II.A.3. ARE THERE LIMITS TO TECHNOLOGICAL CHANGE?

Summary

If there are limits to technological change, there are limits to output growth. We review definitions of technological change, attempts at quantitative measurement of technological change, and the literature on technological limits. An engineering perspective suggests the existence of both "ultimate" and "configuration-dependent" limits, but offers no practical way to assess how close to or far from these any particular technology might be. Economic perspectives identify technological change with productivity improvement. Endogenous growth models are frequently cited in support of the contention that technology exhibits increasing returns to scale, but a review shows that this property is an assumption exogenous to these models.

Declining economic productivity in the industrial economies in the years since 1970 is thought by some to be a secular decline that could point to the end of economic growth. Recent studies suggest that the high productivity growth rates of the post-war period may be anomalous deviations from lower but steady long-term rates of productivity growth beginning as far back as the late 19th century. Other studies suggest that quality improvements and new products, which are not reflected in productivity statistics, represent an increasing share of the "output" of technological innovation.

The studies reviewed in this section give little reason to suspect that we are approaching limits to the ability of technology to generate productivity increases or configurational innovations.

II.A.3. ARE THERE LIMITS TO TECHNOLOGICAL CHANGE?

Introduction

We've seen that technological change is necessary if output is to grow over the long term. If there are limits to technological change, then there are limits to growth.

We begin by defining terms. Then we discuss possible limits to technological change from two perspectives: that of engineering, which focuses on the properties of matter and energy, and that of economics, which focuses on rising costs.[1] Next we discuss the apparent decline in productivity among industrial nations over the past quarter century, which has been cited as evidence that technological change may be approaching its limits.

II.A.3.a. Defining and Measuring Technological Change

What is technology, and what is technological change? Convenient answers from the engineering perspective are that technology is the purposeful manipulation of matter and energy, and that technological change is the purposeful manipulation of matter and energy over increasingly more precise dimensions of space and periods of time.

Convenient answers from the economic perspective are that technology is "the sum of knowledge of the means and methods of producing goods and services (Bannock et al 1992), and that technological change is "the introduction of a new production method, yielding product improvements or cost reduction and thereby raising productivity (Samuelson and Nordhaus, 1989).

Many studies distinguish among "technological change," "technical change," "technological innovation" and similar terms. In these notes I use "technological change" as a broadly inclusive term.

[1] This is an artificial distinction, because in the final analysis the supply curve of a technology depends importantly upon the properties of materials. But its use at this point is convenient.

Engineering approaches to measuring technological change compare changes in performance characteristics, such as the power of internal combustion engines or the speed of microprocessors. These measures are not generally commensurate, and thus don't allow measurement of technological change in an aggregate sense. Attempts to allow aggregate measurement by defining technological change in term of "services" have not proved generally useful. As discussed below, Ayers (1992) suggests that aggregate measures of technological change might be developed in terms of entropy or information content.

The economic definition that identifies technological change with improvements in total factor productivity allows easy measurement, given an accepted set of national accounts. But changes in productivity do not measure changes in the quality of output, which many analysts suspect accounts for an increasing share of total value. Some authors have tried to use rates of patent approvals, or references in technology journals, as proxy measures for aggregate technological change (Kleinknecht, 1993), but with limited results.

II.A.3.b. Engineering Perspectives on the Limits to Technological Change

An exceptional treatment of the nature of technological change from an engineering perspective is provided by Ayers (1992). His account is particularly useful for our purposes because it explicitly seeks to shed light on questions concerning the limits of technological change.

Ayers begins by formally defining technology as "knowledge, combined with appropriate means, to transform materials, carriers of energy, or types of information from less desirable to more desirable states" (p 35). He goes on to note that "Every transformation initiated by man depends upon either the deliberate enhancement or acceleration of some localized natural equilibrium process, or the creation of a temporary disequilibrium by means of one or more artificial 'drivers.'" He cites the combustion of fossil fuels as an example of equilibrium-rate enhancement, and metal ore reduction as an example of artificial disequilibrium.

Ayers continues,

> "Most modern technologies require artificial environmental conditions to stimulate reactions (or suppress competing reactions)...[These] are created by means of high or low temperatures, high or low pressures or densities (evacuation), chemical potentials, electric or magnetic fields or potentials, electromagnetic radiation, electron, ion, proton or neutron fluxes. Technological progress, in a very fundamental sense, results from the increasing ability to create these conditions on demand, i.e., when and where they are desired." (p 36)

Ayers distinguishes two important limits to technological change: "ultimate limits," which are set by the fundamental laws of physics, and "configuration-dependent limits," which reflect the specific properties of materials in particular configurations. He uses these concepts to motivate a "barrier-breakthrough" model of technological innovation:

> "The basic hypothesis...is that the rate of technological progress tends to be higher when a technology is "far" from its limit, and that it tends to slow down as the technology approaches its limit. Thus, technological progress is most difficult and slowest--and R&D is most expensive…as one approaches a technological 'barrier', or configuration-dependent limit… this, in turn, triggers a more intensive search for a new combination that avoids the limits of the previous technology." Thus we see "…an alternation between inventive "leaps forward" --the adoption of new and better combinations--and subsequent incremental improvements and optimizations." (pp 37, 43)

Ayers suggests an approach to rigorizing the notion of "technological distance" from both ultimate limits and configuration-dependent limits (see **IIA-27**), but has not developed it further.

The pattern shown by Ayers' barrier-breakthrough model is a commonplace of studies of technological change. Different analysts tell somewhat different stories to explain the pattern.[2] A schematic is shown in **IIA-28** and several examples from the literature are shown in **IIA-29.**

Authors who argue that concern over limits to technological change--and thus over limits to growth--is unwarranted commonly invoke the apparent ubiquity of barrier-breakthrough trajectories as support for their position; Brinkman (1980) is an example. These appeals typically

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[2] For example, Nordhaus (1992) suggests that a technological breakthrough typically opens up application "niches" that were unanticipated before its intended applications began to be realized. This leads to further development of the new technology, with consequent increases in productivity in different industrial sectors. As the new niches fill, however, further development slows. The entrepreneurs who drive innovation begin to decrease their investment in the diminishing number of less promising niche applications, and begin to invest in developing new breakthrough innovations. This further flattens the development trajectory of the formerly new, now aging, technology, and increases the likelihood of a new breakthrough.

