IMES DISCUSSION PAPER SERIES

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Discussion Paper No. 98-E-16

INSTITUTE FOR MONETARY AND ECONOMIC STUDIES

BANK OF JAPAN

C.P.O BOX 203 TOKYO
100-8630 JAPAN

IMES Discussion Paper Series 98-E-16

December 1998

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Abstract

Economic growth in the last 125 years has increased standards of living in the advanced countries by somewhere between 10- and 90-fold. Modern analysis of economic growth over the last forty years suggests that these enormous changes are associated with the creation and diffusion of new ideas. This paper provides an overview of knowledge-based growth and its global nature. A simple model is presented and calibrated to illustrate precisely how the creation of knowledge by a relatively small set of people can lead to large gains in welfare.

Key words: Human Capital, Increasing Returns to Scale, Externalities, R&D

JEL classification: O40, E10

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This paper was prepared for the Eighth International Conference, “Monetary Policy in a world of Knowledge-Based Economy, Quality Change and Uncertain Measurement,“ held by the Institute for Monetary and Economic Studies, Bank of Japan, on June 18-19, 1998.

1 Introduction

At least since Solow (1956) and Swan (1956), economists have understood that growth in multifactor productivity is essential to sustained growth in per capita income. The question asked in modern growth theory is basically, "Where does this multifactor productivity growth come from?" The growth literature contains many answers to this question, ranging from learning-by-doing (Arrow 1962a) to human capital accumulation (Lucas 1988) to externalities to public capital. An additional possibility, however, is that productivity growth results from the discovery of new ideas. This is the possibility that is examined in detail in this paper.

The recent examination of idea-based growth models in the growth literature is influenced tremendously by the work of Romer (1986, 1990). Romer himself is careful to give credit to a large body of earlier work that includes Arrow (1962b), Phelps (1966), Shell (1966), Nordhaus (1969), and others. And much important work has extended Romer's contributions, including Grossman and Helpman (1991) and Aghion and Howitt (1992). More broadly, work on idea-based economic growth encompasses a wide range of research, far too broad to review here.[1] Suffice it to say that much of this work has been carried out by participants of this conference.

This paper presents an overview of knowledge-based growth, both at a conceptual level and through the presentation and calibration of a simple growth model. Section 2 reviews the important insights that arise when we think of growth as resulting from the creation of new ideas. Issues such as increasing returns to scale, knowledge spillovers and externalities, imperfect competition, and property rights are placed at the center

[1] A more detailed review can be found in Jones (1998), among other places.

of our attention.

Section 3 outlines a simple model of knowledge-based growth to examine these issues more formally. The increasing returns to scale associated with the nonrivalry (or infinite expansibility) of ideas is shown to be an essential feature of idea-based growth. We see not only that growth in per capita income results from growth in the stock of ideas, but also that the growth in the stock of ideas results from growth in the world's research efforts. The global nature of idea-based growth is important from the demand side as well. The fact that entrepreneurs like Bill Gates can sell their creations in a large world market raises the return to research and stimulates research activity throughout the world.

Section 4 provides a simple quantitative look at the idea-based growth model. We see not only that research effort in the G-5 countries (France, Germany, Japan, the United Kingdom, and the United States) has been growing in the last thirty-five years, but also that research intensity — the fraction of the G-5 population engaged in research — has also been growing. Japan is an important component of this growth, making up about 15 percent of G-5 research activity in 1965 but more than 25 percent in 1990.

A simple experiment at the end of the paper emphasizes the importance of research effort and the potential magnitude of the gains, both social and private, from research activity. While measurement problems make precise interpretation difficult, the exercise suggests that a modest shift of labor into research in Japan that costs about 1/30th of a percent of Japanese GDP could raise G-5 GDP by about 1 percent in the long run. This number is perhaps too large to be believed, but it is suggestive that large returns to research can be obtained if we can simply figure out the best way to capture them.

2 Knowledge-Based Growth

What is an idea? In idea-based growth models, an idea is typically defined as the "instructions" for transforming basic raw materials in an economy such as labor or capital into either a new kind of good, a better version of an existing good, or a larger quantity of existing goods. The nature of these instructions is often not important. What matters is that the economy can now use a given collection of raw materials to produce a higher quantity of (quality-adjusted) goods and greater utility.

2.1 The Economics of Ideas

My sense is that the most important insight of the idea-based growth literature can be summarized very concisely by the following relationships:

$$Ideas \longrightarrow Nonrivalrous \longrightarrow IRS \longrightarrow Imperfect\ Competition. \tag{1}$$

Each of these links will be examined in turn.

The first link indicates that a fundamental property of ideas is that they are nonrivalrous. Recall that a good is rivalrous if one person's use of the good diminishes or eliminates the potential for someone else to use the good simultaneously. Most goods that we think of are rivalrous: an airplane seat on a particular flight at a particular time, a unit of computer processing power, or the live performance of Beethoven's Fifth Symphony by the Tokyo Philharmonic Orchestra.

