Technology and the Great Divergence

By

Robert C. Allen

Professor of Economic History
Department of Economics
Oxford University

Nuffield College
New Road
Oxford OX1 1NF

Email: bob.allen@nuffield.ox.ac.uk

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Since the industrial revolution, the world has become increasingly unequal. In 1820, most of today's rich countries had higher incomes than today's poor countries, but the difference was comparatively small. Since then, the rich countries have grown faster, so the gap between rich and poor has increased. The immediate cause of the divergence is clear enough: the rich countries have invented and adopted technologies that have raised labour productivity enormously. Poor countries, on the other hand, have been slower to adopt modern methods. Why they have been slow is a matter of great debate: culture, institutions, property rights, legal systems, education, constitutions all have their advocates. This paper concentrates on the technology itself. The emphasis is on measuring its characteristics, and the conclusion is that much technological progress has been biased towards raising labour productivity by increasing capital intensity. The new technology leads to higher wages, and, at the same time, is only worth inventing and using in high wage economies. The upshot is a spiral of progress in rich countries, but a spiral that it is not profitable for poor countries to join.

This paper is a historical exploration of the 'appropriate technology' theme in recent theoretical and empirical papers dealing with economic growth. The literature takes off from Atkinson and Stiglitz's (1969) concept of 'local technical change'. While most research assumes that technical progress increases output per worker with respect to capital per worker by the same proportion at all capital-labour ratios, Atkinson and Stiglitz explored the possibility that shifts in the production function were limited to a neighbourhood around the capital-labour ratio that was in use. These local changes have come to be called 'appropriate technologies' since they would be adopted only by a firm facing factor prices that led it to operate in that neighbourhood. Basu and Weil (1998) have explored the concept in a theoretical growth model in which rich countries invent techniques appropriate to their high wage environment. These are not appropriate for poor countries; they can grow very rapidly, however, if they sharply increase their savings rates, so that they can adopt the capital-intensive technology perfected by rich countries. Several investigators have studied aggregate data to see whether technical change has been local or whether it tends to raise output per worker irrespective of the capital-labour ratio (Fare et al. 1994, Acemoglu and Zilibotti 2001, Kumar and Russell 2002, Los and Timmer 2005, Caselli and Coleman 2006, Jerzmanowski 2007). This research has been based on Penn World Table data post-1960. These studies have found uniformly that technical progress has been limited to high capital-labour ratios and reflects the research priorities of high wage countries well endowed with physical and human capital. The question we ask here is: Has it always been like that?

The point of departure of this paper is Kumar and Russell's (2002) study of 1965 and 1990 cross-sections of national data. These data describe the 57 countries for which the Penn World Table 5.6 reports both output per worker and capital per worker in 1985 international dollars.[1] Figure 1 plots the data. The diagram has two outstanding features. First, all of the points form a curve that looks like a textbook production function. A Cobb-Douglas function has been fit to these points (Table 1). It is the 'production function of the world.' Second, many of the 1990 points are an extension of the 1965 points–up and to the right. There was

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[1]Kumar and Russell (2002, p. 531) leave out Iran and Venezuela, which are also in PWT 5.6, on the grounds that they are oil producers. I leave them out likewise, and I thank Bob Russell and Daniel Henderson for providing me with a spreadsheet of the data. They have written two more papers adding education to the data and refining the procedures (Henderson and Russell 2005, Badunenko, Henderson, Russell 2008), but the historical data are not yet available to follow them in these extensions.

no increase in output per worker at capital-labour ratios below the highest achieved in 1965, i.e no technical progress of the usual neutral sort. Recent work by Badunenko, Henderson, Zelenyuk (2008) and Badunenko, Henderson, Russell (2008) indicates that this stability held at least through 2000. This was technical progress, but it cannot be detected by fitting a production function to the data and looking for a structural break or by using a total factor productivity index exact for that production function.

Kumar and Russell's solution to the measurement problem is to fit frontier production functions to the two cross sections. Their frontiers are shown in Figure 2. Between 1965 and 1990, there was no technical progress at capital intensities below $17,500 per worker. All of the progress in those years occurred at higher capital-labour ratios and, indeed, pushed those ratios higher. Kumar and Russell reject Hicks neutrality and Harrod neutrality as adequate descriptions of technical change or explanations for the rise in output per worker. Instead they emphasize the central importance of capital accumulation as a cause of economic growth. This is a long standing debate, and this paper considers the question over a much longer time frame.

This paper is concerned with two issues. The first is how the production function estimated in Table 1 was created. Was it due to the process of biased technical change that Kumar and Russell have detected for 1965-1990 or did neutral technical progress also play a role? Were some countries leaders and some followers? The second is what are the implications of this function for economic growth in poor countries?

Data

These questions will be pursued by extending the 1965 Penn world table data back to 1820. This cannot be done for all countries, but it can be done for enough to provide a historical dimension to the modern cross-sections. This paper uses historical reconstructions for the USA, the UK, the Netherlands, Belgium, France, Germany, Italy, Norway, Denmark, Switzerland, Spain, Japan, Taiwan, South Korea, India, Mexico, and Argentina. Not all of the reconstructions are equally long, but all extend back to at least the First World War.

Maddison (1995, 2001, 2006) pioneered this kind of historical reconstruction with his widely used GDP series. He began with a cross section of PPP adjusted GDP estimates (most recently measured in 1990 international Geary-Khamis dollars) and extrapolated them backwards with national estimates of the growth of real GDP to produce estimates of GDP in 1990 dollars for hundreds of years into the past. I proceed similarly. GDP and the capital stock (both measured in 1985 international dollars in Penn World Table 5.6) are projected backwards by using national studies and, for GDP, often using Maddison's results. National estimates of the labour force or occupied population are likewise used to extend the number of workers in 1965 back into the past. The result is a data set beginning in the eighteenth century with GDP per worker and capital per worker measured in 1985 international dollars. In this paper, I concentrate on cross sections of the data for 1820, 1850, 1880, 1913, and 1939, which are compared with the PWT cross sections for 1965 and 1990.

Accounting for Economic Growth with Frontier Production Functions

How was the modern world production function created? The data themselves show that much progress consisted of concurrent increases in output per worker and capital per worker. Figure 3 plots output per worker against capital per worker for 1820 through 1913. In 1820, the points are concentrated in the lower left hand corner where the maximum capital-labour ratio was realized in the Netherlands ($3521/worker) and the highest labour productivity in the UK ($4408 per worker). As the nineteenth century unfolded, the points moved upward and to the right. As the leading economies moved beyond a capital-labour ratio, there was no further increase in output per worker at that capital-intensity.

These patterns continued across the twentieth century (Figure 4). The predominant pattern from one time period to the next is the movement of points upward and to the right, although some countries remain stuck in the lower left. The countries that did not develop had a capital-labour ratio and output per worker in 1990 that were as low as the ratios characteristic of 1820.

These observations can be formalized by fitting frontiers to the data as Kumar and Russell did. Figure 5 shows frontiers for 1820, 1850, 1880, and 1913. The pattern is identical to Figure 2 with all of the change extending the previously highest capital-labour ratio. There was no improvement in output per worker at lower capital intensity. Figure 6 shows twentieth century frontiers, and again both patterns are repeated. Biased technical change amounting to the extension of the production possibilities to higher and higher capital-labour ratios has been a fundamental feature of economic growth since the industrial revolution. Conversely, there has been no improvement in labour productivity for countries that did not accumulate capital.

There are three ways that a country can increase output per worker in the Kumar-Russell framework. First, a country below a frontier could increase its efficiency by rising to the frontier (efficiency improvement). Second, a country could raise capital per worker by moving along a frontier to the right (capital accumulation). Third, a country could jump vertically to a higher frontier (technical progress). The latter two are relevant to long run economic growth. What is their relative importance? Suppose we compare the UK in 1820, which realized $4408 per worker with $1841 capital per worker, to the USA in 1990 with output per worker of $36701 and capital per worker of $34705. Each was on the frontier and defined a high corner, so efficiency improvement does not apply. There are two sequences to convert the UK in to the USA. One is to first increase capital per worker to $34705 by moving along the 1820 frontier and then to jump vertically to the 1990 frontier. In this case, the increase in capital per worker causes no increase in output per worker, and the entire difference in output per worker between the two cases is due to improvements in technology. The second way to raise output per worker in the UK is, first, to jump to the 1990 frontier and then to move along it by accumulating capital. In 1990, a capital-labour ratio of $1841 implies output per worker of $7672. Along this path, technical progress raises output per worker by $3264 (=$7672-$4408), which is 10% of the difference between the UK in 1820 and the USA in 1990. The remaining 90% of the difference is due to capital accumulation. One path attributes economic growth to technical change, the other mostly to capital deepening. When technical progress and capital accumulation occur concurrently, separate contributions cannot be identified. Standard growth accounting rules out this possibility by assuming the technical progress is Hicks neutral.

The frontier production functions suggest two related conclusions. First, technical improvements have been limited to upward shifts in the production function only at the highest capital-labour ratios in use. Second, as a corollary, there have been no improvements in efficiency at any capital labour ratio once the locus of advance has moved to a higher capital-labour ratio.

Accounting for Economic Growth with Cobb-Douglas Production Functions

Technical change can also investigated by fitting production functions to the panel data set. This reveals a more complex pattern of improvement, which includes neutral technical progress.

Table 2 shows Cobb-Douglas functions estimated from the panel of countries with long term historical data. The functions were estimated with and without country fixed effects and dummy variables indicating the cross sections. This specification corresponds to conventional growth accounting and means that technical change is Hicks neutral and measured by the coefficients of the time dummies. Most of the country dummy variables are statistically significant, and the coefficients are generally plausible. The USA and the UK, for instance, were the most efficient countries. Plausibility is also important since it provides some warrant for trusting the data: The country fixed effects would pick up country specific idiosyncrasies in data construction, but none stand out.

With or without the country fixed effects, the coefficients of the time dummy variables are similar and indicate a long run rise in total factor productivity that accelerated after 1880. The cross sections before 1965 have negative coefficients showing that productivity was lower in those years than in 1990. The discount declines in magnitude and significance from 1880 to 1965, as productivity increases. The period from 1965 to 1990 stands out as unusual in that it is the only one without an upward shift in the function. This absence corresponds to Kumar and Russell's finding that there was only non-neutral technical change in this period. However, the significant time dummies suggest that something else was going on between1880 and1965.

The Cobb-Douglas framework indicates that both capital accumulation and technical progress were important sources of growth in output per worker. Analysing the difference between the UK in 1820 and the USA in 1990 in this frame work indicates that about two-thirds of the difference was due to the increase in capital per worker and the remaining third was due to technical progress.

The production functions estimated from the panel data set have another important feature: they correspond closely to the 1965-1990 cross section of Penn World Table data. The intercept and coefficient of the lnK/L variable in Table 1 and Table 2, regression 3, are almost the same. The intercept in the panel regression varies depending on which country dummy is excluded. In Table 2, that is Japan. With that normalization, the modern cross section of countries summarizes the historical path of development experienced by the sample of leading economies.

We can locate more precisely when neutral technical progress occurred by dividing the data set into intervals defined by the capital-labour ratio. Table 3 reports Cobb-Douglas functions estimated over such ranges. The sub-sample with K/L ratio less than $5000 includes observations of the poorest countries today and of the early phase of industrialization in today's richest countries. The time dummies in the estimated production function are insignificant indicating that today's poor countries are no more efficient than the rich countries at the beginning of their growth experience. This remarkable finding is illustrated by Figure 7, which plots the data for these countries. The successive cross sections for the last two centuries overlap impressively.

