Catch-Up and Leapfrog between the USA and Japan

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Abstract: The growth process for a technological leader is different from that of a follower. While followers can grow through imitation and capital deepening, a leader must undertake original research. This suggests that as the gap between the leader and the follower narrows, the follower must undertake more formal R&D and possibly face a slower overall growth rate. This paper examines these ideas by discussing some simple models of technological catch-up and convergence and then applying them to the relative growth experiences of US and Japanese manufacturing. We construct measures of relative total factor productivity for eleven Japanese manufacturing industries and test whether a smaller productivity gap leads to slower growth, and whether R&D takes over as the engine of growth as Japan approaches the technological frontier. Our results suggest that Japanese and US productivity have been growing at similar rates since the mid-1970s, and that some of the Japanese growth slowdown is attributable to the exhaustion of imitation possibilities. Furthermore, since Japanese total factor productivity growth is faster than US growth before the mid-1970s, our results cast doubt on much of the cross-section convergence literature that assumes similar technology parameters across countries.

Keywords: Innovation, Openness, Research & Development, Human Capital, Economic Growth, Total Factor Productivity.

JEL Classifications: C13, C23, O30, O47.

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1. Introduction

In 1952, Japan had a per capita GNP of $188 in the prices of the day, below that of Brazil, Malaysia, and Chile. Like many present-day low income countries, Japan then had a high proportion of its labour force in agriculture; a relatively small capital stock; and a relatively low level of technology. However, it also possessed a highly educated and skilled workforce in manufacturing; large productivity differences between well-developed sectors and under-developed sectors; and significant strengths in management and organisation. By 1992, Japan had the fourth highest GNP per capita in the world, ranking only behind Luxembourg, Switzerland and the USA.[1]

Many estimates have been made of labour productivity levels in Japan, but less effort has been devoted to the estimation of relative levels of *Total Factor Productivity*.[2] This paper advances the literature in two ways. First, it provides detailed estimates of relative total factor productivity levels in eleven US and Japanese manufacturing industries between 1955 and 1989. Second, it estimates the effects of two separate influences on relative Japanese productivity performance - catch-up, and domestic R&D. The paper argues that after Japanese industries exhausted catch-up gains from imitation, they had to increase their R&D efforts to maintain their growth rates. The use of a panel data framework enables estimates to be made of the interactions between various industry characteristics and the effect of the productivity gap on TFP growth.[3]

This paper has six sections. The second discusses the theory behind the convergence hypothesis, especially the roles played by technological lock-in, imitation, and R&D. The third presents a simple model of growth through catch-up and imitation. The fourth discusses the measurement of relative total factor productivity and presents estimates of relative productivity levels in the US and Japan. The fifth develops an econometric model of relative productivity and presents estimates of the effect of imitation and R&D. The sixth draws conclusions. The paper has two appendices. The first outlines the Purchasing Power Parity data used in the paper. The second discusses data sources.

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[1] Good introductions to the phenomenon of Japanese economic growth are provided by Denison and Chung (1976), Patrick and Rosovsky (1976) and Balassa and Noland (1988).

[2] Exceptions to this are provided by Denny et al. (1992), Dollar and Wolff (1994), and Kuroda (1996) who all construct relative measures of Japanese and US TFP. Their results are discussed in section 4.3.

2. Leapfrogging in International Competition

2.1. Concepts of Convergence

Table 1 shows relative labour productivity levels in the Group of Seven nations between 1820 and 1987. During the nineteenth century, the United Kingdom had the highest level of labour productivity, closely followed by the USA. Sometime around the turn of the century, US labour productivity overtook that of the UK, and continued to forge ahead of the UK until the 1930s. However, aside from the performances of the UK and the USA, there are no clear trends apparent over this period, and so it is not clear that any convergence process was at work before the Second World War.[4] Between 1950 and 1987, however, the US productivity advantage diminished, with every other country catching up to some extent.

Table 1
International Levels of Labour Productivity

	1820	**1870**	**1890**	**1913**	**1929**	**1938**	**1950**	**1960**	**1973**	**1987**
	UK=100			**US=100**						
US	83	96	99	100	100	100	100	100	100	100
Japan	31	18	20	18	22	23	15	20	46	61
Germany	62	48	53	50	42	46	30	46	64	80
France	80	54	53	48	48	54	40	49	70	94
Italy	58	39	35	37	35	40	31	38	64	79
UK	100	100	100	78	67	64	57	56	67	80
Canada	..	62	63	75	66	58	75	79	83	92

Source: Maddison (1991)
Note: Labour Productivity is defined as GDP per man-hour

The traditional Solow growth model suggests that per capita growth rates should be inversely related to initial levels of income over a transitional period. Poor countries should grow more rapidly than rich ones through capital deepening, conditional on their having the same determinants of steady states such as preferences and technology parameters. Levels and growth rates of income per capita should converge over time for countries and regions. However, endogenous theories of growth tend to produce a much more complex set of results.

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[3] See Cameron, Proudman and Redding (1998) for a similar analysis of the UK and the USA.

[4] See O'Rourke & Williamson (1995) or Crafts (1996) for fuller discussions of the period before the Second World War.

There are two main convergence concepts - *b-convergence* and *s-convergence*. *Absolute b-convergence* occurs if poor economies tend to grow faster than rich ones. This is typically tested by estimating a cross-section regression of growth rates on per capita income levels, such as:

(1) $$\Delta \log(y_{i,t,t+T}) = a - b \log(y_{i,t}) + e_{i,t}$$

where $y_{i,t}$ is the level of per capita income in country *i*. If $b>0$, there is absolute β-convergence. Some regressions include other explanatory variables on the right hand side, which implies *conditional b-convergence*, that is, countries converge to different steady-states.

There is *s-convergence* if the dispersion of real per capita GDP levels tends to decrease over time. This is if, $s_{t+T}<s_t$ where s_t is the standard deviation of $\log(y_{i,t})$ across *i*. As Sala-i-Martin (1996) and Lichtenberg (1994) note, these concepts are related. Technically, *b-convergence* is a necessary condition for the existence of *s-convergence*, but not a sufficient condition (see Dowrick and Quiggin, 1997).

One reason why much of the initial research on convergence focused on *b-convergence* is that it can be easily derived from a neo-classical growth model. Consider a Solow (1956) world with a Cobb-Douglas production function where output is a function of capital and labour inputs, and technological change is labour-augmenting. The growth rate of capital per unit of effective labour is given by:

(2) $$g_k = sA(k)^{-(1-a)} - (x+n+d)$$

which simply states that the growth of capital per unit of effective labour is equal to net investment minus technological progress, *x*, labour growth, *n*, and depreciation, *d*. As Barro and Sala-i-Martin (1995, pp. 37) show, this implies that the growth rate of output per unit of effective labour in the neighbourhood of the steady-state is:

(3) $$g_y \cong -(1-a)\cdot(x+n+d)\cdot[\log(y/y^*)]$$

where y^* is the steady-state level of output per unit of effective labour. We can re-write this as:

(4) $$g_y \cong -b\cdot[\log(y/y^*)]$$

where $b=(1-a)(d+n+x)$ indicates how quickly output per unit of effective labour approaches its steady-state value. If $b=0.05$, then 5 per cent of the gap between y and y^* disappears every year. In this model, neither the saving rate, s, nor the level of technology, A, affects the speed of convergence.

What would be a reasonable value of b? The typical values for an OECD economy would suggest a capital share a of 0.3, a depreciation rate d of 0.05, labour force growth n of 0.01, and technological progress x of 0.02. We would then expect a b of 0.056. However, absolute-convergence studies typically find $b=0.02$, which implies a value of $a=0.75$. This is interesting because a number of early new growth models suggest that the capital share in output is under-estimated either due to externalities to capital formation or due to human capital. Using similar parameter values, Mankiw (1995) argued that a is around two-thirds. Note that in the AK model of growth, $a=1$, so $b=0$, by analogy.

The Solow model only predicts absolute convergence if the sole difference between the countries is their initial levels of capital. They must have access to similar technologies, hence all growth is through capital deepening. If the economies have different technologies and other structural parameters, they will have different steady states and so will not exhibit absolute convergence. However, the growth rate of each country will be positively related to its distance from its own steady-state. This is known as *conditional convergence*. Two main methods have been used to test conditional convergence. The first is to include extra explanatory variables on the right hand side of equation (1) to capture the different steady-state levels of per capita output. The second is to separate countries into smaller samples within which similar technologies and other parameters might be expected, such as the OECD or sub-Saharan Africa.

Surveying the evidence, Sala-i-Martin (1996) argues that there are four main lessons to be gained from the classical approach to convergence analysis. First, that for the whole world, there was no σ-convergence and no absolute β-convergence in GDP between 1960 and 1990. Second, that for a sample of 110 countries, there is evidence of conditional convergence over that period at around 2 per cent per year. Third, that for the OECD, there is evidence of absolute β-convergence at a rate of around 2 per cent per year, and also of σ-convergence. Fourth, the regions within the US, Japan, Germany, the UK, France, Italy, Spain and other countries display absolute (and therefore also conditional) β-convergence, as well as σ-convergence.

This summary is supported other work. A number of authors have rejected absolute β-convergence except for groups of similar economies such as the OECD (see Durlauf and Johnson, 1995, and Temple, 1998a), while there appears to be more evidence for conditional β-convergence (see Mankiw, Romer, and Weil, 1992, and Levine and Renelt, 1992, although Temple, 1998b, argues that the speed of conditional convergence is highly uncertain). The finding of conditional convergence simply indicates that countries are converging to their respective steady-states.[5]

Quah (1993, 1996 and 1997) provides a strong critique of the relevance of such findings. He argues that the key issue in the convergence literature is not whether a single economy is tending towards its own steady-state but what happens to the entire cross-sectional distribution of economies. Both the β-convergence and σ-convergence concepts discussed above cannot address this issue, particularly because β-convergence is affected by a version of Galton's Fallacy. Instead, Quah suggests that attention should be focused on the distributional dynamics, which suggest that there are convergence clubs as observed by Baumol (1986). Indeed, Quah argues that the distribution is polarising into twin peaks of rich and poor countries.[6]

There are several theoretical reasons that we might expect such a bimodal distribution to develop, such as the existence of a poverty trap. Barro and Sala-i-Martin (1995, pp. 49) define a poverty trap as a stable steady-state with low levels of per capita output and capital stock. This is a trap because, if agents attempt to break out of it, the economy has a tendency to return to the low-level steady-state. Only by a very large change in their behaviour can the economy break out of the poverty trap and move to the high-income steady-state. Similarly, in the Solow model bimodality can arise if there are two steady states to which countries tend. Olson (1996) argues that it is the structure of incentives that

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[5] Barro, Mankiw, and Sala-i-Martin (1995) argue that rates of convergence may be affected by the openness of the economy and by its ability to borrow capital on international markets, as is suggested by the evidence of Sachs and Warner (1995). Islam (1995) and Temple (1998b) argue that cross-section estimates are biased since omitted 'fixed effects' are correlated with the regressors.