BOX IIA-27. Ayers' approach to rigorizing a measure of technological distance
[source: Ayers, 1992]

"[W]hat we seek is a generalizable way of expressing the notion of distinguishability of one reference system (current technology) from another (future technology)...The most general measure of distinguishability--hence of techological distance--is information content in the technical (Shannonian) sense. For thermodynamic systems, this information measure is exactly proportional to the more general thermodynamic potential...; [thus] the higher the temperature or pressure used in an industrial process… the greater the technological distance from ambient conditions--which can be roughly characterized as the technological zero point." (pp 38-39)

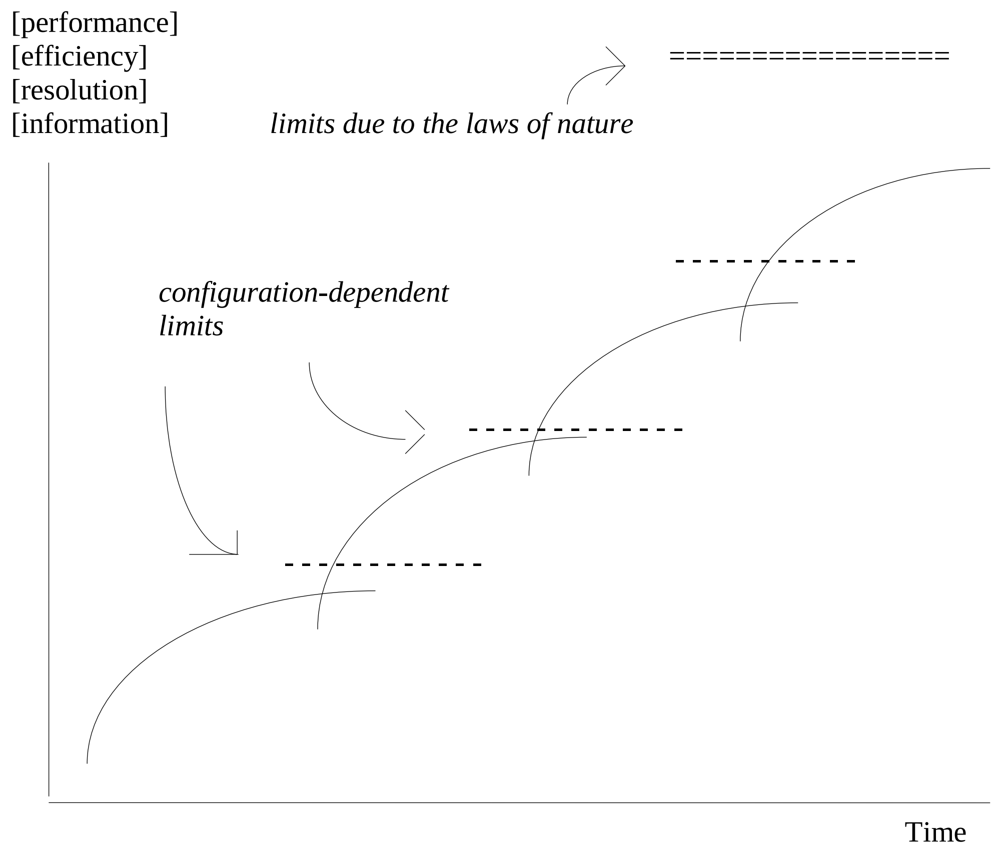
"It is but a short step to envision techniques for computing the information equivalent of non-thermodynamic figures of merit, such as the power-to-weight ratio of prime movers, or the complexity of electronic circuits." (p 39)

Ayers notes his intention to develop such measures of technological distance at a later date. In the meantime he offers "as a somewhat crude substitute, a simple scoring system for technological distance." His approach is to "...assign a difficulty score of 0 for the range corresponding to ambient conditions--presumably achievable without assistance from technology of any sort--and a score of 1 for the first known (or presumed) departure from ambient conditions" (pp 39-40). He applies this method to the case of temperature, as shown below:

score:

0	ambient temperature (a little less than body temp)	=	35 ^{0}C
1	cooking via coal fire	=	550 - 750 ^{0}C
2	ceramics, glass, smelting	=	1100-1300 ^{0}C
3	crucible (and Bessemer, open hearth)	=	1300-1600 ^{0}C
4	practical electric arc (alloys steels, tungsten)	=	2800 ^{0}C
5	plasma torches and cutting lasers	=	3000+ ^{0}C
6	magnetic trapping of ionized gases	=	thermonuclear

BOX IIA-28. The Barrier-Breakthrough Schema of Technological Change



BOX IIA-29. Examples of Uses of the Barrier-Breakthrough Schema

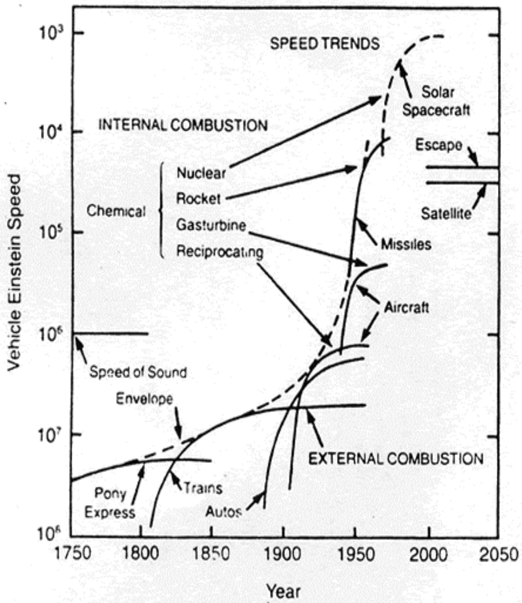


Figure 1. Trends in transportation speed.
Source: P. DeVore (1980)

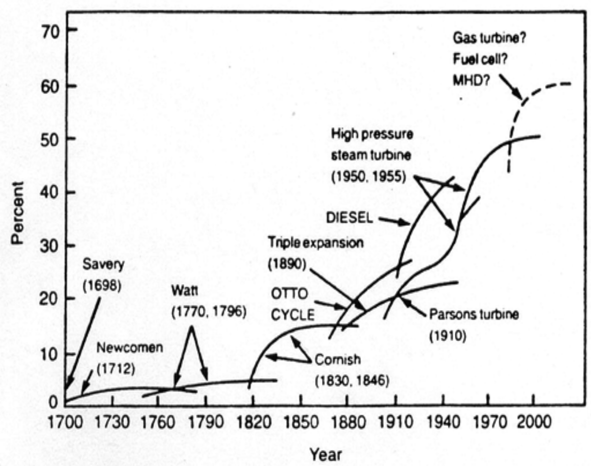
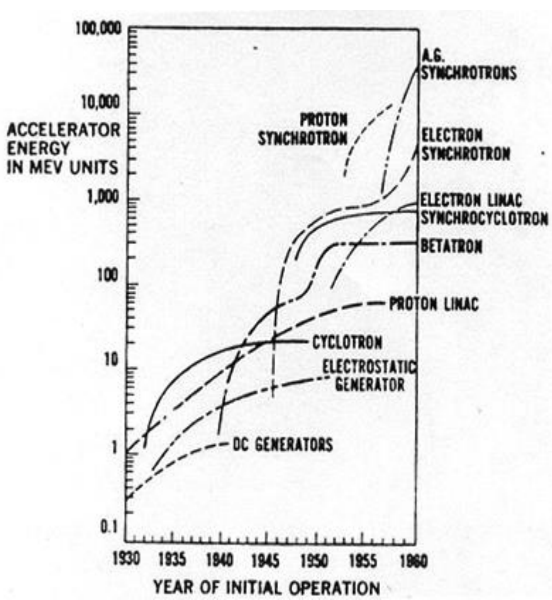


Figure 2. Trends in energy conversion efficiency. Source: H. Thiring (1958)



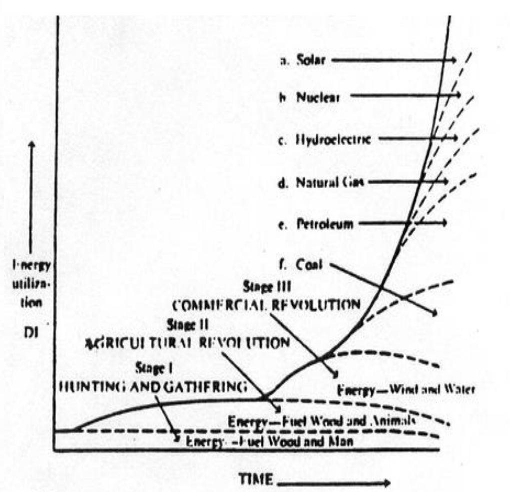


Figure 3. Rate of increase of operating energy in particle accelerators. Source: M.S. Livingston as quoted by Holton (1962)

Figure 4. The Energy Paradigm of Logistic Surges. Source: R.I. Brinkman (1980)

lack an analytic justification. The fact that a pattern has repeated itself in the past is not an explanation of why we might expect it to continue in the future.

