What Does Total Factor Productivity Measure?

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This paper is intended more to ask questions than to assert answers. Most strong assertions that we do make should be taken only as hypotheses. We hope in presenting the paper to learn enough to force us to change our mind on many issues. We do not, however, believe that the confusion around the interpretation of TFP numbers is unique to us. The quotations given below show the different interpretations that various eminent economists put on TFP measures.

(1) "Economists tend to think of productivity as measuring the current state of technology used in producing the goods and services of an economy (or industry or firm), and want to interpret the changes in such a measure as reflecting 'technological change', shifts in the production possibilities frontier. For this purpose, it is usual to focus on one or another version of 'multi-factor productivity'." (Griliches: 1010)

(2) "When economists speak of productivity growth, this is essentially what they mean — the growth rate is the economy's ability to produce output from a given stock of inputs. In ordinary parlance, one can think of productivity growth as 'working smarter' rather than 'working harder'. ... [T]otal factor productivity of an economy only increases if people 'work smarter' and learn to obtain more output from a given supply of inputs. Improvements in technology — the invention of the internal combustion engine, the introduction of electricity, of semiconductors — clearly increase total factor productivity." (Law: 6&7)

(3) "The defining characteristic of [total factor] productivity as a source of economic growth is that the incomes generated by higher productivity are external to the economic activities that generate growth. These benefits "spill over" to income recipients not involved in these activities, severing the connection between the creation of growth and the incomes that result." (Jorgenson, 1995 pp. xvii.)

(4) "The central organising concept...[is] the division of observed growth in output per worker into two independent and additive elements: capital-labour substitution, reflected in movements around the production function; and increased efficiencies of resource use, as reflected by shifts in this function. To maintain additivity, ...the analysis...could not be applied cumulatively without introducing an interaction term between capital substitution and increased efficiency. ...[T]he residual productivity debate never did attempt to answer the question, of what is the residual composed?

This remains the dominant question." (Metcalfe: 620)

(5) "...over the long run...the indices [of TFP] do in fact reveal the increased productivity associated with technological possibilities, either in the form of technical progress or through a better use of all available technologies." (Statistics Canada, March 1996: 119)

(6) "Technological progress *or* the growth of total factor productivity is estimated as a residual from *the* production function.... Total factor productivity is thus the best expression of the efficiency of economic production and the prospects for longer term increases in output." (Statistics Canada 13-568: 50-51, italics added)

(7) "[T]otal factor productivity (TFP) measures the output produced by given amounts of labour and capital together. High TFP indicates a high level of technology and means that both capital and labour can earn large rates of return while cost of production remains low." (Dollar and Wolff: 3).

(8) "The pioneers of this subject were quite clear that this finding of large residuals was an embarrassment, at best 'a measure of our ignorance'." (Griliches, 1994: 1)

(9) "A growth-accounting exercise [conducted by Alwyn Young.] produces the startling result that Singapore showed no technical progress at all." (Krugman: 55) "Singapore will only be able to sustain further growth by reorienting its policies from factor accumulation toward the considerably more subtle issue of technological change." (Young: 50)

Quote (1) says that economists think of changes in TFP as measuring technological change. Quote (2) says that TFP measures all improvements in technology, including such things as the introduction of electricity and the motor car. In direct contrast, quote (3) tells us that TFP measures only externalities and other free gifts associated with economic growth. Quote (4) tells us the TFP measures are valid only for measurements taken over relatively short periods of time. In contrast, quote (5) tells us TFP measures the effects of technological change and increases efficiency over long periods of time. Quote (6) goes even further and says that TFP measures the *prospects* for longer term increases in output. Quote (7) says the height of TFP measures the height of the technology in use and the magnitude of the returns to capital. In direct contrast to all the others, quote (8) cautions us that TFP is a measure of our ignorance, a measure of what we do not know. The quotes in (9) assume that low TFP measures for Singapore indicate that during the period when its per capita income rose from third-world levels to those of industrialised countries, it underwent no technological change and was thus on an unsustainable path such as that followed by the USSR.

It is something of an understatement to say that all of these statements about TFP cannot be correct. We are interested in long run technological change. We believe that much of the world's population has been living through a series of massive technological shocks that are associated with what is called information and communications technologies (ICTs). Some economists doubt this judgement because, among other things, there was no evidence of big technological shocks in the measurements of total factor productivity (TFP) over the 1990s. If anything, judging from the TFP figures, technological change seems to have slowed over the last two decades of the 20th century.