[6] See Lewis (1954), Murphy, Schleifer and Vishny (1989), Azariadis and Drazen (1990), Goodfriend and McDermott (1995), Redding (1996a), and Jovanovic and Nyarko (1996) for related discussions.

prevents a growth breakout from occurring, while Young (1993) argues that market size is important.

Quah (1996) argues that there are two separate aspects of the growth process. The first is the mechanism by which agents in an economy push back technological and capacity constraints. The second is the way in which a poor economy can learn from an advanced economy. Both the *growth process* and the *convergence process* may occur at the same time, or separately, depending on the country in question, but they are distinct concepts. In a related discussion, Bernard and Jones (1996a) argue that the main problem with the convergence literature is that it concentrates on capital accumulation and neglects the role played by technological change.[7]

2.2. Lessons from South East Asia

In 1960 South Korea was poorer than many sub-Saharan African countries, and Taiwan not much richer, but between 1960 and 1989 these two countries grew at over 6 per cent a year.[8] Before the economic crises of 1997 and 1998, there was considerable controversy about whether the astonishing growth rates of these and other East Asian Newly Industrialising Countries were due to factor accumulation or TFP growth.

Young (1995) argues that the TFP performances of Hong Kong, Singapore, South Korea, and Taiwan have not been exceptional, once account is taken of the dramatic rise in factor inputs. Young argues that all these countries were able to expand output very rapidly through increasing levels of participation, education, and investment, and through the transfer of labour into manufacturing. He estimates that between 1966 and 1990, TFP rose at around 2 per cent per annum in Hong Kong, South Korea, and Taiwan, and at only 0.2 per cent per annum in Singapore. This scarcely constitutes a TFP growth miracle.

Young’s findings are supported by the work of Kim and Lau (1994) who also found that capital accumulation is by far the most important source of economic growth of the East Asian NICs, accounting for between 48 and 72 per cent of their growth. In contrast, Kim

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[7] Although, see Maddison (1994) and Dollar & Wolff (1994) for exceptions to this.

[8] This comparison is due to Rodrik (1995).

and Lau found that technical progress played a more important role for the Group of Five industrialised countries (France, Germany, Japan, the UK, and the USA), accounting for between 46 and 71 per cent of economic growth. Kim and Lau found rates of TFP growth of around 2 per cent in Hong Kong and Singapore, and slightly more than 1 per cent in South Korea and Taiwan. Kim and Lau use these estimates to argue that the East Asian NICs have grown largely through factor accumulation and their rates of TFP growth are broadly the same as those of other countries, both industrialised such as the Group of Five, and developing such as Brazil.[9]

In contrast, Singh and Trieu (1996) calculate rates of TFP growth for Japan, South Korea, and Taiwan and argue that their growth is not simply explained by factor accumulation. Using a similar method to Young (1992), they estimate that all three countries show similar TFP growth rates (around 2.5 per cent). They argue that while these growth rates are not miraculous, they are high compared with those of Latin America. They also argue that South Korea and Taiwan grew faster than Singapore, and that Kim and Lau's results are an artefact of their pooling of Hong Kong, South Korea, Singapore, and Taiwan.

Islam (1995) argues that steady state income levels differ across countries not only because of differences in saving rates and population growth, but also because of differences in levels of technology. His panel data model produces an estimate, *logA(0)*, which is similar to a measure of relative total factor productivity[10]. For 1960, he finds the highest level of *logA(0)* in Hong Kong, followed by Canada and the USA.[11] Interestingly, in terms of the above discussion of Alwyn Young's work, the value for Hong Kong is much higher than that of Singapore (58 per cent higher in fact).

Overall, the papers discussed above suggest that much of the East Asian growth miracle is explained by capital deepening and human capital accumulation. Nonetheless, the estimated rates of TFP growth for Taiwan, Hong Kong, and South Korea, although not miraculous,

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[9] Park and Kwon (1995) find that TFP growth in South Korean manufacturing is negative between 1960 and 1987, and ascribe this to lack of investment in R&D and a reliance upon imitation, capital deepening, and scale economies to increase output. See Krugman (1994) for a non-technical discussion of the East Asian miracle.

[10] Islam's estimate of *logA(0)* is the country-specific effect in his dynamic panel data model and is therefore similar to a total factor productivity level, but is not calculated on the basis of a time-series comparison.

[11] The value of *logA(0)* in Hong Kong is 9.08, compared with 8.69 in Canada, 8.65 in the USA, 8.41 in Japan, 8.31 in the UK, and 8.26 in Germany.

compare favourably with those of other developing countries and with the OECD. Singapore stands out as an exception, seemingly having experienced little TFP growth along with very high rates of capital accumulation.

2.3. Theories of Endogenous Leapfrogging

Grossman and Helpman (1991a: chapter 8) examine the relationship between growth and trade. They identify three kinds of international openness. First, the international transmission of ideas. Second, the international flow of goods and services. Third, international movements of capital. Overall, openness encourages growth in four main ways:

- Openness allows the transmission of technical information.
- Openness encourages entrepreneurs to innovate and to pursue best-practise technologies.
- Openness enlarges the size of the market which means more sales and profits for a given market share, but also may mean more competitors.
- Openness leads to a reallocation of resources that may affect growth.

Two of the main conclusions of Grossman and Helpman’s work are that, first, when knowledge spillovers are small and countries are dissimilar in size, the small country may find its world market share declining over time because of economies of scale in research, and second, that technologically backward countries will tend to remain backward.[12]

Despite these pessimistic arguments, however, many other authors have suggested that we are likely to observe convergence, rather than divergence, in practice (see Barro and Sala-i-Martin, 1991, Benhabib and Spiegel, 1994, Sachs and Warner, 1995, and Bernard and Jones, 1996a). This may be because leaders eventually stumble, allowing their rivals to catch-up, or because international knowledge spillovers are sufficiently large. Olson (1982) suggests a rather more complex sociological analysis whereby successful nations eventually

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[12] See also Boldrin and Rustichini (1994) for a model of endogenous growth where persistent differences in growth rates are possible.

accumulate so many institutional rigidities that other nations can catch-up and surpass them.[13]

Some researchers have argued that leaders may become ‘locked-in’ to old-fashioned technologies.[14] Redding (1996b) develops a model of competition, where there are both primary and secondary innovations, in the spirit of Aghion and Howitt (1992). This model can be applied to international competition. Primary innovations can be adopted by any country and represent new best-practise technologies, while secondary innovations are country-specific (they may, for example, by related to physical investment). When a new primary innovation arises, its relative profitability at first will depend on how much secondary innovation has occurred in the previous best-practise technology in each country. The lead nation may have done so much secondary innovation that it is not profitable to adopt the new primary innovation immediately, whereas a nation without a presence in the industry may find it profitable to adopt and so reap rapid ‘learning-by-doing’ economies and overtake the leader. This argument can also be applied to a variety of two-sector models, whether the sectors are food and manufactures (as in Brezis et al., 1993) or labour-intensive and capital-intensive techniques (as in Broadberry, 1994).

An alternative to the technological lock-in theories is provided by Barro and Sala-i-Martin (1997). In their model, firms can choose to grow through either imitation or research. In the long run, growth is driven by innovation in technological leaders, but followers converge towards the leaders because imitation is cheaper than innovation for some range of technology gaps. As the technology gap closes, the cost of imitation rises so that convergence in total factor productivity occurs.

Redding (1997) makes the distinction between the traditional, or *static*, notion of comparative advantage and a second concept of *dynamic* comparative advantage. His model assumes that there are two countries, one of which is the technological leader (that is, has an absolute advantage) in both sectors of production, the high-technology sector and the low-technology sector. In order for the incomes of two countries to converge, the backward country must be incompletely specialised under free trade, while the leader specialises in high-technology goods. If the backward country has a dynamic comparative

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[13] See Lazonick (1994) for another view of the role of social organisation in growth.

advantage (that is, has the potential eventually to acquire a static comparative advantage), then per capita income in the backward country will converge towards that of the leader. Clearly, even if the backward country has a dynamic comparative advantage in the high-technology sector, it will not converge if, in free-trade equilibrium, it specialises in the low-technology good, since there are few opportunities for learning in this sector.[15]

3. A Simple Model of Catch-Up and Imitation

Benhabib and Spiegel (1994) present a model of endogenous growth where countries grow through imitation and research.[16] Following Nelson and Phelps (1966), they argue that simply including an index of human capital in a growth regression is a mis-specification. They argue that human capital helps with the adoption and implementation of new technologies, rather than causing growth directly. Nelson and Phelps suggest that the growth of technology, or the Solow residual, depends on the gap between its level and the level of 'theoretical knowledge', T_t:

(5)
$$\frac{\dot{A}_t}{A_t} = c(H_t)\left[\frac{T_t - A_t}{A_t}\right]$$

The rate at which the gap is narrowed depends upon the level of human capital, H, through the function, $c(H)$, where $dc/dH>0$ and $T_t>A_t$. In Nelson and Phelp's model, the level of theoretical knowledge grows at a constant exponential rate, such that $T_t=T(0)e^{lt}$. In the short run, the rate of growth of total factor productivity is a function of human capital and the productivity gap, but in the long run it grows at the rate l.

Benhabib and Spiegel, in the context of convergence regressions, extend this analysis to allow both for a higher level of human capital leading to a higher level of technology in its own right, and also to allow for international knowledge spillovers. For a country i, they specify the growth rate of total factor productivity as:

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[14] See Arthur (1989), David (1985), Nelson and Winter (1982), and Redding (1996a) for discussion.

[15] See Amiti (1995) for further discussion of the effect of trade liberalisation on industrial structure, and Piermartini and Ulph (1996) for discussion of the effect of unionised labour markets on innovation when liberalisation occurs.

(6) $$\frac{\dot{A}_{it}}{A_{it}} = g(H_i) + c(H_i)\left[\frac{\max_j A_{jt} - A_{it}}{A_{it}}\right], \qquad i=1,....,n,$$

where the endogenous growth rate $g(H_i)$ and the catch-up coefficient are non-decreasing functions of H_i. In their view, the level of education both increases the ability of a country to develop new technologies, and its ability to import and adapt technologies from abroad.