Irvin (1993) suggests that the barrier-breakthrough pattern may be largely an illusion that results from particular ways of categorizing technological artifacts. He notes that "data-sifting," consciously or otherwise, can generate almost any pre-conceived type of technological trajectory.

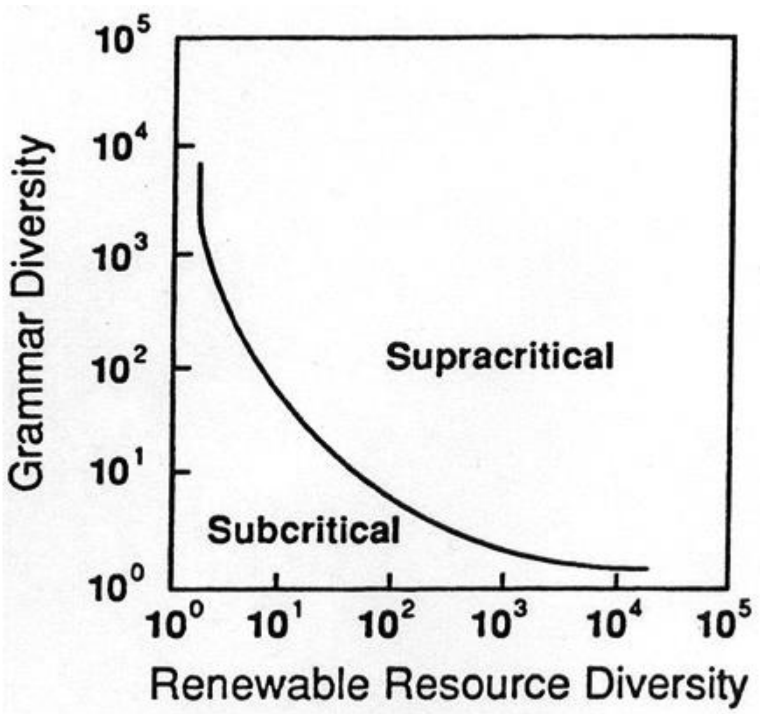
Other authors take strong exception to such technological agnosticism. Ausubel (1994) says,

> "The essential fact is that technological trajectories exist. Technical progress in many fields is quantifiable. Moreover, rates of growth or change tend to be self-consistent over long periods of time… Thus, we may be able to predict quite usefully certain technical features of the world of 2050 or 2070 or even 2100." (pp 509-510)

Some authors draw upon work in complexity theory to suggest that not only can breakthroughs be expected to continue but that the envelope of barrier-breakthrough trajectories can be expected to increase over time. Kauffman (1995) proposes that any existing suite of technologies, artifacts or services defines a potential set of additional technologies, artifacts or services that could result from processes that might be thought of as "combinations" of the existing elements of the set. The size of the potential new set depends on the size of the existing set and on the number of ways the elements can be usefully combined (its "grammar"). If either the number of elements or the number of combinatorial rules is large enough the system will exceed a "threshold of criticality" and new technologies, artifacts or services will grow indefinitely at an increasing rate (see **IIA-30**). However, many authors charge that such accounts are at best metaphors for processes that can be better described and understood using more conventional analytic tools.[3]

[3] Complexity theory is discussed further in Section II.A.4.

BOX IIA-30. Kauffman's Schema of "Technological Co-evolution"
[source: Kauffman 1995]



Kauffman says, "The number of renewable goods with which an economy is endowed is plotted against the number of pairs of symbol strings in the grammar, which captures the hypothetical "laws of substitutability and complementarity." A curve separates a subcritical regime below the curve and a supercritical regime above the curve. As the diversity of renewable resources or the complexity of the grammar rules increases, the system explodes with a diversity of products." (p 293)

Most engineers and scientists writing today on the topic of future prospects for technological innovation are “optimists.” They believe that breakthroughs in computer and information technologies, molecular biology, genetics, neurobiology, materials sciences, manufacturing technologies and other fields could usher in a period of truly revolutionary technological change.[4]

Contrarian voices are fewer. Horgan (1995) notes that the theoretical studies that occupy the attention of the top scientists in a wide range of fields are increasingly less amenable to testing. He suggests that this is precisely the condition we should observe as we approach the limits of scientific knowledge. Horgan's views have been sharply rejected by many critics [B. Hayes (1996), Gross and Witten (1996)]. In any event, Horgan sees no reason that the application of our (now nearly final) stock of scientific knowledge can’t continue to supply us with a steady stream of technological innovations.

The optimists appear to have most of their eggs in a relatively small number of baskets, albeit big ones: information, biology and materials. If these fields don’t produce big breakthroughs it is difficult to imagine where else to look. Technological innovation that results in productivity gains is intimately associated with the process of miniaturization. If the manipulation of matter and energy at the molecular level (“nanotechnology”) turns out to be prohibitively difficult, further technological innovation will be much constrained.

Assessment

Our attempt to find analytic grounds within the engineering perspective for determining whether or not there are limits to technological change has been largely unsuccessful. Ayers’ schema of ultimate and configurational limits is intuitively reasonable, but in the absence of an empirical measure of technological distance it doesn’t enable us to devise and test theories that have predictive power. Expert opinion is heavily weighted to the view that our current

[4] We discuss the future of technological change in more detail in Section II.E.

understanding of the natural world points to the possibility—many would say likelihood—of great technological breakthroughs over the coming several to many decades.

II.A.3.c. Economic Perspectives on Limits to Technological Change

The economic perspective looks at technology as both a factor necessary for the production of goods and services, and as something which itself requires goods and services, including technological ones, in order to be produced.

The production of technology itself was for many years schematized in the "linear model." Three versions are shown in Section 1 of **Box IIA-31.** But the linear model doesn't show the complex cross linkages that are central to the process of technological production. Section 2 of IIA-31 displays a recent attempt at a more complete model.

More formally, we might think of the model shown in Section 2 of IIA-31 as a set of linked differential equations. A change in one variable of the model might generate greater or lesser changes in the other variables, and thus in itself. If any one of these variables exhibits decreasing returns, the growth of all the variables will eventually come to a halt unless at least one of them shows sufficiently increasing returns, or grows exogenously.

This observation identifies the critical question at the heart of the current debate over technology and long term economic growth: does an increase in the "stock" of technology imply that the production of further technology is likely to be more difficult or less difficult?

