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Why growth rate differences persist

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Chapter 3

Technology diffusion in the long run: the Anglo-American case

3.1 Introduction

What is the role of changes in technology congruence and social capability for technology diffusion and long run growth differences? As described in the previous chapter, technology congruence determines how well a new technology from abroad fits with the domestic technology system, which is characterized by country-specific factor proportions and market conditions. Social capability is shortly defined as crucial to absorb foreign technology. Absorptive capacity rests upon the innovation system, mainly on human capital and research institutions. Social capability particularly benefits countries which want to absorb technology from a country with a different technology system.

The main research question of the current chapter is how comparative Anglo-American productivity and capital intensity in the 19th and 20th century are affected over time and across sectors by international technology diffusion between the two countries and how this is related to underlying long run changes in technology congruence and social capabilities. I chose the Anglo-American case for three reasons. First, the two countries were subsequent productivity leaders at the macro-economic level: the UK in the 19th century and the US in the 20th century. Hence not only catching up but also leapfrogging has occurred. Second, the two countries differed in terms of technology systems and social capabilities.

Third, only for the US and the UK, very long run comparative time series can be constructed which are reasonably reliable.

Section 3.2 describes how changes in the technology system and innovation system affects the production structure of an economy over the long run. I use a framework based on the economic-historical models of David (1975) and Broadberry (1994a). In Section 3.3, I present quantitative evidence on the technology congruence between the US and UK in the 19th and 20th century. The long run time series of productivity and capital intensity and their trend breaks show that the 19th century technology systems in the US and the UK were quite different and that their incongruence increased until the Second World War.

This evidence provides the setting for a more qualitative and descriptive analysis in Section 3.4 of long run changes in the technology systems and innovation systems of the US and the UK, and how these are related to technology diffusion between the two countries. I discuss the economic-historical literature, attempting to highlight the evidence on international technology diffusion during sub-periods. It appears that the literature mostly used is explaining US-UK growth differences. The 'Habakkuk literature' emphasizes on international differences in technology systems, and the 'open economy literature' (see O'Rourke and Williamson, 2000) stresses changes in relative factor prices due to international flows of traded goods, capital and labour. This literature does not systematically address international technology diffusion. The section shows the subtleties in the mechanism of technology diffusion which are not so easy to model.

Section 3.5 sums up what the quantitative and qualitative evidence tells us about the working of the mechanism of international technology diffusion in the long run. The main conclusion is that changes in local institutions due to international transfer of institutions might have been more important to economic growth than international technology diffusion as such. Section 3.6 concludes.

3.2 The conceptual framework

This section sets up a basic framework for an international technology transfer mechanism that determines long run growth. First I provide a simple formalization of the aggregate production structure with technological progress (Section 3.2.1). Here I operationalize the concepts of technological congruence and social capability. Then I present a simplified representation of the mechanism of international technology diffusion (Section 3.2.2). I link the basic framework to the David-Broadberry model of path dependent development of technology systems (Section 3.2.3), and discuss how this model may be linked to the innovation system (Section 3.2.4).

3.2.1 Aggregate production with technological change

Assume the aggregate output of an economy grows with technological progress and the accumulation of factors of production. Formally, the production function is a relationship between output, inputs with technological progress evolving over time t (loosely based on Chambers, 1988):

$$Y_t = F_t\left(\tilde{X}_t, t\right) \quad \textit{given} \;\; Z_{1t}, Z_{2t} \tag{3.1}$$

where Y_t is output and $\tilde{X}_t$ a vector of inputs measured in effective units. $\tilde{X}_t$ in turn depends on the state of technology at time t and a vector of non-negative inputs X_t

$$\tilde{X}_t = \tilde{X}_t\left(X_t, t\right)$$

X_t contains choice variables which are under the control of producers at time t. These include, among other things, the input of land, natural resources, capital, crude labour, human capital and R&D. The functional relationship $F_t(.)$ is the production structure, in which factors of production or inputs are combined in some particular way by producers.[1] Technological progress is embodied in the production structure over time. This leads to new production processes and new types of inputs, but also to increases in the efficiency of inputs (factor-augmenting technological progress).