Benhabib and Spiegel then discuss the system of *n* differential equations that equation (6) represents. First, note that a leading country with the highest initial level of A, say $A_L(0)$, will be overtaken by a country that has a higher level of education. This follows because the lead country grows at the rate $g(H_L)$, or:

(7) $$A_{Lt} = A_L(0)e^{g(H_L)t}$$

while the growth rate of a laggard country with a higher level of human capital, say H_i, will be higher since it also benefits from catch-up. So:

(8) $$A_{it} = A_i(0)e^{g(H_i)t}$$

and since $g(H_i)>g(H_L)$, there exists some τ such that, for $t>t$, $A_{it}>A_{Lt}$. Even so, once country *i* is the leader, it can also be overtaken by another country with a lower initial level of technology, but a higher level of education. Benhabib and Spiegel also show that A_i and A_L asymptotically grow at the same rate $g(H_i)$. In the long-run the country with the highest level of *H* acts as the 'locomotive' of growth by expanding the production frontier, and all other countries are pulled along by the catch-up effect and grow at the same rate.

We now move from the theoretical model of Benhabib and Spiegel to a formulation that can be implemented empirically. Assume a Cobb-Douglas technology and aggregate to the industry level:

(9) $$Y = AK^{a-g} L_Y{}^{1-a} (D/K)^g$$

where *A* is the level of technology, *K* denotes the aggregate physical capital stock, L_Y represents the total employment of labour in the final goods industry, and *D/K* represents the ratio of R&D capital to physical capital. We define the natural logarithm of *measured* total factor productivity to be:

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[16] Bernard & Jones (1996b and 1996c) and Cameron, Proudman and Redding (1998) use a similar theoretical framework.

(10) $$\log A \equiv \log Y - a \log K - (1 - a) \log L_Y$$

We assume that imitation is easier, the larger is the gap between foreign productivity, T_t, and domestic productivity, A_t, so we write an equation for the change in log total factor productivity as follows:

(11) $$\Delta \log A = a + g\Delta \log(D/K) + z\Delta \log(H / L) + b(\log T_{t-j} - \log A_{t-j})$$

This expression shows that the change in *log A* is a function of the exogenous constant; the change in the ratio of R&D capital to physical capital; the change in the ratio of skilled labour to total labour; and the gap between foreign TFP and domestic TFP. A constraint is placed upon the value of the productivity gap: if $A>T$ then the gap is set to 0, otherwise it would imply that if domestic TFP were higher than foreign TFP, domestic TFP would regress back to the foreign TFP level. In addition, the econometric specification discussed later adds interaction terms which interact industry characteristics with the TFP gap. This allows us to capture differences in industry coefficients in a parsimonious manner.

4. International Comparisons

4.1. The measurement of relative Total Factor Productivity

The simplest way to calculate a measure of productivity is to apply fixed weights to the appropriate inputs. When the factor shares are changing over time, however, an alternative approach to a fixed weight index is to use a Divisia index (see Diewert, 1976). Instead of comparing discrete situations, a Divisia index analyses the continuous effect of changes. In this section, we discuss how to construct, and analyse, discrete-time approximations to Divisia indices for total factor productivity.

We assume that gross output, *Y*, is produced using *three* factors of production - capital, *K*; labour, *L*; and materials, *M*. The aggregate input, *F*, is the weighted sum of the capital, labour, and material inputs, using a discrete time Tornqvist-Divisia index to aggregate the inputs. Consequently, the rate of growth, *DlogF*, of the aggregate input *F*, may be written as:

(12) $$\Delta \log F_t = wk_t . \Delta \log K_t + wl_t . \Delta \log L_t + wm_t . \Delta \log M_t$$

where t and $t\text{-}1$ are time periods, $w_{it}=(s_{it}+s_{it-1})/2$, and s_{it}=cost share of input i in year t, $i=K,L,M$.

The growth rate of TFP, *DlogTFP*, equals the rate of growth of aggregate output minus the rate of growth of the aggregate input. *DlogTFP* is therefore defined as:

(13) $$\Delta \log TFP_t = \Delta \log Y_t - \Delta \log F_t$$

The last term on the right-hand side of the equation equals the rate of growth of the aggregate input, $dlogF_t$. We can write equation (13) more fully as:

(14) $$\Delta \log TFP_t = \Delta \log Y_t - wk_t . \Delta \log K_t - wl_t . \log L_t - wm_t . \Delta \log M_t$$

So far, we have been concerned with the estimation of total factor productivity growth rates in individual countries or individual industries. While it may be informative to compare, say, the rate of productivity growth in the Japanese chemicals industry with that of the US chemicals industry, it does not reveal anything about relative *levels* of productivity. In fact, given an appropriate set of exchange rates, it is possible to analyse changes in relative productivity levels using the Divisia methodology. Following Denny et al. (1992), we define theta, q, as the relative productivity level in country A relative to country B, where:

(15) $$\log q = \log(Y_A / Y_B) - 0.5 \cdot (sk_A + sk_B) \cdot \log(K_A / K_B)$$

$$-0.5 \cdot (sl_A + sl_B) \cdot \log(L_A / L_B) - 0.5 \cdot (sm_A + sm_B) \cdot \log(M_A / M_B)$$

The first term on the right-hand side of the equation is the log difference in the output levels of the two countries. The other three terms adjust the relative output levels for differences in relative input levels. Simply put, if country A produces twice as much output from twice as many inputs as country B, relative efficiency is one (i.e. $q=1$). If country A produces twice as much output with only the same level of inputs, relative efficiency is two. [17]

In order to estimate relative output and input levels it is necessary to convert the series into a common currency. This task is far from easy. This paper uses the industry-specific

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[17] See Jorgenson and Nishimizu (1978) and Denny and Fuss (1983a and 1983b) for further discussion of relative productivity measures.

Purchasing Power Parities (PPPs) calculated by Kuroda (1996), and discussed in the first appendix to this paper. A number of earlier studies, such as Dollar and Wolff (1994) have used a PPP deflator based on spending in the whole economy, which does not allow for differences in prices between outputs and inputs in different sectors. The use of an aggregate deflator is a particular problem for estimates of relative Japanese TFP in the 1960s and 1970s, when the relative price of labour in Japan was about one-fifth of that in the USA. Use of the GDP-based PPP therefore understates the number of workers in Japanese manufacturing in that period, and hence over-estimates their relative productivity.

4.2. Growth of TFP in Japan and the USA

The Japanese data cover the period 1955-89. Data on output and input (capital, labour hours, and material) quantities and price indices for 12 Japanese manufacturing industries were supplied by Ichiro Tokutsu.[18] From these data we constructed estimates of total factor productivity for all years 1955 to 1989, and were able almost exactly to replicate the growth rates reported in Denny et al. (1992) and obtain broadly similar estimates to those of Kuroda (1996). The manufacturing data set consists of eleven industries, which cover all of Japanese manufacturing except petroleum and coal products[19], and miscellaneous manufacturing.[20] We also constructed an index of total factor productivity in total manufacturing (excluding petroleum and coal products and miscellaneous manufacturing) by taking the gross-output weighted average of the sectoral TFP levels. Data for 19 US two-digit industries and for manufacturing as a whole were supplied by the US Bureau of Labour Statistics. The data comprised estimates of nominal values of output, labour input, capital services, energy inputs, materials inputs, and purchased services, for the industries between 1949 and 1991.[21] In addition there were complementary data on price indices, indices of real output and inputs, and indices of total factor productivity.

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[18] See appendix 2 and also Tokutsu (1994) for further details of this dataset.

[19] Data on petroleum and coal products were available, but it was decided to exclude this sector because of the unreliability of its deflators in the 1970s.

[20] In this dataset, miscellaneous manufacturing comprises the following industries - clothing (21), lumber (22), furniture (23), printing (25), rubber (28), leather (29), ordnance (38) and other manufacturing (39). See appendix 2 for further details of the industries examined.

[21] Note that the US data breaks the intermediate input category down into three components - energy, materials, and purchased services. The sum of these components is equivalent to the material category of Japanese inputs.

Figure 1 shows the log level of total factor productivity in the whole of Japanese and US manufacturing industry (with 1987=1), using the respective country's cost shares. There is a clear slowdown in Japanese growth in the mid 1970s. Table 2 shows the rates of growth of total factor productivity in 11 Japanese manufacturing industries and in total manufacturing. We chose to divide the years 1955 to 1989 into three periods - 1955 to 1973, 1973 to 1980, 1980 to 1989, and to compare them with the whole sample 1955 to 1989. The first period represents the so-called 'Golden Age' of economic growth, when the majority of advanced nations experienced an unprecedented economic expansion (see Maddison, 1991). The second period represents the period immediately after the 1973 oil shock, and broadly corresponds with the peak to peak business cycle. The third period represents the remainder of the sample. The fourth period is for the whole sample, and shows the long-run growth rate between 1955 and 1989.