We saw that a defining feature of the neoclassical growth model was the existence of decreasing returns to labor and capital. Continued economic growth was made possible via the *deus ex machina* of an exogenous technology that grew exponentially, indefinitely. This feature had long been recognized by economists as something of an embarrassment, but during the steady-growth decades of the 1950's and 60's there was little motivation to refine it. By the late 1970's growth in the West had begun to slow and in most developing countries had failed to reach expected levels. In the mid-1980's economists began to re-examine the neoclassical growth

BOX IIA-31. Models of the Production of Technology

1. Four versions of the linear model

A and B from Mahdjoubi (1997); C from Mahdjoubi (1996); D from Martino (1993)

A. Basic Research ➔ Applied Research ➔Development ➔ Commercialization

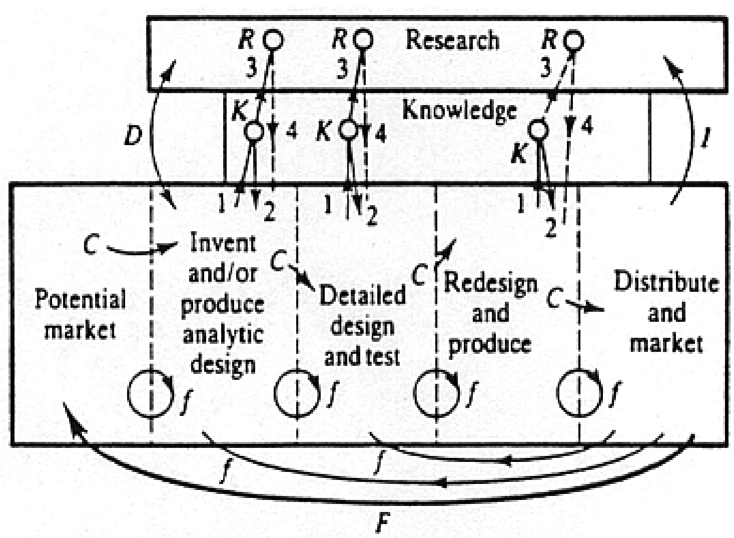
B. Research Exploratory Development ➔Advanced Technology Development➔Advanced Development ➔ Engineering Development ➔ Management and Support ➔ Operational Systems Development.

C. Basic (Fundamental) Research ➔Industrial Research & Development ➔ Design & Development ➔ Industrial Production Enterprises ➔ Market

D. Science Findings ➔ Lab Feasibility ➔ Operating Prototype ➔ Commerical Introduction ➔ Widespread Adoption ➔ Diffusion & Adaptation ➔ Social & Economic Impact

2. A non-linear model:

[reprinted from Hall 1994]



model. One important result has been called "new growth theory," "theory of endogenous growth" or "theory of endogenous technology."

In the notes that follow I review what the endogenous growth models purport to tell us about possible limits to technological change. The models reviewed are those of:

1. D. Romer (1994): Endogenous growth using an R&D production function
2. P. Romer (1990): An R&D production function with human capital
3. Grossman & Helpman (1994): Increasing returns via product diversity
4. Ayers & Miller (1980): Decreasing returns due to natural limits
5. Becker & Murphy (1993): Differential returns to specialization and coordination costs

1. D. Romer (1994): Endogenous growth using an R&D production function

The central ideas of new growth theory can be understood by use of the simple growth model shown in **IIA-32**.[5] It is similar to the Solow model but in addition to the output production function (equation 1) includes a technology production function (equation 2). Labor and capital are treated as a single variable L, here called labor-capital, without loss of generality. A portion of labor a_L produces new technology and the balance produces output.[6] Labor grows exponentially (equation 3).

The technology production function can be logarithmically differentiated to derive formulas for the relative growth rate of technology (equation 4), and for the time rate at which the growth rate might change (equation 5). We can show that the growth rate of per capita output will equal the growth rate of technology, as in the Solow model. But now that value is determined by values endogenous to the model.

As noted, the critical question of modern growth theory is whether greater stocks of technology encourage or discourage the production of additional technology. This relationship is modeled in equation 2. Consider three cases of the parameter θ:

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[5] This model was presented by David Romer (1994) to illustrate the key concepts of new growth theory, as originally developed by Paul Romer (1990).

[6] In this model the term "technology" can be taken to mean "technological knowledge," or just "knowledge," without harm to the narrative.

BOX IIA-32. Endogenous Growth Using an R&D Production Function [D. Romer 1994]

Equations of the Model:

(1) $$Y_t = A_t\left[(1-\alpha_L)L_t\right]$$

(2) $$\dot{A}_t = [a_L L_t]^{\gamma} A^{\theta}_t$$

(3) $$\dot{L}_t = nL_t$$

Derived equations:

(4) $$\frac{\dot{A}}{A} = g_A = [a_L L_t]^{\gamma} A_t^{(\theta-1)} = \frac{\dot{y}}{y}$$

(5) $$\dot{g}_A = (\theta-1)[g_A]^2 + \gamma n[g_A]$$

Where:

Y = Output
A = Technology ("blueprints")
L = Labor-capital
a_L = share of labor-capital devoted to producing new technology
γ = elasticity of the growth rate of technology with respect to labor
θ = elasticity of the growth rate of technology with respect to the level of technology
n = growth rate of labor-capital
g_A = growth rate of technology

1) If $\theta < 1$ then the accumulation of technology has a diminishingly positive impact on the growth rate of technology, which will converge on the constant value $g_A = \gamma n/(1-\theta)$. We see that if, for example, $n = .02$, $\gamma = .67$, and $\theta =.30$, the constant growth rate of technology, and thus of per capita income for economy as a whole, would be $g_A = .019$.[7]

2) If $\theta > 1$ then each addition to the stock of technological knowledge makes it easier for new knowledge to be produced. Inspection of equation 4 shows that the growth rate of technology g_A is increasing and the stock of technology is accelerating. Under this assumption economic output will go to infinite in a finite period.

3) If $\theta =1$ the key equations become: $g_A(t) = [\, a_L\, L(t)\,]^{\gamma}$ and $g_A(t) = \gamma\, n\, [g_A(t)]$. If population and capital growth come to an end ($n = 0$) technological knowledge no longer grows explosively but does so at a constant rate.

The notion of increasing returns to the stock of technological knowledge as described in this simple model lies at the core of a great many more sophisticated treatments of endogenous growth. Many growth economists use extensions of the model described in case 3 above, in which $\theta = 1$. This has the simple structure $Y = AK$, and is commonly referred to as the "linear model."[8]

The new endogenous growth models are frequently cited as evidence that technology can overcome resource and other constraints on economic growth (e.g., Wysocki 1997). But the models don't support this claim. In a discussion of his work, Paul Romer (1990) says,

> "Linearity in A [$\theta = 1$] is what makes unbounded growth possible, and in this sense, unbounded growth is more like an assumption than a result of the model… [This specification] was chosen because there is no evidence from recent history to support the

[7] This is the average rate of growth of per capita output in the United States over the period 1880 through 1987.

[8] Not to be confused with the "linear models" shown in Box IIA-31 that were considered by a prior generation of technology scholars.

> belief that opportunities for research are diminishing. Moreover, linearity in A is convenient analytically…" (p 84)

2. P. Romer (1990): An R&D Production Function With Human Capital

Box IIA-33 shows the central equations of a model of endogenous technology developed by Paul Romer that highlights the important role of human capital.