In this paper, we discuss this objection. To do this, we discuss what TFP does and does not measure, relating productivity measures to details of what is known about technological change as a result of the writings of such students of technology as Nathan Rosenberg, Christopher Freeman and Paul David. We conclude that standard TFP measures that purport to measure technological change do not do so;

nor do they measure the importance of externalities and other "free gifts" in the growth process.

Indeed, we argue that looking for the importance of new technological knowledge in measures of the type of externalities studied by Arrow in his classic 1962 article, or in observed discrepancies between private and social rates of return to R&D, is to look in the wrong place. The importance of technological change for economic growth is in the technological complementarities that it creates, not in the externalities. These complementarities go largely unmeasured by TFP calculations. Understanding these issues is a key to understanding the place of technological change in the growth process and is also important in avoiding some common misinterpretations of empirical measures of productivity change. We go on to argue that whatever may or may not be measured by TFP, it cannot be understood as measuring technological change or technological dynamism.

The Technological Background

We conceive of society as starting with two basic factors, labour, L, and the endowments provided by nature, R.[1] Society then produces output, Y, using these endowments along with two main bodies of created assets, physical capital, K, and human capital, H. The measurement of output poses massive problems, which we assume to be solved as we want to focus on the input side.[2]

We use a wider definition of technology than is usual. For us, technology is the idea set of how to create economic value, while the economic structure includes the embodiment of these ideas in such things as machines, plant layout, firm organization and location, infrastructure and financial institutions. Our definitions of technology and structure are described in full in the Appendix of the unabridged version of this paper.

Technological Change

The overall technology systems of all growing economies evolve along paths that include both small incremental improvements and occasional jumps. To distinguish these, investigators often define two categories. An innovation is *incremental* if it is an improvement to an existing technology. An innovation is *radical* if it could not have evolved through incremental improvements in the technology that it displaces-e.g., artificial fabrics could not have evolved by incremental improvements out of the natural fabrics that they displaced in many uses.

An extreme form of radical innovation is called a general purpose technology (GPT). GPTs share some important common characteristics: they begin as fairly crude technologies with a limited number of uses; they evolve into much more complex technologies with dramatic increases in their efficiency, in the range of their use across the economy and in the range of economic outputs that they help to produce. As they diffuse through the economy, they are improved in efficiency and expanded in their range of use.

As mature technologies, they are widely used for a number of different purposes, and they have many *technological complementarities* in the sense of co-operating with, and sometimes requiring amendments to, many other technologies, as well as creating myriad possibilities for the invention of new technologies.[3] The steam engine, the dynamo and the internal combustion engine are examples of major GPTs in the field of energy generation. An important thing about a GPT is that it creates a new research program for invention and innovation. As the research program proceeds, new opportunities open up exponentially. Then as the GPT matures, the number of new opportunities created per unit of time may fall steadily, causing the returns to further investment in invention and innovation to fall steadily. Note this is not the diminishing returns as the capital stock grows with technology constant.

Instead, it is diminishing returns caused by a reduction in the new rate of creation of new investment opportunities as a GPT matures.

Most technology is embodied in new capital equipment whose accumulation is measured as gross investment. So technological change and investment are interrelated, the latter being the vehicle by which the former enters the production process. Anything that slows the rate of embodiment through investment, such as unnecessarily high interest rates, will slow the rate of growth, just as any slowdown in the development of new technology will do so in the long term. So, from the fact that new investment and growth in employment can statistically "account for" most economic growth, it does not follow that these are the main causes of growth. Both technological change and investment are needed.[4]

Holding technology constant

Since we are considering attempts to measure technological change, the concept of constant technology is critical. To hold technology constant conceptually we need to do the following: hold all product, process, and organizational technologies constant at what was known at some base period; accumulate more physical capital that embodies the technologies then in use, or others that were known but not in use; accumulate more human capital in the form of more education in what was known at that time. Then calculate the increase in output. This is a measure of what could have been achieved without any alteration in technological knowledge. Now calculate the actual increase in output. The difference is "due to" or "enabled by" technological change in the sense that it could not have happened without such change.

Measured over the long run, say a century, the difference due to technological change would be massive. Here are just a few illustrative examples of what the constant-technology experiment would reveal.

- Feeding 6 billion people with the agricultural technologies of 1900 would have been literally impossible.[5] Sooner or later Malthusian checks would have become a reality as ever expanding populations would have encountered increasing food shortages. (Among other things this shows that population and the labour force cannot be taken as independent of technology.)
- Pollution would have become a massive problem. By our standards, 1900 technologies were heavily polluting and to increase production sufficiently to employ all the new capital would have led to major increases in pollution.
- Resource exhaustion would have been serious. Most new technologies are absolutely saving in resources.[6] Thus to produce today's manufacturing and service output with 1900 technologies would have required vastly more resources than are currently used.