In contrast, ideas are not like most other economic goods. They are nonrivalrous in that one person's use of an idea does not in any way diminish the usefulness of the idea to someone else simultaneously. Examples include the fundamental theorem of calculus, the just-in-time inventory method, and the sequence of musical notes that make up the Fifth Symphony. While your sitting in the front row, center seat for a performance of the symphony means that I cannot be sitting there, there is no technological limitation that precludes several different orchestras from performing the symphony simultaneously. The instructions for performing the symphony are nonrivalrous. Drawing on a letter written by Thomas Jefferson in 1813 brought to his attention by Paul David, Quah (1996) uses the term "infinite expansibility" in place of nonrivalry: once an idea is created, it can be expanded infinitely to any scale of production.

The second link in equation (1) states that the nonrivalrous nature of ideas implies that production of goods in the economy is characterized by increasing returns to scale. Let Y be the quantity of output (or GDP) produced by an economy, let A represent the level of knowledge in the economy, and let X represent a vector of rivalrous inputs that are used to produce output, such as capital and labor. We might relate inputs and outputs using a production function such as

$$Y = F(A, X). \tag{2}$$

The standard replication argument says that in order to double the output produced in this fashion, we simply duplicate every rivalrous input. We build an identical factory and hire an identical number of workers, and we obtain twice the output. This argument is used to justify an assumption of constant returns to scale in X. That is, for any number $\lambda > 1$, $F(A, \lambda X) = \lambda Y$.

But what happens if we also double the stock of knowledge in the economy? Provided the marginal product of knowledge is always positive, it is easy to see that $F(\lambda A, \lambda X) > \lambda Y$. If we double both knowledge and all rivalrous inputs, we will more than double output. Production is characterized by increasing returns to scale. Notice that the nonrivalry or infinite expansibility of ideas is essential to this argument. One can double output simply by building a new factory and duplicating the number of workers because the instructions for producing the output do not need to be reproduced or invented again. The instructions can be used at any scale of production once they have been created.

For example, consider the production of the compact disc player by Sony. Producing the very first CD player required an enormous research investment. One might think of the invention as the discovery of the precise instructions for assembling a CD player. After the invention, subsequent units could be produced much more cheaply because the instructions did not need to be reinvented. This is the hallmark of increasing returns to scale.

The final link in equation (1) connects increasing returns to scale and imperfect competition. It is well known that in the presence of increasing returns to scale, all factors cannot be paid their marginal products; firms would make negative profits under these circumstances. From a modeling standpoint, there are two ways to handle increasing returns. We can assume the increasing returns are entirely external and maintain perfect competition. This is the case in the Arrow (1962) learning-by-doing story or in Shell (1966), where ideas are thought of not only as nonrivalrous, but also as nonexcludable; i.e. as pure public goods. However, in part because of the patent system and in part because of trade secrets, inventors seem to be able to capture some part of the value of a new idea. For either of these reasons, an inventor may have, at least temporarily, some market power. This suggests the second way of handling increasing returns: imperfect competition.

The importance of imperfect competition in the economics of ideas has been long understood. If Sony is required to sell CD players at marginal cost, there will be no way to recoup the large fixed cost that is incurred in order to invent the CD player in the first place. Some ex post market power allows Sony to earn quasi-rents that make the invention worthwhile.

2.2 Some Policy Implications

From the previous section, it is clear that the economics of ideas is very different from the economics of wheat or other traditional, rivalrous goods. Ideas are different in that they are nonrivalrous, which leads to increasing returns and imperfect competition. And ideas are different in that they are only partially excludable. Issues related to property rights and spillovers naturally arise. The individual or organization that creates a new idea may not be fully compensated on the margin for the social value of the idea. This may occur both because of the direct benefits of the idea to consumers, but also because future researchers benefit from the knowledge created by current researchers (the "standing on shoulders" effect alluded to by Isaac Newton).

A large body of research reviewed by Griliches (1992) and Nadiri (1993), among others, generally finds that the social rates of return to research are appreciably greater than the private rate of return. Jones and Williams (1998) argue that the difference between these rates of return indicates that firms may underinvest in research by at least a factor of two, with much larger factors possible.

This raises the very interesting but very difficult question of what is to be done. The patent system is one policy response that grants monopoly power to an inventor for a limited period of time in order to allow the inventor to capture some of the social value that is created. But this system is far from perfect. Patents are in effect for only a short period of time, they require costly adjudication by the legal system for their scope to be defined, they can be "invented around," and they slow the adoption and diffusion of the idea because the price of the good is kept above marginal cost. Kremer (1996) proposes a novel mechanism through which the government purchases some patents from the private sector and then places them in the public domain. The purchase price could be set to reflect the social value of the innovation, if that can be determined. An example that Paul Romer has provided is the polymerase chain reaction (PCR). Biotech researchers in private as well as university and government settings use the PCR technique extensively, but at a price which is much higher than the underlying marginal cost. It might make sense for both the U.S. and Japanese governments to purchase a license covering all current and future domestic use of the idea and then allow researchers to use the idea without paying an additional fee.

More generally, it is important to recognize that the patent system and the way in which a government attempts to line up private and social returns to research are essentially ideas themselves. And there is no reason to think that the best ideas have already been discovered and implemented.