In this model the economy has three productive sectors. A research sector (equation 4) uses technological knowledge and human capital to generate new designs for producer durables. Capital is modeled as the sum of producer durables (equation 3). At any point in time there are as many types of producer durables as there are number of designs for them. Final output is generated by human capital, labor, and the stock of producer durables (equation 1). Any final output that is not consumed is invested in the production of new producer durables (equation 2). For convenience Romer treats population as constant and assumes that each person has accumulated the maximum possible stock of human capital.

The critical equation for our purposes is (4). As in case 3 of the D. Romer model discussed above, the rate of change of technological knowledge is a linear function of the stock of knowledge. If the stock of knowledge doubles the rate of increase of knowledge doubles as well. There are no diminishing returns. Similarly there are no diminishing returns to the use of human capital with respect to the production of knowledge. Thus the technology production function shows increasing returns: if the stock of both productive factors doubles, the rate of increase of knowledge quadruples.

Note that the growth of technological knowledge has a two-fold impact on the eventual growth of output. It enables new producer durables (x) to be built, which directly increases output, and it increases the marginal productivity of human capital used to produce new technology.

Romer uses a conventional utility function to help compute the optimal growth paths of the key variables. He finds that the growth rate of technological knowledge, and thus per capita

BOX IIA-33. An R&D Production Function with Human Capital [P. Romer 1990]

Equations of the Model:

(1) $$Y = H_Y^{\alpha} L^{\beta} \sum_{i=1}^{\infty} x_i^{1-\alpha-\beta}$$

(2) $$\dot{K} = Y - C$$

(3) $$K = \eta \sum_{i=1}^{A} x_i$$

(4) $$\dot{A} = \delta H_A A$$

Where

Y = output
H = total human capital (= $H_A + H_Y$)
H_A = human capital used to produce technological knowledge
H_Y = human capital used to produce final goods
L = labor
x_i = the quantity of producer durable i used to produce output
C = consumption
K = physical capital (equal to the sum of the producer durables)
η = number of units of foregone consumption used to create one unit of a durable
A = technological knowledge
δ = productivity parameter
α = elasticity of output with respect to human capital
β = elasticity of output with respect to labor

output, is $g = (\delta H - \Lambda\rho) / (\sigma\Lambda + 1)$, where Λ is a constant determined by the technical parameters of the production function, $\Lambda = \alpha / (1 - \alpha - \beta)(\alpha + \beta)$.

This result shows that the rate of per capita output growth is a function of a single productive resource—the stock of human capital, H. We see that positive output growth can be maintained even if the stock of human capital is constant. This happens because technological knowledge can increase the productivity with which a unit of human capital produces new technological knowledge, as shown in equation 4. But this is an assumption of the model, not a result.

3. Grossman & Helpman (1994): Increasing returns via product diversity

Grossman and Helpman present a model in which the driving force of technological innovation is the "preference for product diversity" held by consumers. Profit-maximizing producers will invest in R&D in order to develop new products that satisfy this preference.

Equation 1 in **IIA-34** shows consumer utility as the log function of D, which is a measure of consumption indexed for product diversity. D is given analytic rigor in equation 2, where x(j) is the amount x of product j consumed, n is the total number of products available, and α is a measure of "preference for diversity." Equation 2 shows that $100 spent on 10 goods at $10 each gives a higher value of D than does that same $100 spent on 5 goods at $20 each.

In the model the level of technology is given by n, the number of product varieties available. Grossman and Helpman derive equation 5, which shows that the rate of innovation in the economy (i.e., the production of new product varieties) is a function of the stock of labor and capital, and of the efficiency of research labs that generate blueprints for new products.

The most important equation in the model is equation 3, which shows that the stock of *general* knowledge in society, K_n, is a linear function of the current level of product-specific knowledge in society, n. This equation is analogous to equation 2 in Romer 1 and equation 4 in Romer II. It expresses Romer's insight that knowledge produced by firms when they engage in

BOX IIA-34. Increasing Returns Driven by the Preference for Product diversity
[Grossman and Helpman, 1994]

Equations of the model:

(1) $$U_t = \int_0^\infty \ln D(\tau) e^{-\rho(\tau-1)} d\tau$$

(2) $$D = \left[\int_0^n x(j)^\alpha dj \right]^{\frac{1}{\alpha}}$$

(3) $$K_n = n$$

(4) $$\dot{n} = \frac{L_n K_n}{a}$$

Derived equation:

(5) $$g = (1-\alpha)\frac{L}{a} - \alpha\rho$$

where:

U = utility
D = consumption index incorporating a measure of product diversity
ρ = subjective discount rate
x(j) = quantity x of each variety of product j consumed
α = preference for diversity (low α = high preference)
n = index of the diversity of products (i.e., of the ”number of blueprints”)
L_n = labor force employed in the production of blueprints
K_n = stock of general knowledge (i.e., “public knowledge”)
g = growth rate of innovation and output
a = efficiency of research labs in generating blueprints for new products

R&D to develop new products for the market generates knowledge spillovers which other firms can use at little cost and which can thereby offset the declining returns to resources as production grows.

Grossman and Helpman nicely summarize their key results as follows:

> "We have studied the economic conditions that give rise to ongoing technological progress. The spillover benefits from research must not decline too rapidly over time, and the economy must be sufficiently large, sufficiently productive in the research lab, sufficiently desirous of new products, and sufficiently patient, for R&D to remain a viable activity through time." (p 74)

Earlier they catalogued these relationships:

> "A larger resource base means…more employment in every activity, (including those) which generate new knowledge. A smaller discount rate means more savings, a lower cost of capital, and so more innovation and faster growth. Finally, a smaller value of α implies a greater taste for variety, thus a less elastic demand for each product, a larger opportunity for monopoly profits, and a higher return to R&D." (p 63)

Note that while the importance of the size of the resource base, discount rate, lab productivity and α are indeed analytic results of the model, the importance of the fact that "the spillover benefits from research must not decline too rapidly over time" was built into the model at the beginning when the production of new knowledge was modeled as a linear function of the current level of knowledge. Grossman and Helpman acknowledge that choices other than this one of constant returns could have been made:

> "The process of knowledge accumulation might be characterized by increasing returns, for example, if there existed important complementarities between different ideas. On the other hand, the relationship between research and knowledge might be one of decreasing returns, if science were characterized by a limited 'store of ideas,' and if earlier contributions were more significant than later ones." (p 58)

Grossman and Helpman give no explicit rationale for their choice of the linear knowledge production function:

> "We choose, however, to concentrate our attention in the main text on a formulation [the linear production function] that ignores these potential complications… After deriving our results for this simplest of specifications, we shall discuss how they would be modified in more general cases." (p 58)

In an appendix Grossman and Helpman do explore the results their model gives if the knowledge production function were characterized by decreasing or increasing, rather than linear, returns. Under decreasing returns the rate of innovation, and thus economic growth, will inevitably slow to zero, while under increasing returns the rate of innovation and economic growth will increase continually. The most important feature of the model depends upon an exogenous assumption for which little justification is given.

4. Ayers and Miller (1980): Decreasing Returns Due to Natural Limits

Ayers and Miller use an unconventional production function (equation 1 in **IIA-35**) to model the fact that some minimum level of natural resource use is essential to the production of a unit of output. As the ratio between output and the stock of available resources increases, the growth of output is increasingly constrained. At the limit, output is shown as a constant fraction of the available resources.

