undergraduate students learn economic growth theory through the seminal Solow model, which takes the growth rate of technology as given. To understand the origin of technological progress, we need a model of endogenous technological change. The Romer model fills this important gap in the literature. However, given its complexity, undergraduate students often find the Romer model difficult. This paper proposes a simple method of teaching the Romer model. We add three layers of structure (one at a time) to extend the familiar Solow model into the less familiar Romer model. First, we incorporate a competitive market structure into the Solow model. Then, we modify the competitive market structure into a monopolistic market structure. Finally, we introduce an R&D sector that invents new products.

1. Introduction

Economic growth is an important topic in economics. As Acemoglu (2013) argues, "economics instructors should spend more time teaching about economic growth and development at the undergraduate level because the topic is of interest to students, is less abstract than other macroeconomic topics, and is the focus of exciting research in economics." Undergraduate students often learn the theory of economic growth through the seminal Solow model originated from Solow (1956). This elegant model provides the following important insight: in the long run, economic growth must come from technological progress instead of capital accumulation. However, the Solow model takes the growth rate of technology as given, and hence, it does not provide any insight on the determinants of technological progress. Taylor (2000) writes that "teaching beginning students the Solow model, augmented with endogenous technology, is the first step toward teaching them modern macroeconomics."

Romer (1990) greatly enhances economists' understanding of endogenous technological change by developing a growth model known as the Romer model in which technological progress is driven by the invention of new products, which in turn is due to research and development (R&D) by profit-seeking entrepreneurs. Unfortunately, the Romer model is relatively complicated, and undergraduate students often find it difficult. In particular, although it is not difficult to demonstrate the key assumption that technological change is driven by R&D, it is much more difficult to demonstrate how the level of R&D is determined in the market equilibrium within the Romer model. Therefore, macroeconomic textbooks at the intermediate level, such as Jones (2017) and Barro et al. (2017), often assume a given level of R&D when presenting the Romer model without showing how the equilibrium level of R&D is determined in the market economy. However, Jones (2017) writes that "[i]n Romer's original model, he set up markets for labor and output, introduced patents and monopoly power to deal with increasing returns, and let the markets determine the allocation of labor. What Romer discovered is fascinating […] but unfortunately beyond the scope of this text."

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To address the above issue, this paper proposes a simple method to solve the market equilibrium level of R&D in the Romer model by adding three layers of structure (one at a time) to extend the familiar Solow model into the less familiar Romer model. First, we incorporate into the Solow model a competitive market structure in which final goods are produced by competitive firms that employ labor and rent capital from households. Then, we modify the competitive market structure into a monopolistic market structure in which differentiated intermediate goods are produced by monopolistic firms. Finally, we introduce to the monopolistic Solow model an R&D sector, which invents new varieties of intermediate goods and gives rise to endogenous technological progress. Once we derive the endogenous growth rate of technology, we can then perform experiments in this mathematical laboratory by using comparative statics to explore the determinants of technological progress. All mathematical derivations are based on simple calculus and algebra at the level of intermediate microeconomics. We hope that by presenting it as a step-by-step extension of the Solow model, we have made the Romer model more accessible, at least to advanced undergraduate students in economics.

The rest of this paper is organized as follows. Section 2 presents the step-by-step transformation of the Solow model into the Romer model. Section 3 offers concluding thoughts.

2. From Solow to Romer

Section 2.1 reviews a basic version of the Solow model with *exogenous* technological progress. Section 2.2 discusses a simple version of the Romer model with *exogenous* R&D. Section 2.3 incorporates a competitive market structure into the Solow model.[2] Section 2.4 modifies the competitive market structure into a monopolistic market structure. Section 2.5 introduces an R&D sector to the monopolistic Solow model, which becomes the Romer model with *endogenous* R&D and *endogenous* technological progress.

2.1. The Solow model

In this subsection, we consider a basic version of the Solow model with exogenous technological progress. Output Y is produced by an aggregate production function $Y = K^{\alpha}(AL)^{1-\alpha}$, where A is the level of technology that grows at an exogenous rate $g > 0$, K is the stock of capital, and L is the size of a constant labor force. The parameter $\alpha \in (0, 1)$ determines capital intensity α and labor intensity $1 - \alpha$ in the production process. The key equation in the Solow model is the capital-accumulation equation given by $\Delta K = I - \delta K$, where the parameter $\delta > 0$ is the depreciation rate of capital. Investment I is assumed to be a constant share $s \in (0, 1)$ of output Y. Substituting the investment function $I = sY$ and the production function $Y = K^{\alpha}(AL)^{1-\alpha}$ into the capital-accumulation equation yields

$$\frac{\Delta K}{K} = \frac{\text{sY}}{K} - \delta = s\left(\frac{\text{AL}}{K}\right)^{1-\alpha} - \delta. \tag{1}$$

Eq. (1) can then be used to explore the transition dynamics of an economy from an initial state to the steady state, which is a common analysis in macroeconomic textbooks at the intermediate level. In the long run, the economy is on a balanced growth path, along which capital K grows at a constant rate implying that Y/K and A/K are constant in the long run. This in turn implies that in the long run, output Y and capital K grow at the same rate as technology A; i.e.,

$$\frac{\Delta Y}{Y} = \frac{\Delta K}{K} = \frac{\Delta A}{A} \equiv g.$$

This is an important insight of the Solow model, which shows that in the long run, economic growth comes from technological progress (i.e., $g > 0$), without which the growth rate of the economy would converge to zero due to decreasing returns to scale of capital in production (i.e., $\alpha < 1$).[3]

2.2. A simple Romer model with exogenous R&D

To understand the origin of technological progress in the Solow model, we can follow Romer (1990) to assume that the technology growth rate g is determined by R&D labor L_R. For example, we specify $g = \theta L_R$, where $\theta > 0$ is a parameter that determines the productivity of R&D labor. Then, to close the model, we modify the production function to $Y = K^{\alpha}(AL_Y)^{1-\alpha}$, where L_Y denotes production labor. Finally, the total amount of labor in the economy is $L_Y + L_R = L$. The rest of the model is the same as above. If we assume that production labor is given by $L_Y = (1 - l)L$ and R&D labor is given by $L_R = lL$, where $l \in (0, 1)$ is the exogenous R&D share of labor, then we can proceed to explore the implications of changes in l as in Jones (2017). While this analysis is interesting, it has a similar limitation as the analysis in Solow (1956). Solow (1956) assumes an exogenous technology growth rate g and is silent on its origin. The simple Romer model here assumes an endogenous technology growth rate $g = \theta L_R$ but an exogenous R&D labor share $l = L_R/L$, and hence, it is silent on the determination of R&D in the market economy. Unfortunately, solving for the market equilibrium level of R&D is often difficult for undergraduate students.[4] In the following subsections, we use a step-by-step approach to extend the Solow model in Section 2.1 into a fully-specified Romer model in Section 2.5.

[2] Solow (1956) also discusses the implications of his model in a competitive market.

[3] If the production function features constant returns to scale of capital (i.e., $\alpha = 1$), then the long-run growth rate of output and capital would be $\Delta Y/Y = \Delta K/K = s - \delta$. However, this is an unrealistic way to generate endogenous growth in the long run.

[4] See Aghion and Howitt (2009) and Jones and Vollrath (2013) for an excellent treatment of the Romer model at the advanced undergraduate level.