3 A Simple Model

This section presents a simple model of idea-based growth to illustrate some of the themes highlighted above as well as some of the important results developed in the idea-based growth literature.[2] It is helpful to view the model as a toy experiment, like that which a chemist might set up in a laboratory. We will build a miniature economy populated with simple economic agents and endowed with simple production possibilities. At the appropriate time, we will flip the "ON" switch and then watch the toy economy to see how it behaves. Key parameters in the model will be picked so as to match some elements of the data for Japan, the United States, and other advanced economies, so that when we conduct experiments with the toy model, they may have some relevance for the way economic growth works in the world today.

3.1 The Economic Environment

Suppose our toy model consists of a number of separate "countries" or economies, all of which are basically similar. Each economy produces a consumption/capital good that is identical to that produced in other countries. Each economy also produces ideas which are shared across economies. This sharing of ideas is the only way the different economies interact.

The first piece of the economic environment in this model is a production technology for an output/consumption good. We assume that some quantity Y of this good is produced by combining capital K and labor L_Y with the available stock of

[2] The model is largely taken from Jones (1995, 1998).

knowledge A:

$$Y = A^{\sigma} K^{\alpha} L_Y^{1-\alpha}, \tag{3}$$

where $\sigma > 0$ and $0 < \alpha < 1$ are parameters of the production function. This kind of production function can be motivated in a number of different ways. In particular, it is worth noting that it emerges from a Romer (1990)-style setup in which output is produced by combining labor and an expanding range of intermediate capital goods, where A indicates the range of goods for which designs have been invented. Notice that the production function exhibits constant returns to scale to the rivalrous inputs K and L_Y, and therefore increasing returns to scale to the inputs and technology together. As discussed above, this critical feature of the model results from the fact that the nonrivalrous stock of knowledge A can be used at any scale of production without having to be reproduced.

The next part of the economic environment describes how the various inputs are themselves "produced." For capital and labor, we follow the standard setup of Solow (1956). Capital is simply the accumulation of foregone consumption:

$$\dot{K} = s_K Y - dK, \quad K_0 > 0, \tag{4}$$

where $0 < s_K < 1$ is the saving/investment rate in the economy and $d > 0$ is a parameter measuring the rate of depreciation of capital.

One can easily allow utility-maximizing agents to choose a time path for the saving rate s_K. Alternatively, one can follow Solow (1956) and take the allocative decisions to be given exogenously. This is the method pursued here. We will assume that s_K (as well as other allocative decisions) are simply exogenous parameters of the model.

Looking ahead, it also greatly simplifies the analysis to assume that the fraction of the population that works as researchers to produce new ideas is exogenously given. In this simple model, we will not undertake the very important analysis of the economic incentives that lead individuals to produce ideas. We only pause here to note that such analysis is one of the main contributions of recent work on economic growth.

Let L be the total quantity of labor in a particular economy, and assume that it grows exogenously over time at rate $n > 0$:

$$L = L_0 e^{nt}, \quad L_0 > 0. \tag{5}$$

Every economy in this toy world will have the same rate of population growth.

In addition to producing output, labor in each economy can also be used to produce new ideas or new knowledge. However, unlike the production of goods, the production of ideas occurs at the "world" level. This way of modeling ideas is motivated by the simple but important fact that ideas used in any particular economy are invented throughout the world. Singapore does not grow simply because of ideas invented by Singaporeans. Rather, Singapore benefits from ideas created in Japan, the United States, etc. Once this consideration is introduced, issues of technology transfer and the diffusion of ideas become extremely important. In the simple model analyzed here, we finesse this issue by assuming instantaneous diffusion of knowledge. As soon as a new idea is invented, it becomes useful in every economy in the world. This is clearly a weakness of the model, but there are already enough things going on that it is a convenient simplification to make at the moment.

Let A represent the total stock of ideas discovered in the world. Then, $\dot{A}$ represents the number of new ideas invented at a point in time. We assume that new ideas are produced according to

$$\dot{A} = \bar{\delta} R, \tag{6}$$

where R is the total number of researchers throughout the world looking for new ideas and $\bar{\delta}$ measures the number of new ideas that can be produced by a single unit of research effort. We assume that the economy begins at time 0 with some stock of ideas $A_0 > 0$ already given.

While individual researchers, who are small relative to the aggregate, might take $\bar{\delta}$ as given, one can imagine that the productivity of research might depend on characteristics of the economy. For example, the productivity of research may depend on the number of ideas discovered in the past, i.e. $\bar{\delta} = \delta A^{\phi}$. A value of $\phi > 0$ would indicate that ideas discovered in the past raise the productivity of current research effort. Such positive "knowledge spillovers" probably characterize at least some ideas, such as the discovery of calculus or the semiconductor. On the other hand, it is also possible that ϕ is negative. For instance, suppose that the best ideas are discovered first and then it is harder and harder to find a truly original and useful idea. This case might correspond to what has been called "fishing out": in a fixed pool of fish, as more fish are caught it becomes harder and harder to catch a new fish. Finally, one could also imagine that the knowledge spillovers and fishing out concerns offset, in which case one might want to consider $\phi = 0$ so that the productivity of research is simply some constant $\delta > 0$.