Capital and Labor are modeled in the conventional manner (equations 2 and 3). The amount of available resources R is the sum of the constant flow of renewables and the current flow of exhaustible resources (equation 4). Consumption is equal to output less investment and that portion of output that represents the embodiment of technological knowledge in machine or labor skills (equation 5). The growth rate of technological knowledge depends on the total size of the population and rate of knowledge embodiment per capita (equation 6). Technological efficiency increases with respect to the stock of technological knowledge, towards a fixed asymptotic limit (equation 7).

Ayers and Miller solve for the dynamic equilibrium and show that "…the optimal path leads to a stationary state with finite capital and finite technological knowledge, resulting in maximum technical efficiency less than unity."

This result is largely determined by the assumption implicit in the choice of the production function--that there is a minimum level of resource use beyond which capital, labor

BOX IIA-35. Decreasing Returns due to Natural Limits
[Ayers and Miller 1980]

Equations of the model:

(1) $$Y = F(K, L, R) = \left[1 - e^{\left[\frac{-\pi(K,L)}{R}\right]}\right] R$$

(2) $$\dot{K} = I - dK$$

(3) $$\dot{E} = b\dot{N} = bgN\left(1 - \frac{N}{\bar{N}}\right)$$

(4) $$R = \bar{R} - \dot{S}, \qquad \dot{S} \leq 0$$

(5) $$C = F - I - J$$

(6) $$\dot{T} = J$$

(7) $$E = \left(1 + e^{(T_0 - T)}\right)^{-1}$$

Derived equations:

(8) $$\dot{E} = E(1 - E)J$$

(9) $$y = f(k, b, E) = \frac{-\pi(k,b)E}{\ln(1 - E)}$$

Where:
Y = total output
K = invested capital
L = labor force
R = available flow of energy resources; $\bar{R}$ = flow of renewable energy resources
I = investment
d = rate of physical depreciation
b = workers/population
N = total population
g = growth rate of population
$\dot{S}$ = flow of exhaustible energy resources
C = consumption
$\dot{T}$ = growth rate of technological knowledge
J = rate of embodiment of technological knowledge in machines or skill
E = technical efficiency
T_0 = accumulated level of new knowledge where E = .5 and T = T_0

and technology cannot substitute--and in the finite limits to technological efficiency imposed by equation 7.

Ayers and Miller motivate their choice of functional forms that show limits to technological change in the same manner as Romer, Grossman and Helpman motivated their choice of functional forms that showed no limits: by anecdote and plausibility appeals. Ayers and Miller say:

> "It is important to emphasize here, that ultimate technological efficiency is inherently limited, even though knowledge *per se* may be accumulated indefinitely. There are definite and well-know limits on physical performance in almost every field…For instance, there is a definite lower limit to the amount of electricity required to produce a horsepower of mechanical work. There is a lower limit, similarly, to the amount of electricity required to produce a given amount of illumination. And, of course, there is a lower limit to the amount of available work derived from fossil fuels that is needed to generate a given amount of electricity… Temperatures and pressures cannot be less than zero. Velocity cannot exceed the speed of light. And so on." (p 359)

5. Becker and Murphy (1993): Increasing returns to specialization, decreasing returns to coordination costs

Becker and Murphy present a model that identifies the specialization of labor as the engine of economic growth. Their production function (equation 1 in **IIA-36**) shows that per capita income will increase along with increases in technology (A), human capital (H), and the degree of specialization among workers (n). But as specialization increases so do coordination costs, here modeled by the term λn^B. Becker and Murphy cite principle-agent conflicts, hold-up problems (in which some members of a team shirk in order to extract concessions from others), and breakdowns in supply and communication, as examples of coordination costs.

Becker and Murphy derive the optimum per capita output (equation 4) and the per capita output growth rate (equation 5). The growth rate is the sum of the adjusted growth rates of technology and the stock of human capital, less the adjusted growth rate of coordination costs.

The mechanism that generates increasing returns in this model is the possibility of a mutually reinforcing relationship between specialization and the stock of human capital. As human capital grows the optimal level of specialization grows, as shown in equation 3. With

BOX IIA-36. Increasing Returns to Specialization; Decreasing Returns to Coordination Costs [Becker and Murphy 1993]

Equations of the model:

(1) $$y_t = A_t H_t^{\gamma} n_t^{\theta} - \lambda_t n_t^{\beta}$$

(2) $$U = \frac{1}{\sigma}\sum_{t=0}^{\infty} \alpha^t c_t^{\sigma}$$

derived equations:

(3) $$n_t^* = \left(\frac{\theta}{\beta\lambda}\right)^{\frac{1}{\beta-\theta}} A_t^{\frac{1}{\beta-\theta}} H_t^{\frac{\gamma}{\beta-\theta}}$$

(4) $$y_t^* = k_t A_t^{\frac{\beta}{\beta-\theta}} H_t^{\frac{\beta\gamma}{\beta-\theta}}$$

(5) $$\frac{\dot{y}}{y} = \frac{\beta}{\beta-\theta}\frac{\dot{A}}{A} + \frac{\beta\gamma}{\beta-\theta}\frac{\dot{H}}{H} - \frac{\theta}{\beta-\theta}\frac{\dot{\lambda}}{\lambda}$$

Where:

y = per capita output (y* = optimal per capita output)
A = technology
H = human capital
U = utility
n = index of specialization/division of labor (n* = optimal level of specialization/division)
λ = coordination cost parameter
γ = elasticity of output with respect to human capital
θ = elasticity of output with respect to specialization/division of labor
β = elasticity of coordination costs with respect to specialization/division of labor
k = a constant of the output parameters (See BOX IIA-37)
σ = elasticity of utility with respect to consumption
α = subjective discount factor
c = consumption

greater specialization, output increases, and this raises the marginal product of additional units of human capital.

Becker and Murphy use a conventional utility function (equation 2) to solve for the optimal paths over time for output, consumption, and human capital stock. They find that in equilibrium these variables change at the same rates, and that they will grow, decline or remain constant depending upon the particular values of the parameters n, B, γ, and θ, as shown in **IIA-37**. Becker and Murphy speculate that $\gamma < 1$, and state that $B > \theta > 0$ for small values of n, but otherwise do not offer opinions about the values that these parameters might take in the real world.

Assessment

Although the endogenous growth models have been hailed as pointing the way to unlimited economic growth, we saw that in one case after the other this feature was produced by assumptions of the model, not by results derived from it. Whether the returns to knowledge, technology, human capital, the division of labor or other factors is increasing, decreasing or constant is a complex empirical question that the models themselves do not address.

II.A.3.d. The Post-War Productivity Growth Slowdown

Productivity in the industrialized nations grew steadily in the two decades after World War II, but in 1973 this growth abruptly slowed and has remained at lower levels since, as shown in **IIA-38, IIA-39 and IIA-40**.

Was this slowdown the result of a particular shock or structural change that might be remedied by policy or the passage of time? Or has industrial technology reached a level of development beyond which we can expect only diminishing returns, perhaps forever? A list of explanations of the productivity slowdown appears in **IIA-41**.

In the mid-1980's many analysts believed that the oil price shocks of 1973 and 1978 were the likely cause. The timing was right, the oil shocks had indeed had a global impact, and

BOX IIA-37. Results of the Becker/Murphy Model

Let g = steady-state growth rates of human capital (H), output (y) and consumption (c).