Z_{1t} and Z_{2t} are two sets of socio-economic conditions, which are given for the producers in the domestic economy at time t. These conditions are the operationalizations of the theoretical concepts of technology congruence and social capability.

First, Z_{1t} represents the economy's technology system involving the current state of technology, the prevailing factor proportions and market conditions. For instance, a country might have relatively abundant natural resources and relatively few skilled workers. Market conditions are,

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[1] The relationships between the factors of input and the relationship of input with output are not known beforehand. Moreover, output is not specified in per capita terms, allowing returns to scale to differ between ranges of output.

for instance, a large market size, and homogeneous demand. The technology system is thus strongly related to economic forces. If countries differ in the conditions Z_{1t}, they are technologically incongruent.

Second, social capability is operationalized by the set of conditions Z_{2t}, which encompasses the national innovation system. I define this system as a set of institutions and organizations in the public and private sector, whose interactions determine the flow of knowledge and diffusion of technology within an economy (cf. Freeman and Soete, 1987; Nelson, 1995; Edquist, 1997). Institutions are specific rules that provide incentives for organization of economic behaviour, and may be intentionally designed or not (cf. North, 1990; Williamson, 2000). I consider the intellectual property rights system and institutions for research and human capital as the basis for absorption capacity.

At a certain time t, the production structure is the basis for profit-maximizing producers to make a choice among various techniques of production, subject to the constraints of prices and supplies of factors of production, the current technology, market demand and size, and institutions. In the long run, the production structure changes due to changes in the underlying technology system Z_{1t} and innovation system Z_{2t}, which change only slowly.

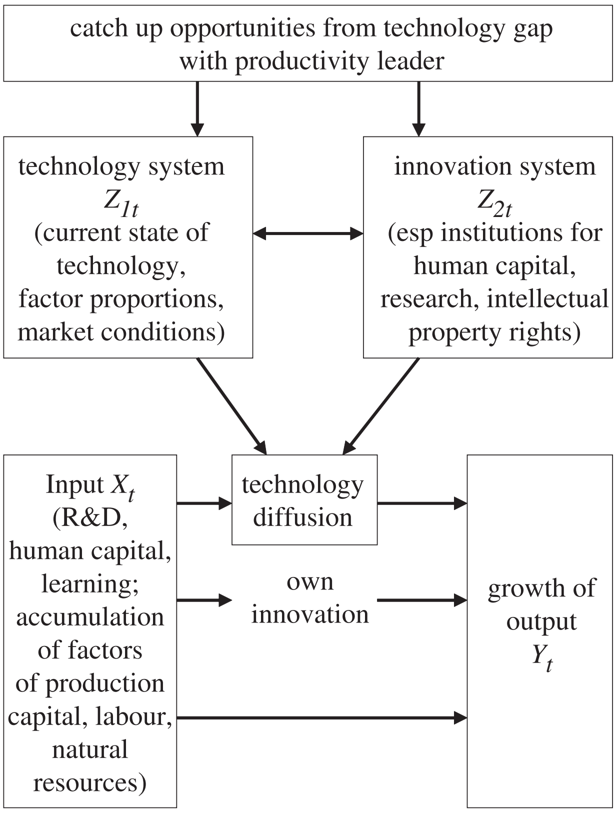
3.2.2 International technology diffusion

Figure 3.1 presents a highly simplified representation of a long run international technology diffusion mechanism for a follower country at a certain time t.

Leading foreign technology provides opportunities to catch up in terms of technology. At time t, the technology system Z_{1t} and innovation system Z_{2t} (the upper half of the figure) are given for producers in the production structure of Equation (3.1). They absorb foreign technology supported by research and human capital investments, thereby ultimately affecting production (the lower half of the figure). Chapters 4 and 5 aim to quantify these relationships with help of a formal model, given that international differences in technology systems and innovation systems are fixed.