It was a different story at higher capital-labour ratios. 1880 was the first cross section in which any county was operating with a capital-labour ratio above $5000 per worker. Today's rich countries had capital-labour ratios between $5000 and $10000 for the next fifty to seventy-five years, and they were joined by middle income countries in this period. There was a stead upward shift in the production function in this K/L range between 1880 and 1965. No further improvements in efficiency have been made since then, however.

This process was replicated at K/L ratios above $10000. Today's rich countries began operating in this region in the 1913 cross section. Productivity increased in successive cross sections until 1965. Between 1965 and 1990, there were no further improvements.

These episodes of Hicks neutral technical progressive have two important implications. First, there have been many growth accounting exercises covering the period since 1850. Most of these identify long periods of residual productivity growth. That productivity growth corresponds to the upward movements of the production function estimated in Table 2. The growth slowdown conventionally dated from the 1973 oil shock shows up as the absence of productivity growth between the 1965 and 1990 cross sections.

Second, the production surface sketched out in Figure 1 and represented by the 1990 frontier or the production function in Table 1 is the culmination of these time limited bursts of neutral productivity growth following each increase in the capital-labour ratio. Specifically, the predicted values from the regressions in Tables 1, 2, and 3, when evaluated using the 1990 time dummies, are very close to each other. Today's world production function was constructed in stages by the rich countries as they developed.

<u>The Process of Technical Change</u>

The set of production possibilities that the world faces today were invented by a limited number of rich OECD countries–the UK, USA, Netherlands, Germany, France, Belgium, Norway, and Switzerland (although only the first five are present in the 1820 sample). They increased the capital-labour ratio in steps, which can be seen in Figures 8-9 Between 1820 and 1850, the average position of the leading economies moved upward and to the right, but there was little increased in maximum output per worker. Considerably larger shifts in a northeasterly direction occurred in 1850-1880, when capital-labour ratios between $5000 and $9000 where first explored, and in1880-1913, when capital per worker rose to $9000-$12,000. Output per worker rose little between 1913 and 1939, but capital intensity was pushed to $20,000 per worker. Between 1939 and 1965, output per worker was pushed to new heights and capital per worker raised to $40,000. By 1990, the pioneers increased capital per worker to over $73,000 per worker, and output per worker reached $38,000.

Different countries played different roles in this upward progression. We can distinguish high flyers from accumulators. In the period 1850-80, three countries kept capital per worker at about $4000 but raised output per worker to about $7000. These countries were the USA, the UK, and the Netherlands, and they remained leaders over the entire period. These high flyers defined the corners of the frontiers–the UK and the USA in 1880 and 1913, the UK and the Netherlands in 1939, and the USA in 1965 and 1990. In these years, the UK and the Netherlands were just below the frontier. The high productivity of these countries stands out if their growth trajectories are plotted against the background of the 1965 and 1990 cross sections. The UK trajectory runs along the top of these points (Figure 10), and the USA trajectory jumps above them when the USA overtook the UK (Figure 11).

The inventiveness of the high flyers was underpinned by favourable institutions. The US and the UK had modern patent systems throughout. The Netherlands operated without patents from 1869 to 1912. In all three countries, businesses and government agencies carried out research. Universities in these countries, as well as in countries like Germany, also undertook basic and applied research. Professional and trade associations created research networks that contributed to progress. Collective invention in which firms shared technical information and built on each others successes was also important. As the twentieth century progressed, governments spent more and more money on research, often with military applications in mind. Some technological advance was due to scientific breakthroughs, but most improvements were either the result of 'learning by doing' or were produced by research and development projects aimed at solving immediate problems or, more generally, increasing the profitability of the firms undertaking the research. As a result, the new technology was most appropriate for the factor prices and other circumstances of the rich countries doing the inventing.

The second group of leading countries–Germany, Belgium, France, Norway, and Switzerland–were the accumulators. Their movements were more horizontal than vertical. The accumulators operated with higher capital-labour ratios and realized lower output per worker than the high flyers. Investment banks were more important sources of industrial finance in continental Europe than they were in the UK or USA, and that institutional difference may be the reason that capital-labour ratios were higher on the continent.

The greater emphasis on the role of capital accumulation in the continental countries meant that their growth trajectories were on the low side of the scatter of point defined by the 1965-90 PWT cross section. Germany and Switzerland are cases in point (Figures 12 and 13)

One to two generations were spent perfecting the technology at one capital-labour ratio before the leading countries moved on to greater capital intensity. In 1850, for instance, the pioneers got about $4000 per worker from a capital stock of $3000-5000 per worker. By 1880, the high fliers realized close to $8000 per worker with the same stock. By 1913, this had increased to $9000, but by then inventive activity had shifted to higher capital-labour ratios. Much of this improvement was realized by the accumulators who gained on the high fliers. An important case was Germany's catching up with Britain. France also made considerable progress at the same time. Because the capital-labour ratios of the accumulators wre at least as great as those of the high flyers, there was little difference between the accumulators and the high fliers in their relative factor prices. As a result, technology was easily transferable among them. The catch-up of the accumulators corresponds to some of the convergence among OECD countries that has been measured.

A similar development occurred at capital-labour ratios between $15,000 and $20,000 per worker in the twentieth century. There was a small advance between 1913 and 1939 and a very much greater increase in output per worker between 1939 and 1965. This was achieved with only a small increase in capital per worker. After that, the pioneer countries moved to higher capital-labour ratios, and improvement ceased at capital-labour ratios below $30000 per worker.

The high flyers led the advances among the pioneer economies, and the accumulators were always playing 'catch up'. One should not, however, exaggerate the backwardness of the accumulators. Their productivity was never static, and they did not fall far behind. Technological histories of these countries emphasize the creativeness of their science and engineering. It is difficult to say what they would have done without the example of the high fliers, but the accumulators were never very far behind them.

Economic Growth in Late Developers

While the accumulators began to grow in the early nineteenth century, economic growth in most countries did not begin until the late nineteenth or twentieth centuries. An important group are the convergers who have successfully industrialized and become rich themseleves. This group includes peripheral countries in Europe (Italy, Spain, Denmark) as well as in East Asia (Japan, S. Korean, and Taiwan). The convergers have never pushed output per worker or capital per worker beyond existing limits. Instead, they have grown by accumulating capital and moving up the world production function. This is shown by plotting their growth trajectories against the 1965-90 cross sections.

The late developers have faced a problem, which has grown over time, namely, the inappropriateness of the technology invented by rich countries. This problem is manifest in the curvature of the world production function. The technology invented today, with its very high capital-labour ratio, is only cost effective when the wage is high relative to the price of capital. The easiest technology for poor countries to adopt is that of the late nineteenth century, which was invented when wages were much lower relative to the price of capital. Indeed, the export industry that is most successful in most poor countries is clothing and apparel. The basic machine is the sewing machine, which was developed in the 1850s. Electric sewing machines were first marketed in 1889. This technology was invented in rich countries when their wages were low and is the basis of industrial development in many poor countries today.

The European convergers began to grow when these disincentives were comparatively minor. Italy is a case in point. Figure 14 shows the history of output per worker and capital per worker arrayed against the background of data points from the 1965 and 1990 cross sections. Italy's growth follows the pattern defined by the world production function. When it began to grow in the late nineteenth century, the difference between its capital-labour ratio and that of the leading countries was not great, so factor-price impediments to importing modern technology were small. From 1861 to 1951, the Italian economy grew mainly by importing technology from advanced countries, and this required the concurrent accumulation of capital. Investment banks facilitated accumulation by channelling cheap capital to large scale industry. Productivity was always about two-thirds of the value implied by the Cobb-Douglas production function in Table 1. The only period in which neutral productivity growth played a major role was 1951-73 when TFP in Italy rose to 35% above the level implied by the Cobb-Douglas production function. That shift is noticeable in Figure 14 when the Italian growth trajectory shifts from the low side to the high side of the scatter of points. The motor of Italian growth, however, has been the importing of technology and the accumulation of capital as the country has worked its way up the world production function.

Some of the convergers are famous for the speed of their catch-up. These bursts were preceded by longer periods of slow growth. Japan, for instance, had a capital-labour ratio of only $569 in 1870. Growth over the next seventy years raised this to $2409 in 1940. This was a radical enough transformation to generate a vast literature on the economic consequences of the Meiji restoration. Capital per worker was, however, still no higher than it had been in the UK in 1860.

Japan followed an unusual technology policy in this period, which has been called 'labour-intensive industrialization.' (Sugihara 2002, 2010) The first state initiatives to import Western technology in the 1870s were unsuccessful since foreign plants were too capital-intensive for Japan. Systematic efforts were made to alter western technology to increase the productivity of capital, the scarce input. The changes spanned the gamut from increasing the number of hours per day that cotton mills operated to standardizing products with the aim of boosting output per machine to redesigning equipment. These changes increased output per worker at low capital-labour ratios by allowing modern methods to be used in a less capital-intensive manner (Otsuka et al. 1988). Likewise, agrarian research aimed to raise land productivity rather than mechanize farming (Hayami and Ruttan 1971). This also boosted output per worker without increasing capital per worker. The results were manifest in an unusual increase in total factor productivity: in 1870, Japan operated at only 38% of the efficiency implied by the world production function; by 1940, the country's productivity rose to 77% of that standard.

The theoretical literature on appropriate technology indicates that a rise in the savings rate can have unusually powerful effects on growth since it allows a country to jump up to a higher point on the world production function. Japan's post-war growth was a big push from this gradually accumulated base, as Figure 15 suggests. Output per worker, however, sagged during the great catch-up. The rapid growth of Taiwan and South Korea since 1965 was also preceded by a period of gradually economic growth when their were Japanese colonies. Rapid growth was realized by accumulating capital and moving up the world production function rapidly, although Taiwan shows a similar tendency to low efficiency as Japan (Figure 16).

The final group of countries are the slow movers that have not grown rapidly. India is the most extreme example in the data set (Figure 17). Between 1860 and 1990, it accumulated little capital and achieved little growth. Its capital-labour ratio in 1990 ($1946) and labour productivity ($3235) were like Britain's in 1820 ($1841 and $4408, respectively). Mexico and Argentina have grown more but not caught up with the leading economies. Both countries have exhibited above average efficiency for many years (Figures 18 and 19), but have not imported enough advanced technology nor accumulated enough capital to catch up with the leaders. On the contrary, Argentina was a rich country before the first World War. The immediate reason it fell behind was because its capital stock per worker in 1965 ($5555) was little above its 1913 value ($4779). These countries need to accumulate capital in the massive way that East Asian economies have done since 1960 in order to close the gap with the West.

conclusion

The PWT data set for 1965 and 1990 does act as a world production frontier for the period 1820-1990. The frontier was not known to people in 1820, however. It was discovered in the nineteenth and twentieth centuries.

The process of discovery had earlier roots. Already in 1820, income per head was considerably higher in northwestern Europe and the United States than it was elsewhere in the world. Capital intensity was also much higher. The USA and the countries of northwestern Europe all used several thousand dollars of capital per worker. India and Japan in the mid-nineteenth century were only using about $500. The effects of high capital intensity were also visible in the labour market: real wages were much higher in England, the Netherlands, and the USA than elsewhere in the world (Allen 2001, 2007, 2009, Allen, Bassino, Ma, Moll-Murata, van Zaden 2007).

The nineteenth and twentieth centuries saw great improvement in technology. Advance was accomplished in two stages: First, pioneer economies invented technology that was more capital intensive and had higher labour productivity than was used previously.

Second, labour productivity was pushed up as the newly invented technology was perfected. This phase of improvement lasted several generations. Since that phase was completed, there have been no improvements in efficiency at the level of capital intensity in question. The production function has been stable since only the rich invent new technology. Once they have progressed beyond a capital-labour ratio, they stop investing in technological improvements below that ratio. The result is the 'world production function' defined by the 1965 and 1990 PWT cross sections.

