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CAPITAL-LABOR COMPLEMENTARITIES IN R&D PRODUCTION AND THE LINGERING EFFECTS OF ECONOMIC SLOWDOWNS

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In an attempt to advance our understanding of the potential long-run benefits of macroeconomic stabilization policies, the paper studies the long-term effects of economic slowdowns. We construct a discrete-time endogenous growth model, in which a recession, defined as a reduction in resource utilization for a limited number of periods, may have long-lasting detrimental effects on the growth path of the economy. We study the long-term consequences of recessions of various durations and intensities by comparing an economy that grows at steady state rates to one that experiences a recession. The long-run effects of a recession are estimated as the discounted present value of the output differences of the two economies. Our results show that even mild recessions, such as those observed in the last 50 years in the U.S., can have long-lasting adverse level effects on output. A typical recession that causes a 1% reduction in GDP for one year, after which the economy returns to its steady-state 3% growth rate, may result in output losses whose present value is equivalent to 6.5% of the pre-recession output.

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JEL classification: O30, O41, E27

1. INTRODUCTION

In the classical Solow (1956) model, there is no obvious theoretical avenue via which business cycle stabilization policies have long-run effects. As a result, economic growth and business cycle stabilization had been studied as more or less separate fields until at least late-1980s. Based on such a dichotomy, researchers have been considering arguments on whether policymakers and academics should focus their energies on

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improving short-run stabilization policies or devising those that promote long-run growth. Lucas (1987), for example, argues that the welfare gain from further refining stabilization policies to eliminate all cyclical fluctuations is extremely small (just 0.008% of the GNP), while the returns to growth-promoting policies are potentially large. Consequently, policymakers and researchers should concentrate on growth policies. Lucas' calculations have resulted in a series of papers that either support (Imrohoroglu (1989), Atkeson and Phelan (1994), Obstfeld (1994), Pemberton (1996), Dolmas (1998), Krusell and Smith (1999), Otrok (2001)) or reject (Campbell and Cochrane (1999), Tallarini (2000), Beaudry and Pages (2001)) his results.

Very recently, several important attempts have been made in the direction of challenging the implicit dichotomy between business cycles and growth. For example, the effects of transitory shocks on endogenous growth are carefully studied by de Hek (1999), Jones, Manuelli, Siu and Stacchetti (2005), and Comin and Gertler (2006). Unlike the Solow model, the recent endogenous growth models do have apparent theoretical avenues via which short-term stabilization policies can affect long-run performance. These avenues pertain mostly to the processes used to introduce the endogenous production of technology. Specifically, technological change can be endogenized by either explicitly modeling the human capital accumulation process (Lucas (1988)), or explicitly modeling the knowledge accumulation process (Romer (1990)).

One way to allow for effective stabilization policies in a growth model is to adjust the neoclassical growth model in a way that policies will affect the marginal product of capital. This is achieved either by imposing a lower bound on the marginal product of capital that fiscal policy may affect (as in Jones and Manuelli (1990)), or by introducing diminishing returns to investment (as in Barlevy (2004)).

Martin and Rogers (2000) review work, stemming mainly from the ideas of Aghion and Saint-Paul (1998), that focuses on the effect of the business cycle on the human capital accumulation process. Aghion and Saint-Paul (1998) argue that if accumulation of human capital that results in productivity growth has disruptive effects on current production, then human capital accumulation will be undertaken during recessions, i.e., recessions may have a beneficial effect on growth. If, on the other side, human capital accumulation is independent of current production levels, then recessions will have adverse effects on growth. Martin and Rogers (1997, 2000) argue that if human capital accumulation is achieved via learning-by-doing, which in turn depends on cumulative output, then recessions, by disrupting cumulative output, have adverse effects on human capital accumulation and the overall growth process.

Fatás (2000) is probably one of the most important attempts to move away from the conventional separate treatment of short-run fluctuations and long-run growth. Fatás' work is also the closest to ours in spirit (but not the mechanics). In his model, exogenous shocks to aggregate demand affect the incentives to innovate. As a result, business cycles can alter the growth path of the economy: after a recession, output remains at a permanently lower level. In our paper the propagation mechanism is also through the

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innovations channel, but the technical implementation is quite different. We don’t make some of the rather serious assumptions that Fatás has to rely on (e.g., memoryless research process, absence of capital). More important, our model does not lead to the dramatic prediction that business cycles alter the growth path of the economy indefinitely. In our model, the growth rates eventually go back to the pre-recession steady-state levels, and we only suggest that in the time that it takes the economy to revert back to the long-run growth, the present value of lost output may be quite substantial.

This paper’s analysis focuses on the knowledge accumulation channel. A Leontief-type knowledge production function is introduced to account for the complementarities between capital and labor in technology production. In such a setup, it is possible that an economic slowdown may adversely affect knowledge production via its detrimental effect on the knowledge-producing capital. The cumulative nature of knowledge accumulation makes it possible that the current adverse effect of a recession may affect output for an extended period via the effect of a lower knowledge level.

It is shown that for relatively mild economic slowdowns, the knowledge accumulation process remains intact. But for more severe slowdowns, the adverse effect on knowledge accumulation is potentially large. For example, simulations show that a mild slowdown when the resource utilization rate of the economy falls from 100% to 98% for just one period will cause a reduction in the present value of output over the next 97 periods, equivalent to about 2.7% of the pre-slowdown output level. A more severe fall to 96% utilization rate for one period reduces the present value of output by 6.5% of the pre-slowdown output. On the extreme, a depression-like reduction in output to 70% resource utilization rate for 4 periods will result in a reduction equivalent to 216% of the pre-slowdown output. In other words, the U.S. economy may still be “paying” for the Great Depression!

The corollary of the analysis is that recessions probably have long-run effects that are potentially large and, therefore, policymakers should be vigilant in preventing the economy from sliding into a severe recession. In what follows, Section 2 describes the model, Section 3 examines the solutions, Section 4 provides a number of interesting simulations, and Section 5 concludes.

2. THE MODEL

The analysis uses an endogenous knowledge accumulation growth model in the spirit of Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992). A discrete version is presented here to derive results that can be used in subsequent simulations.

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2.1. R&D Sector

The novel feature of this paper is the treatment of the technological progress. It is assumed that the economy trains a fraction a_L of its labor force to be knowledge- (or technology-) producing workers. Knowledge production is a cumulative process in which the existing level of knowledge is an input along with capital and labor, and additions to the knowledge stock are the output. An implication of the nature of the knowledge production process is that, most likely, in order to produce new knowledge, technology workers need to be equipped with capital that already embodies all the necessary existing knowledge.[1] This requirement is captured by assuming that knowledge workers are equipped with new capital goods (the latest vintage capital) every period, i.e., they only use new investment. A fraction a_I of the new investment goods are devoted to equipping the knowledge workers.[2]

Overtime, technological progress requires that each knowledge worker needs to be equipped with increasingly more capital, so that expenditures on required research capital increase. This is hardly a surprising observation when one notes that overtime new technologies become more complex and it becomes costlier for them to be embodied in new investment goods.