Another consideration in the production of ideas is the possibility of duplicative research. If we double the number of researchers looking for new ideas at a point in time, will we in expectation double the number of new ideas that get discovered?

Perhaps not. This congestion effect can be included in the model by supposing that it is R^λ that enters the production function, where $0 < \lambda \leq 1$ potentially captures the duplication effect. Therefore, we replace equation (6) with

$$\dot{A} = \delta R^\lambda A^\phi. \tag{7}$$

We use the notation L_A to represent a particular economy's stock of researchers, so that R is simply the sum of L_A across countries. The resource constraint for any particular economy is

$$L_Y + L_A = L. \tag{8}$$

Finally, we assume that a constant fraction of the labor force works in research:

$$L_A = s_A L \tag{9}$$

and therefore $L_Y = (1 - s_A)L$.

3.2 The Balanced Growth Path

Given this setup, one can show that the economy will converge over time to a balanced growth path, i.e. a situation in which all variables are growing at constant exponential rates. This is the situation that we will focus on.

Along a balanced growth path, it is easy to show that the following relationships hold:

$$g_y = g_k = \frac{\sigma}{1-\alpha} g_A, \tag{10}$$

where g_x denotes the exponential growth rate of some placeholder variable x along a balanced growth path, and lower case letters correspond to the "per capita" version of the upper case letters. For example, $y \equiv Y/L$ denotes output per capita. The first equality in this equation comes from the capital accumulation equation ($\dot{K}/K$ is constant only if Y/K is constant). The second equality comes from log-differentiating the production function.

Equation (10) illustrates the Solow (1956) result that long-run growth in per capita income results from growth in productivity. Here, however, productivity is related to the stock of ideas, and per capita income grows in the long-run only if the stock of ideas that can be used in the economy grows. Therefore, we have

> *Result 1.* Long-run growth in per capita income occurs because the stock of ideas (or knowledge) in the economy grows in the long-run.

What, then, determines the growth rate of ideas along a balanced growth path? To answer this question, rewrite equation (7) as

$$\frac{\dot{A}}{A} = \delta \frac{R^{\lambda}}{A^{1-\phi}}. \tag{11}$$

By definition, $\dot{A}/A$ will be constant along a balanced growth path. But this will be the case only if the numerator and denominator on the right-hand-side of equation (11) grow at the same rate. Therefore,

$$g_A = \frac{\lambda}{1-\phi} g_R. \tag{12}$$

That is, the growth rate of the stock of ideas is proportional to the growth rate of the number of researchers.

Combining this last equation with (10), we find:

$$g_y = \gamma g_R, \tag{13}$$

where $\gamma \equiv \frac{\sigma}{1-\alpha}\frac{\lambda}{1-\phi}$. This gives us our second main result:

> *Result 2.* Long-run growth in the stock of ideas and therefore in per capita income is proportional to the long-run growth rate of the world's stock of researchers.

The intuition for this result is straightforward. Researchers produce ideas, and growth in the stock of ideas requires growth in the number of researchers. A simple example illustrates the point. Consider the case in which $\lambda = 1$ and $\phi = 0$. Therefore, the productivity of research is constant. Suppose that each researcher produces one new idea every period. If the number of researchers is constant, then the stock of ideas will rise over time, but at a declining rate: for example, if there are 10 new ideas each period and the economy begins with a stock of 100 ideas, then the growth rate will be very high initially, but will decline as the stock of ideas accumulates. If each researcher produces one new idea, then clearly sustained growth in the stock of ideas will require sustained growth in the effective number of researchers.

One can also solve this model for the (growing) level of per capita income along a balanced growth path. The first part of this argument is exactly that in Solow (1956). From the capital accumulation equation, equation (4), one can easily see that the capital-output ratio along a balanced growth path is equal to $s_K/(n + g_y + d)$. Substituting this into the production function, one finds

$$y^*(t) = \left(\frac{s_K}{n + g_y + d}\right)^{\frac{\alpha}{1-\alpha}} A^*(t)^{\frac{\sigma}{1-\alpha}}, \tag{14}$$

where the time index t is explicitly included to indicate which variables are changing over time, and the superscript $*$ indicates a value along a balanced growth path.

Notice that log-differentiating this relationship gives (part of) equation (10): output per worker along the balanced growth path is proportional to the stock of ideas raised to some power.

The value of $A^*(t)$ can be found by rewriting equation (11). Notice that this equation implies that

$$A^*(t) = \left(\frac{\delta}{g_A}\right)^{\frac{1}{1-\phi}} R(t)^{\frac{\lambda}{1-\phi}}. \tag{15}$$

That is, the stock of ideas along a balanced growth path is proportional to the number of researchers (raised to some power).

Combining these last two equations, we have the solution for the level of output per capita along a balanced growth path:

$$y^*(t) = \left(\frac{s_K}{n + g_y + d}\right)^{\frac{\alpha}{1-\alpha}} \left(\frac{\delta}{g_A}\right)^{\frac{\gamma}{\lambda}} R(t)^{\gamma}, \tag{16}$$

where $\gamma \equiv \frac{\sigma}{1-\alpha}\frac{\lambda}{1-\phi}$. This gives us our third main result:

> *Result 3.* The level of output per capita along a balanced growth path is proportional to the world's effective number of researchers, raised to the power γ.