If A and λ are constant, and:	then:	which means:
1) $\beta\gamma < \beta - \theta$	$g = 0$	output slows and comes to a stop
2) $\beta\gamma = \beta - \theta$	$g = \left(R\alpha^{-1}\right)^{\frac{1}{1-\sigma}}$	output grows at a steady rate*
3) $\beta\gamma > \beta - \theta$	$g > 0$	output grows at an accelerating rate

* $R = \dfrac{\beta\gamma}{\beta-\theta} kA^{\frac{\beta}{\beta-\theta}} H^{\left(\frac{\beta\gamma}{\beta-\theta}\right)-1}$ where $k = \lambda^{\frac{-\theta}{\beta-\theta}}\left[\left(\dfrac{\theta}{\beta}\right)^{\frac{\theta}{\beta-\theta}} - \left(\dfrac{\theta}{\beta}\right)^{\frac{\beta}{\beta-\theta}}\right] > 0$

BOX IIA-38. THE POST-1972 SLOWDOWN IN OUTPUT GROWTH

[Sources: Mankiw (1994); World Development Report 1996]

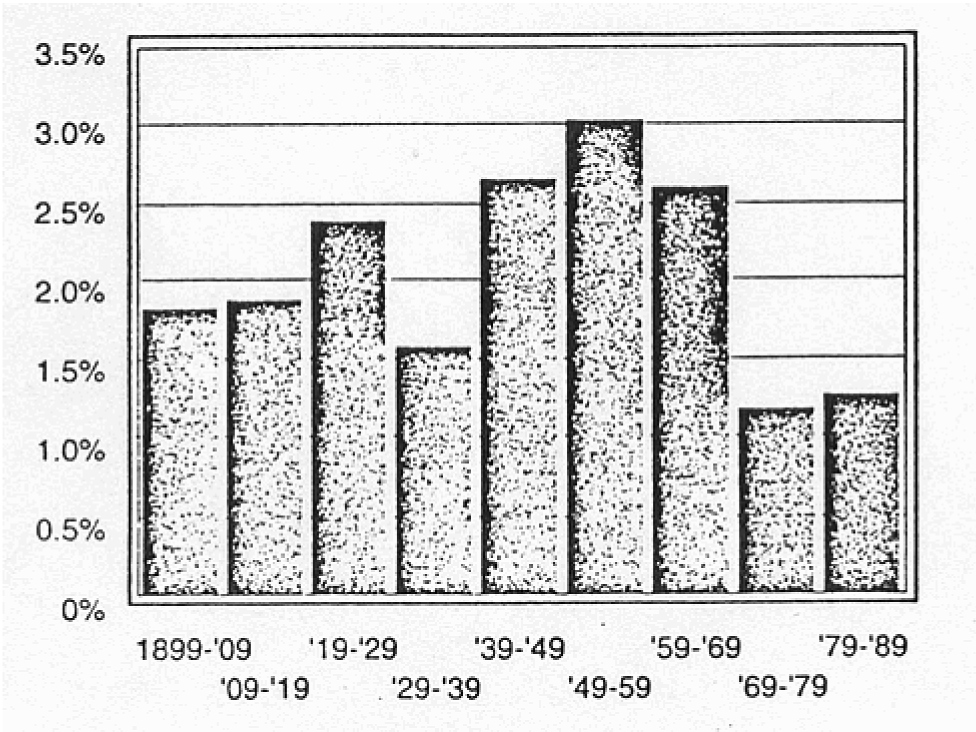
Country	Growth in Output per Person (percent per year)		
	1948-1972	1972-1991	1990-1994
Japan	8.2	3.6	.9
West Germany	5.7	2.3	.5
Italy	4.9	2.8	.5
France	4.3	2.1	.3
Canada	2.9	2.3	.1
United Kingdom	2.4	1.9	.4
United States	2.2	1.7	1.5

BOX IIA-39. ACCOUNTING FOR OUTPUT GROWTH IN THE UNITED STATES

[Source: Mankiw (1995)]

Years	Output Growth	Capital Growth	Labor Growth	Total Factor Productivity
1950-1959	4.0	0.4	0.5	3.1
1960-1969	4.1	0.9	1.2	2.0
1970-1979	2.9	1.1	1.5	0.3
1980-1989	2.5	0.9	1.3	0.3
1990-1992	0.6	0.6	-0.1	0.1

BOX IIA-40. U.S. Productivity Growth, 1899-1989
[reprinted from Krugman, 1994]



The two decades since 1970 have seen the worst U.S. productivity performance of the century.

BOX IIA-41. Suggested explanations for the post-1973 productivity slowdown

1. The composition of the labor force has been changing. Younger workers are less productive.
2. More government regulations, especially environmental regulations, have stifled growth.
3. The 1970's oil price shocks forced early retirement of capital stocks, and sparked a recession.
4. The sectoral shift to a service economy means lower productivity.
5. We are experiencing diminishing returns to technological innovation.
6. Fundamental scientific breakthroughs now require increasing effort to achieve.
7. We have reduced expenditures on R&D from earlier levels.
8. Young people are no longer motivated to pursue productivity-enhancing goals.
9. We are experiencing diminishing marginal utility for goods; persons are choosing leisure.
10. The slowdown represents a return to "natural" rates of growth after a period of "catch-up" following the shocks of the Great Depression and World War II.
11. There is no slowdown; flawed statistics have overestimated the rate of inflation and underestimated the rate of output growth.

plausible mechanisms involving forced retirement of capital stock were available. But oil prices fell dramatically in the late 80's without sparking any return to the high rates of productivity growth. Today the oil price shock hypothesis is not widely supported.

Other explanations invoke demographic changes, increased government regulations, shifts to a service economy, a loss of entrepreneurial and materialistic motivation among young people, the increasing cost of research, cutbacks in funding for R&D, and a declining rate of return on investment in technological skills. Most studies suggest that these mechanisms can only explain a small portion of the growth slowdown.

The figures in **IIA-42** suggest that growing stocks of scientists and engineers appear to have been unable to prevent a decline in productivity in the United States, France and Japan, and have just barely been able to keep Germany at a constant level of productivity. This pattern is consistent with the proposal that the stock of scientists and engineers has now become subject to decreasing returns.

A 1996 study by a commission chaired by Michael Boskin, chief economic advisor to President George H.W. Bush, concluded that the consumer price index (CPI) overstates annual inflation by 1.1 percentage points. The major portion of this error is due to the inability of the CPI to easily account for qualitative changes in output. If the rate of inflation has been overestimated then the rate of economic growth has been underestimated. An increase of 1.1 percentage points in each of the two columns in IIA-40 representing economic growth since 1969 makes the productivity slowdown appear significantly less dramatic. These revised statistics suggest that technological innovation may be playing an increasing role in qualitative improvements in output, even as product prices, and thus the CPI, remain nearly constant. Other analysts disagree with the findings of the Boskin commission and suggest that the CPI overstates inflation by not more than 0.6 percentage points.

Some analysts suggest that the productivity slowdown represents a return to a more typical long-run rate of productivity growth. On this view the high post-war growth rates, not the

BOX IIA.42. Scientists and Engineers as Productivity Factors
[reprinted from C. Jones 1995]

Figure 1. Scientists and Engineers Engaged in R&D –The countries shown are France, Germany, Japan and the US.