The nature of the relationship between technology workers and their capital is complementary (i.e., there is no substitutability). In other words, each knowledge worker has to be equipped with a certain amount of capital to be productive. Equipping the worker with more capital (beyond the required amount) will not affect the worker's productivity, while providing less capital will render the worker less effective.[3] Much of the recent theoretical literature points out to the strong complementarities between skilled labor and capital (e.g., Acemoglu (1998), Krusell, Ohanian, Rios-Rull and Violante (2000), Hornstein and Krusell (2003)). A Leontief-type production function is used to capture the above-described knowledge production process:

$$\Delta A_t = B \min\{\beta_t a_I I_t, \gamma a_L L_t\} A_t^{\theta}, \tag{1}$$

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[1] Pakko (2002) shows that most of the technological advancements in the last decades are embodied into capital goods. Similarly, Greenwood, Hercowitz and Krusell (1997) find that "approximately 60 percent of postwar productivity growth can be attributed to investment-specific technological change." (p. 359) Implications of capital-embodied technology have been studied by Krusell, Ohanian, Rios-Rull and Violante (2000) and Hornstein and Krusell (2003), among others.

[2] Casual empiricism suggests that one would hardly expect to find relatively old (say, 3-5 years old) equipment in the research labs of the government and major corporations.

[3] As an example, consider a lab with five X-ray technicians. Equipping the lab with five X-ray machines will maximize output. Having six machines will not add to the output noticeably, while having only four machines will produce the same output as four workers, i.e., one worker will be effectively redundant.

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where

$$\beta_t = \beta_0 \left(1 + g_\beta\right)^{-t}, \text{ with } B > 0,\ \beta_0 > 0,\ \gamma > 0,\ \theta > 0, \text{ and } g_\beta > 0.$$

Variable A_t describes the existing stock of technology, ΔA_t is the output, i.e., the newly produced addition to the knowledge stock, β_0 and γ are parameters, a_I and a_L are the fractions of investment and labor devoted to the production of knowledge.[4] The assumed increase in the cost of knowledge-producing capital is captured in β_t. This variable is assumed to shrink at a rate g_β to capture the cost increase.[5] Since $1+\theta > 1$, the function exhibits increasing returns to scale.[6]

In periods when new investment is scarce, knowledge production becomes $\Delta A_t = B\beta_t a_I I_t A_t^\theta$, and some of the knowledge workers remain idle. In periods when investment is plentiful, labor becomes the limiting factor, so that $\Delta A_t = B\gamma a_L L_t A_t^\theta$, and the excess investment either remains idle or is transferred to the goods-producing sector. These arguments suggest the existence of a critical (or optimal) level of investment I_t^c, defined as[7]

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[4] The exogeneity assumption with respect to a_I and a_L is made in the interest of simplicity and tractability. Without this simplification it would be difficult to solve the model even using numerical methods. Previous studies that made the same assumption include Englmann (1994), who assumes that entrepreneurs split their profits between investing in R&D and investing in capital accumulation. Thus Englemann's model is similar to ours in that the behavior of agents in his model is governed by routines.

[5] Note that if β_t is treated as constant (i.e., $g_\beta = 0$), as in the traditional Leontief production function, and, as in our model, investment grows faster than labor, technology workers will require an ever smaller investment fraction to equip the workers. That is, after a number of periods there will be a large excess of technology capital (see the behavior of I_t^c below).

[6] This setup is different from the conventional Cobb-Douglas technology: $\Delta A_t = B\left(a_I I_t\right)^\beta \left(a_L L_t\right)^\gamma A_t^\theta$. The Leontief function makes more sense since firms cannot produce innovations with workers alone and no capital.

[7] The critical level of investment is the level necessary to fully equip the existing technology workers. Thus, investment levels above this critical level will produce surplus of capital in the R&D sector. Note that if $g_\beta = 0$ (i.e., β_t is constant), then I_t^c will grow at the same rate as L_t (that is, at the rate of growth of the technology workers). If the rate of growth of output is larger than the population growth rate, then the surplus $\left(I_t - I_t^c\right)$ will be ever expanding, as noted in footnote 5. By choosing the value of g_β appropriately, the full employment surplus $\left(I_t - I_t^c\right)$ can be kept near constant.

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$$I_t^c = \frac{\gamma a_L}{\beta_t a_I} L_t \,. \tag{2}$$

Combining the knowledge production function (1) and the critical level of investment (2) yields:

$$\begin{cases} \Delta A_t = B\beta_t a_I I_t A_t^{\theta} & if \quad I_t < I_t^c \\ \Delta A_t = B\gamma a_L L_t A_t^{\theta} & if \quad I_t \geq I_t^c . \end{cases}$$

Note that when $I_t = I_t^c$, the two equations are equivalent.

There are at least three sets of arguments to be made in justifying the use of Leontief function in R&D production. First, many previous studies rely heavily on the existence of complementarity between skilled labor and capital (e.g., Krusell, Ohanian, Rios-Rull and Violante (2000), Hornstein and Krusell (2003)). The use of Leontief function allows one to explicitly acknowledge complementarity among the inputs. Ever since Griliches (1969) hypothesized that skilled labor may not be as easily substitutable for capital as unskilled labor, many studies found the capital-skill complementarity (as indicated by small estimated partial elasticities of substitution) in various industries, countries and time periods. The list of studies that confirm Griliches’ hypothesis include Fallon and Layard (1975), Bergström and Panas (1992), Duffy, Papageorgiou and Perez-Sebastian (2004), among others.[8] Much of the recent theoretical literature also points out to the strong complementarities between skilled labor and capital (e.g., Acemoglu (1998), Krusell, Ohanian, Rios-Rull and Violante (2000), Hornstein and Krusell (2003)). Clearly, the R&D sector requires the highest levels of skill and education of the workers, ergo one should expect a very high degree of complementarity between capital and labor in R&D production. Accordingly, we use Leontief function to capture this complementarity.

Second, and perhaps more straightforwardly, several researches used Leontief production function in many contexts, including R&D production. For example, Basant and Fikkert (1996) use a generalized linear Leontief function to describe the evolution of the stock of knowledge. Eicher (1996) uses the Leontief function of the *min* form, just as the one we have in our model, to describe technological vintage in the education sector. In Gilchrist and Williams (2000), a capital-labor ratio is a choice variable, and the *ex post* production function is Leontief even for the goods sector. Jones (2005) also uses the Leontief function of the *min* form in the goods sector for tractability and the ability to obtain analytical results.

Finally, Luna (2004) offers yet another justification for the use of the Leontief function that does not rely on the assumption of perfect complementarity: “The

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[8] Studying U.S. aggregate manufacturing data, Appelbaum (1979) finds that the (generalized) Leontief function is a preferred functional form for any direct production function.