The pioneer economies over these centuries have been the UK, the USA, and the Netherlands. The first two are the usual suspects; the Dutch are a surprise. The Dutch Republic, however, was the wonder economy of the seventeenth century, and the country had a very high income into the nineteenth century. Perhaps because they had no domestic cotton industry and lacked coal, the Dutch did not invent the technology of the industrial revolution. Instead, high incomes yielded high savings that were invested in low profit projects like land reclamation. This was manifest in the high capital-labour ratio in 1820. However, that imbalance was overcome by 1850, and the Dutch joined the Americans and Brits in pushing capital-intensive technology forward.

It is not a surprise why these economies were the leaders. They had supportive institutions and culture, but they also had powerful economic incentives leading them on. It is very important in this regard that technological progress has been biased. If it were neutral, then every country in the world would have faced the same incentive to invent it since costs would have fallen by the same percentage irrespective of factor prices. With biased technical change, however, the cost saving depends on the factor prices. The technology invented in the West cut costs more where wages were high relative to capital costs than where wages were low. Furthermore, invention was never free: the economic benefits of new technology had to be set against the R&D costs of inventing it. At the end of the eighteenth century, the economies with high wages were England, the USA, and the Low Countries. Those were the places in the world where it paid to invent labour saving technology (Allen 2009).

The process of development became self-reinforcing. The wide-spread adoption of the new technology raised wages in northwestern Europe and North America. Higher wages created an incentive to invent even more capital-intensive technology. The result was a ascending spiral of progress.

The spiral led to unequal development since the newly invented technology was not cost-effective in low wage economies. There have been exceptions: Sometimes techniques have been perfected enough to lower costs even in low wage countries. Then some economic growth happens on the periphery. Otherwise, the poor countries can only grow by accumulating capital and crawling up the world production function estimated in Table 1. The most successful countries have developed institutions to lower the cost of capital to industry, thereby, making capital-intensive technology more profitable than it otherwise would have been. Investment banks performed that function in countries like Italy. In East Asia, where the challenges were greater because the countries were further behind at the start of their industrialization, a panoply of government industrial and financial policies have played the same role.

Table 1

World Production Function: PWT 1965-90 Cross Section

Dependent variable is ln(Y/L). T-ratios in parentheses.

constant	3.951
	(16.352)
ln(K/L)	.586
	(21.604)
R^2	.806
observations	114

Table 2

World Production Function: Historical Panel Data Set

dependent variable is ln(Y/L) in all regressions. T-ratios in parentheses.

	(1)	(2)	(3)
constant	2.665 (10.218)	3.852 (10.818)	3.972 (8.178)
ln(K/L)	.714 (24.012)	.607 (17.651)	.570 (11.204)
D1820		-.513 (-2.975)	-.780 (-4.513)
D1850		-.521 (-3.436)	-.693 (-4.640)
D1880		-.553 (-4.157)	-.625 (-4.633)
D1913		-.378 (-3.031)	-.439 (-3.799)
D1939		-.222 (-1.858)	-.288 (-2.908)
D1965		.017 (.156)	-.022 (-.283)
country fixed effects?	No	No	Yes
R^2	.872	.910	.978
observations	87	87	87

Table 3

Perfection of Technology at Various Capital-Labour Ratios
Historical Panel Data Set

dependent variable is ln(Y/L) in all regressions. T-ratios in parentheses.

	(1)	(2)	(3)
	K/L < \$5000	\$5000 ≤ K/L < \$10000	\$10000 ≤ K/L
constant	3.359 (4.624)	6.604 (4.336)	6.144 (4.072)
ln(K/L)	.593 (6.974)	.268 (1.508)	.352 (2.262)
D1820	-.305 (-1.242)		
D1850	-.247 (-1.146)		
D1880	-.169 (-.844)	-.939 (-4.056)	
D1913	-.058 (-.315)	-.571 (-3.419)	-.803 (-5.743)
D1939	.079 (.487)	-.326 (-2.671)	-.544 (-5.912)
D1965	-.090 (-.583)		
R^2	.982	.998	.979
observations	37	20	30

note: All regressions include country fixed effects.