Figure 1 US and Japanese Log Total Factor Productivity (1987=1)

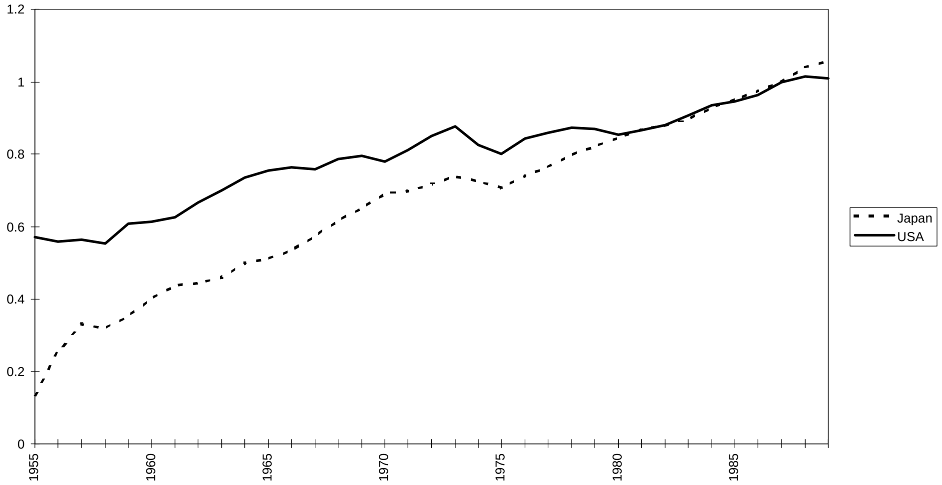

Table 2

Annual Average Growth Rates of TFP in Japanese Manufacturing

percentage change per annum

	1955-73	1973-80	1980-89	1955-89
Total	**2.24%**	**0.75%**	**1.13%**	**1.66%**
Food	0.79%	-0.09%	-0.39%	0.31%
Textiles	2.88%	3.44%	0.14%	2.29%
Paper	2.42%	-0.86%	1.34%	1.49%
Chemicals	2.46%	-0.53%	2.82%	1.96%
Minerals	2.78%	-2.48%	1.68%	1.45%
Primary Metals	1.73%	0.51%	0.06%	1.06%
Metal Products	2.80%	-1.39%	1.75%	1.69%
Machinery	2.96%	2.29%	0.85%	2.28%
Electricals	3.78%	2.65%	2.37%	3.19%
Transport	3.94%	1.35%	0.53%	2.55%
Instruments	3.99%	1.69%	0.54%	2.64%

Table 3

Annual Average Growth Rates of TFP in US Manufacturing

percentage change per annum

	1955-73	1973-80	1980-89	1955-89
Total	**1.81%**	**-0.31%**	**1.73%**	**1.35%**
Food	0.91%	0.44%	0.82%	0.80%
Textiles	2.27%	2.00%	1.32%	1.89%
Paper	1.37%	-1.15%	0.88%	0.77%
Chemicals	2.98%	-2.26%	2.06%	1.66%
Minerals	0.74%	-1.26%	1.04%	0.37%
Primary Metals	0.45%	-1.50%	-0.46%	-0.17%
Metal Products	0.85%	-0.49%	0.96%	0.64%
Machinery	1.10%	1.28%	3.75%	1.74%
Electricals	2.34%	1.95%	3.53%	2.42%
Transport	1.64%	-1.15%	1.50%	0.98%
Instruments	1.79%	1.77%	2.21%	1.91%

Although total factor productivity growth slowed dramatically after 1973 (from around 2.2 per cent per year in total Japanese manufacturing between 1955 and 1973, to around 0.8 per cent between 1973 and 1980), the data suggest that there was a pick-up in growth rates after 1980. Nonetheless, TFP growth does not appear to have returned to its pre-1973 rate. Indeed, the TFP growth rates of the transport, instruments, machinery, and electricals industries are lower in the 1980s than in the 1970s.

Returning to Figure 1, which shows log levels of US and Japanese total factor productivity, it suggests that US total factor productivity is more volatile than that of Japan, with a particularly large cycle in the early 1970s. For the US we can also look at four different time periods. Table 3 shows the annual average rate of growth of total factor productivity in US manufacturing for these. Once again, 1973 to 1980 stands out as being a time of slow or negative productivity growth. In contrast to Japan, however, there is good evidence that TFP growth rates returned to broadly their long-run average rate after 1980.

4.3. Relative TFP in the USA and Japan

Table 4 shows levels of Japanese Total Factor Productivity relative to the US (with the USA=100), for the eleven industries that are comparable and for manufacturing as a whole. The data show that in 1955, total factor productivity in total Japanese manufacturing was around sixty percent of that in the US, and that by 1980, that gap had been eliminated.[22] This suggests a fairly high rate of 'catch-up'. Figure 2 shows the relative productivity level of total manufacturing over the entire period, and suggests that from around 1980 onward, Japanese productivity has been growing at broadly the same rate as that of the US, or has perhaps fallen slightly relative to the US.[23]

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[22] Note the estimates in table 4 are equivalent to q in equation 15, while figure 2 presents log q.

[23] This may be a result of utilisation mis-measurement, given that the business cycles of the two countries are not necessarily synchronised.

Table 4

Relative TFP Level of Japanese Industry (US=100)

	1955	1973	1980	1989
Total	**61.0**	**86.7**	**101.1**	**98.8**
Food	77.9	83.4	82.7	73.9
Textiles	55.0	71.6	79.0	68.9
Paper	63.8	95.9	102.2	112.4
Chemicals	81.4	90.0	108.0	122.6
Minerals	38.6	81.5	78.5	85.3
Primary Metals	57.2	99.1	124.0	122.0
Metal Products	42.0	75.8	72.5	78.9
Machinery	19.4	82.4	101.0	90.7
Electricals	56.4	93.7	117.9	119.9
Transport	42.3	79.1	89.4	83.0
Instruments	42.4	74.8	75.6	66.2

As mentioned earlier, Dollar & Wolff (1994) and Kuroda (1996) also calculate estimates of Japanese manufacturing TFP relative to the US. Kuroda's estimates are constructed on a similar basis to those in this paper, but extend only to 1985. Dollar & Wolff's estimates use a value-added production function with labour and capital as the only inputs, and use a final expenditure PPP to convert Japanese prices into US prices, rather than the industry and factor specific PPPs used by Kuroda and in this paper (the PPP estimates used in this paper are taken from Kuroda; however, output and input data are taken from Tokutsu, 1994). Pilat (1996) constructs estimates of relative manufacturing TFP for the OECD economies in 1987 using a value-added production function, the final expenditure PPP, and constant factor shares.

How do these other estimates of relative Japanese TFP compare with those in table 4? Let us consider 1970, a year for which all three estimates are available. In 1970, Kuroda estimates a relative Japanese TFP level of 0.83, compared with a Dollar & Wolff estimate of 0.92 and this paper's estimate of 0.89. By the end of the 1970s the estimates had diverged further, with a Kuroda estimate of 0.89 for 1980, compared with this paper's estimate of 1.01 and a Dollar and Wolff estimate for 1979 of 0.77. By 1985, Kuroda estimates a relative TFP level of 0.88 while this paper estimates 0.98. The latest estimate in Dollar & Wolff is 0.88 for 1982. Pilat (1996) estimates a relative Japanese TFP level in manufacturing of 0.74, rather lower than this paper's 1987 estimate of 0.97. In general, the estimates in this paper are rather higher than those of Kuroda and Dollar & Wolff.

However, the latter are likely to be biased because they use a single deflator and also appear excessively cyclical - in 1970 Dollar & Wolff estimates a relative TFP level of 0.92, compared with 0.77 in 1979 and 0.88 in 1982. It seems unlikely both that there was technological regress in Japan between 1970 and 1979, and also that there was such a sharp burst of catch-up between 1979 and 1982.[24]

Turning back to the Kuroda estimates, they are generally lower than those contained in this paper but both sets peak in 1980 and both estimates suggest that Japanese TFP was stable relative to that of the US after 1980. The lack of relative Japanese progress after 1980 is more straightforward to explain if Japanese TFP had reached similar levels to that of the US as estimated in this paper, than if there still existed a ten per cent TFP gap as estimated by Kuroda. In 1980, table 4 suggests that five Japanese industries had overtaken or had achieved parity with US TFP levels, namely the paper, chemicals, primary metals, machinery, and electricals industries. Kuroda also estimates that the Japanese chemicals and electricals industries had overtaken the US by 1980, and that paper, primary metals and machinery were almost at parity. Overall, the mean difference between Kuroda’s estimates of 1980 relative TFP and those in table 4 is 0.01, with a standard deviation of 0.14.

The aggregate data shown in Figure 2 seem to suggest that the Japanese productivity growth slowdown started in the 1980s rather than the 1970s. However, the aggregate data conceal some important industry trends. In terms of the catch-up process, it is possible to divide the Japanese industries into three groups. The leading industries (see figure 3), chemicals, primary metals, paper, and electrical machinery caught up with the US quickly and have tended to move ahead since the early 1980s. The middling industries (see figure 4), machinery, minerals, transport[25], and metal products, have not caught up to the same extent and have generally maintained their positions against the US since the early 1970s. The lagging industries (see figure 5), food, textiles[26], and instruments, also appear to have stopped converging by the early 1970s, but the productivity gap remains substantial. It

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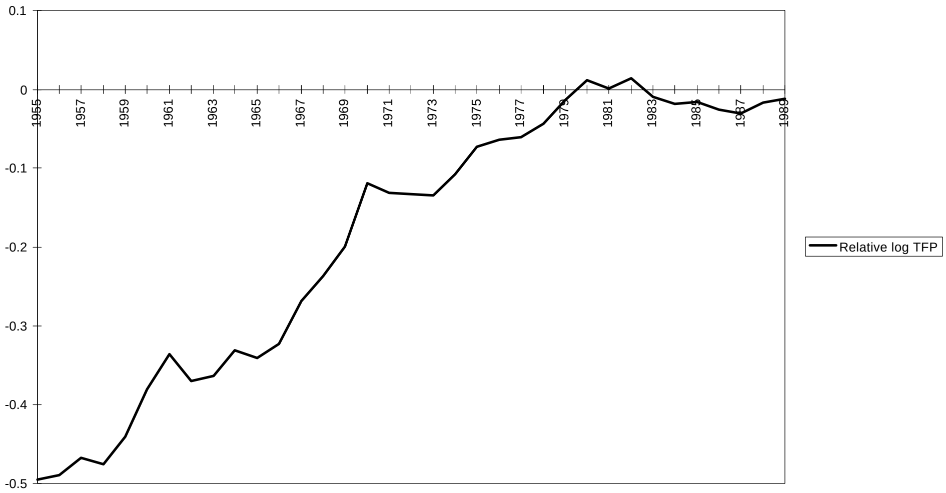
[24] Estimates taken from a value-added production function are typically more volatile than from a gross-output production function.

[25] The gap in transport equipment may appear surprising, but this may reflect some mis-measurement, and also the different output compositions of the industries in the two countries. The transport sector includes automobiles, ships, railway engines and carriages, aerospace, motorcycles, and buses. While the US has a large aerospace sector, Japan has had little aerospace manufacturing until recently. See Fuss and Waverman (1990, p. 85), and Denny et al. (1992) for discussion on this point.

[26] Note that the definition of the textiles industry in this paper does not include clothing.

appears that the leading industries continued to perform well enough relative to the US in the 1970s, and this disguised the slowdown in the middling and lagging sectors that appeared in the early 1970s.