In another demonstration of these points, the calculations of the Club of Rome in the 1970s showed the folly of believing that production could long be increased at current rates with no change in technology. The Club's predictions of doom were falsified by continued technological advance, which invalidated their calculations on resource exhaustion and unsustainable pollution. But these mistaken predictions do show for how few decades current world growth rates could be sustained in a world of static technology.[7]

Continuity and discontinuity in technological change

Aggregate growth models use an aggregate production function of the form:

$Y= F(K, H, L)$. Such models display a continuously declining marginal product of physical and human capital that is only increased by continual gradual increases in the productivity constant *A*. But one of the most important propositions that matter later in this paper is that technological change is not like that. It does not cause continuous variations in the marginal productivity of capital as more capital is accumulated and as technological change slowly and continuously alters the relation between inputs and outputs. Instead major technological advances of the sort now called new GPTs cause discontinuities in the opportunities for new investment and radically alter the relation between inputs and outputs at the microeconomic level. As Lipsey and Bekar put it some time ago in another context:

> "[As] any one technology evolves over time ...its productivity [may] approach an upper limit beyond which further improvements are difficult if not impossible. [However] when there is a shift from one technology to another and then to a third, there is no reason to expect any particular relation between the increments of output that arise in moving between technologies... Consider, for example, successive energy technologies... The factories of the First Industrial Revolution were powered by water power (K_1). Then, in the early nineteenth century, the transition was made to steam (K_2). Then in the period from 1890 to 1930 electricity replaced steam... (K_3). At some future time, nuclear fission and/or fusion may replace fossil fuels as the main generators of power for electricity (K_4). Still later, electricity itself will give way to some hard-to-imagine, new energy source... (K_5).
>
> Now consider the increment in total constant-dollar value of production $[Y(K_{n-1}) - Y(K_n)]$ that is due to each shift from one technology to the next technology. No matter how the impact is measured, there is nothing in physics or economics to suggest that the increments in going from one technology to the next have to be ordered in the following way:
>
> $[Y(K_2)-Y(K_1)] > [Y(K_3)-Y(K_2)]>[Y(K_4)-Y(K_3))]>[Y(K_5)-Y(K_4)]$
>
> Indeed, there are no currently known general principles to suggest any particular relation, and we can see may different ones in history. Historical experience suggests that, as time passes, one technological change may bring massive gains, to be followed by another that brings smaller gains, to be followed by a shift that brings larger gains — and that this is true on each of the many fields in which technology is used."

Interpreting the potential of each GPT in terms of the research program for invention and innovation that it creates, Lipsey and Bekar are saying that the richness of successive programs associated with successive GPTs may stand in any relation to each other. A GPT will only be introduced if it is more efficient than the technology it replaces. But GPTs that meet that criteria, some will have very much richer potential for dependant innovation than others. Some will therefore lead to more rapid and more fundamental changes in technology and productivity than others.

Is there a productivity paradox?

Models of both exogenous and endogenous growth that use an aggregate production function do not explicitly model technology. They conceal technology and technological change in the black box of the aggregate production function that transforms inputs into total output

(GDP). Technology is itself unobservable in these models, while changes in technology are observed only as a residual when changes in measured outputs are not fully matched by changes in measured inputs. Changes in the TFP residual are assumed to measure changes in the production function and hence to be related to changes in technology. The so-called productivity paradox relates to the observation at the micro economic level of major technological changes associated with the ICT revolution combined with the observation of low rates of productivity growth at the macro level as measured by TFP (and other productivity measures).

We do not accept the existence of a productivity paradox (assuming productivity can be properly measured). We argue two key points briefly in the text and in more detail in the appendix, which compares the model we use for viewing long term growth and technological change with standard macro models.

First, new fundamental technologies, even where they do greatly raise productivity and living standards over the long term, typically have long gestation periods. They often need decades to develop their full potential.[8] Also, the whole structure of the economywhat we call the facilitating structure as outlined in the appendixoften needs to be altered. As Paul David (1991) has emphasized, this requires much time, so that these technologies may show only small macro benefits in the short term of several decades, and but big payoffs over the very long term of half a century or more.