The focus of the current chapter is on long run changes in the technology system Z_{1t} and the innovation system Z_{2t} of the follower country. How do such changes affect the absorption of leader technologies from abroad? When Z_{1t} and Z_{2t} change, a follower country may absorb foreign leader technology more successfully. Sometimes the changes may be

Figure 3.1: The international technology diffusion mechanism



so substantial, that the follower forges ahead and takes the productivity lead. I now elaborate which forces play a role in the long run changes of technology systems and innovation systems, using the David-Broadberry model.

3.2.3 The technology system

Technological incongruence is central to the economic-historical models developed by David (1975) and extended by Broadberry (1994a).[2] These usefully serve as a tool to explain Anglo-American comparative

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[2] See also Section 2.2.

performance. In the David-Broadberry model as displayed in Figure 3.2 (adapted from Broadberry, 1994a), there are two available technologies which differ in the proportion of factors of production, here in the ratio of machinery capital K_M to human capital K_H (Figure 3.2a). Once a technology is chosen, the substitution possibilities are limited. Assuming fixed coefficient technology functions, the combination of the technologies determine the available process frontier *APF*. There is also a set of latent technologies, represented by the fundamental production frontier *FPF*.

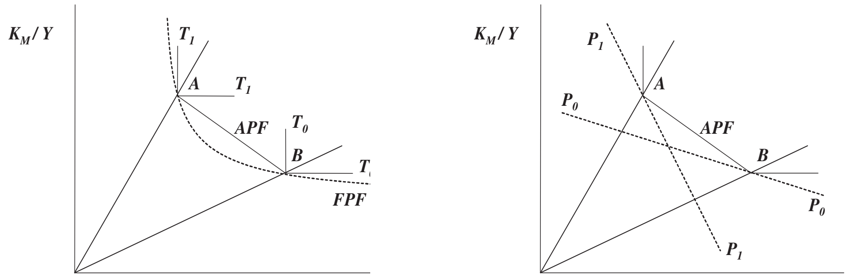
If a country, say America, has relatively more machinery than skilled labour, and skilled labour is relatively expensive, then it will opt for the technology with a relatively high machinery intensity. Conversely, a country, say Britain, with relatively cheap skilled labour, will choose the technology with a relatively high skilled labour intensity. That is, the two countries have chosen different technology systems. This while they have access to the same technology pool *FPF* (Figure 3.2b).

Subsequent investments in the chosen technology and time bring about a cumulation of experience within the own technology. That is, technological change is localized through learning. As technology progresses in America, it moves towards the origin around the process ray α (Figure 3.2c). The two lines along the process ray represent non-convexities bounded to the technology. While technology progresses in America, the new knowledge can be absorbed by Britain and adapted to its own technology system. Britain then progresses along the process ray α (Figure 3.2d). Because it faces cheap skilled labour, Britain will not switch to the American machinery intensive system.

As long as Britain adjusts American technology to its own technology system, the two systems can coexist. It may happen though, that America advances so rapidly that it becomes technologically superior at all relative factor prices (Figure 3.2e). Then Britain is forced to abandon its technology, otherwise it becomes 'locked in'. However, it will not simply copy the American system, but rather search for a new technology that is more complementary to the salient features in its factor proportions.