Figure 2 Log Relative TFP Level (Japan - US)



It is also possible to estimate relative levels of labour, capital, and material productivity (that is, gross output divided by the relevant input).[27] Table 5 presents estimates of relative capital productivity and shows that Japanese capital productivity has risen substantially over the period relative to the US. Even so, relative capital productivity fell in the food, textiles, chemicals, and metal products sectors. This is probably due to the extremely low level of the measured Japanese capital stock in the early 1950s not representing a steady-state level. Table 6 presents estimates of relative labour productivity levels, and shows that Japanese progress here has been startling, with several industries having forged ahead of the US, while food, textiles and metal products have been left behind somewhat. Table 7 shows relative material productivity levels, and shows that Japan has made some progress relative to the US, but still has some way to go. It is also important to remember that a series of accounting identities link together the estimates of relative total factor productivity and relative factor productivities. Adapting equation (15) we find that log relative labour

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[27] The rate of growth of relative labour productivity can be decomposed into two components: the rate of growth of total factor productivity and the rate of growth of relative factor substitution. In this case, we have to consider both the relative capital to labour ratio and the relative materials to labour ratio. The same analysis, with appropriate substitutions, applies to relative capital productivity and relative material productivity.

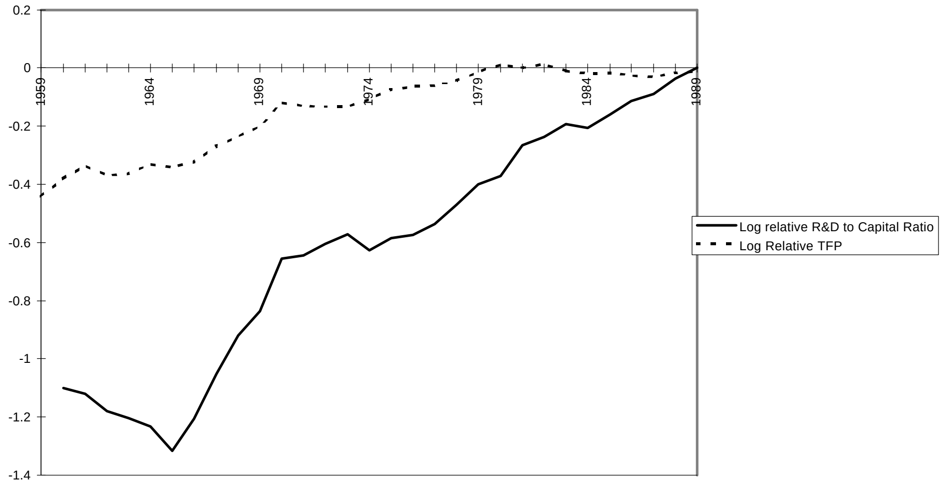
productivity is a function of log relative TFP, q, and the relative capital to labour and material to labour ratios for the two countries, weighted by the capital and material shares:[28]

$$\textbf{(16)}\quad \log(Y_A / Y_B) - \log(L_A - L_B) \equiv \log q + 0.5 \cdot (sk_A + sk_B) \cdot \left[\log(K_A / K_B) - \log(L_A - L_B)\right]$$

$$+ 0.5 \cdot (sm_A + sm_B) \cdot \left[\log(M_A / M_B) - \log(L_A / L_B)\right]$$

Finally for this section, figure 6 shows the log of US total factor productivity relative to Japan and the log of the US R&D capital to physical capital ratio relative to Japan. Between 1960 and 1969, Japanese R&D efforts increased relative to those of the US by around 50 per cent. Between 1969 and 1975, Japanese R&D efforts stagnated relative to those of the US. Between 1975 and 1989, they improved by around 60 per cent, such that by 1989, the countries had roughly similar R&D capital to physical capital ratios. Over the entire period, Japanese total factor productivity catches up considerably on the US as well, but as in figure 3, the majority of this catch-up is completed by the mid 1970s. Despite the relative lack of Japanese progress on total factor productivity levels since the mid 1970s, their R&D capital to physical capital ratio has continued to rise faster than that of the US, suggesting that higher levels of R&D effort were more necessary after the virtual elimination of the productivity gap in the mid 1970s.

Figure 6 Log Relative TFP and Log Relative R&D to Capital Ratio
US relative to Japan 1959 to 1989



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[28] To make this identity more concrete, consider the food industry. In 1989, its relative log total factor productivity (US minus Japan) was 0.3 and its log relative labour productivity was 0.90. The average capital share was around 16½ per cent and the average material share about 67 per cent. The relative log capital to labour ratio (US minus Japan) was 0.133 and the relative log material to labour ratio was 0.863. Therefore log relative labour productivity was approximately 0.3+(0.165*0.133)+(0.67*0.863)=0.90, as stated above.

Figure 3 Leading Industries - Log Relative TFP Levels (Japan - US)

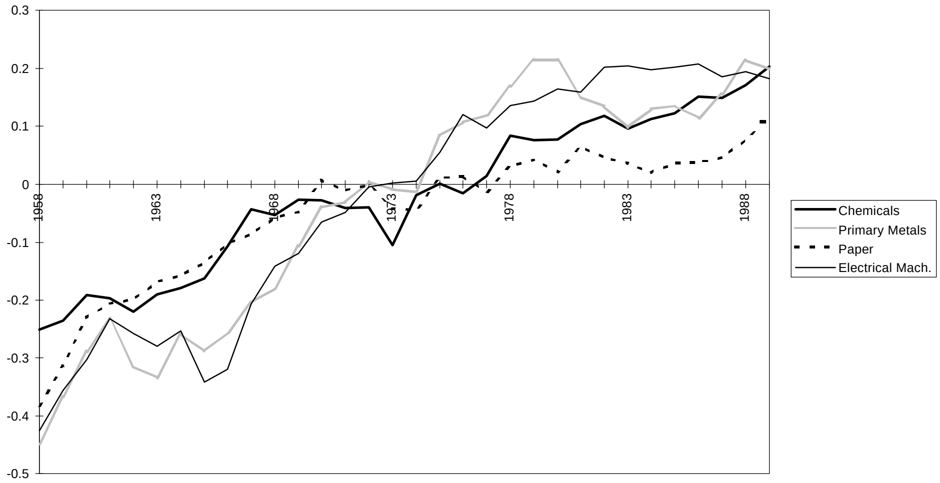

Figure 4 Middling Industries - Log Relative TFP Levels (Japan - US)

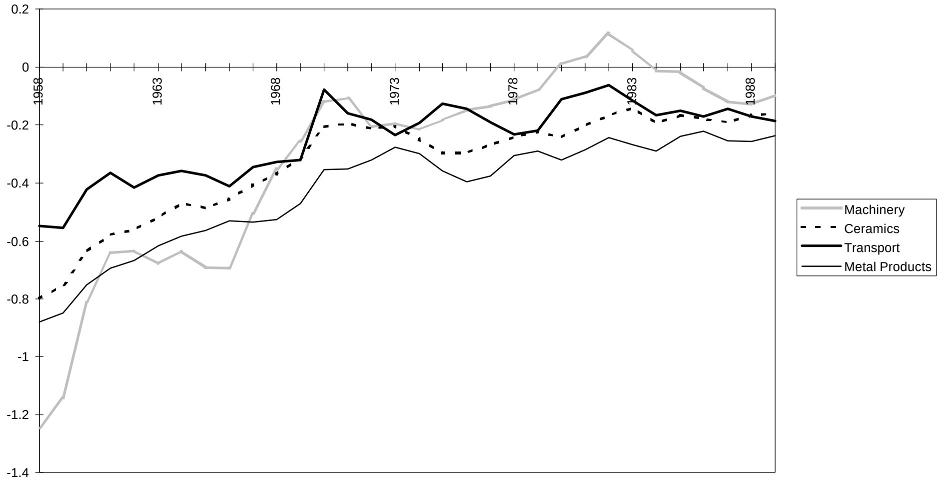

Figure 5 Lagging Industries - Log Relative TFP Levels (Japan - US)

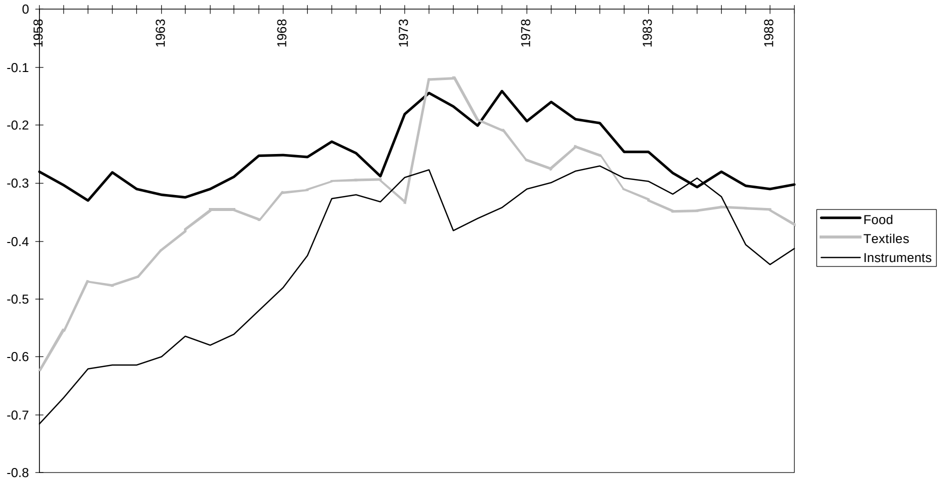

Table 5

Relative Capital Productivity Level of Japanese Industry (US=100)

	1955	1973	1980	1989
Total	**163.4**	**169.1**	**195.3**	**190.4**
Food	130.8	69.8	59.4	46.4
Textiles	286.1	218.9	199.7	107.7
Paper	142.0	178.1	171.2	154.9
Chemicals	203.3	110.0	140.5	135.0
Minerals	78.3	120.3	109.2	91.8
Primary Metals	102.2	175.3	207.5	168.0
Metal Products	221.8	130.8	91.2	82.2
Machinery	153.0	150.5	193.6	188.1
Electricals	104.4	193.9	237.7	297.3
Transport	158.4	300.0	396.7	344.0
Instruments	40.8	60.6	44.8	36.0

Table 6

Relative Labour Productivity Level of Japanese Industry (US=100)

	1955	1973	1980	1989
Total	**30.6**	**103.0**	**143.5**	**129.4**
Food	22.8	40.8	40.7	40.6
Textiles	34.6	57.5	64.1	45.1
Paper	38.1	130.0	140.1	137.4
Chemicals	32.7	97.0	142.9	175.1
Minerals	14.6	71.7	72.1	82.7
Primary Metals	54.7	213.1	307.5	217.8
Metal Products	9.1	47.2	44.2	60.9
Machinery	15.6	87.5	127.9	108.8
Electricals	28.1	113.9	151.6	187.8
Transport	9.0	49.7	78.5	100.4
Instruments	16.5	76.8	85.7	92.7