Second, and much more fundamentally, we argue, in contrast to the macro models mentioned above, that there is no necessary relation between technological changes and productivity changes, however the latter are measured. For example, from 1770-1820 the whole of British society and the whole basis of the economy was transformed by the First Industrial Revolution that took work out of the homes and put it into proto-factories — sheds containing hand-powered machines — and actual factories containing water-powered machinery. Although this was a fundamental social and technological transformation that contained the seeds of most of what followed later in the 19th century, changes in productivity and real wages were small or nonexistent (Crafts 1985).[9] In contrast, changes associated with the second phase of the Industrial Revolution when steam power was brought into the factories and combined with improved versions of automated textile machinery caused productivity and real wages to rise substantially over the period 1820-1870.

The conclusion to be drawn from these and other similar historical events is that the only thing we can say about a new technology that replaces an existing one is that it must be expected to bring some gain (or else it would not be adopted). But the margin of gain measured in terms of such things as reduced cost and/or increased revenues may be small or large or anything in between. In other words, *productivity changes and technological changes do not stand in any invariant quantitative relation to each other*: *nor are measured productivity changes any necessary indication of the depth of some technological transformation that the society is undergoing.*

Natural Resources Made Explicit

The problems with total factor productivity as a measure of technological change can be illustrated with a preliminary contrast between two positions. (The problems are studied in detail in the unabridged version of this paper.)

Contrasting predictions

The first is the prediction following from the standard neoclassical aggregate production function that measured capital and labour could have been increased at a constant rate from 1900 to 2000 with constant technology and no change in living standards. The second is our argument in a previous section that such an event would have had catastrophic effects on living standards.

To reconcile these conflicting positions we need to recognize that for the neoclassical prediction to hold the capital that would need to grow would include such resource inputs as agricultural land, mineral resources, "waste disposal" ecosystems, fresh water resources, and a host of other things that the standard measurements of capital ignore. Following Solow (1957), however, economists typically define the stock of physical capital used in their growth models to include the stock of natural resources, land, minerals, forests etc. Yet everything that is then assumed about capital is appropriate to physical and human capital and takes no account of the specific problems of natural resources. For example, although the stocks of plant and equipment can be increased more or less without limit, the stocks of arable land and mineral resources are constrained within fairly tight limits.

Since we see society as starting with people and what nature provides, and since the evolution of stocks of capital often obey laws that differ from those that govern the evolution of the stocks of natural resources, we find it conceptually useful in our theorizing to separate the stock of natural resources from the stock of created physical capital. Natural resources are used up in the process of production and some, such as petroleum, cannot be replaced while others, such as trees and the fertility of land, typically (although not invariably) can be. The problems associated with renewable resources are not unlike those associated with physical capital. Most renewable resources such as the air and water that remove pollution and nurture fishing stocks, are naturally renewable up to some maximum rate of exploitation, after which help is needed up to some higher rate of exploitation, above which the stocks may deteriorate even when helped.

To account for these stocks, we need to deduct the natural resources used in current production, and treat as gross capital investment the amounts spent in maintaining existing resources (e.g., the productivity of land) restoring those used up (e.g., reforestation) and discovering new supplies (such as mineral exploration).

Importantly, technological advance alters the economic value of existing natural resources. Some values may be lowered, such as when the invention of the electric motor and the internal combustion engine lowered the value of coal reserves, while other values may be greatly enhanced (sometimes starting from a base of zero value), such as when the introduction of the gasoline engine and the automobile greatly increased the value of petroleum reserves.

These changes in resource values are sometimes consciously created by technological change, as when methods of using low grade iron ore and tailings from previous operations, were invented. At other times, they are the unconscious result of technological advances pursued for other purposes, as when the internal combustion engine, which started out as a stationary engine driven by coal gas, finally settled on petroleum products as its most efficient fuel.

The absence of explicit resource inputs from the neo-classical growth model, poses no problem as far as income goes because all of the value of consumed resources must show up as income for the labour and capital involved in extracting and processing them. But we know that resources are important inputs into any real production function. Rosenberg (1994) has shown, for example, that the so-called American System of Manufacturers, which was the basis of America's overhauling Europe as the prime industrial country, was based on processes that made lavish use of natural resources while economizing on scarce labour. (Capital was also lavishly used at first but, later, the innovations became capital saving as well as labour saving.)

Modeling resources

To illustrate some of the problems associated with the omission of natural resources let the underlying production function be:

(1) $Y = AK^{\alpha}L^{\beta}R^{\delta} \quad \alpha+\beta+\delta = 1$

where K is produced capital and *R* is natural resources, agricultural land, forests, minerals, air, water, etc.