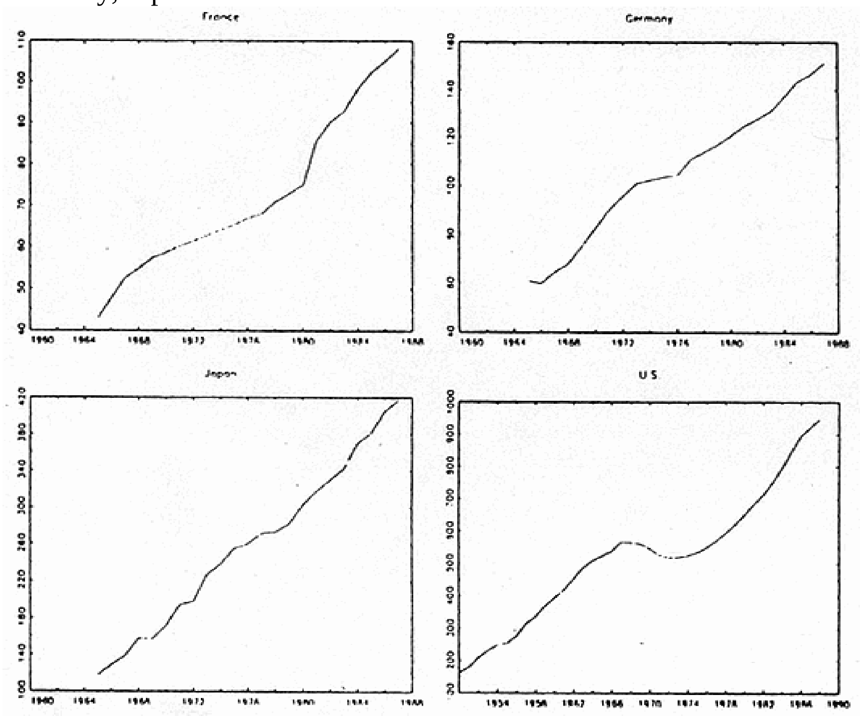
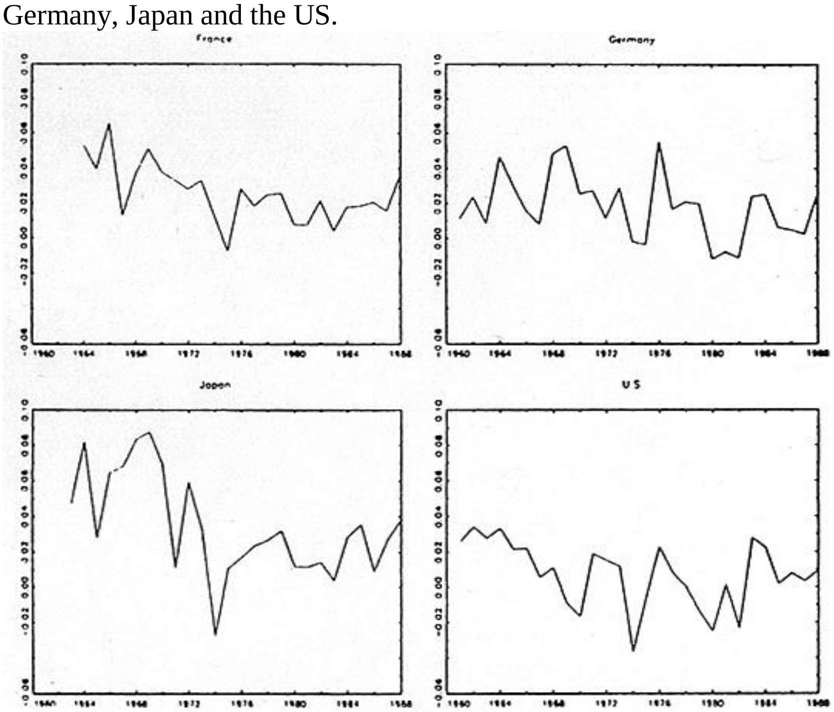


Figure 2. Aggregate Total Factor Productivity Growth The countries shown are France, Germany, Japan and the US.



slowdown, are the anomaly. These high growth rates are explained as a “catch up” phenomena following the disruptions of the Great Depression and World War II, further bolstered by a stock of new technologies in communications, transport, electronics, and materials generated by World War II.

Box IIA-43 shows that the growth of per capita GDP for the United States since 1900 (in logs) fits a simple linear trend line quite nicely. This line describes a nearly constant average rate of growth for most intervals over that period of 1.9% per year. The higher growth rates of the post-war period and the slowdown after 1973 are discernible in this figure but do not appear to be great deviations from the trend.

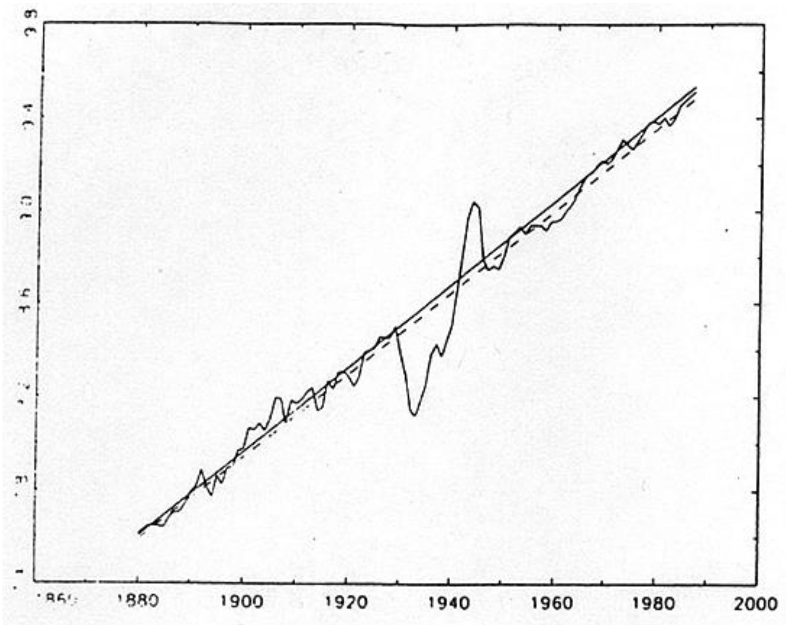
Why should we expect productivity to grow at a constant rate over so long a period of decades, and why should it be 1.9% rather than some other value? One answer is that the growth rate is determined by a so many different factors that a change in any one of them is unlikely to make a big difference. The value of 1.9% just happens to be the one that our mix of resource and technological endowments, time preferences, institutional and/or cultural factors generate.

In a review of theories concurring the post-1973 productivity slowdown, Krugman (1995) declared that “We have no idea” why it happened, or whether it can be expected to continue or not.

Beginning in 1997 the first gains in productivity in the United States since the mid-1970’s began to appear in the national income accounts. Some of these were attributed to labor force restructuring in the face of increased global competition. Others were attributed to the new information technologies, which, having passed through a fifteen-year period of high transition and learning curve inefficiencies, were now paying off with real net productivity gains.[9]

[9] See Uchitelle (1997)

BOX IIA-43. Per Capita GDP in the United States, 1880-1987
[reprinted from C. Jones 1995a]



"The solid trend line represents the time trend calculated using data only from 1880 to 1929. The dashed line is the trend for the entire sample." (p 498)