Table 7

Relative Material Productivity Level of Japanese Manufacturing (US=100)

	1955	1973	1980	1989
Total	**69.1**	**76.4**	**85.2**	**80.7**
Food	84.1	100.1	102.2	96.2
Textiles	53.4	69.9	81.3	83.8
Paper	64.4	71.3	83.5	93.4
Chemicals	81.5	80.6	94.6	103.8
Minerals	68.7	76.6	72.1	85.4
Primary Metals	51.5	68.5	83.5	98.3
Metal Products	78.3	89.7	95.5	90.7
Machinery	64.9	76.7	77.6	59.4
Electricals	75.2	76.2	88.3	76.2
Transport	67.6	63.1	72.7	56.7
Instruments	99.3	76.5	75.2	59.8

5. Econometric Results

The model of growth through imitation and research presented in section 2 readily lends itself to econometric estimation. We wish to estimate equations of the following form:

(17)
$$\Delta \log TFP_i = b_{0i} + b_1 \log(R_i / K_i) + b_2 \log(Theta) + b_3 \log(H_i / L_i)$$
$$+ b_4 \cdot j\,(Z) \cdot \log(R_i / K_i) + b_5 \cdot j\,(Z) \cdot \log(Theta) + b_{6i} \Delta cap + b_{7i} \Delta pr$$

where TFP is an index constructed from equation (14). *R/K* is the log ratio of the R&D capital stock to the physical capital stock, and *H/K* is the ratio of non-production to total workers (we test for both levels and differences in *R/K* and *H/K*). The industry fixed effects help to capture differences in steady-state levels of relative TFP. The productivity gap, *log Theta*, is the log level of US TFP in industry *i* minus the log level of Japanese TFP in industry *i*, and is set to zero if the Japanese level is above that of the USA.

Each industry also has its own capacity utilisation change rate (Δcap) and price bias change term (Δpr). Capacity utilisation is based on a MITI survey (similar to the CBI survey for the UK), and the price bias term is the log ratio of input to output prices. Both the capacity utilisation rate and the price bias term are constructed analogously to those in Cameron (1996) and Muellbauer (1991).

The functions *j (Z)* are the industry interaction terms explained in the next section (the capital to labour ratio; the energy to capital ratio; the ratio of non-production to total workers; the ratio of R&D capital to physical capital; exports divided by output; and imports divided by output). These are interacted with the productivity gap, *log Theta*, in order to allow the effect of the productivity gap to vary across industries.

5.1. Data Description

Table 8 reports the interaction terms used in the panel regressions. There are six industry characteristics, each measured relative to the manufacturing average. Therefore a value of 0 for the log *K/L* ratio term means that the industry has the same capital to labour ratio as manufacturing as a whole. The interaction terms are the physical capital to labour ratio; the energy input to physical capital ratio; the ratio of non-production workers to total workers;

the ratio of R&D capital to physical capital; the export to output ratio; and the import to output ratio.

The aim of the interaction terms is to allow for industry heterogeneity in productivity responses without the need to estimate single-equation models. They can be interpreted as follows: if the response to the productivity gap was estimated as 0.04 and the coefficient on the capital to labour ratio interacted with the gap was 0.05, then an industry with a capital to labour ratio ten per cent higher than manufacturing would have an effective productivity gap coefficient of 0.045 (i.e. 0.04 + 0.1*0.05).

Table 8

Interaction Terms

1.	$\log(\frac{K_i}{L_i}) - \log(\frac{K}{L})$	Capital:Labour
2.	$\log(\frac{E_i}{K_i}) - \log(\frac{E}{K})$	Energy: Capital
3.	$\log(\frac{H_i}{L_i}) - \log(\frac{H}{L})$	Non-Production workers:Total workers
4.	$\log(\frac{R_i}{K_i}) - \log(\frac{R}{K})$	R&D Capital:Physical Capital
5.	$\log(\frac{X_i}{Q_i}) - \log(\frac{X}{Q})$	Exports:Output
6.	$\log(\frac{M_i}{Q_i + M_i - X_i}) - \log(\frac{M}{Q + M - X})$	Imports:Home Sales

Note: For an industry with the same value of the characteristic as total manufacturing, the value of the log interaction term will be zero.

Table 9 reports the relative values of the industry characteristics for the eleven industries for the year 1985. The first column also reports the actual values of theta in 1985 (TFP relative to the US) for the industries concerned and is comparable with the data in table 4. For the capital to labour ratio, paper & pulp, chemicals, and primary metals stand out as especially capital intensive. These industries, along with minerals, are also the most energy intensive. There is surprisingly little variation in the ratio of non-production to production workers, with chemicals, machinery, electricals and instruments having the highest ratio. As for the ratio of R&D capital to physical capital, the most intensive industries are chemicals, electricals, transport, and instruments. Cameron (1996) shows that for the UK, export to output and import to output ratios are highly correlated across industries. This is not the case for Japan. The pattern of relative export to output ratios finds that electricals, transport, and instruments have high ratios, while food exports are very low. In contrast, food, textiles, and chemicals, as well as instruments have high import to output ratios. Electricals and transport have low relative import to output ratios.

Table 9

Relative Industry Characteristics for Japanese Manufacturing in 1985

	Theta	**K/L**	**E/K**	**H/L**	**R&D/K**	**X/Q**	**M/Q**
Total	0.98	1.00	1.00	1.00	1.00	1.00	1.00
Food	0.74	0.63	0.69	1.00	0.53	0.06	1.20
Textiles	0.71	0.54	0.68	0.70	0.53	0.96	3.25
Paper&Pulp	1.04	1.31	1.61	0.86	0.44	0.22	0.87
Chemicals	1.13	4.35	3.73	1.79	2.18	0.91	3.38
Minerals	0.85	0.98	1.37	0.85	0.58	0.37	0.27
Metals	1.14	4.06	2.17	0.83	0.58	0.59	0.71
Metal Prod.	0.79	0.66	0.64	0.85	0.49	0.64	0.31
Machinery	0.98	0.63	0.78	1.17	0.93	0.87	0.35
Electricals	1.22	0.57	0.85	1.18	8.50	1.64	0.55
Transport	0.86	0.84	0.58	0.98	1.59	2.14	0.42
Instruments	0.75	0.66	0.49	1.12	1.77	1.82	1.40

Notes:		*Actual data for manufacturing in 1985*
K/L	*Capital to Labour Ratio*	*17.92*
E/K	*Energy to Capital Ratio*	*0.06*
H/L	*Non-production to total workers*	*0.36*
R&D/K	*Ratio of R&D Capital to Physical Capital*	*0.24*
X/Q	*Ratio of Exports to Output*	*0.17*
M/Q	*Ratio of Imports to Output*	*0.06*

The low correlation between Japanese export intensive and import intensive industries deserves further examination. Table 10 reports simple correlations between the industry characteristics. The table confirms the low correlation between exports and imports. Furthermore it suggests that import ratios are not especially correlated with any of the other characteristics except for the ratio of non-production to production workers. Of the other correlations, the capital to labour ratio is highly correlated with the energy to capital ratio as noted above in the discussion of table 9. High capital to labour ratios are exhibited by the traditional heavy industries, such as chemicals and primary metals.

Table 10

Correlation Matrix for industry characteristics

	K/L	**E/K**	**H/L**	**R&D/K**	**X/Q**	**M/Q**
K/L	1.00					
E/K	0.84	1.00				
H/L	0.24	0.13	1.00			
R&D/K	-0.13	-0.17	0.61	1.00		
X/Q	-0.21	-0.37	0.09	0.50	1.00	
M/Q	0.33	0.12	0.63	0.30	0.36	1.00

Table 11 reports t-statistics for Augmented Dickey-Fuller tests (see MacKinnon, 1991), along with the corrected critical values for our variables of interest. It suggests that the orders of integration of our variables are different between industries. The differenced variables are fairly mixed - for the hypothesis that they are I(0) cannot be rejected, while the hypothesis that all the *log Theta* terms are I(0) can be rejected. It is interesting that the productivity gap terms do not test as being I(0), given that one strand of the convergence literature regards this as a test of convergence (see Bernard and Jones, 1996b).

Table 11

Augmented Dickey-Fuller Tests

	Δlog(TFP)	**Δlog(R&D/K)**	**Δlog(atc)**	**log(Theta)**
Food	-4.45**	-3.61*	-3.04	-0.53
Textiles	-5.28**	-2.27	-4.03*	-1.16
Paper & Pulp	-3.2	-2.51	-5.92**	-2.07
Chemicals	-3.39	-2.97	-3.88*	-1.16
Minerals	-2.85	-2.12	-3.01	-1.63
Primary Metals	-3.59*	-3.27	-3.83*	-0.86
Metal Products	-3.57*	-2.05	-5.36**	-0.52
Machinery	-3.68*	-4.38**	-5.04**	-1.63
Electricals	-4.30**	-3.56*	-3.78*	-1.16
Transport Equip.	-5.24**	-1.68	-3.51*	-0.46
Instruments	-3.48*	-2.29	-3.19	-1.47

Notes:

Critical values: 5%=-3.442 1%=-4.025 (from MacKinnon, 1991), Constant and Trend included. Sample Period is 1960 to 1989. denotes significant at 5% level. ** denotes significant at 1% level. Δlog(TFP) is the change in log total factor productivity. Δlog(R&D/K) is the change in the log of the ratio of R&D capital to physical capital. Δlog(atc) is the change in the log of the ratio of non-production workers to total workers. Log(Theta) is the log of Japanese total factor productivity relative to the US.*

5.2. Panel Data Results

We estimate panel regressions in the spirit of equation (17). We are interested in the effect on the TFP growth rate of the productivity gap, R&D, and human capital (as measured by the ratio of non-production to total workers). The discussion in section 2 suggests that the R&D capital to physical capital ratio and the human capital ratio should enter in first differences. Therefore an increase in the rate of growth of either R&D capital or human capital leads to a rise in the rate of growth of TFP. An alternative view might be that these variables should enter as levels effects, so that a rise in the level of R&D capital or human capital would lead to a rise in the rate of growth of measured TFP. Such a rise in the growth rate is in the spirit of the Benhabib & Spiegel (1994) view of human capital. We test whether the levels or differences effect is the most significant.