Now let *K* and *L* increase at a constant rate *u*. If nothing else happens, there will be diminishing returns as more labour and capital are applied to a given resource base. Output will be increasing at the rate $(\alpha+\beta)u$ and so per capita real income will be shrinking. ($Y_t = Y_o e^{(\alpha+\beta)t}$, which, since $\alpha+\beta < 1$, is a declining series.)

Now reallocate some of the capital formation to creating technological change in the resource industries. The new technologies are resource saving (as the evidence cited earlier in this paper shows that they are). Assume that as a result of the R&D, resources are also growing at the rate *u*, measured in *efficiency units*. (This is exactly the same as Harrod neutral technological change, only the input whose efficiency is growing is resources rather than labour.) Total income, capital and labour are now all growing at the rate *u* while per capita income is no longer falling. However, if we measure *R* in physical units, *R* will be constant, while *A* will be growing at the rate δu.

If we now take the data generated by (1) and fit a constant returns to scale production function without *R* in it, we will get a perfect fit with the equation :

(2) $Y = BK^{\varepsilon}L^{1-\varepsilon}$

where $B = AR^{\delta}$ and ε will exceed α by the share of capital in the costs of producing resources and $1-\varepsilon$ will exceed β by the share of wages in resources costs. Thus we can fully explain the growth process that is actually being driven by "resource enhancing technological change" in terms of a constant returns production function containing only two inputs, *K* and *L*, and with an unchanged productivity parameter. So measured TFP will be zero and all the increase in output will be ascribed to increases in measured labor and measured capital.

We conclude that because resources are not specifically modelled in the neoclassical growth model, much of the substantial amount of technical change that goes into increasing the productivity of given natural resources will show up as increases in capital, labour (and depending on accounting procedures, possibly also as R&D) and, not as shifts in the production function.

Notice that this conflicts with Griliches' treatment of unrecorded inputs in his discussion of errors in measuring TFP. He argues, not implausibly, that an increase in any unmeasured input would raise output without raising measured costs and so would add to measured TFP. *The present discussion shows that technological change that increases the efficiency of an unmeasured input may show up as an increase in measured costs and hence leave TFP unchanged. This is one of the many reasons why changes in TFP do not measure technological change.*[10]

Conclusions

Here are some of the conclusions that the present study has reached and concerns that it has raised about TFP.

- TFP cannot simultaneously measure all technological change and just the free gifts from externalities and scale effects.
- All improvements in technology, such as the internal combustion engine, do not "clearly raise TFP".
- Increases in output that would not have occurred without technological change (i.e., for which technological change is a necessary condition) do not necessarily cause TFP to increase.
- TFP does not measure "prospects for longer term increases in output" since, among other reasons, new GPTs tend to be associated with up-front costs and downstream benefits.
- There is reason to suspect that TFP does not adequately reflect the increase in a firm's capital value created by R&D activities that are realised through sale rather than exploitation by the developing firm. Yet these are often technological advances created by the use of valuable resources.
- TFP does not adequately capture the effects of those technological changes that operate by lowering the cost of small firms and then allowing large subsequent increases in sales and outputs.
- TFP does not adequately measure the massive amount of technological change that gets embodied in physical capital where the change tends to be recorded as an increases in capital rather than a change in productivity.
- When full equilibrium does not pertain, as in the midst of any lagged adjustment process, the marginal equivalencies needed for successful aggregation do not obtain and there is every likelihood that increases in productivity of labour and capital will be recorded as increases in the quantities of labour and capital inputs.
- New technologies often lead to large up front costs of R&D and learning by doing and using that are incurred in the expectation of future benefits that will be missed when current outputs are related to current costs. The amount of this activity may vary with the life cycle of GPTs and other major technologies and so, thus, may measured TFP.
- Neither TFP nor externalities measure the technological complementarities by which an innovation in one sector confers benefit on other sectorsbenefit for which those in other sectors would be willing to pay but do not have to do so.
- Low TFP numbers for the Asian Tigers do not mean they are in the same boat as was communist Russia; they are quite compatible with successful technology enhancing policies and technological transformation of a country through domestically generated or imported capital.
- TFP is as much a measure of our ignorance as it is a measure of anything positive.