Figure 1

The 1965 and 1990 Cross Sections

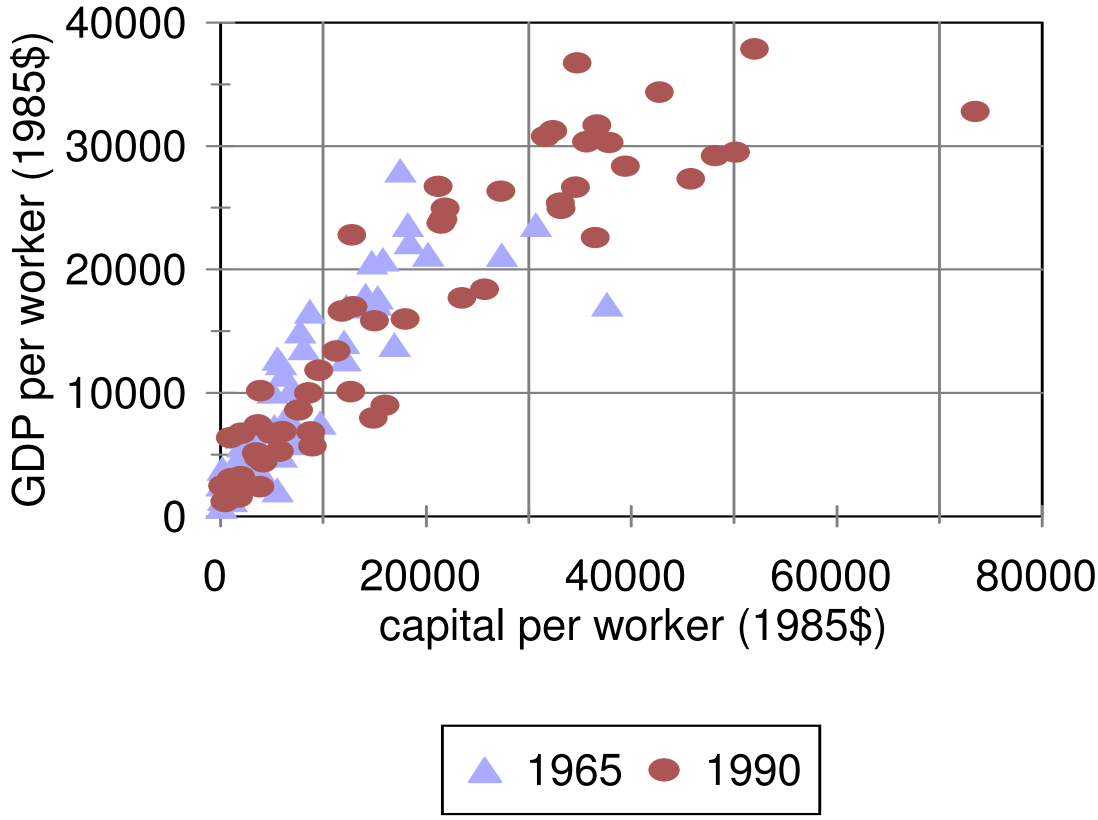


Figure 2

Kumar-Russell Frontier Production Functions

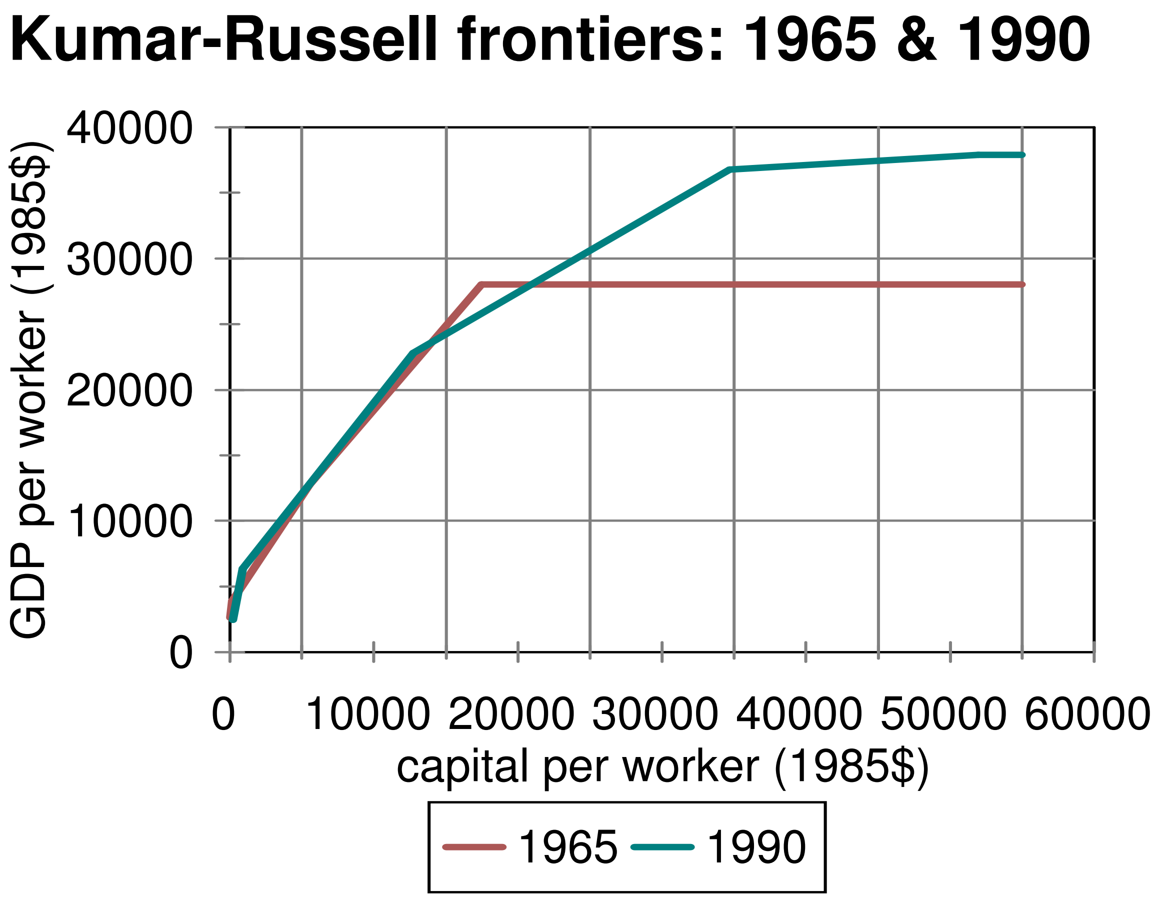


Figure 3

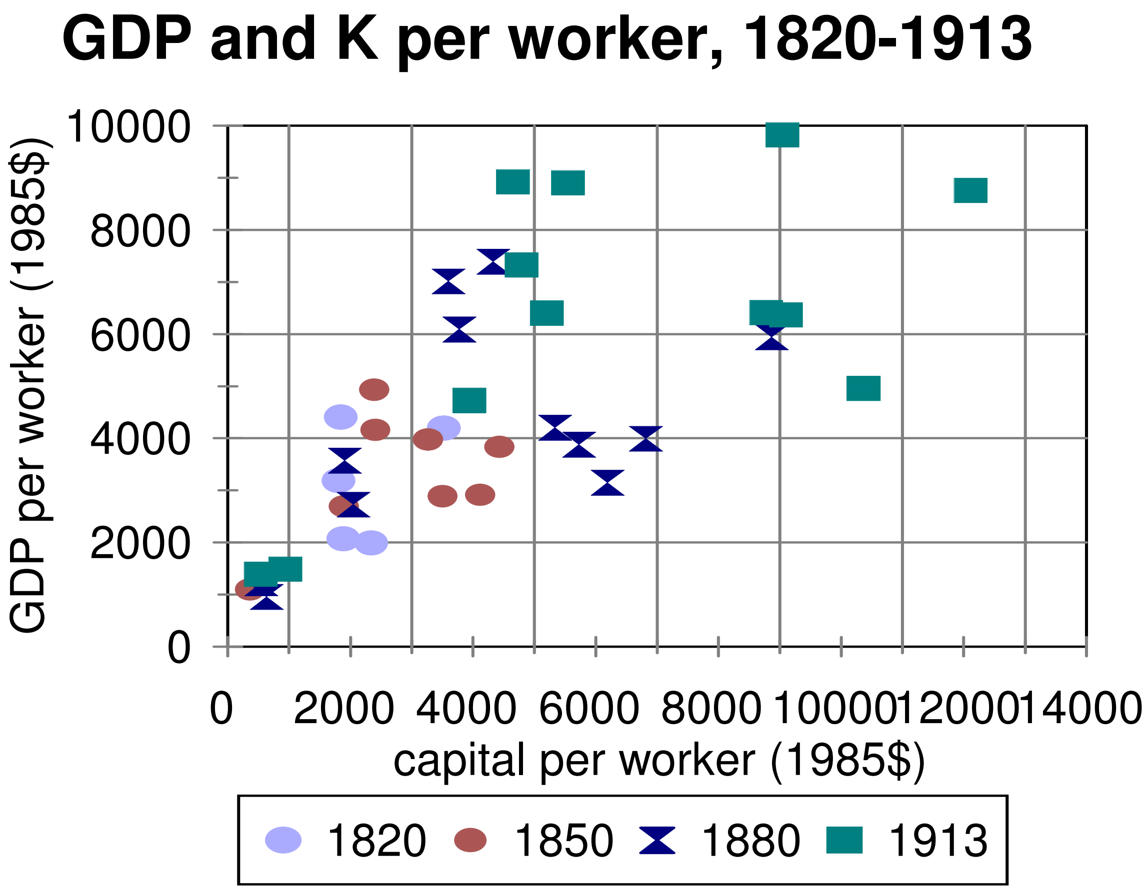

GDP and K per worker, 1820-1913
GDP per worker (1985$)
10000
8000
6000
4000
2000
0
0
2000
4000
6000
8000
10000
12000
14000
capital per worker (1985$)
1820
1850
1880
1913

Figure 4

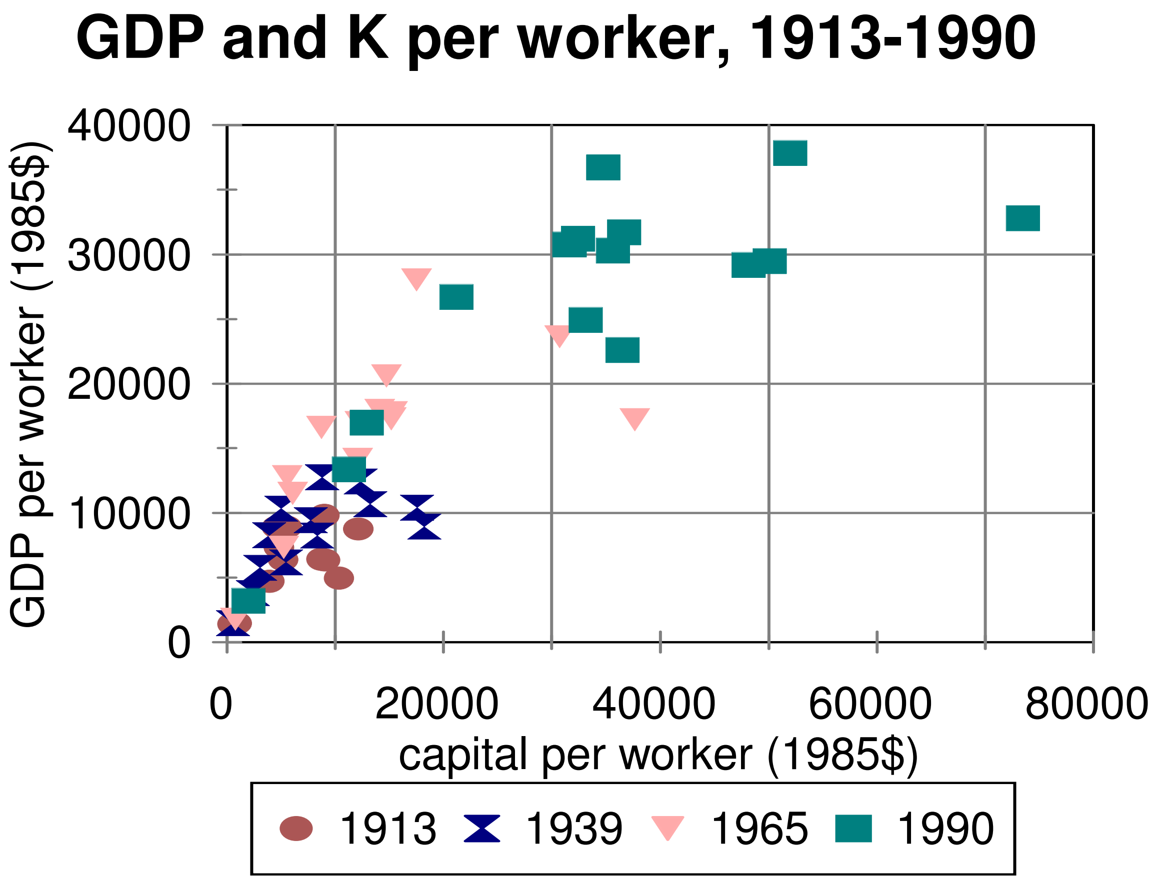

GDP and K per worker, 1913-1990
GDP per worker (1985$)
40000
30000
20000
10000
0
0
20000
40000
60000
80000
capital per worker (1985$)
1913
1939
1965
1990

Figure 5

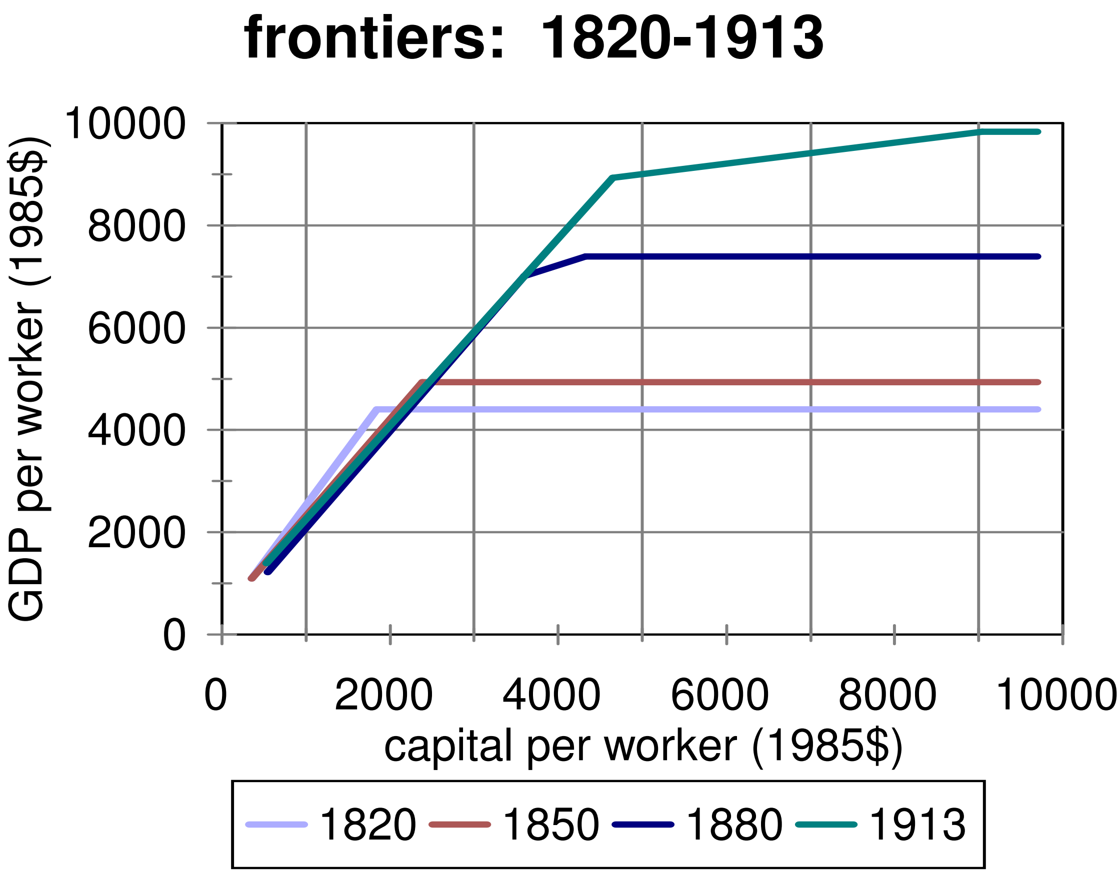

frontiers: 1820-1913
10000
8000
6000
4000
2000
0
GDP per worker (1985$)
0
2000
4000
6000
8000
10000
capital per worker (1985$)
1820
1850
1880
1913

Figure 6

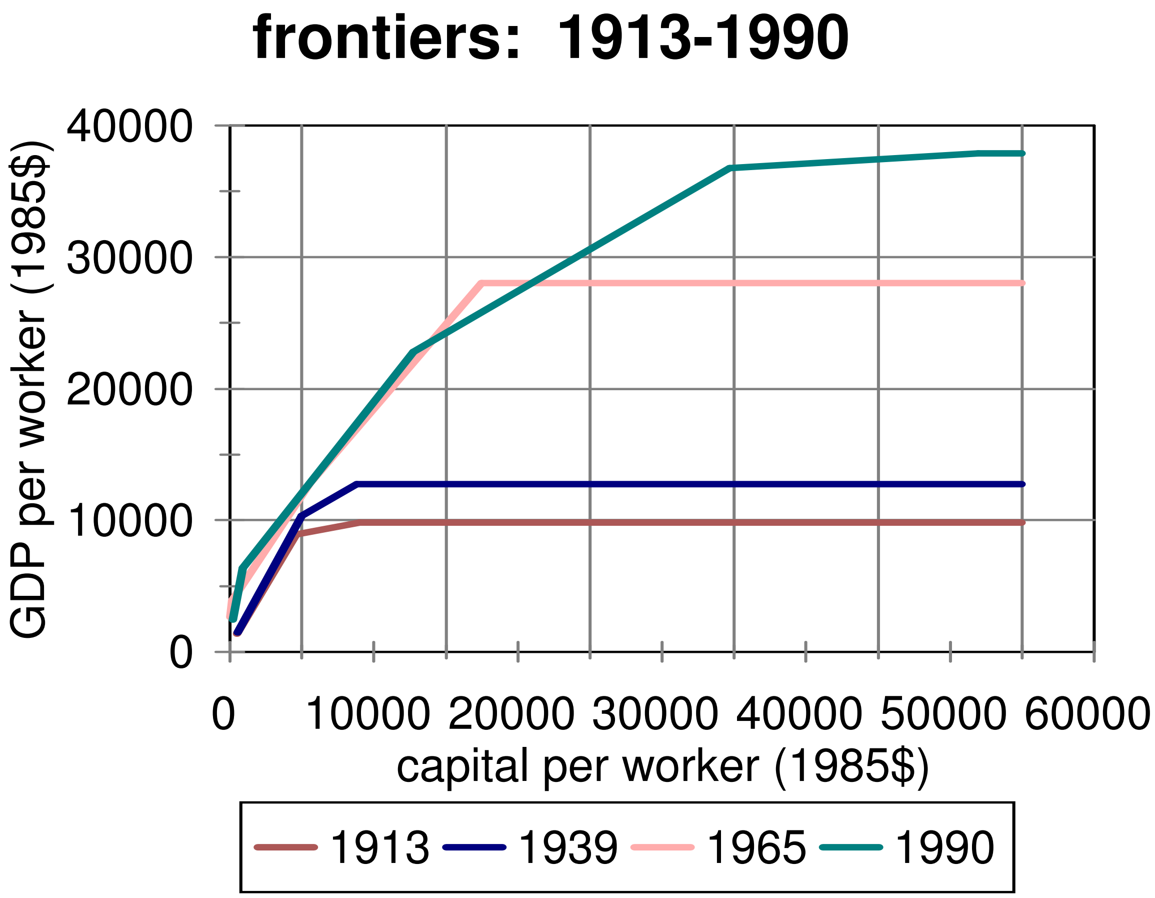

frontiers: 1913-1990
GDP per worker (1985$)
40000
30000
20000
10000
0
0
10000
20000
30000
40000
50000
60000
capital per worker (1985$)
1913
1939
1965
1990