As above, the number of researchers determines the number of ideas, and the number of ideas determines the level of per capita income.

4 Relating the Model to Data

In this section, we consider how the simple toy model outlined above can help us to interpret various facts observed about the advanced countries of the world.

4.1 The World's Effective Research Stock

Based on the results given so far, a critical determinant of economic growth is the world's effective research stock. Economies grow because of growth in the stock of ideas, and this stock grows because of growth in R. The question, then, is why does R grow over time?

There are at least three sources of growth in R. First, the number of (world) researchers can grow simply because the population of the world is growing. Second, the number of researchers can grow because of a rising research intensity — a rise in the fraction of the population that searches for new ideas. Finally, the effective number of researchers may grow if the quality of the researchers grows, for example because of human capital accumulation.

As a historical matter, all three of these sources appear to be relevant. The first two are quite easy to document. Figure 1 shows the rise in population and researchers for the G-5 countries of France, (West) Germany, Japan, the United Kingdom, and the United States. For present purposes, these aggregates will represent "world" research effort. This is likely to be a conservative judgment since one suspects that an increasing number of countries are now capable of conducting frontier research.

One sees in the figure two things. First, there is a basic rise in the population of the G-5 countries, at an average rate of 0.8 percent per year during the period 1965 to 1991. This means that more people are available to conduct research, which should serve as a source of research and idea growth. Second, there has been an even larger rise in the number of researchers in the G-5 countries. The series plotted is the number of scientists and engineers engaged in R&D, according to the U.S. National Science

Foundation.[3] The number of researchers has grown at an average annual rate of 3.4 percent over the 1965 to 1991 period, increasing by nearly a factor of two and a half.

The implication of these two facts is a rise in research intensity in the G-5 countries, defined as the fraction of the population that works as researchers. This implication is illustrated in Figure 2. Research intensity rises from slightly less than two-tenths of one percent of the population in 1965 to slightly less than four-tenths of one percent in 1991, roughly doubling.

This observation is quite striking and is consistent with the popular notion that the importance of "knowledge" and ideas is rising. It is interesting to speculate on the causes of the rise in research intensity. Jones (1997) proposes that the increased openness and development of the world economy is one likely source: the scale of the market over which an innovator can spread the fixed cost of research is much larger today than thirty years ago, and is likely to be even larger in the future. Transportation and communication costs are lower, barriers to international trade have fallen, and the fraction of the world's population that has an income greater than the poverty line has risen. These changes raise the return to research and could explain the rise in research intensity.

Growth in the world's stock of researchers, R, can then easily explain the growth in the world's stock of ideas, which underlies growth in per capita income.

[3]There are enormous difficulties in measurement in this respect. Who really counts as a researcher? And are researchers counted in the same way across countries? These issues are ignored here.

4.2 The Magnitude of Long-Run Level Effects

In the long-run, a country's growth rate is determined by the rate of growth of the world's stock of ideas. Therefore, in this model, all countries share the same long-run growth rate. This is not to say that differences in policies are not important, however. Differences in policies translate into differences in the level of income across countries. As one simple example of this, the United States and Malawi grew at nearly identical rates over the period 1960 to 1990. The enormous differences in policies and institutions between these two countries is reflected in the fact that per capita income in Malawi is only about 3 percent of that in the United States.

These differences are reflected explicitly in equation (16), reproduced here:

$$y^*(t) = \left(\frac{s_K}{n + g_y + d}\right)^{\frac{\alpha}{1-\alpha}} \left(\frac{\delta}{g_A}\right)^{\frac{\gamma}{\lambda}} R(t)^{\gamma}. \tag{17}$$

While income levels are proportional to the world's effective stock of researchers, the factor of proportionality depends on country-specific variables. In this simple model, the main country-specific variable is the investment rate in physical capital, but in more general models, investment in human capital and barriers to technology transfer will presumably matter as well.

Although the model predicts that all countries will share the same long-run growth rate, this does not mean that countries cannot grow at different rates for long periods of time, such as decades. In the model, such growth differences are understood as transition dynamics. Consider a country that begins on a balanced growth path with a low investment rate (or with low human capital investment and high barriers to technology transfer). According to the equation above, the country will therefore have a low income level. If this country undergoes a reform which raises its investment rate, its long-run income level will rise. In the medium run, the country's growth rate will be faster than the rate implied by the world stock of ideas as the country transits to its higher income level.

This is simply the result of simple transition dynamics like that in the standard Solow (1956) model: countries grow more rapidly the further they are below their steady state balanced growth path. As they approach the balanced growth path, the growth rate declines to the long-run growth rate, determined as above by the growth rate of world research effort.

One might naturally inquire as to the magnitude of the long-run level effects. For example, if a country raises its investment rate, by how much does its level of income along the balanced growth path rise in the long run? Or, more pertinent to the R&D spirit of the model, if a country raises its own research intensity, what is the effect on the long-run level of income?