It seems to us that, whatever TFP does measureand there is cause for concern as to how to answer that question — it emphatically does not measure technological change. In the long term, we are interested in increases in output per unit of labour, resources (and waiting in the Austrian sense of the term). While people are of course free to measure anything that seems interesting to them, the degree of confusion surrounding TFP, particularly the assumption that low TFP numbers imply a low degree of technological dynamism, would seem to us to justify dropping the measure completely from all discussions of long term economic growth. Even if that does not happen, as we are sure it will not, every TFP measure should carry the caveat: *changes in TFP do not in any way measure technological change.*

Notes

* This article is drawn from a much longer paper of the same title that can be found at www/sfu.ca/~rlipsey. References omitted from these excerpts are given in the full version. Note that the excerpts give the first part of the paper in its entirety and then jump to the conclusions most of which depend on arguments not given in these excerpts. Email: Richard G. Lipsey: rlipsey@sfu.ca; Ken Carlaw: k.carlaw@econ.canterbury.ac.nz

1 What is provided by nature is exogenous but similar resources may also be created by human effort as when a forest is replanted or a like restocked.

2 As we later argue, the importance of technological change is in preventing the decline of the marginal productivity of capital that would inevitably occur with constant technology. A similar force operates on the output side. If the technology of consumers goods and services were to have been held constant at those existing at some earlier point in time, say 1900, diminishing utility of income would be a reality, as consumers wondered what to do with a third and fourth horse and buggy and train trip to the nearby seaside. Technological changes in consumers goods constantly present consumers with new consumption possibilities and removes at least the inevitability of rapidly declining marginal utility of income as income rises over time, (which does not prevent marginal utility of income from declining at a point in timewhen, of necessity, technology is constant).

3 For a detailed consideration of these characteristics and a development of the definition that follows in the text see Lipsey, Bekar and Carlaw, Ch. 2 in Helpman (1998). The entire book is of value in studying GPTs.

4 Nonetheless consider the choice between two polar cases, one could either live in a society in which technology advanced but was only embodied through "replacement investment" since net investment (and hence measured capital accumulation) was zero, or in a society in which nothing was known that was not known in 1900 and more and more investment had been made in 1900-style productive facilities to produce 1900-style goods and services. We wager that most people would prefer the former alternative. As Solow long ago observed: "One could imagine this [growth] process taking place without net capital formation as old-fashioned capital goods are replaced by the latest models, so that the capital-labour ratio need not change systematically." (Solow, 1957:316)

5 Of course, population is endogenous and it is not clear how much population would have increased if food producing technologies had remained frozen at their 1900 levels. However, Western practices of cleanliness had already lowered death rates in the West and had led to large increases in life expectancy with a resulting population boom, and these practices were already being extended to the less developed countries. Thus some large population expansion would certainly have occurred.

6 "Total materials requirements per unit of (constant) GDP have declined between 1.3% per year in Germany, 2% per year in Japan, and 2% per year in the Netherlands" (Grubler: 240).

7 A further problem arises in altering the capital labour ratio with fixed technology. In so far as the population increase and new capital is merely replicating existing productive facilities staffed by new workers, production can be expanded at more or less constant returns to scale. But this process employs more persons while leaving constant their productivity and hence their real wages and living standards. Raising living standards with static technology requires increasing the capital labour ratio. Although new technologies often do this, existing technologies, especially in manufacturing, typically have little scope for varying the capital labour ratio, factor proportions being more or less built into them. It would be impossible, for example, to take a plant designed in 1900 to produce steam engines and increase the amount of capital per worker by 500%. There was room for some substitution of capital for labour within the confines of existing technology of steam engine construction, but not much. So, if the economy were to grow by increasing the capital per head from its level in 1900 to its level in 2000 without altering technology, it would become increasingly difficult to find places in which the extra capital could be profitably employed. Much of it would end up in non-manufacturing activities, while manufacturing areas, which were, in actuality, some of the main sources of rising living standards throughout the 20th century, would be carried on in unchanged ways with little increase in capital per head.

8 For a more detailed description of the evolution of a GPT see Lipsey, Bekar & Carlaw, Chapter 2 in Helpman (1998).

9 For another interesting piece of evidence, the old technology of hand loom weavers persisted side by side with the new technology of automated weaving for more than 50 years. The number of weavers and their wages fell steadily but the process took a very long time. This could not have happened if the new technology had been radically more efficient than the old, illustrating that there is no necessary likes between big technological change and big productivity gains.

10 This is a caution for macro modellers and those who calculate TFP from aggregate data. However, industry studies that include resources as inputs of downstream industries and as outputs of basic industries may catch these productivity gains by showing a ceteris paribus decline in resource inputs. (Although we would have to know much more than we now do to say whether or not this gain would be washed out when aggregating over all the sectors.)