Figure 7

Output per Worker versus Capital per Worker
when Capital-Labour ratio is less than $5000

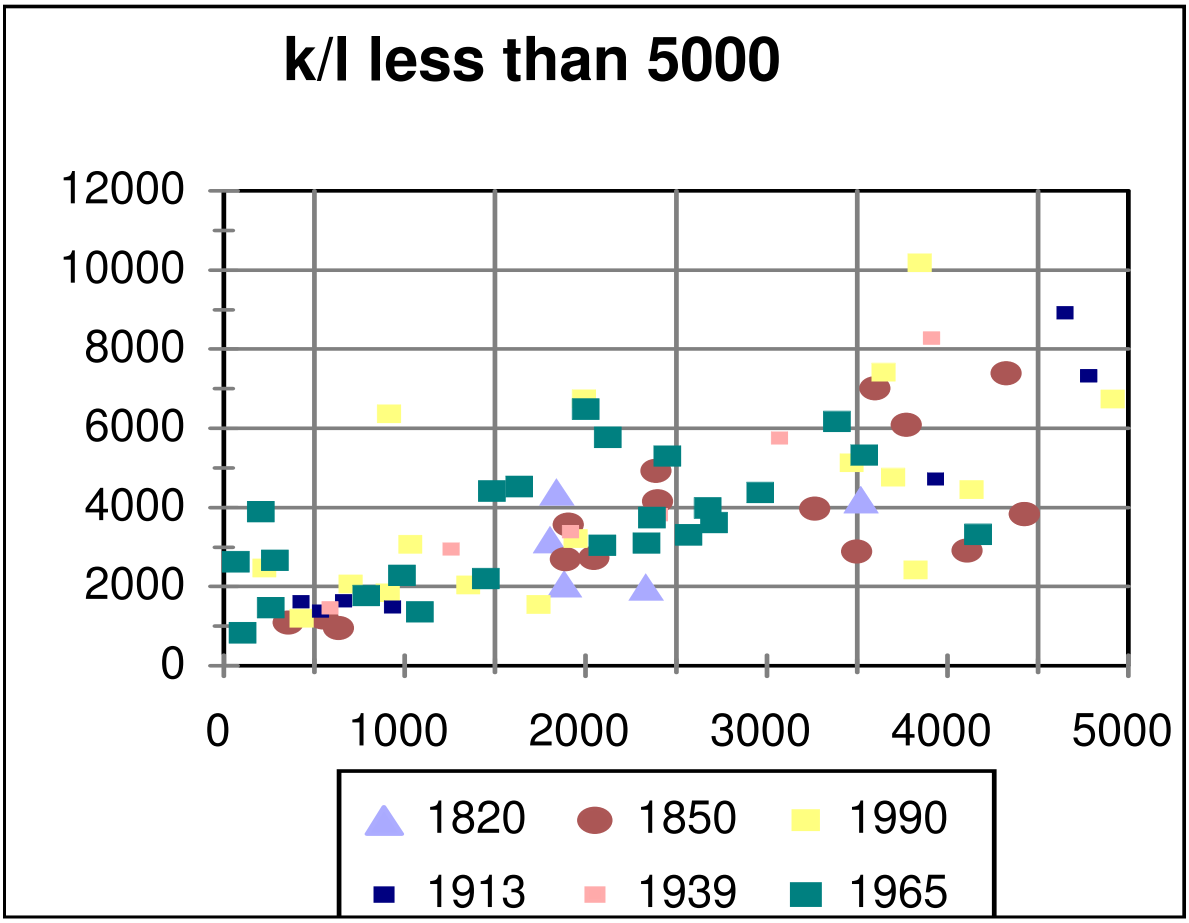


Figure 8

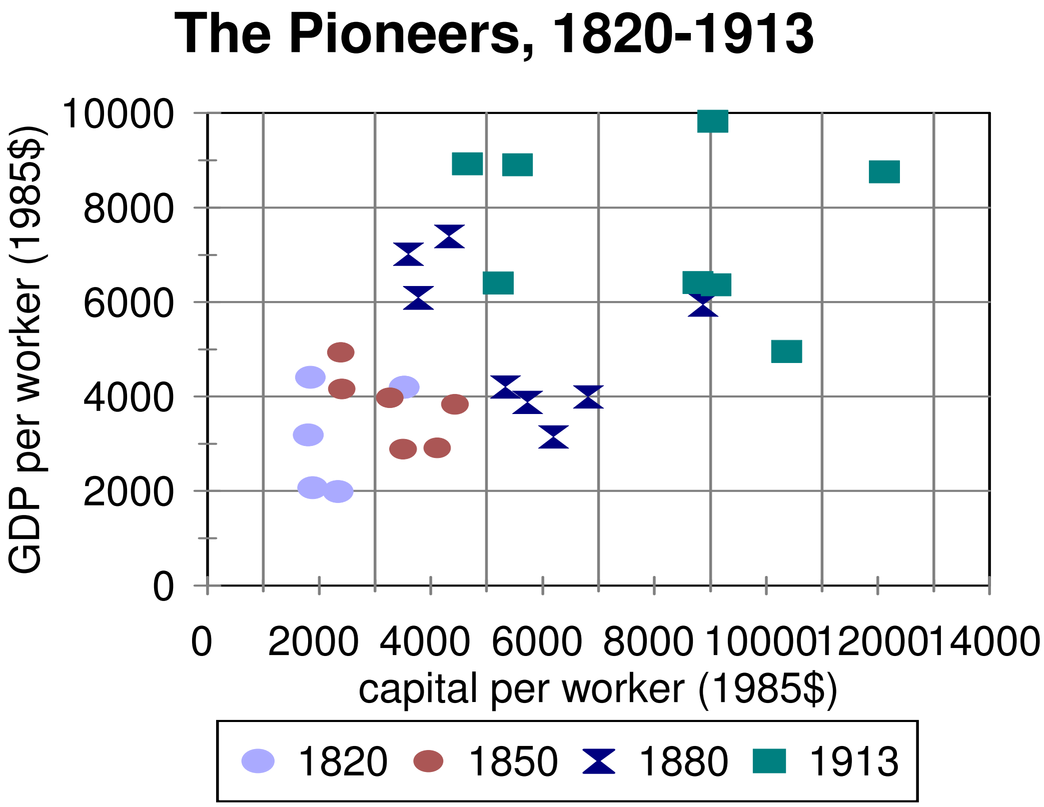

The Pioneers, 1820-1913
10000
8000
6000
4000
2000
0
GDP per worker (1985$)
0
2000
4000
6000
8000
10000
12000
14000
capital per worker (1985$)
1820
1850
1880
1913

Figure 9

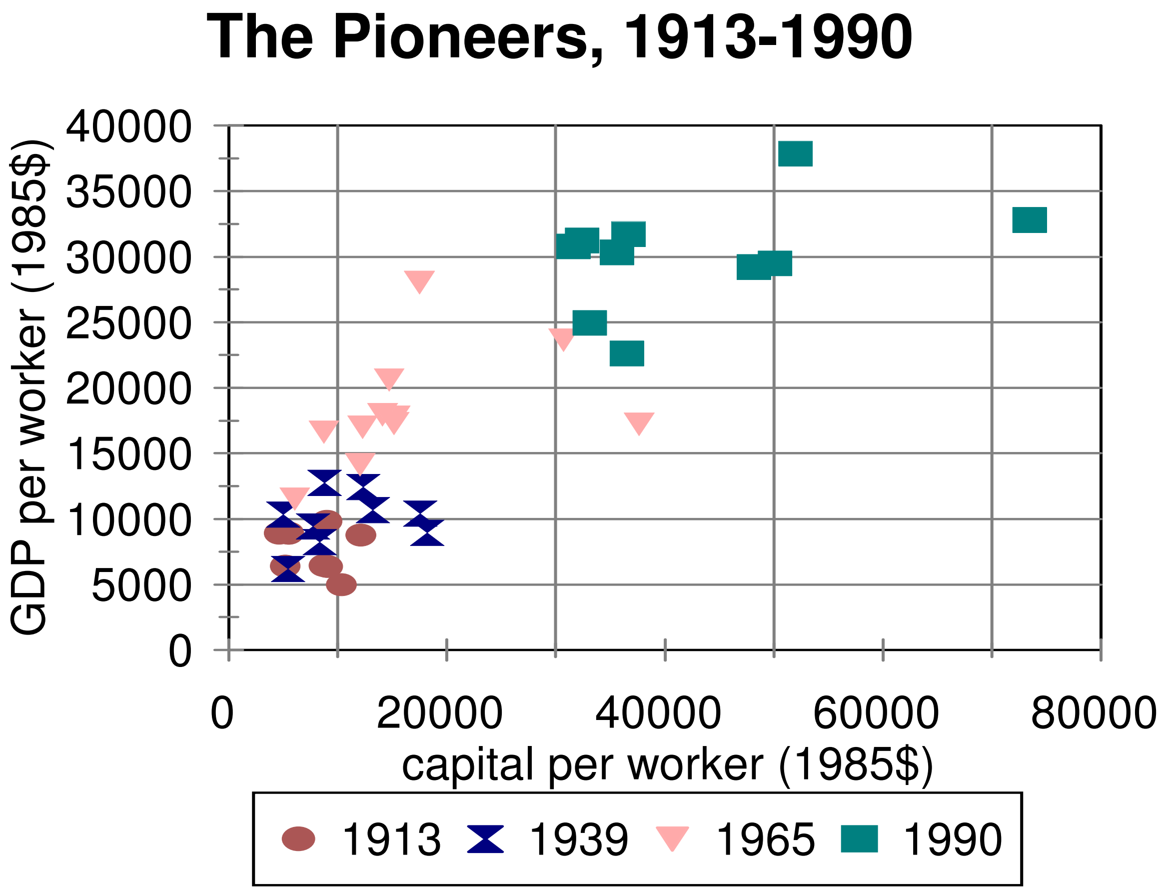

The Pioneers, 1913-1990
40000
35000
30000
25000
20000
15000
10000
5000
0
GDP per worker (1985$)
0
20000
40000
60000
80000
capital per worker (1985$)
1913
1939
1965
1990