The first of these questions is straightforward to answer, so we begin by considering the investment rate. According to equation (17), the elasticity of per capita income along a balanced growth path with respect to the investment rate is $\alpha/(1-\alpha)$. With perfect competition, α corresponds to the capital share of income (and even in many models with imperfect competition it can be computed as one minus labor's share of income), so it is conventional to pick a value of $\alpha = 1/3$. This means that the elasticity is $1/2$, so that it is the square root of the investment rate that affects the level of income in equation (17): doubling the investment rate will, in the long-run, result in the level of income being higher by a factor of $\sqrt{2}$, or about 40 percent higher than what it would otherwise have been.

To conduct the same exercise for a country's own research effort is slightly more complicated because it is world research effort rather than an individual country's effort that matters in the long run. For this exercise, we will be more specific and focus on an increase in Japanese research intensity.

If research intensity is measured simply as the number of scientists and engineers engaged in R&D (as above), then

$$R = L_A + \bar{L}_A, \tag{18}$$

where L_A will denote the number of researchers in Japan and $\bar{L}_A$ will denote the number of researchers in the rest of the world. (This "overbar" notation will continue to be used to denote the rest of the world.) With some algebraic manipulation, this equation can be rewritten as

$$R = (s_A \ell + \bar{s}_A \bar{\ell}) L^w, \tag{19}$$

where s_A denotes the fraction of a country's population that works in research and ℓ denotes the fraction of the G-5 population that lives in a particular country. L^w stands for the G-5 population as a whole. Therefore, this equation simply says that G-5 research intensity R/L^w is a weighted average of Japan's research intensity and the rest of the G-5's research intensity, where the weights reflect population shares.

In this simple model, a rise in Japanese research intensity will raise the number of researchers in the world and therefore raise the number of new ideas that get produced. To determine the magnitude of the effect, however, we need to know several things. First, from equation (17), we need to know the elasticity γ in order to translate the rise in research intensity into a rise in income. Second, we need to know the elements in equation (19) so that we can determine by how much world research intensity is raised.

Recall that γ is a function of four parameters in the model; in particular, it is equal to $\frac{\sigma}{1-\alpha}\frac{\lambda}{1-\phi}$. It is very difficult to obtain values for each of these parameters individually. However, also recall that γ multiplied by the growth rate of the research stock is equal to the growth rate of per capita income in the long run. Based on recent data on U.S. growth, and using a measure of the growth rate of research effort, Jones (1997) calculates a rough value for γ that is about 1/3. This is the value we will use.

The elements of equation (19) are reported in Table 1, together with some additional statistics. Japan's share of the G-5 population is about 22 percent, while its share of the G-5 research effort is 25 percent. This difference reflects the fact that research intensity s_A in Japan is 0.34 percent, slightly higher than the average of 0.31 percent in the other G-5 countries. Another interesting statistic in this table is the contribution of G-5 research effort to patents granted in the United States. Only 59 percent of patents in the United States granted to the G-5 countries originate in the United States. The remainder, the bulk of which are Japanese, originate from foreign research efforts. This emphasizes the importance of a global perspective in understanding the contribution of idea-based growth.[4]

Now consider the following experiment. Suppose we raise Japanese research intensity from 0.34 percent to 0.39 percent, i.e. by 5 percentage points or about 15 percent of its level in 1987. Because Japan's population is only 22 percent of the G-5 total,

[4]A more detailed analysis of this last statistic can be found in Eaton and Kortum (1994).

this raises G-5 research intensity by only about 1 percentage point, from 0.32 percent to 0.33 percent.

This means that G-5 research intensity rises by about 3 percent. Now recall that the elasticity of balanced growth path income with respect to research, the parameter γ, is about 1/3. This means that the net effect on Japan (and the entire G-5) in the long run is a rise in balanced growth path income by about 1 percent.

Is this a big number or a small number? For this purpose, it is helpful to measure the shift in labor in units of GDP instead of bodies. We are moving .05 percent of Japan's labor force. To get a cost, we multiply by the total wage bill in Japan, which is about 2/3 of Japan's GDP (recall, we're assuming $\alpha = 1/3$). Therefore, the cost of this experiment is about .05*2/3=.033 percent of Japan's GDP each period. In exchange, we get (eventually) a 1 percent higher G-5 GDP each period, or perhaps even a 1 percent higher *world* GDP. With such calculations, it is not hard to see why economists' generally find large social returns to R&D![5]

An important qualification of this calculation is that it hinges on the magnitude of research effort being measured correctly. If research effort is mismeasured by a factor of 10, so that, for example, 3.2 percent of the G-5 population works in research instead of 0.32 percent, then the cost of this improvement will be mismeasured by a factor of 10 as well. Of course, the calculated gain is so large as to appear to be robust to even an order of magnitude mismeasurement, but one needs to recognize this degree

[5]One must be careful in evaluating this statement. While it is possible to calculate the social return to R&D from the production possibilities of the model and observations on allocations, one must also say something about the private rate of return in order to determine whether or not there is too little research. This requires an analysis of the market economy. Still, most of the evidence supports the claim that social rates of return to research are much greater than private rates of return.

of uncertainty in the calculation.