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fixed-proportion technology may simply be the outcome of an incomplete and on-going experimentation which, for the time being, has delivered only ‘one point’ for each isoquant. Equivalently, the search has been stopped after the first successful outcome because of cost-benefit considerations.” (p. 187) The “experimentation” argument is, clearly, most relevant in the R&D sector that produces innovations.[9]

2.2. Resource Utilization

A capacity (or resource) utilization parameter λ, where $0<\lambda\leq 1$, is introduced to describe periods of full employment and periods of economic slowdown. The economy is fully utilizing its resources when $\lambda=1$. During a slowdown, some resources are idle, which is captured by setting $\lambda<1$, so the economy uses only $\lambda\times 100\%$ of its resources. Note that a slowdown is not necessarily a recession. If, for example, an economy’s resources (or potential output) grow by 3% per year, a reduction in resource utilization to 98% will slow the growth rate to approximately 1%, but it will not register as a recession. Nevertheless, this slowdown results in lost output and is a cause of concern. It will take a reduction in resource utilization to below 97% to produce a negative output growth and register as a recession. Actual output is λY^{FE}, where Y^{FE} is the full employment or potential output. Investment then becomes

$$I_t = sY_t = s\lambda Y_t^{FE} > 0 .$$

2.3. Goods Sector

The goods-producing sector is characterized by a Cobb-Douglas production function. The capital input equals all non-depreciated past vintage capital, plus the part of the current investment that is not used in technology production. The paper considers the scenario where excess capital in the technology-producing sector is reallocated to the goods sector in the next period (i.e., it remains idle for one period).[10] Additionally, the non-depreciated portion of the capital that was used in R&D production is relocated from the R&D sector to the goods sector after one period. Capital input in the goods sector (K_t^G) is thus given by

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[9] Our results should not change drastically if another functional form is used in R&D production, so long as there is a relatively low elasticity of substitution (or, equivalently, high complementarity) between capital and labor in R&D production. Jones (2005) uses simulations to confirm that other production function specifications can be used instead of the Leontief.

[10] If we relax this simplifying assumption and have all new capital used this period, our results become even stronger in a sense that the estimated costs of a downturn become larger.

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$$K_t^G = (1 - a_I)I_t + (1 - \delta)K_{t-1},$$

where δ is the depreciation rate and K_{t-1} encompasses the total stock of capital that has been used the previous period in either sector.

The labor input consists of the part of the labor not used in knowledge production, and is enhanced by technology. Thus, output (*Y*) is produced using capital (K^G), labor (*L*) and technology (*A*):

$$Y_t = \lambda_t \left[K_t^G\right]^{\alpha} \left[A_t (1 - a_L) L_t\right]^{1-\alpha}, \quad 0 < \alpha < 1.$$

The fact that investment is financed by saving implies:

$$I_t = \lambda_t s \left[K_t^G\right]^{\alpha} \left[A_t (1 - a_L) L_t\right]^{1-\alpha},$$

with $\lambda = 1$ at full employment and $\lambda < 1$ during recession. The potential output is given by

$$Y_t^{FE} = \left[K_t^G\right]^{\alpha} \left[A_t (1 - a_L) L_t\right]^{1-\alpha}.$$

3. SOLUTIONS AND DYNAMICS

Our growth model consists of the following equations:

$$\begin{cases} \Delta A_t = B \min\{\beta_t a_I I_t, \gamma a_L L_t\} A_t^{\theta} \\ \Delta L_t = n L_t \\ \Delta K_t = I_t - \delta K_{t-1} \\ I_t = s Y_t \\ Y_t = \lambda_t \left[(1 - a_I) I_t + (1 - \delta) K_{t-1}\right]^{\alpha} \left[A_t (1 - a_L) L_t\right]^{1-\alpha}, \end{cases}$$

where *n* is the exogenous growth rate of labor. The solution of the model involves the endogenous determination of the steady-state rates of growth for capital and technology. These are defined as:

$$g_A \equiv \frac{\Delta A_t}{A_t} \quad \text{and} \quad g_K \equiv \frac{\Delta K_t}{K_{t-1}}.$$

Note that the definition of the rate of growth of capital is measured relative to existing

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capital because of the role of existing capital in the income equation.

3.1. Full Employment $(\lambda = 1)$

Here investment is abundant and labor is the limiting factor in technology production. Assuming that excess capital in the technology sector cannot be redirected to the goods sector, we solve

$$\begin{cases} \Delta A_t = B\gamma a_L L_t A_t^{\theta} \\ \Delta L_t = nL_t \\ \Delta K_t = I_t - \delta K_{t-1} \\ I_t = sY_t \\ Y_t = \left[(1-a_I)I_t + (1-\delta)K_{t-1}\right]^{\alpha}\left[A_t(1-a_L)L_t\right]^{1-\alpha}, \end{cases}$$

for g_A and g_K.

The solution to this model is

$$g_A = \frac{\Delta A_t}{A_t} = B\gamma a_L L_t A_t^{\theta-1} \Rightarrow \frac{\Delta g_A}{g_A} = (\theta-1)g_A + n,$$

and

$$\begin{aligned} g_K = \frac{\Delta K_t}{K_{t-1}} &= s\left[\frac{(1-a_I)I_t + (1-\delta)K_{t-1}}{K_{t-1}}\right]^{\alpha}\left[\frac{A_t(1-a_L)L_t}{K_{t-1}}\right]^{1-\alpha} - \delta \\ &= s\left[(1-a_I)(g_K+\delta) + (1-\delta)\right]^{\alpha}\left[\frac{A_t(1-a_L)L_t}{K_{t-1}}\right]^{1-\alpha} - \delta \\ &\Rightarrow \frac{\Delta g_K}{g_K+\delta} = \frac{(1-\alpha)\left[(1-a_I)g_K + (1-a_I\delta)\right]}{(1-\alpha)(1-a_I)g_K + (1-a_I\delta)}(g_A + n - g_K), \end{aligned}$$

or

$$\begin{aligned} \frac{\Delta g_K}{g_K} &= \left(\frac{g_K+\delta}{g_K}\right)\frac{(1-\alpha)\left[(1-a_I)(g_K+\delta) + (1-\delta)\right]}{(1-\alpha)(1-a_I)(g_K+\delta) + (1-\delta)}(g_A + n - g_K) \\ &= \left(\frac{g_K+\delta}{g_K}\right)\frac{\left[(1-a_I)g_K + (1-a_I\delta)\right]}{(1-\alpha)(1-a_I)g_K + (1-a_I\delta)}(g_A + n - g_K). \end{aligned}$$

The steady-state solution requires that the growth rate of capital and labor remain

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constant, i.e., $\Delta g_K = \Delta g_A = 0$. Hence[11]

$$g_A^{FE} = \frac{n}{1-\theta},$$

$$g_K^{FE} = \begin{cases} g_A^{FE} + n > 0 \\ -\delta < 0 \\ \dfrac{a_I \delta - 1}{1 - a_I} < 0. \end{cases}$$

In a "positive" steady state ($g_A > 0$, $g_K > 0$), $g_A = \dfrac{n}{1-\theta}$ and $g_K = n + \dfrac{n}{1-\theta} = \dfrac{n(2-\theta)}{1-\theta}$.