Figure 10

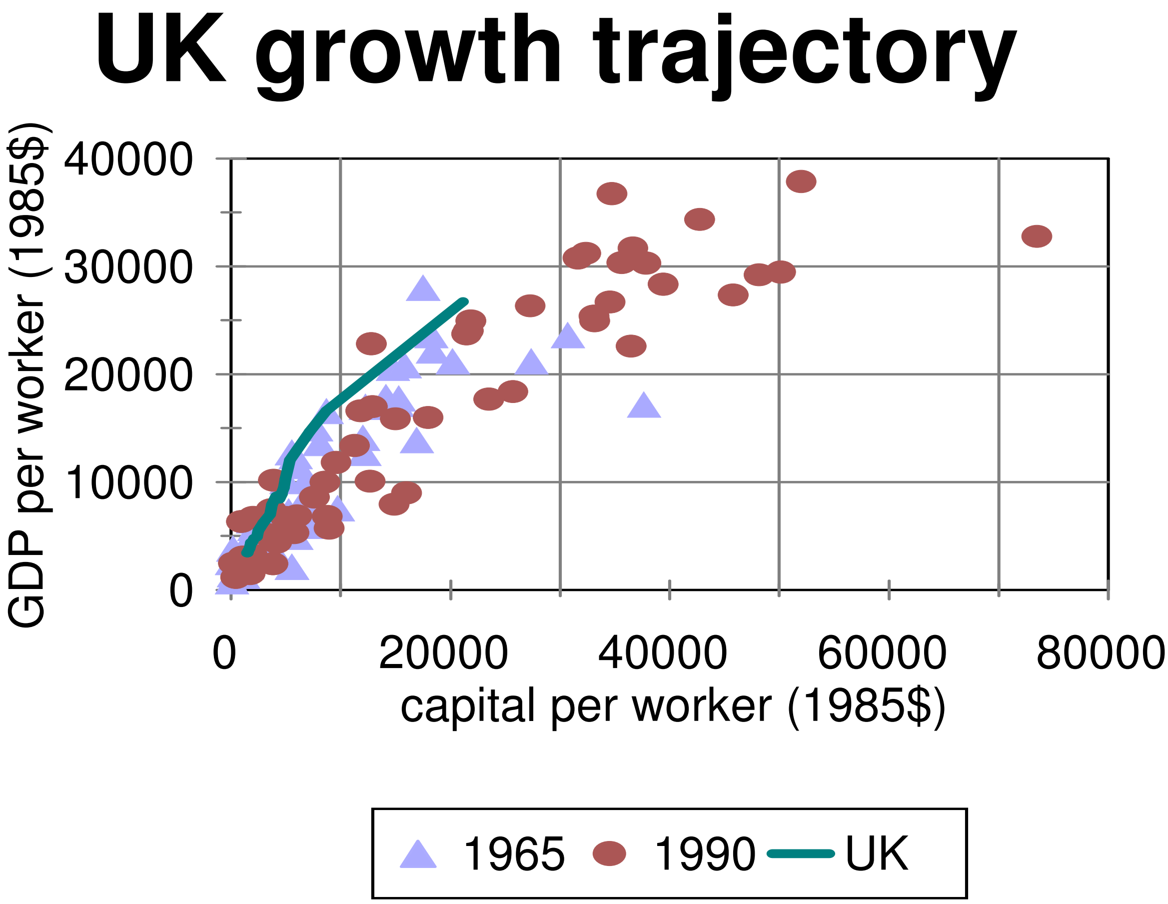

UK growth trajectory
GDP per worker (1985$)
40000
30000
20000
10000
0
0
20000
40000
60000
80000
capital per worker (1985$)
1965
1990
UK

Figure 11

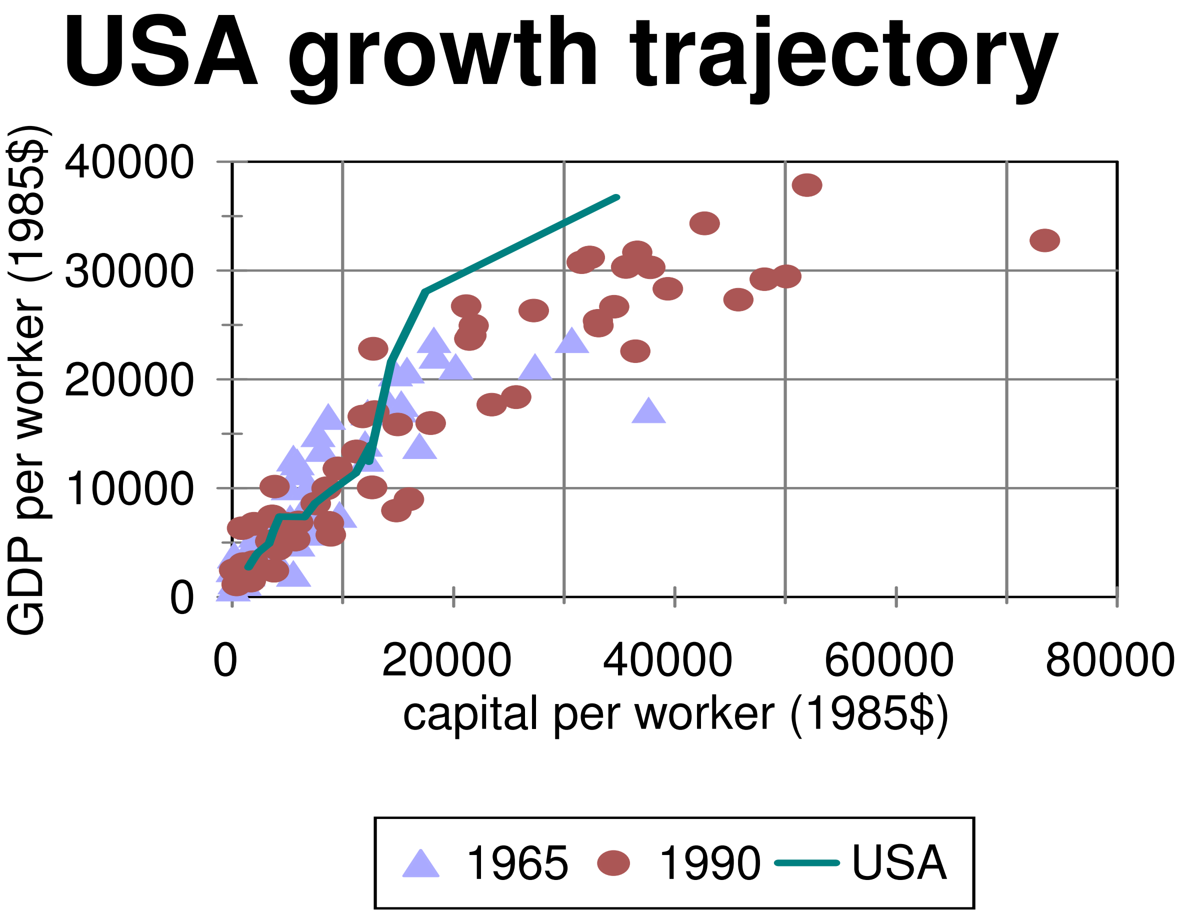

USA growth trajectory
GDP per worker (1985$)
40000
30000
20000
10000
0
0
20000
40000
60000
80000
capital per worker (1985$)
1965
1990
USA

Figure 12

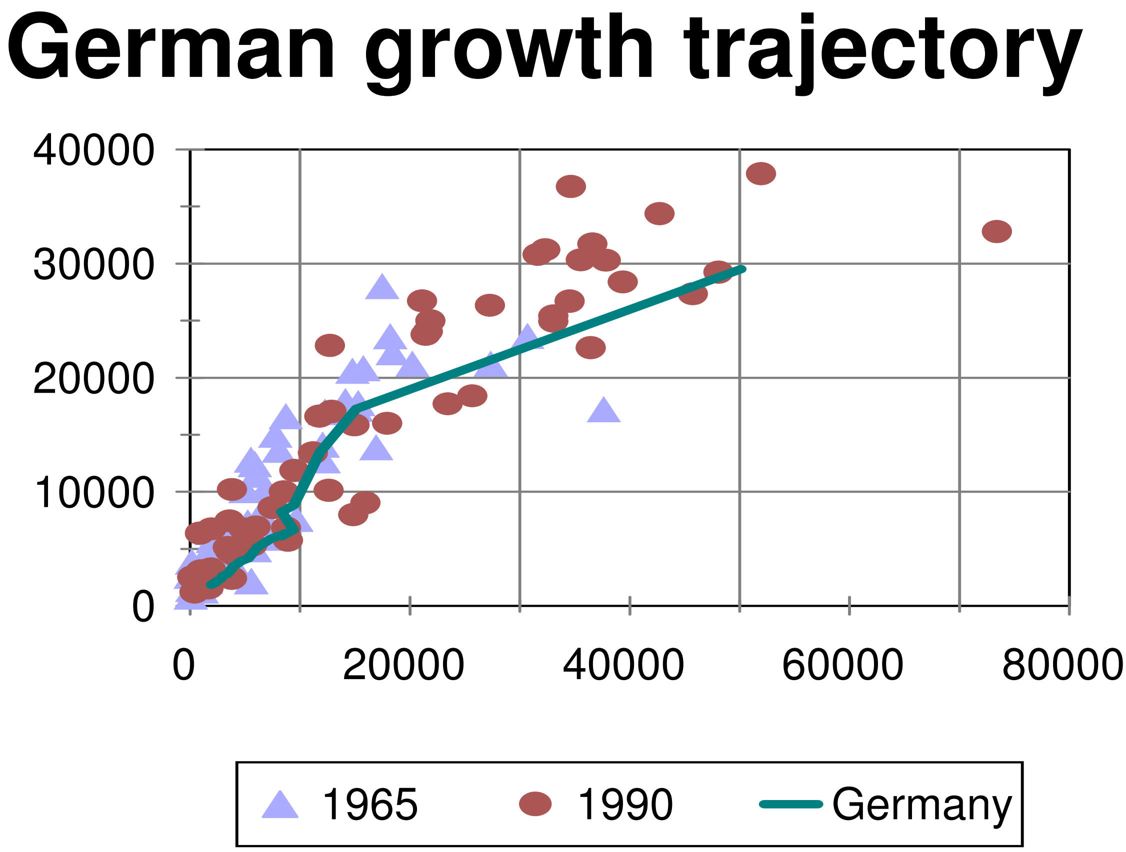

German growth trajectory
40000
30000
20000
10000
0
0
20000
40000
60000
80000
1965
1990
Germany