Along these lines, one might wonder if it is plausible to think that less than one percent of the population is essentially responsible for creating the ideas that underlie all of economic growth. On the one hand, this seems extraordinarily low. Any time someone creates a new business, one might think of this as a contribution to knowledge. The creation of the Big Mac by MacDonald's was a very valuable idea that probably didn't show up in the research statistics. On the other hand, one can also think of key individuals whose creations were extremely valuable, such as Isaac Newton, Thomas Edison, and Kyota Sugimoto, the inventor of the Japanese typewriter.

A very important question to ask is how much of this increase would be captured by Japan's researchers (which is relevant for whether or not they will undertake this change by themselves) and by Japan's economy as a whole. For this latter question, a natural minimum estimate would be 1 percent of Japan's own GDP, so even the *domestic* social return to research seems very high.

A final question to ask in this environment is how long does it take to reach the long-run? The answer is that it depends on the detailed parameterization of the simple model. Growth rates can (obviously) either be very high for a short period of time or not very high for a longer period of time. With a relatively low social discount rate, the differences along this front are relatively unimportant.

5 Conclusion

Economic growth has resulted in the last 125 years in enormous increases in standards of living. According to Maddison (1995), U.S. per capita income is higher today by a factor of 10 than in 1870, and Japanese per capita income is higher by a factor of 26. If the prices indices that are used to compute these ratios overstate inflation by one percent per year on average, then U.S. income would have risen by a factor of 35 and Japanese income by a factor of 90. Understanding these extraordinary changes is clearly one of the most important problems in economics.

Research on economic growth over the last 50 years points to the importance of knowledge and ideas as the source of these enormous improvements in incomes. Economic growth occurs as we discover newer and better ways to use the resources at our disposal. A central source of the growth in ideas that underlies the growth in per capita income is the growth in the number of researchers throughout the world. In the G-5 countries alone, there are nearly two and a half times more researchers in 1991 than in 1965. And this rise is surely augmented by the increase in researchers made possible by the increased development of economies outside of the G-5.

The continued growth and development of the world economy suggests that the market for new ideas continues to expand. In particular, the rapid growth of China and India, with 40 percent of the world's population, represents an enormous potential source of research and demand for the products of innovation.

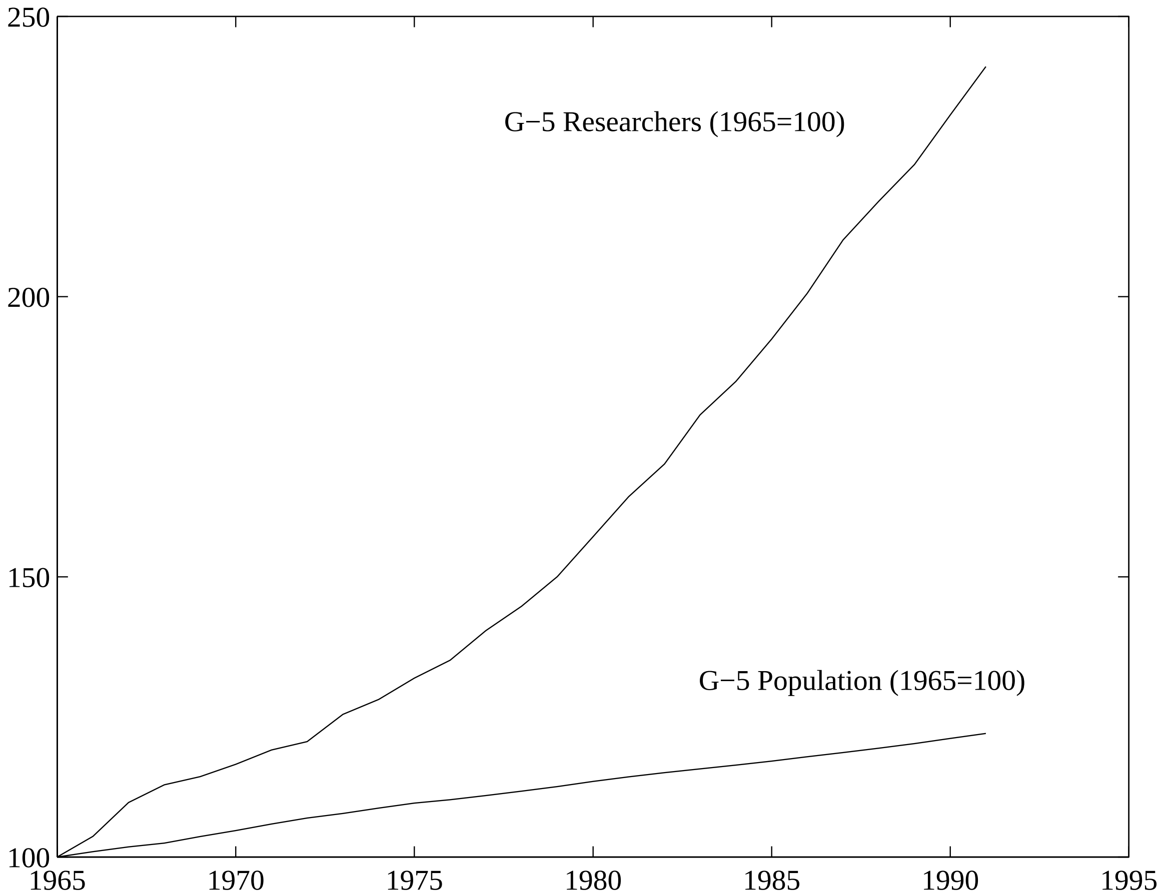
Simple calculations, as well as detailed studies, suggest that the social returns to research, both domestically and worldwide, are enormous, and potentially much larger than the private returns. This wedge suggests that private agents may not have appropriate incentives to engage in the search for new ideas. One implication is that the search for new institutions and arrangements to encourage the creation of new ideas could be one of the most socially valuable activities around.