3.2. Economic Slowdown $(\lambda < 1)$

Next we examine the effects of a slowdown on the growth rate of capital. The slowdown decreases output, saving and investment. Lower investment leads to a slowdown in the rate of growth of capital. The slowdown level of investment is

$$I_t^S = sY_t = s\lambda_t Y_t^{FE}, \quad \lambda < 1.$$

The reduction in investment between the full employment state and the slowdown state is given by:

$$\Delta I_t^S = I_t^{FE} - I_t^S = sY_t^{FE} - s\lambda Y_t^{FE} = (\lambda_t - 1) sY_t^{FE} < 0.$$

The rate of growth of capital falls from g_K^{FE} to $g_K^S = g_K^{FE} + \Delta g_K^S$. It can be shown that:[12]

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[11] The first "negative" solution ($g_A = 0$, $g_K < 0$) yields $g_A = 0$ and $g_K = -\delta$, so the implicit assumption is that there is no investment undertaken at all. The other solution, $g_K = \dfrac{a_I \delta - 1}{1 - a_I}$, is less than -1 for the baseline parameter values. Thus, those two solutions do not deserve consideration.

[12] From

$$g_K = \frac{I_t - \delta K_{t-1}}{K_{t-1}} = \frac{I_t}{K_{t-1}} - \delta, \quad \frac{\Delta I_t^S}{I_t^{FE}} = \frac{(\lambda_t - 1) sY_t^{FE}}{sY_t^{FE}} = \lambda_t - 1, \text{ and } \frac{I_t}{K_{t-1}} = g_K + \delta,$$

it follows that

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$$g_K = n + \frac{n}{1-\theta} + \left(g_K^{FE} + \delta\right)\left(\lambda_t - 1\right).$$

This equation determines the growth rate of capital during the slowdown. The second term is negative, implying, as expected, that the rate of growth of capital falls during the slowdown. Obviously, the deeper the slowdown, i.e., the lower the value of λ, the lower the growth rate of capital.[13]

3.2.1. Mild Slowdown

A slowdown is defined as mild if the level of investment is still above the critical value I_t^c required to fully equip workers in the knowledge accumulation sector. In this case the growth of knowledge production will not be affected by the slowdown and will remain at g_A^{FE}. Figure 1 demonstrates graphically the change occurring during a mild slowdown. Starting from the steady state point *E*, the economy enters a slowdown. The growth rate of knowledge remains unaffected, while the rate of growth of capital falls to g_K^S, and the economy jumps to point *S*. When the slowdown is over, the economy returns to its steady state *E*.

$$\begin{aligned}\Delta g_K^S &= g_K^S - g_K^{FE} = \left(\frac{I_t^S}{K_{t-1}} - \delta\right) - \left(\frac{I_t^{FE}}{K_{t-1}} - \delta\right) = \frac{I_t^S - I_t^{FE}}{K_{t-1}} \\ &= \frac{\Delta I_t^S}{K_{t-1}} = \frac{\Delta I_t^S}{I_t^{FE}} \frac{I_t^{FE}}{K_{t-1}} = \left(\lambda_t - 1\right)\left(g_K^{FE} + \delta\right) < 0.\end{aligned}$$

[13] Readers might be curious as to whether an economic boom has a long-lasting beneficial effect on the growth path of the economy. The nature of our model implies that during periods of full employment of resources ($\lambda = 1$), vintage capital is abundant and labor is the limiting factor in technology production. Hence, further increases in the availability of new capital will not affect knowledge production. On the other side, as the model shows, scarcity of capital during recessions has a negative impact on the technology production.

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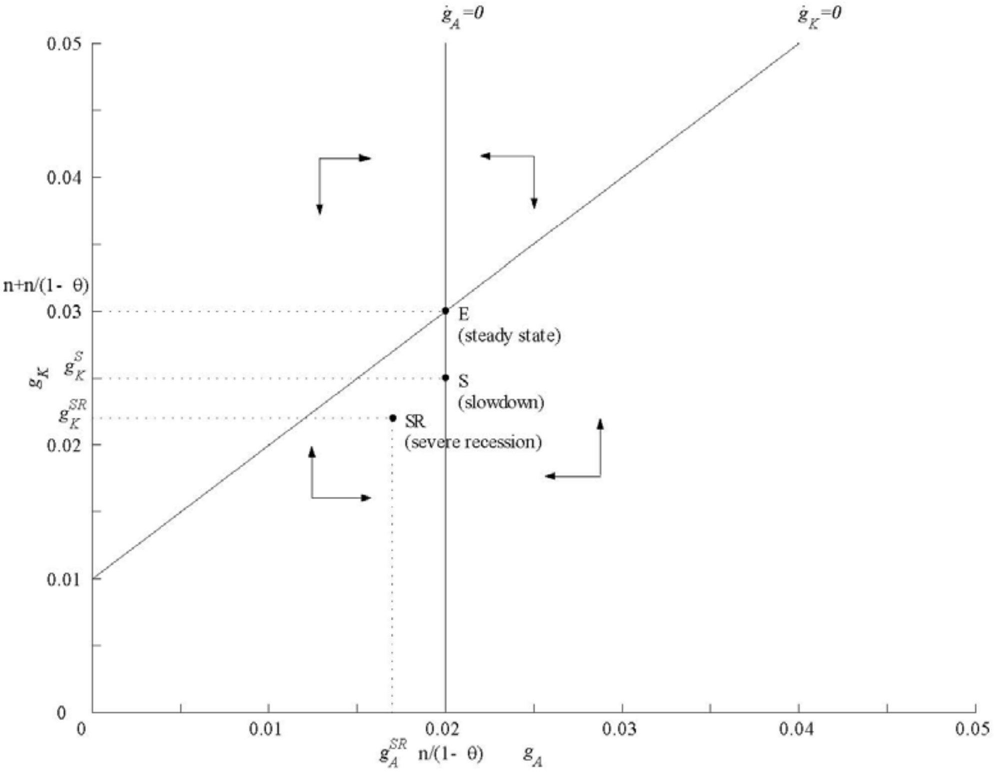

Figure 1. The Dynamics of the Growth Rates of Capital and Knowledge, $\theta < 1$

3.2.2. Severe Slowdown/Recession

A slowdown is defined as severe if it results in an investment level below the critical value I_t^c.[14] In all probability, a severe slowdown will register as a recession. A severe recession (*SR*) will not only reduce the rate of growth of capital but also the rate of growth of technology. Since now capital is scarce, technology production becomes:

$$\Delta A_t^{SR} = B\beta a_I I_t^{SR} A_t^{\theta}, \quad I_t^{SR} < I_t^c ,$$

and

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[14] Note that the recession is severe if

$$\lambda < \lambda^c \equiv \frac{\gamma a_L}{\beta a_I} \frac{L_t}{sY_t^{FE}} .$$

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$$g_A^{SR} = \frac{\Delta A_t^{SR}}{A_{t-1}^{\theta}} = B\beta_t a_I I_t^{SR} A_t^{\theta-1} .$$

It should be noted that when investment is exactly at its critical level, technology is growing at its full employment rate. Thus it holds that

$$g_A^{FE} = B\gamma a_L L_t A_t^{\theta-1} = B\beta_t a_I I_t^c A_t^{\theta-1} ,$$
$$g_A^{FE} - g_A^{SR} = B\beta_t a_I I_t^c A_t^{\theta-1} - B\beta_t a_I I_t^{SR} A_t^{\theta-1} = B\beta_t a_I I_t^c A_t^{\theta-1} \left(\frac{I_t^c - I_t^{SR}}{I_t^c} \right) > 0 ,$$

and

$$\Delta g_A^{SR} = g_A^{SR} - g_A^{FE} = g_A^{FE} \left(\frac{I_t^{SR} - I_t^c}{I_t^c} \right) < 0 .$$