Figure 13

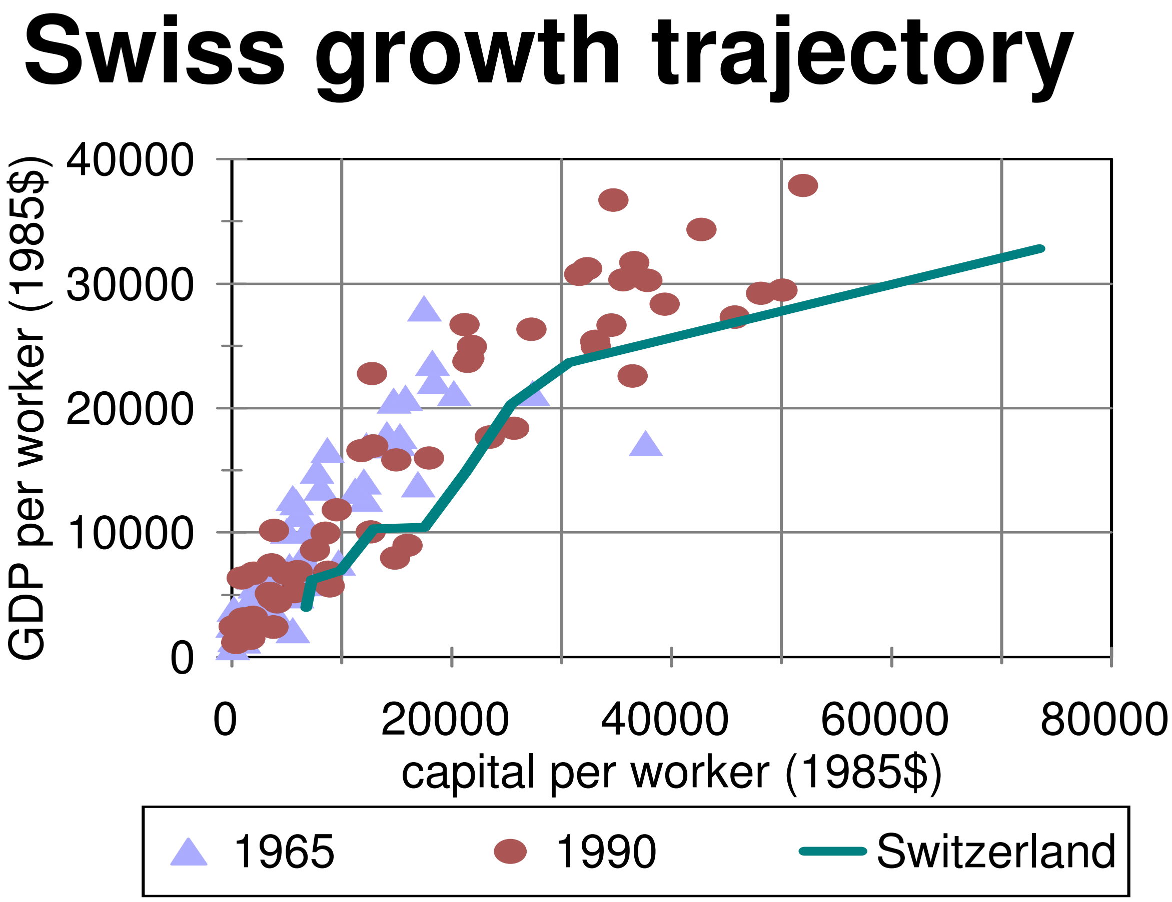

Swiss growth trajectory
GDP per worker (1985$)
40000
30000
20000
10000
0
0
20000
40000
60000
80000
capital per worker (1985$)
1965
1990
Switzerland

Figure 14

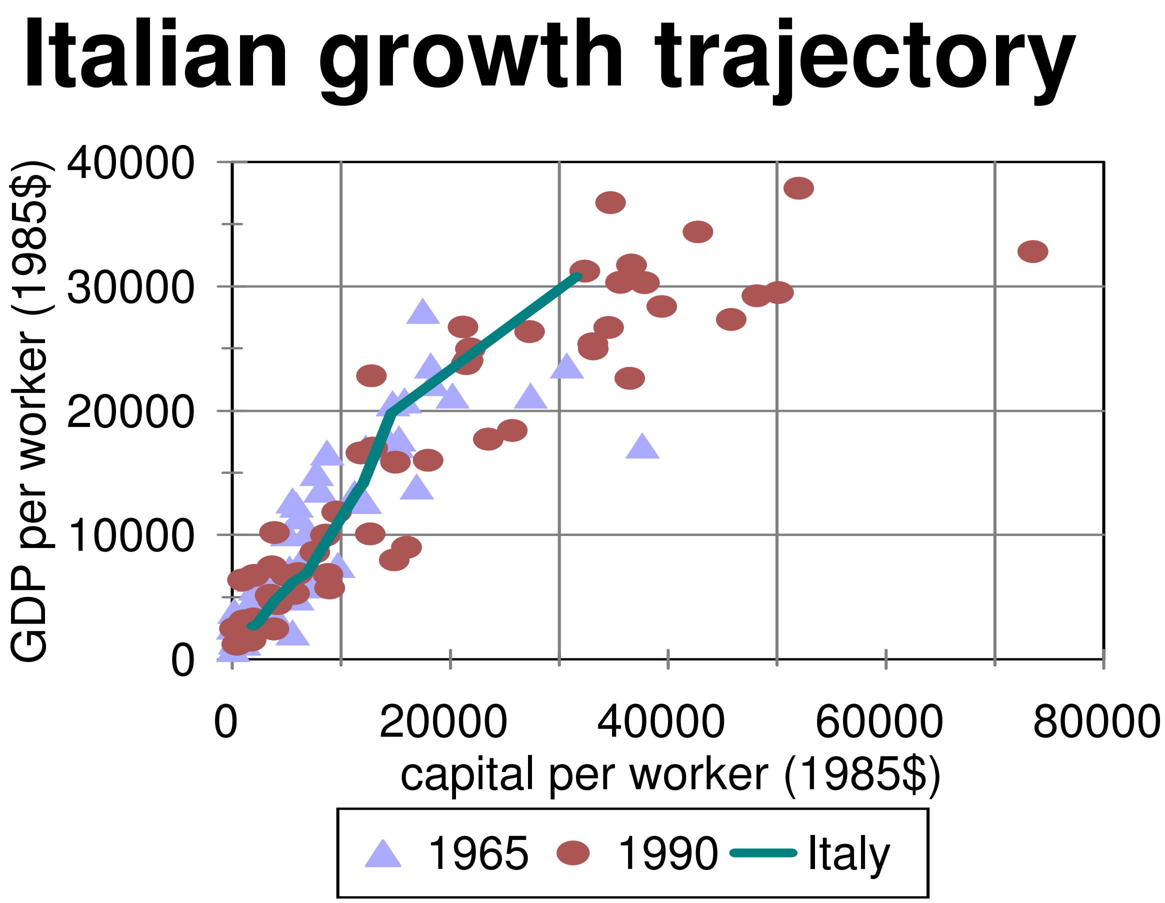

Italian growth trajectory
GDP per worker (1985$)
40000
30000
20000
10000
0
0
20000
40000
60000
80000
capital per worker (1985$)
1965
1990
Italy

Figure 15

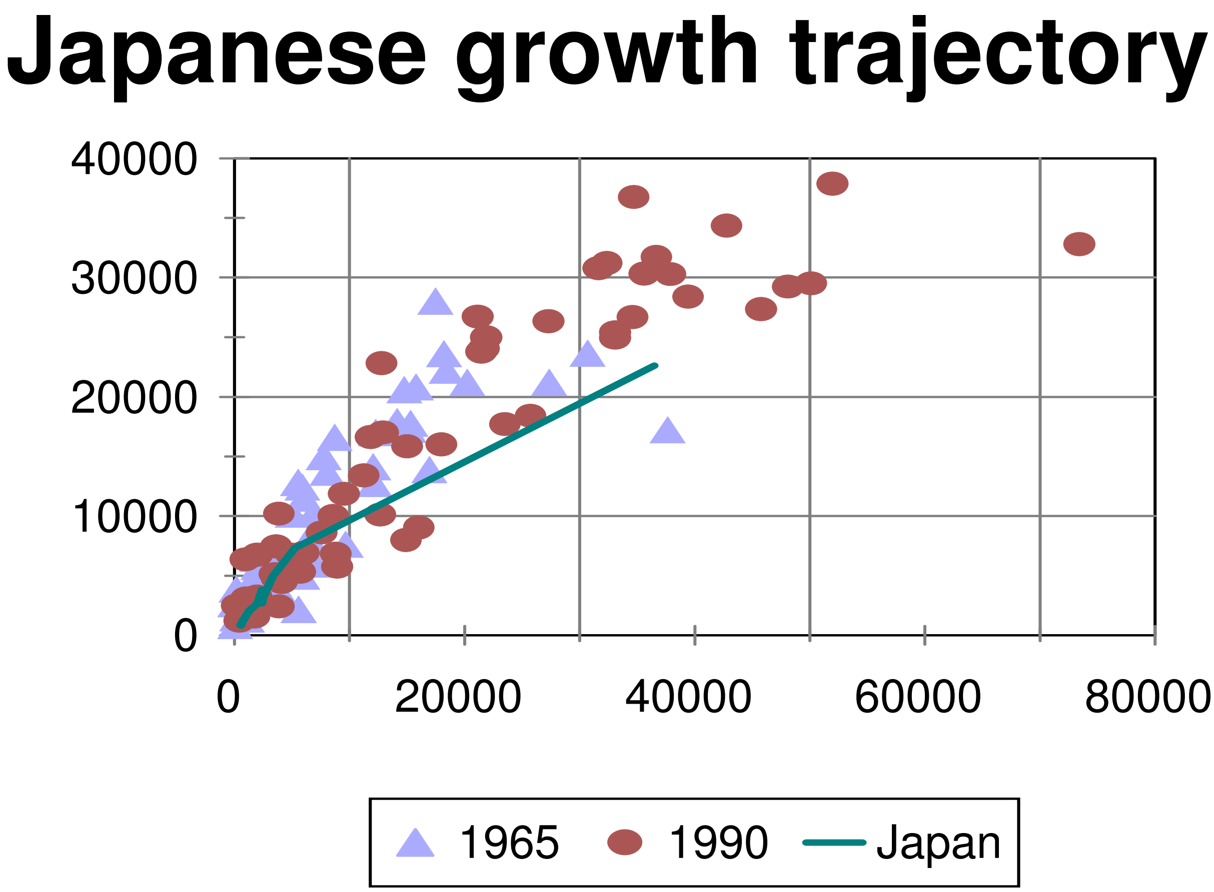

Japanese growth trajectory
40000
30000
20000
10000
0
0
20000
40000
60000
80000
1965
1990
Japan

Figure 16

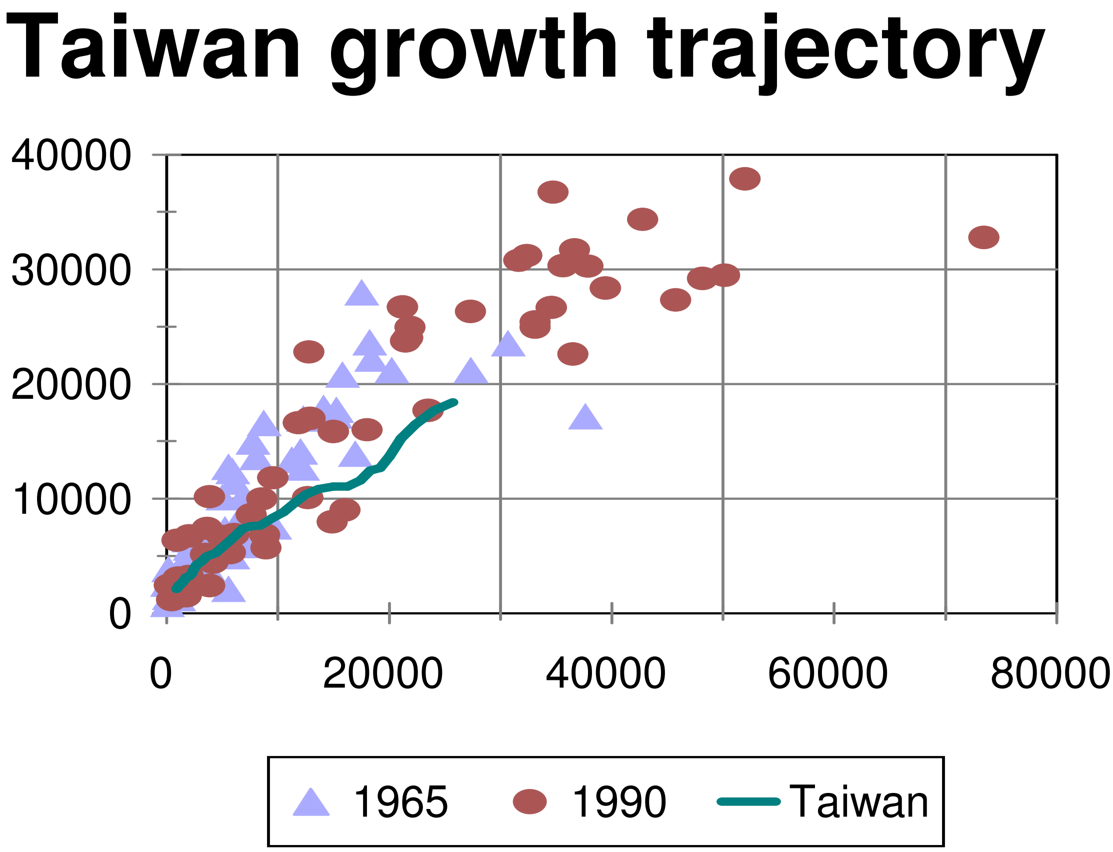

Taiwan growth trajectory
40000
30000
20000
10000
0
0
20000
40000
60000
80000
1965
1990
Taiwan