Table 12 presents our first set of results. All the regressions in table 12 contain interactions of the industry characteristics with the productivity gap. The first four columns report variants of equation 17 where the R&D and human capital effects enter either in differences or levels. The fifth column tests whether R&D capital should enter in levels or differences. Regression 1 estimates a productivity gap effect (*log theta*) of 0.039, and an R&D elasticity (Δ*log R&D*) of 0.078, both of which are significant, while the human capital (Δ*log atc*) effect is negative and insignificant. The pattern of the interaction terms is interesting. The capital to labour ratio and the human capital ratio have negative but insignificant coefficients. The energy to capital ratio; the R&D to capital ratio; import to output ratio and export to output ratio interactions, all have positive coefficients, but the energy to capital ratio and import to output ratio are insignificant.

Regression 2 includes the level of human capital (*log atc*) rather than its difference. Once again it has a negative sign, and is insignificant. The coefficients on the productivity gap and the change in R&D capital do not change significantly when the level of human capital is included. Regression 3 includes the level of R&D capital (*log R&D*) and the change in human capital (Δ*log atc*). Once again, the level effect is insignificant, as is the human capital effect. Regression 4 includes the level of R&D capital and the level of human capital. Both variables are insignificant. Regression 5 contains both the level of R&D capital and the change in R&D capital, and suggests strongly that it is the change in R&D capital that is significant in this context.

Taken together, the results in table 12 suggest that the productivity gap and the change in R&D capital have a positive and significant effect on TFP growth in Japanese manufacturing. Interestingly, human capital appears to have no significant effect, either as a levels effect or in differences (the ratio of non-production workers to total workers is a rather imprecise measure of human capital). Furthermore, the human capital interaction term is also negative and insignificant. The interaction terms do not present a clear picture at this stage, although industries with high ratios of R&D capital to physical capital appear to catch up faster (*inter4*).

Turning now to table 13, we wish to explore a number of auxiliary hypotheses and to derive a more parsimonious set of productivity gap interactions. Regression 6 restricts the effects of human capital and the level of R&D capital to be zero. The productivity gap and change in R&D capital remain significant, and the restriction cannot be rejected (F(1,220)=0.69 [P=0.41]). Note that the absence of levels effects in human capital and R&D imply that the steady-state level of relative TFP is determined simply by the industry fixed effects and the catch-up rate. It has often been argued that there was a major structural break in Japanese growth in 1973 (see Denny et al., 1992, for example). In order to test this hypothesis, regression 7 includes break terms for 1973 for both the productivity gap and the change in log R&D. The change in both the productivity gap effect and in the R&D effect is negative but insignificant. The joint hypothesis of no structural break in these two variables cannot be rejected (F(2,219)=0.22 [P=0.80]).

In table 13, regressions 8 to 10 sequentially delete the three productivity gap interaction terms that are not significant: the import to output ratio; the energy to capital ratio; and capital to labour ratio. The hypothesis that their coefficients are jointly zero cannot be rejected (F(3,221)=0.95 [P=0.41]). Regression 10 estimates a productivity gap coefficient of 0.038 and an R&D elasticity of 0.072. It contains three interaction terms that allow the effect of the productivity gap to differ with industries. It suggests that TFP growth has been faster, ceteris paribus, in those industries with lower ratios of non-production to total workers; with higher R&D capital to physical capital ratios; and higher export to output ratios. Regression 10 is the specification used later to calculate point elasticities for industry coefficients on the productivity gap.

A few comments on the robustness of these results may be of interest at this point. A number of checks were conducted. First, all regressions report heteroscedasticity-consistent standard-errors, and there is no evidence of problems with autocorrelation or heteroscedasticity. Second, the results are not sensitive to the inclusion of particular industries. Any individual industry can be omitted from the panel without a significant effect, that is, no variable of interest changes by more than one standard error and usually by much less. This suggests that the results are not being driven by outliers in any particular industry. Third, although the R&D capital variables are all deflated by the physical capital stock, this normalisation is not important. For example, in regression 10, the change in log of the R&D capital stock divided by the physical capital stock can be replaced by the change in the log of the R&D capital stock and its coefficient falls only slightly to 0.068, although it is less precisely estimated.

A fourth check on the robustness of the results was performed by the inclusion of interaction terms with the R&D capital variable as well as with the productivity gap. None of the former interactions has any significant effect. Fifth, although the estimates of the productivity gap use the industry-specific Purchasing Power Parities of Kuroda (1996), the results are not sensitive to the use of the Unit Value Ratios of van Ark (1996). Lastly, within the dynamic panel data framework used here, the estimated coefficients may be subject to a finite-sample bias (see Baltagi, 1995, chapter 3). This bias disappears asymptotically at the number of time periods rises, but not as the number of units of observation rises. In the present context, with 27 annual observations, the bias is likely to be small.

Table 12

Japanese Sectoral DlogTFP Regressions

	Regression Number				
	1	2	3	4	5
log(Theta)$_{t-1}$	0.039	0.038	0.041	0.041	0.042
	(0.015)	*(0.015)*	*(0.016)*	*(0.016)*	*(0.019)*
Δlog(R&D/K)$_{t-1}$	0.078	0.074			0.074
	(0.035)	*(0.035)*			*(0.037)*
log(R&D/K)$_{t-1}$			0.011	0.011	0.006
			(0.015)	*(0.015)*	*(0.015)*
Δlog(ATC)$_{t-1}$	-0.020		-0.023		
	(0.033)		*(0.033)*		
log(ATC)$_{t-1}$		-0.024		-0.032	
		(0.034)		*(0.033)*	
Inter1	-0.016	-0.015	-0.013	-0.012	-0.016
	(0.014)	*(0.014)*	*(0.014)*	*(0.014)*	*(0.014)*
Inter2	0.024	0.026	0.013	0.017	0.022
	(0.019)	*(0.019)*	*(0.018)*	*(0.019)*	*(0.019)*
Inter3	-0.073	-0.066	-0.080	-0.070	-0.077
	(0.058)	*(0.060)*	*(0.058)*	*(0.062)*	*(0.057)*
Inter4	0.029	0.030	0.024	0.026	0.029
	(0.015)	*(0.015)*	*(0.014)*	*(0.014)*	*(0.015)*
Inter5	0.042	0.047	0.037	0.044	0.044
	(0.021)	*(0.022)*	*(0.021)*	*(0.022)*	*(0.021)*
Inter6	0.018	0.014	0.022	0.017	0.019
	(0.015)	*(0.017)*	*(0.015)*	*(0.017)*	*(0.015)*
R^2	0.6918	0.6919	0.6864	0.6869	0.6915
s.e.	0.0197	0.0197	0.0198	0.0198	0.0197
AR $\chi^2(2)$	4.03 [0.13]	3.97 [0.14]	2.02 [0.37]	2.00 [0.37]	4.00 [0.13]
HS F(13,273)	0.92 [0.34]	0.95 [0.32]	0.51 [0.47]	0.48 [0.49]	0.96 [0.33]
RESET F(2,283)	1.18 [0.32]	1.32 [0.27]	1.30 [0.27]	1.13 [0.33]	1.34 [0.27]

Key to Interaction Terms (interacted with log(Theta)$_{t-1}$, the productivity gap):
INTER1 Capital to labour ratio.
INTER2 Energy input to physical capital ratio.
INTER3 Ratio of non-production workers to total workers.
INTER4 Ratio of BERD capital to physical capital.
INTER5 Exports divided by output.
INTER6 Imports divided by output.

Notes:

Sample Period 1963 to 1989, heteroscedasticity-consistent standard-errors in parentheses. Dependent Variable is the change in log Total Factor Productivity. Theta is the productivity gap. R&D/K is the ratio of the stock of R&D capital to the physical capital stock. ATC is the ratio of non-production workers to total workers. All equations include industry fixed effects, industry utilisation terms, industry bias terms and year dummies. Estimation is by OLS (Ordinary Least Squares).

AR $c^2(2)$ LM test for 1st and 2nd order serial correlation, Breusch-Pagan (1980).
HS F-test for heteroscedasticity, White (1980).
RESET F(j,T-j-K)F-version of the RESET test for j powers, Ramsey (1969).

Table 13

Japanese Sectoral DlogTFP Regressions

	Regression Number				
	6	7	8	9	10
log(Theta)$_{t-1}$	0.040	0.043	0.031	0.034	0.038
	(0.018)	*(0.020)*	*(0.015)*	*(0.015)*	*(0.014)*
c73*log(Theta)$_{t-1}$		-0.002			
		(0.018)			
Δlog(R&D/K)$_{t-1}$	0.076	0.090	0.081	0.072	0.072
	(0.34)	*(0.043)*	*(0.037)*	*(0.034)*	*(0.033)*
c73*Δlog(R&D/K)$_{t-1}$		-0.006			
		(0.092)			
Inter1	-0.016	-0.016	-0.012	-0.006	
	(0.014)	*(0.016)*	*(0.013)*	*(0.011)*	
Inter2	0.023	0.023	0.018		
	(0.019)	*(0.019)*	*(0.019)*		
Inter3	-0.080	-0.078	-0.103	-0.122	-0.121
	(0.057)	*(0.057)*	*(0.060)*	*(0.054)*	*(0.053)*
Inter4	0.028	0.028	0.027	0.023	0.024
	(0.015)	*(0.015)*	*(0.015)*	*(0.013)*	*(0.012)*
Inter5	0.042	0.042	0.045	0.033	0.035
	(0.021)	*(0.021)*	*(0.021)*	*(0.016)*	*(0.015)*
Inter6	0.018	0.019			
	(0.015)	*(0.015)*			
R^2	0.6913	0.6919	0.6891	0.6877	0.6873
s.e.	0.0196	0.0197	0.0197	0.0197	0.0196
AR χ^2(2)	3.75 [0.15]	4.02 [0.13]	3.94 [0.14]	4.30 [0.12]	3.63 [0.16]
HS F(19,379)	1.00 [0.32]	0.98 [0.32]	0.99 [0.32]	0.87 [0.35]	0.98 [0.32]
RESET F(2,396)	1.20 [0.30]	1.20 [0.30]	1.25 [0.29]	1.27 [0.28]	1.25 [0.29]

Key to Interaction Terms (interacted with log Theta$_{t-1}$, the productivity gap):
INTER1 Capital to labour ratio.
INTER2 Energy input to capital ratio.
INTER3 Ratio of non-production workers to total workers.
INTER4 Ratio of BERD capital to physical capital.
INTER5 Exports divided by output.
INTER6 Imports divided by output.