Consequently, during a severe recession the rate of growth of technology falls to

$$g_A^{SR} = g_A^{FE} - \Delta g_A^{SR} = \frac{n}{1-\theta} + \frac{n}{1-\theta} \left(\frac{I_t^{SR} - I_t^c}{I_t^c} \right) < \frac{n}{1-\theta} .$$

Figure 1 also illustrates the case of a severe recession. Starting from the steady state point *E*, the economy jumps to the point *SR* whose coordinates are (g_A^{SR}, g_K^{SR}). As the simulations below demonstrate, when the recession is over, the economy returns to *E*. But recession is costly in the sense that while the economy returns to growth rates $g_A = \frac{n}{1-\theta}$ and $g_K = n + \frac{n}{1-\theta}$, these rates apply to lower levels of knowledge and, therefore, output.[15] Thus, the cumulative nature of knowledge implies long-lasting effects of a recession. As compared to full capacity (or mild slowdown), lower knowledge levels lead to lower potential output, which lowers investment and capital, and so on.

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[15] For example, *X=100* and growing at 7% will reach 200 in 10 years, while *X=90* will only reach 180 after 10 years.

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4. SIMULATIONS: THE EFFECTS OF SLOWDOWNS

This section presents the results of simulations that study the short- and long-term consequences of slowdowns of various durations and intensities by comparing an economy that operates at full capacity and grows at steady-state rates to one that experiences a slowdown. The slowdown is modeled as a one-time adverse shock that reduces the economy's resource utilization rate and may last one or more periods. When the adverse effect expires, the economy returns to full capacity and resumes its growth at (nearly) steady state rates.[16] Consequently, the analysis will mainly be concerned with the level effects of the adverse shock.

The simulations use the parameter values given in Table 1. An effort has been made to approximate the values applicable to the U.S. economy. These values produce a steady-state output growth rate of 3%, capital grows also at 3%, while knowledge accumulates at a 2% rate. These parameters also produce a critical value of λ equal to approximately 0.98.[17]

The economy is assumed to operate at full capacity at steady state rates for the first 2 periods. In the third period a shock slows down the economy's resource utilization rate. The effects of the slowdown are followed for the next 97 years, i.e., until period 100. The loss in output is calculated as the present value over the next 97 years:

$$Loss = \Delta Y_t + \beta \Delta Y_{t+1} + \beta^2 \Delta Y_{t+2} + \cdots .$$

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[16] The slowdown does not affect labor growth. If the slowdown is sufficiently mild, it does not affect knowledge accumulation either. It has a small effect on investment, through the reduced output, but since investment is a small part of the existing capital stock, it will not affect that stock significantly. Thus, as the economy returns to full capacity, it will resume operating at steady state or very close to it.

[17] To simulate the steady-state growth (the benchmark economy), we calculate the initial levels of all variables consistent with the growth experience by normalizing $L_t = 1$ and simultaneously solving

$$\begin{cases} \dfrac{n}{1-\theta} - B\gamma a_L L \left(\dfrac{A}{1+\dfrac{n}{1-\theta}} \right)^{\theta-1} = 0 \\ n + \dfrac{n}{1-\theta} - \dfrac{sY\left(1+n+\dfrac{n}{1-\theta}\right)}{K} - \delta = 0 \\ \left[(1-a_I)sY + (1-\delta)\dfrac{K}{1+n+\dfrac{n}{1-\theta}} \right]^{\alpha} \left[A(1-a_L)L \right]^{(1-\alpha)} - Y = 0 \end{cases}$$

for A, K and Y.

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Table 1. Parameter Values

Parameter	Description	Value
α	Capital Share	0.3
n	Population Growth Rate	0.01
a_I	Fraction of Investment in Knowledge Production	0.2
a_L	Fraction of Labor in Knowledge Production	0.1
δ	Depreciation Rate	0.025
θ	Exponent in the Knowledge Equation	0.5
β_0	Initial Cost of Knowledge-Producing Capital	0.715
g_β	Rate of Increase in the Cost of Knowledge-Producing Capital	0.029
γ	Parameter on L_t in the Knowledge Equation	0.64
s	Savings Rate	0.05
B	Constant in the Knowledge Equation	1
λ	Capacity Utilization	$0 < \lambda \le 1$

A 5% discount rate is used and the output differences refer to the difference between potential (i.e., full resource utilization) and actual output. Two metrics are used to evaluate the output loss due to the simulated slowdowns. The first metric is the output loss as a percentage of the present value of the potential output over the next 97 years. The second metric is the output loss as a percentage of the pre-slowdown potential output, i.e., the period 2 output.

Table 2 provides a detailed picture of the output behavior for 100 periods, under 3 scenarios: full resource utilization ($\lambda = 1$), which provides the benchmark values in column 2; mild slowdown ($\lambda = 0.99$), which has no effects on knowledge production, and is described in columns 3 and 4; and a more severe slowdown ($\lambda = 0.96$), which actually produces a recession and gives the output levels and losses in columns 5 and 6. In both slowdown scenarios it is assumed that the adverse shock slows down the economy's resource utilization rates for 3 periods. Looking at column 4, it is apparent that the mild slowdown does not have any long-term effects. The reduction of the utilization rate by 1% for 3 periods reduces output by about 1% per period. The lost output is about 0.11% of the discounted present value of potential output or about 3.9% of the benchmark period 2 output, i.e., output losses are relatively small. Figure 2 provides five panels that describe the effects of the mild slowdown on the levels of output and knowledge, as well as the growth rates of output, capital and knowledge. The mild slowdown has a small effect on output (panel (*a*)), no effects on knowledge level and growth rate (panels (*b*) and (*e*)), a minor reduction in the growth rate of capital for 3 periods--from 3% to 2.95% (panel (*d*)), and a cycle-type effect on output growth (panel (*c*)). As expected, the 1% reduction in resource utilization slows the rate of growth of output from 3% to 2% in period 3. In period 4 and in period 5 the output growth returns to slightly less that 3% since there is no change in the resource utilization rate and the economy grows at a rate consistent with the growth of the available resources. During

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period 6, the output growth increases to 4% since 3% is the regular growth, plus 1% gained from the return of the economy to full resource utilization.