Figure 17

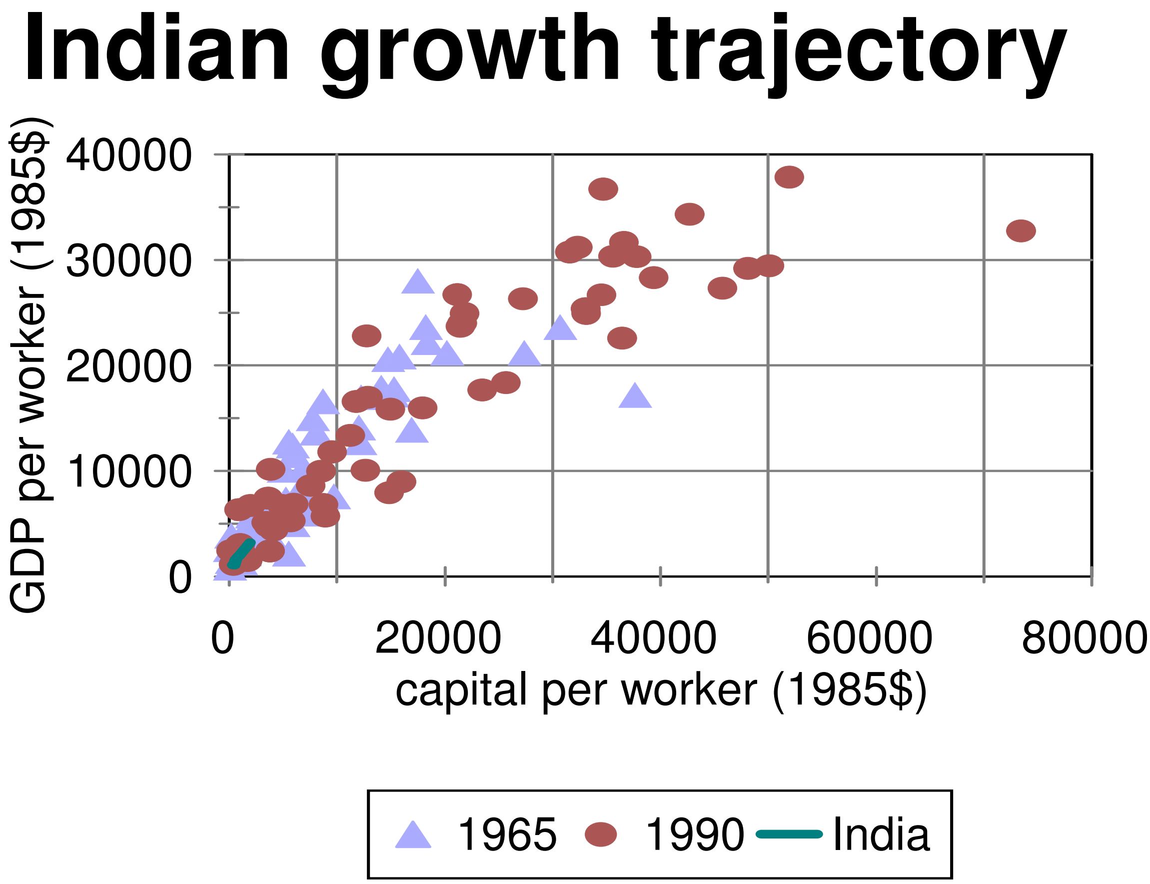

Indian growth trajectory
GDP per worker (1985$)
40000
30000
20000
10000
0
0
20000
40000
60000
80000
capital per worker (1985$)
1965
1990
India

Figure 18

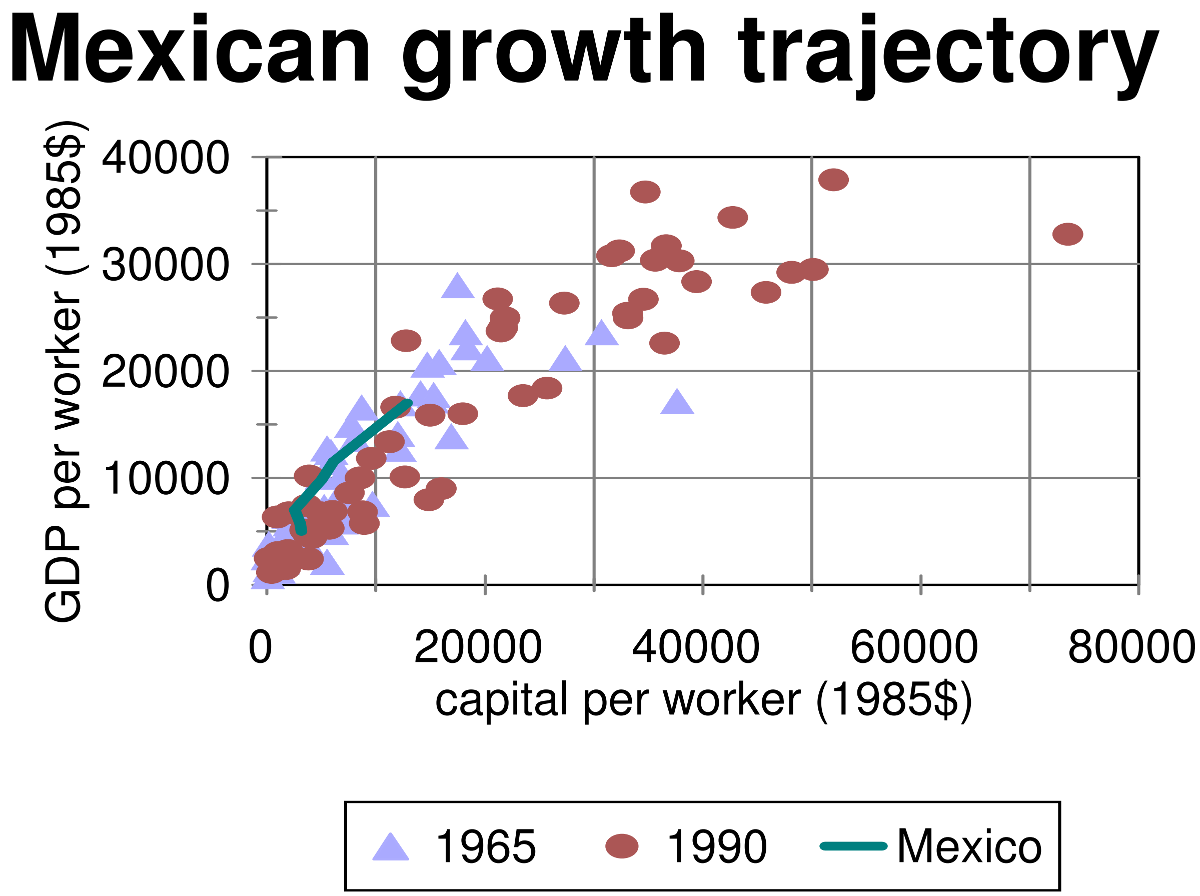
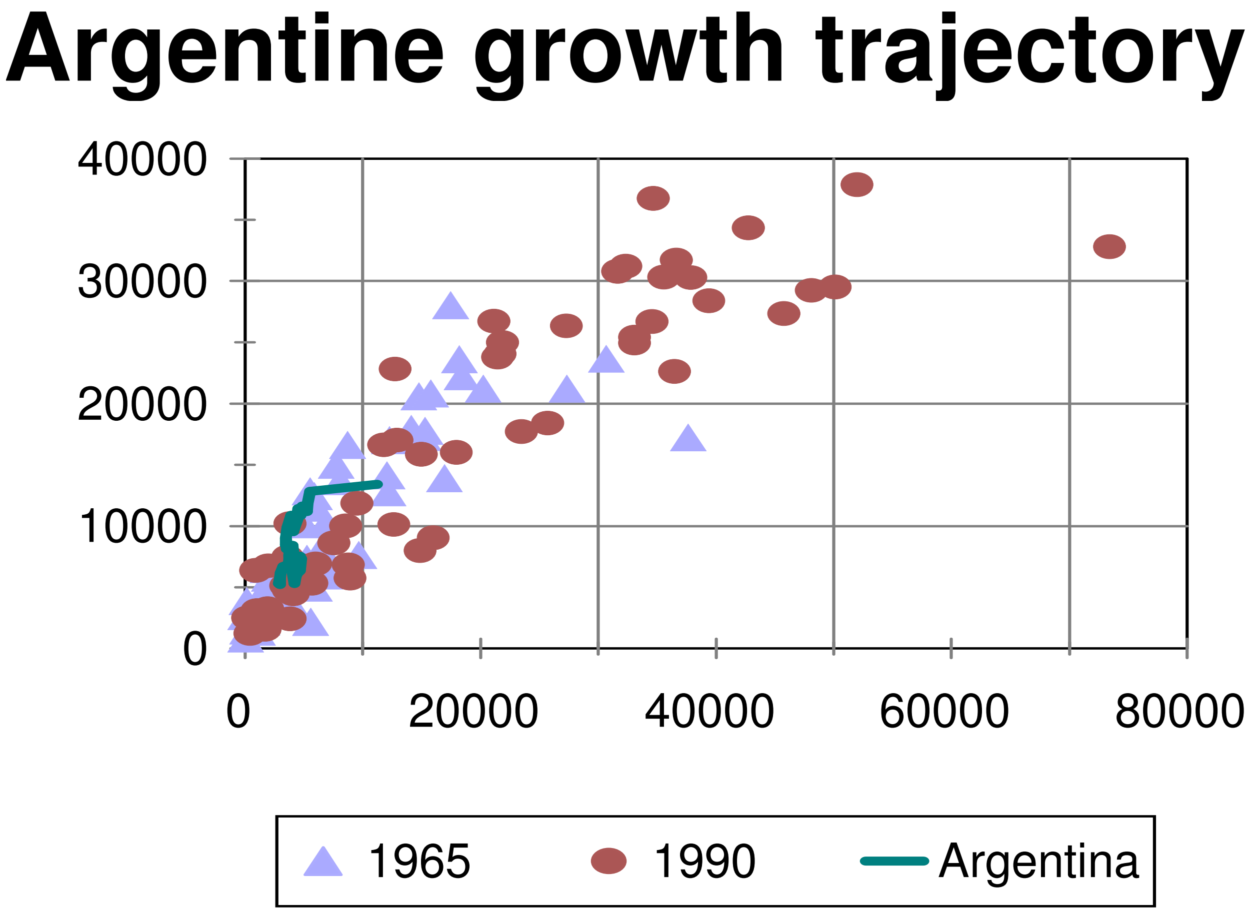

Mexican growth trajectory
GDP per worker (1985$)
40000
30000
20000
10000
0
0
20000
40000
60000
80000
capital per worker (1985$)
1965
1990
Mexico

Figure 19


Argentine growth trajectory
40000
30000
20000
10000
0
0
20000
40000
60000
80000
1965
1990
Argentina

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