Notes:

Sample Period 1963 to 1989, heteroscedasticity-consistent standard-errors in parentheses. Dependent Variable is the change in log Total Factor Productivity. Theta is the productivity gap. R&D/K is the ratio of the stock of R&D capital to the physical capital stock. c73 is a dummy variable taking the value zero before 1973 and 1 thereafter. All equations include industry fixed effects, industry utilisation terms, industry bias terms and year dummies. Estimation is by OLS (Ordinary Least Squares).

AR c^2(2) LM test for 1st and 2nd order serial correlation, Breusch-Pagan (1980).
HS F-test for heteroscedasticity, White (1980).
RESET F(j,T-j-K)F-version of the RESET test for j powers, Ramsey (1969).

5.3. Catch-Up and R&D Elasticities

The estimates presented in regression 10 can be used to derive estimates of the productivity gap effect. Table 14 presents point estimates of the implied industry coefficients.

Table 14

Point Estimates of Catch-Up Elasticities in Japanese Manufacturing

	Theta		**Theta**
Total Manufacturing	0.038 *(0.014)*		
Food	0.023 *(0.017)*	**Metal Products**	0.057 *(0.016)*
Textiles	0.100 *(0.027)*	**Machinery**	0.020 *(0.012)*
Paper	0.039 *(0.016)*	**Electricals**	0.155 *(0.034)*
Chemicals	0.035 *(0.024)*	**Transport**	0.075 *(0.023)*
Minerals	0.050 *(0.018)*	**Instruments**	0.046 *(0.020)*
Primary Metals	0.058 *(0.017)*		

Notes:
Point elasticities calculated using results of regression 10. Heteroscedasticity-consistent standard errors (in parentheses) are calculated from estimated covariance matrix of parameter estimates of regression 10.

Just as in regression 10, the coefficient for total manufacturing on the productivity gap is 0.038. However, the pattern across industries is also interesting. Recall that the productivity gap effect will be higher in the industries with high R&D capital to physical capital ratios and high export to output ratios, and with low ratios of non-production workers to total workers.

Low coefficients are reported for food and machinery. Above average productivity gap effects are found in textiles, primary metals, metal products, minerals, electricals, and transport. Average coefficients are found in paper, chemicals and instruments. Electrical machinery appears to have benefited most from catch-up, with a productivity gap coefficient of 0.155.

6. Conclusion

This paper has argued that the process of economic growth is very different for a follower than it is for a leader. A follower is able to import foreign technology, machinery, and work practices and consequently able to grow more rapidly than the leader. However, as the follower's productivity level approaches that of the leader, these imitative gains become more and more difficult. Eventually the follower has to undertake significant amounts of R&D in order to raise productivity levels.

This paper has applied these ideas to the post-war experience of Japan. In 1955, it estimates that total factor productivity in Japan was about 60 per cent of the US level, but that by 1980 it had reached a level equal to that of the USA. As the technological gap narrowed, particularly after 1973, Japan began to devote substantial sums to R&D. While Japan may previously have undertaken research in order to adapt foreign technologies, much of this informal research would not be captured by the R&D data. It is only when formal R&D facilities begin to be developed that the R&D data begin to capture the full R&D effort of Japan, and this is the stage at which genuinely innovative research begins to occur.

The productivity performances of the two countries are similar in two ways. First, there was a dramatic productivity growth slowdown in the 1970s, followed by a speed-up in the 1980s. Second, there appear to be greater similarities between the performance of the same industries in the different countries than between different industries in the same countries - for example, electrical engineering and instruments have performed well in both countries, whereas minerals, primary metals, and food have performed less well.

The countries differ in at least one important way. Japanese productivity growth in the 1980s does not appear to have returned to its 1955 to 1973 rate, but has settled at broadly the same rate as that of the US. This would be consistent with the argument that Japanese and US productivity *levels* are now broadly similar, and that Japan can no longer exploit catch-up effects.

The econometric results presented in this paper suggest that the productivity gap with the USA had a significant effect on TFP growth in Japanese manufacturing. This effect has both a direct element and a indirect element mediated by the industry interaction effects. Regression 10 suggests that the direct effect has a coefficient of around 0.038, meaning that 3.8 per cent of any productivity gap disappears each year. The indirect effects mean that industries with higher ratios of R&D capital to physical capital and higher ratios of exports to imports, catch up faster. Industries with higher ratios of non-production workers to total workers catch up more slowly. These effects can be used to estimate implied catch-up effects that vary across the industries. These estimates suggest that the highest catch-up effects occur in electricals, textiles and transport. In contrast, food and machinery do not appear to benefit from catch-up effects.

The paper also examined the role played by the level of R&D capital and that of the level and rate of change of the ratio of non-production workers to total workers. The results presented above suggested that the *level* of R&D capital (as opposed to the *change* in R&D capital) and the measure of human capital had little effect on TFP growth in Japanese manufacturing over the period studied.

Appendix 1 International Price Comparisons

In order to construct measures of relative productivity it is necessary to convert output and inputs in the different countries into the same currency. This is a difficult task, as the discussion in van Ark (1996) fully conveys. Three main approaches have been taken.

Final Expenditure Deflators: The first is to deflate by some aggregate deflator such as the Purchasing Power Parity for whole economy final expenditure (GDP), as calculated by the OECD. However, as van Ark shows, this can lead to surprisingly large differences since the price of manufacturing output is often different from the price of the output of the whole economy. For example, France and Germany have lower expenditure price levels than manufacturing price levels, while the opposite is true of Japan.

Unit Value Ratios: The second approach is to use Unit Value Ratios (UVR) to construct deflators for individual sectors. These UVRs are obtained from each country's production census for a benchmark year by dividing producers' sales values by the corresponding quantities of sales. Matches are then made between countries for as many products as possible. Typically this leaves around 75 to 85 per cent of output unmatched. UVRs for individual products are then aggregated to create an index for each sector under study. In his UVR calculations, van Ark matches 31 products in the food, beverages and tobacco sector for the UK and the US, accounting for 24.4 per cent of UK output in that sector. For manufacturing as a whole, he finds 176 pairs of UVR matches, accounting for 17.6 per cent of UK output. This approach has a number of drawbacks. First, the UVRs are based on a limited sample of products and make strong assumptions about the representative nature (in both quantity and quality) of these products. Second, UVRs only provide deflators for output, while our previous discussion emphasises the need for double-deflation where feasible.

Industry-Specific PPPs: The third approach provides an answer to this second problem but can still be criticised as not necessarily creating representative indices. Kuroda (1996), building on the earlier work of Jorgenson and Kuroda (1990), constructs PPPs between the USA and Japan for each input and output within each sector of the economy. These PPPs are constructed using the relative price data contained within Kravis, Heston and Summers (1978), who provide PPPs between the yen and the US dollar for 153 commodity groups for the year 1970. These commodity groups are components of gross domestic product of each country, corresponding to final demand at purchasers' prices. Kuroda maps these commodity groups to sectors and their inputs using the 1970 inter-industry transactions tables, and make adjustments for indirect taxes paid and transportation margins. The resulting indices may still be questionable since they are derived from final demand prices only; there are considerable mapping problems; and it is not possible to adjust for the price of imports (which should be taken out) and exports (which should be included). Nonetheless, they do enable the avoidance of the single-deflation problem that is common to studies using UVRs.[29] Table A1.1 presents the calculated relative PPPs for industry output, capital, labour, energy and other intermediate inputs for 1970.

Table A1.1
Purchasing Power Parity Index by Industry in 1970 (US=1.00)

Industry	**Output Price**	**Capital Price**	**Labour Price**	**Energy Price**	**Material Price**
Total	0.79	1.80	0.23	1.19	0.78
Food	1.04	2.16	0.22	1.19	0.92
Textiles	0.78	1.16	0.24	1.12	0.80
Paper&Pulp	0.59	1.21	0.22	1.16	0.68
Chemicals	0.68	1.05	0.25	1.21	0.74
Minerals	0.72	1.39	0.23	1.18	0.71
Primary Metals	0.82	2.47	0.25	1.19	0.78
Metal Products	0.81	2.08	0.21	1.20	0.79
Machinery	0.63	1.49	0.23	1.23	0.73
Electricals	0.68	2.65	0.22	1.17	0.74
Transport Equip.	0.91	1.01	0.22	1.20	0.79
Instruments	0.72	1.58	0.23	1.19	0.75

Source: Kuroda (1996)

According to these data, the price of manufactures in Japan in 1970 was rather lower than the final expenditure PPP would suggest. Labour costs in Japanese manufacturing were substantially lower while capital costs were higher. The cost of intermediate inputs (estimated by a weighted average of output PPPs) was around 78 per cent of the US level, while the PPPs for energy inputs in 1970 are greater than unity, implying that the cost of energy was higher in Japan.

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[29] Dollar and Wolff (1994) also construct measures of Japanese TFP relative to that of the USA, but they use a single PPP for the whole economy to convert to a common currency. As explained above, this method is biased to the extent that PPPs for industry inputs and outputs diverge from that of the economy as a whole. Consider Japan in 1970, where labour was relatively cheap (with a manufacturing labour PPP of around 23 per cent of the final expenditure PPP). Use of the final expenditure PPP leads them to understate the number of workers in Japanese manufacturing and hence to over-estimate their relative productivity.

Appendix 2 Data Sources

Japan

Data on Japanese outputs and inputs were supplied by Ichiro Tokutsu (see Tokutsu, 1994). These consisted of data on gross output and labour, energy, material, and capital inputs, in current and constant prices for the years 1955 to 1989:

- Gross output at market prices and 1985 constant prices.
- Intermediate input at market prices and 1985 constant prices.
- Aggregated energy input at market prices and 1985 constant prices.
- Capital income at market prices and gross capital stock at 1985 constant prices.
- Compensation of employees and persons engaged.

The following data were supplied by the Japanese Ministry of Labour, the Economic Planning Agency and MITI:

- Percentage of workers who are unionised.
- Percentage of workers who are operatives.
- Normal and overtime hours worked.

Purchasing Power Parities

Data on Japan-US Purchasing Power Parities in 1970 were supplied by Masahiro Kuroda (see Kuroda, 1996). See appendix 1 for further details.

USA

Data on US output and inputs were supplied by the Bureau of Labour Statistics (see BLS, 1994) for the years 1948 to 1992.

- Gross output at market prices and 1980 constant prices.
- Intermediate input at market prices and 1980 constant prices.
- Aggregated energy input at market prices and 1980 constant prices.
- Capital services at market prices and gross capital stock at 1980 constant prices.
- Compensation of employees and labour hours.

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