Table 2. Output Loss over Time

Period	Benchmark Model ($\lambda = 1$)	Adequate Knowledge Investment Model[a]		Inadequate Knowledge Investment Model[b]	
		Output	Difference from Benchmark[c]	Output	Difference from Benchmark[d]
1	9.37	9.37	0.00	9.37	0.00
2	9.65	9.65	0.00	9.65	0.00
3	9.94	9.84	-0.10	9.54	-0.41
4	10.24	10.14	-0.11	9.82	-0.43
5	10.55	10.44	-0.11	10.10	-0.45
6	10.87	10.87	0.00	10.84	-0.03
7	11.20	11.19	0.00	11.17	-0.03
8	11.54	11.53	0.00	11.51	-0.03
9	11.89	11.88	0.00	11.86	-0.03
10	12.24	12.24	0.00	12.21	-0.03
11	12.61	12.61	0.00	12.58	-0.03
12	12.99	12.99	0.00	12.96	-0.03
13	13.39	13.38	0.00	13.35	-0.03
14	13.79	13.79	0.00	13.76	-0.03
15	14.21	14.20	0.00	14.17	-0.03
16	14.64	14.63	0.00	14.60	-0.03
17	15.08	15.07	0.00	15.04	-0.03
18	15.53	15.53	0.00	15.50	-0.03
19	16.00	16.00	0.00	15.97	-0.03
20	16.48	16.48	0.00	16.45	-0.03
:	:	:	:	:	:
40	29.89	29.88	0.00	29.85	-0.04
:	:	:	:	:	:
60	54.22	54.22	0.00	54.17	-0.05
:	:	:	:	:	:
80	98.39	98.39	0.00	98.31	-0.08
:	:	:	:	:	:
100	178.58	178.58	0.00	178.47	-0.11

Notes: [a] $\lambda = 0.99$ in periods 3 through 5; $\lambda = 1$ otherwise. [b] $\lambda = 0.96$ in periods 3 through 5; $\lambda = 1$ otherwise. [c] The sum of the present discounted differences (with discount factor $\rho = 0.95$) for periods 3 through 100 is $\sum_{t=3}^{100} \rho^{(t-3)} \Delta Y_t = -0.37$, or a loss of 0.11% of the present discounted value of all potential output (periods 3 through 100), this is a 3.86% reduction relative to the period 2 output (the last year before the recession). [d] The sum of the present discounted differences is -1.84, or a loss of 0.53% of all potential output; this is a 19.04% reduction relative to the period 2 output.

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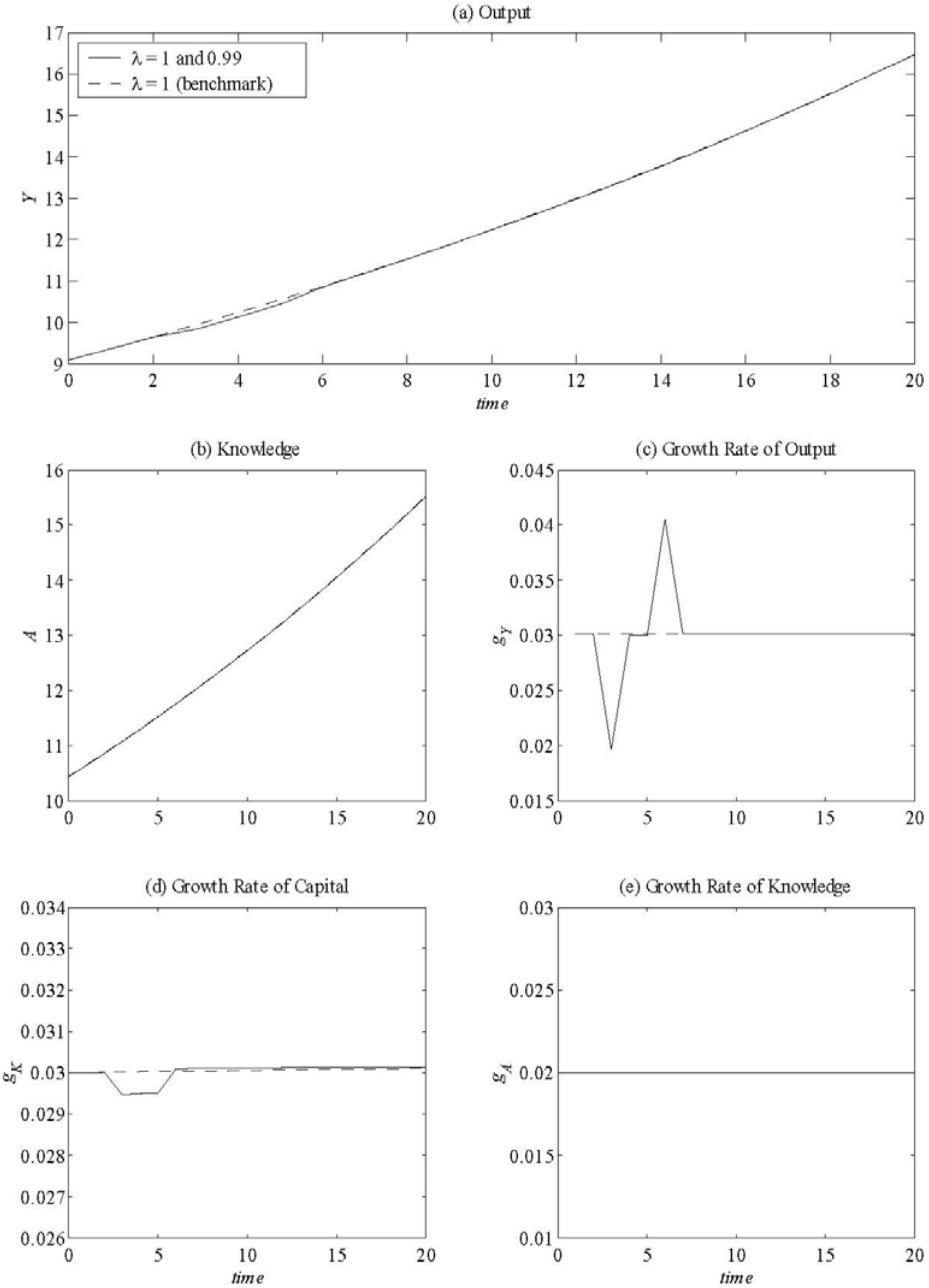

Figure 2. Mild Economic Slowdown with Adequate R&D Investment: $\lambda = 0.99$ in periods 3 through 5 (solid line), and $\lambda = 1$ (dashed line)