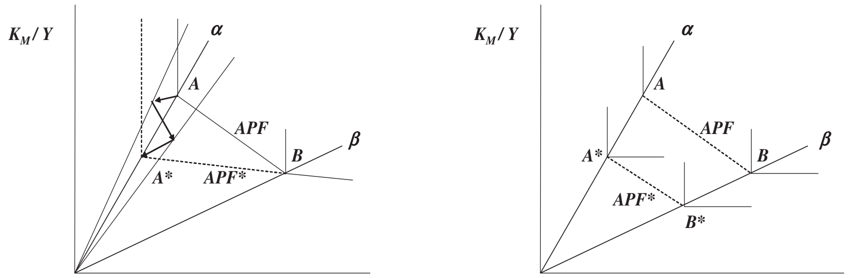
Broadberry (1994a, 1997a) used this model to show that technology leadership does not imply productivity leadership. He argues that in the mid-nineteenth century, US manufacturing had already higher productivity than UK manufacturing, before the US took technological leadership

Figure 3.2: Technology choice and progress



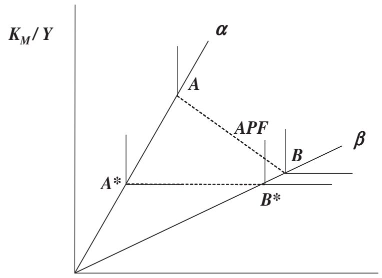
(a) Available process frontier and fundamental process frontier

(b) Role of factor prices



(c) Localised technical change

(d) Competition between technologies



(e) β-technology redundant

from the UK in the late nineteenth century. Their long run productivity ratios were determined by the choice of technique. The latter is determined by country-specific factor endowments and demand conditions.

But what role does technology diffusion play if local conditions are crucial? Here, the David-Broadberry model remains implicit on international technology diffusion and absorption. First, the model only implicitly touches upon the necessity of social capability to adopt, or innovation systems.[3] I elaborate on this in the next subsection. Second, the characteristics of the technology system which allow for or hinder absorption and adaptation of foreign technology require further explanation. The more technologically incongruent countries are, the higher the cost of absorption will be.

To start with, technological progress is usually biased towards a certain factor, increasing the relative productivity of this factor. This is because some directions of technological progress are more fruitful than other directions, given the local circumstances. Such local biased technological change eventually creates different technology systems, such as the David-Broad-berry model shows.

Complementarities between factors of production can reinforce local biased technological change. For instance, capital intensive technology was complementary with land and natural resources in a number of US industries in the 19th century (Ames and Rosenberg, 1968). Other examples are the capital-skill complementarity in the continuous processing system in the early 20th century US (Goldin and Katz, 1998), and complementarity between a general purpose technology and subsequent 'minor' technologies (see Harberger, 1998).[4] These complementarities differ across industries (James and Skinner, 1985), sometimes inducing sectoral shifts.

Factor substitution may take place if relative factor supplies change (e.g., through international migration) or if the relative demand for factors changes (e.g., through trade), so that relative factor prices change.[5]

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[3] Though David mentions the importance of social capability in joint work with Abramovitz (Abramovitz and David, 1996).

[4] Examples are the spread of steam power, railways and ocean shipping in the 19th century, discoveries in chemical science and electricity in the early 20th century, and automation and ICT in the late 20th century. These breakthrough technologies enhanced the introduction of minor technologies, which might not have been profitable without the major technology. General purpose technologies may also facilitate a switch to a new technology system.

[5] Note that factor prices change relatively quickly and affect the entrepreneurs'

But factor substitution is usually limited and does not lead to a switch between technology systems. For instance, the mass migration to the US in the 19th century did not induce a shift to a labour intensive system. Instead, the capital intensive technology was developed further using the mass of unskilled labour.

Finally, economies of scale can vary across technologies and across industries. For instance, manufacturing industries are more likely to have increasing returns to scale than business service sectors. Increasing returns to scale may reinforce comparative advantage and path dependent technological progress, despite international technology diffusion.

3.2.4 The innovation system

Besides the implications of differences in technology systems for international technology diffusion, the David-Broadberry model is also implicit on the necessity of social capability to adopt technology from elsewhere. The greater this social capability, the more cost effective absorption will be. Social capability to adopt mainly benefits follower countries which are technologically incongruent to the leader. I operationalized social capability as determined by the national innovation system with its institutions and organisations.[6] The innovation system Z_{2t} as defined in the basic framework thus creates social capability to adopt.