Table 1: Data on the G-5 Economies (Percentages)

	— Shares of the G-5 —			Research
	Population 1990	Researchers 1987	U.S. Patents 1990	Intensity s_A, 1987
Japan	22	25	24	0.34
Rest of G-5	78	75	76	0.31
U.S.A.	46	53	59	0.36
W. Germany	12	10	9	0.27
France	10	6	4	0.20
U.K.	10	6	3	0.24

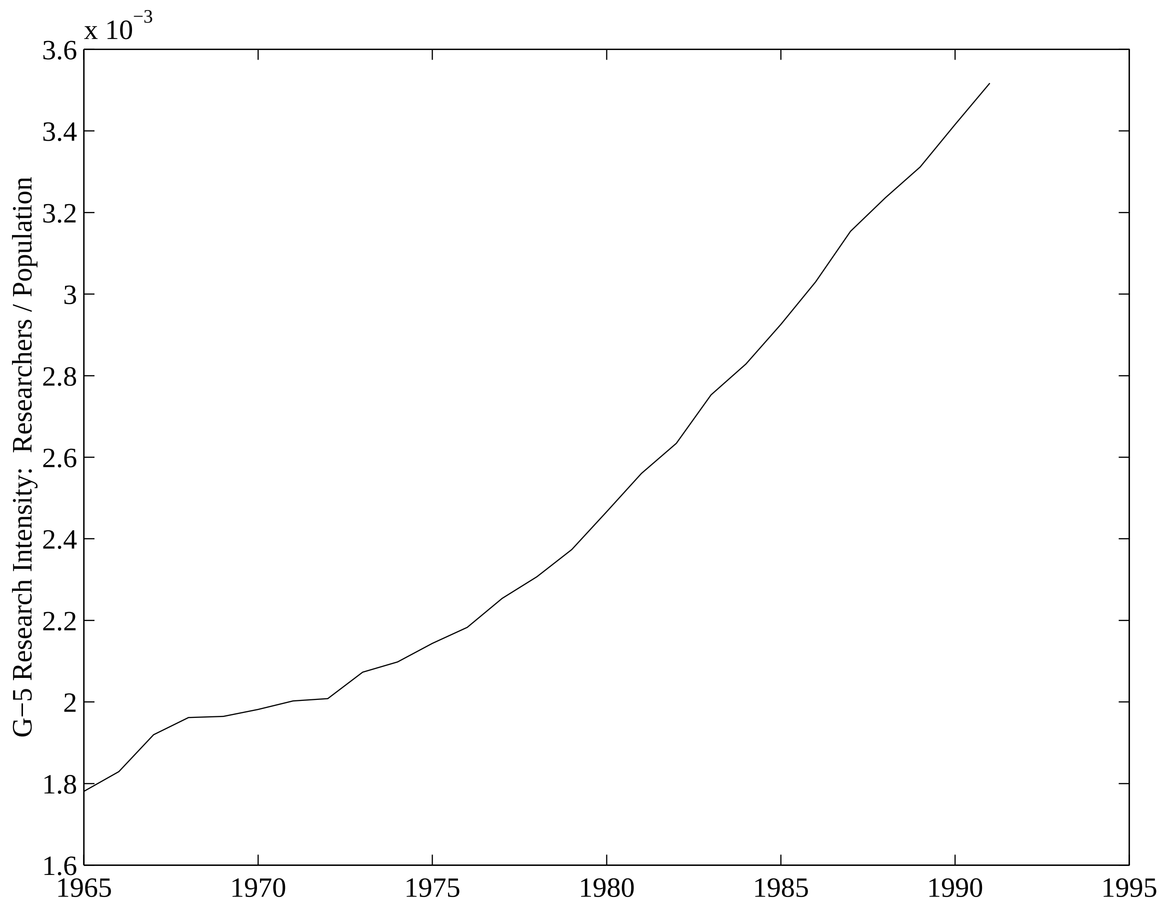
Notes: These data are taken from National Science Board (1993) and the Penn World Tables Mark 5.6.

Figure 1: Researchers and Population in the G-5 Countries



Source: Research data comes from the National Science Board (1993, 1996). The data are spliced together at the year 1979 and log-linearly interpolated for some countries. Population data is taken from the Penn World Tables Version 5.6 of Summers and Heston (1991).

Figure 2: Research Intensity in the G-5 Countries



Source: See notes to Figure 1.

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