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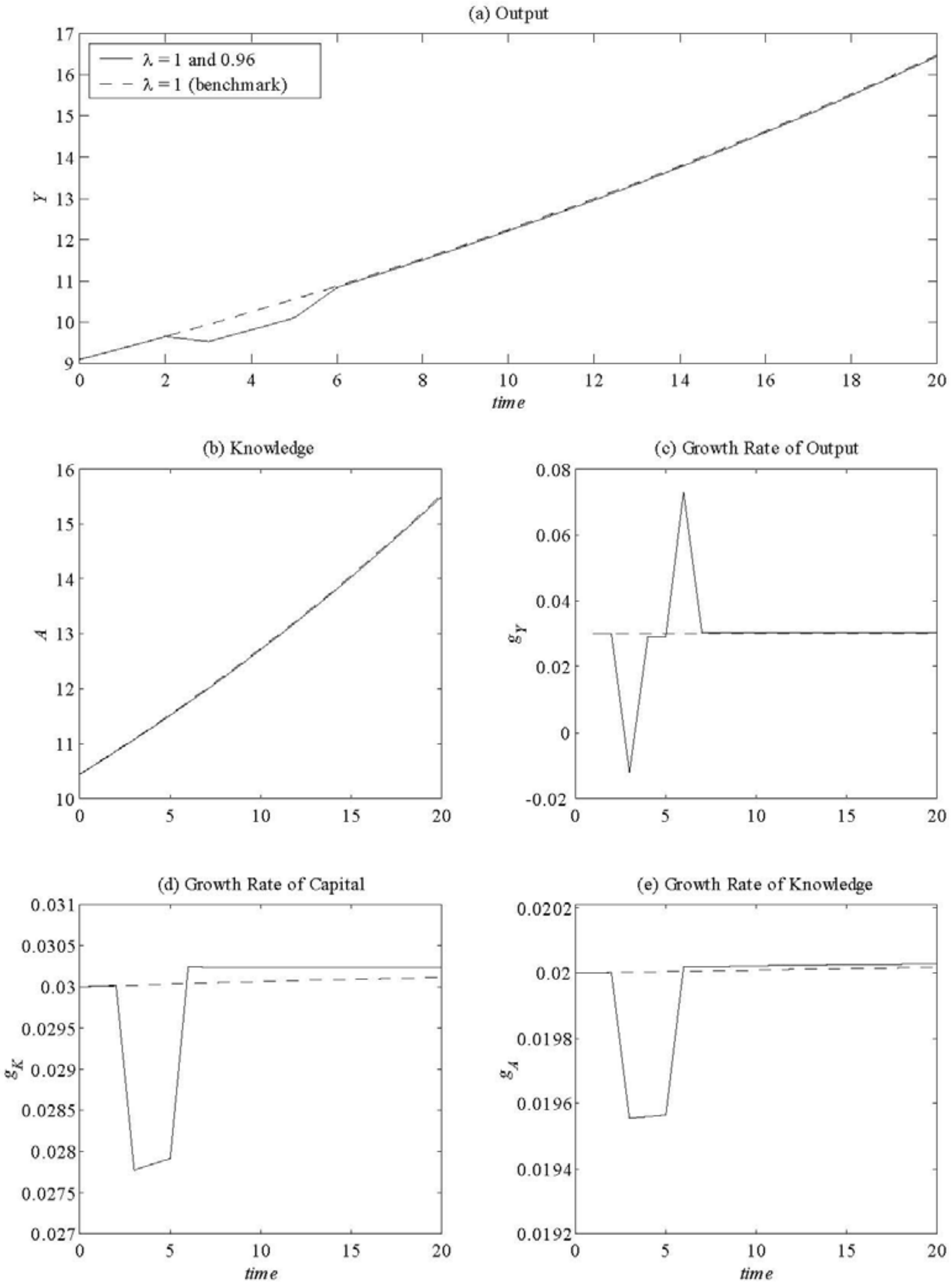

Figure 3. Severe Economic Slowdown with Inadequate R&D Investment: $\lambda = 0.96$ in periods 3 through 5 (solid line), and $\lambda = 1$ (dashed line)

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Columns 5 and 6 in Table 2, as well as panel (*a*) in Figure 3, describe the output behavior when a 3-period shock reduces resource utilization to 96% of capacity. Since the utilization rate is below the critical rate of 98%, the slowdown will adversely affect knowledge accumulation. This adverse effect is responsible for the long-term effects of the slowdown. The resource utilization reduction reduces output by about 4%, as compared with the full utilization output, and produces a 1% recession during period 3 (output falls from 9.65 in period 2 to 9.54 in period 3). The magnitude of the recession is rather typical of the U.S. after-war recessions. Now output losses extend beyond the end of the resource utilization slowdown. Although these losses look small, the output never quite catches up with the full utilization output. In terms of the metrics, the loss is 0.53% of the present value of the discounted output or 19% of the pre-slowdown full capacity output. Compared with the previous case, here a 4 times larger utilization rate reduction resulted in a 5 times larger loss of output. Figure 3 provides more information about the 96% scenario. Panel (*c*) plots output growth and shows the recession in period 3 followed with a return to slightly less (due to the slight reduction in capital and knowledge levels as compared to the benchmark) that 3% growth in periods 4 and 5, and a 7% growth in period 6, as the utilization rate recovery to 100% adds 4 percentage points to the regular 3% growth. Panels (*d*) and (*e*) show the temporary slowdown in capital growth (from 3% to 2.8%) and knowledge accumulation (from 2% to 1.96%).

Figure 4 presents an extreme case designed to roughly represent the 1930s depression. In this scenario the resource utilization rate falls to 70% for 3 periods. In this case the growth rates of capital (panel (*d*)) and knowledge accumulation (panel (*e*)) show the large adverse effects of the severe slowdown. Capital growth falls from 3% to about 1.4%, while knowledge growth falls from 2% to about 1.4%. Output experiences a deep reduction of the order of 27% in period 3. Panels (*a*) and (*b*) demonstrate that output and knowledge levels remain permanently below their benchmark forever.[18] The loss of output in this case is about 4.55% of the present value of the (total) potential output or about 162% of the pre-slowdown output. The costs of an economic failure like the Great Depression are staggering.

Table 3 presents the values of the two loss metrics for a series of slowdown depths, ranging from 99% to 70%, and lengths, ranging from 1 to 5 periods. As implied above, costs are relatively small for mild slowdowns, but as the utilization rate falls below its critical value of 98%, output losses accelerate and become quite large. It should be noted that the results presented in this paper are conservative estimates of the true costs of economic slowdowns. If only the critical level of investment (I_t^c) was devoted to technology production each period (i.e., all excess vintage investment is redirected to the goods sector), then even a small reduction in resource utilization would result in adverse effects on knowledge production. In that case the long-run costs of slowdowns would be higher than what is reported in this paper.

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[18] In other words, we still feel the effects of the Great Depression!

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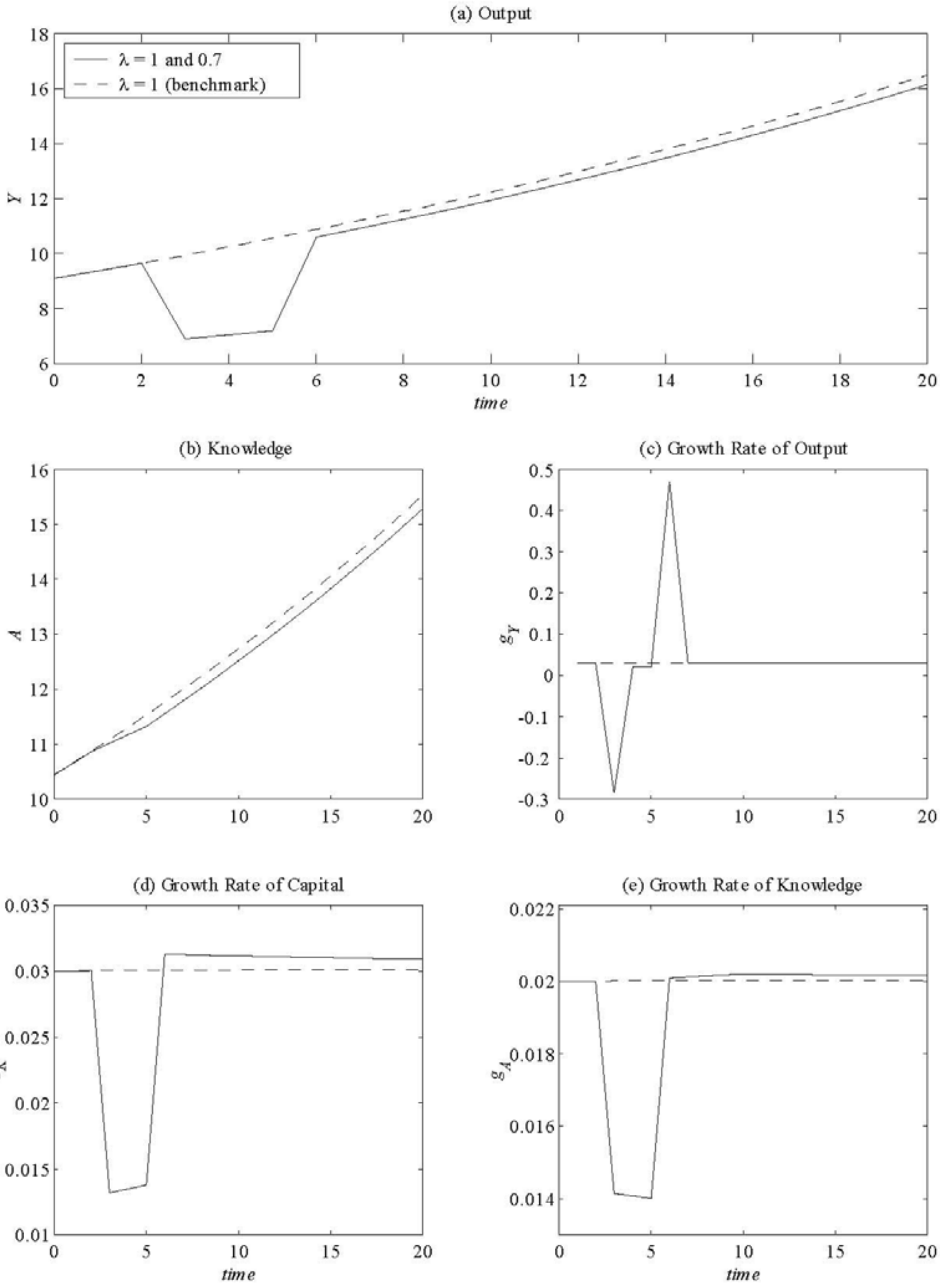

Figure 4. Depression with Inadequate R&D Investment:
$\lambda = 0.7$ in periods 3 through 5 (solid line), and $\lambda = 1$ (dashed line)

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Table 3. Output Loss due to Slowdowns of Various Lengths and Severities

Depth of Slowdown	Duration of Slowdown				
	1 year	2 years	3 years	4 years	5 years
$\lambda = 0.99$	-0.04%[a] -1.31%[b]	-0.07% -2.60%	-0.11% -3.86%	-0.14% -5.09%	-0.18% -6.29%
$\lambda = 0.98$	-0.08% -2.71%	-0.15% -5.33%	-0.22% -7.86%	-0.29% -10.32%	-0.36% -12.73%
$\lambda = 0.97$	-0.13% -4.60%	-0.25% -9.08%	-0.38% -13.45%	-0.50% -17.71%	-0.61% -21.85%
$\lambda = 0.96$	-0.18% -6.49%	-0.36% -12.83%	-0.53% -19.04%	-0.70% -25.10%	-0.87% -31.02%
$\lambda = 0.95$	-0.23% -8.38%	-0.46% -16.58%	-0.69% -24.62%	-0.91% -32.48%	-1.13% -40.18%
$\lambda = 0.90$	-0.50% -17.80%	-0.99% -35.27%	-1.47% -52.41%	-1.94% -69.23%	-2.40% -85.43%
$\lambda = 0.80$	-1.02% -36.57%	-2.03% -72.42%	-3.01% -107.54%	-3.97% -141.96%	-4.93% -176.22%
$\lambda = 0.70$	-1.55% -55.25%	-3.06% -109.25%	-4.55% -162.55%	-6.06% -216.49%	-7.58% -270.65%

Notes: [a] The first number in each cell represents the present discounted value of lost output relative to all potential output. [b] The second number in each cell represents the present discounted value of lost output relative to the period 2 (i.e., pre-recession) output.

The simulation results present a number of challenges to policy-makers. First, policy-makers should keep a watchful eye and use all tools available to combat severe economic slowdowns. Second, they should make sure that the knowledge accumulation process is not affected by a slowdown. The critical value of λ is inversely affected by the savings rate and the shares of capital and labor devoted to knowledge accumulation. Our analysis suggests that, to avoid severe recessions, the government should strive to reduce the critical value of λ. It follows from our results that reasonable policy tools would include raising the savings rate (s) and increasing the fractions of investment (a_I) and labor (a_L) in knowledge production. Anecdotal evidence suggests that higher education funding, as well as corporate R&D funding, seems to suffer disproportionately during economic slowdowns. Apparently, such policies exaggerate aggregate output losses in the long run and should be carefully evaluated.

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5. CONCLUSIONS

This paper contributes to the body of research that explores the link between economic slowdowns and long-term economic performance. Our endogenous growth model allowed us to calculate short-term and long-term output costs of economic slowdowns. As a point of departure-and consonant with Krusell, Ohanian, Rios-Rull and Violante (2000), among others-we acknowledged that skilled labor is complementary to capital, while unskilled labor is substitutable for capital. In our model, severe slowdowns can have detrimental effects to the extent that they limit investment in knowledge accumulation and, as a result, hinder technological progress in the long run. Technological stagnation translates into loss of output relative to full employment. Even if the recession is short-lived, the costs of slow technological progress are felt for years to come: it could take decades for the actual output to catch up with the potential output level path.

Our model is in line with a large body of empirical evidence on both business cycles and growth. We capture the stylized fact that innovation is procyclical. Also, if one believes that a reduction in resource utilization is normally a direct result of a lower aggregate demand, our simulation results are also compatible with the evidence on the lingering effects of demand shocks (e.g., Bernanke and Mihov (1998), Galí (1999)).

Our results indicate that:

- When slowdowns are mild, the reduction in investment is not enough to affect knowledge production. Thus there are no long-run effects on potential output.
- When recessions are deep, investment reductions hinder knowledge production and the slowdown in potential output is long-lived.

These results are consistent with several recent attempts to link short-lived fluctuations in the key economic variables and long-run performance. For example, Comin and Gertler (2006) find that there is a high positive correlation among R&D, technological change and intensity of resource utilization. Similar to our results, Comin and Gertler conclude that short-term movements in productivity can do a fairly good job at explaining persistence of economic fluctuations.

Thus, active countercyclical policies that prevent economic slowdowns, as well as countercyclical policies that prevent knowledge accumulation slowdowns, are advocated. These policies include lower interest rates to stimulate investment during slowdowns; ensuring that knowledge production budgets are not cut disproportionately during slowdowns; ensuring that training of new knowledge workers does not slow down markedly during recessions; and, stimulating savings, domestic or foreign, to finance investment.

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