Institutions which I consider of particular importance to the innovation system are the institutions for generating human capital and research (Engerman and Sokoloff, 2003), and the intellectual property rights system. Research and human capital are assigned a dual role (Cohen and Levinthal, 1989). They are not only an input in the production structure at a certain time t, but also create absorptive capacity in the long run. Human capital institutions lead to formal education, on-the-job training and learning. The research system exists of public and private research organisations, and the interaction between these organisations and researchers. The intellectual property rights system

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decisions, while factor proportions change only in the longer run.

[6] Social capability does not imply efficient working of markets. Market failures may still be present even if a country has a high social capability, because the mechanisms differ between the firm level and the macro-economic level. If a firm chooses not to invest in R&D to absorb a new technology from abroad because of market failures in R&D, government policy may increase domestic R&D investments, thereby increasing social capability.

supports patenting and licensing of innovations, and thereby diffusion of technology.[7]

Institutions may be more or less receptive to absorption of foreign knowledge, which may change over time and differ across countries. Usually, a follower county needs a different type of institutions than a leader country. This is consistent with Gerschenkron's (1962) concept of 'appropriate institutions' to adopt. If they are not appropriate, the country under consideration will fall short of social capability to adopt. Institutional reforms might be necessary then. Over the long run, institutions may change through intentional government policy, or in response to economic behaviour (Engerman and Sokoloff, 2003).

The mutual relation between the innovation system and the technology system comes to the forefront in the long run. If, for instance, the education level increases, new management techniques are developed, new research methods are introduced, the property rights system modifies, and people learn from their actions, the innovation system changes and social capability may increase. This affects the production structure and technology system. Conversely, changes in relative factor supplies and market conditions may lead to changes in innovation institutions and organizations.

I suppose that for the US and Western European countries, which are traditionally technologically incongruent, an appropriate innovation system is necessary for technology diffusion between these countries. Absorption of leader technology implies that the institutions of the follower country should be equipped with an understanding of this technology. Taking this one step further, this might imply that diffusion of institutions from the technology leader to the follower is a necessary condition for absorption of the leader technology by the follower. Putting this in the context of the David-Broadberry model, I expect that the innovation system of the follower develops together with its technology system in order to absorb leader technology.[8]

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[7] Other institutions which create preconditions for innovation and diffusion target at the allocation of factors of production and the efficient accumulation of factors of production. Examples are financial institutions, industrial relations and competition in product markets (Crafts, 2003a).

[8] There are situations where this is certainly not the case. For instance, Korea resembles Western European economies in its technology system but not in its innovation system.

Table 3.1: Comparative UK/US performance in technology, institutions and economy, 1840-1990

	1840-1870	1870-1913	1913-1950	1950-1990
Technology diffusion	UK ⇒ US Effective absorption by US of UK technology	UK ⇔ US Mutual flows, only reinforcing domestic technology	UK ⇐ US Limited, except for some general purpose technologies	UK ⇐ US Copying US system in UK manufacturing, later on increasing adaptation
Local technology progress	Transition to mass production technology in US manufacturing	Establishment of mass production technology, but still room for UK flexible production system	Progress mass production in US, relative standstill flexible production in UK	First limited progress UK system, later on more progressive
Difference in technology systems	Rapidly increasing in manufacturing and agriculture	Increasing in all sectors, also services	Relatively stable	Some decrease of UK gap in manufacturing and services
Diffusion of education/ research institutions	UK ⇒ US Absorption UK institutions to serve US economy	UK ⇐ US Rather limited, but rational given technology system	UK ⇐ US Very limited, hampered by institutional problems in UK	UK ⇐ US Increasing, but with some delay
Local institutional development	Relatively flexible environment in US	Rise in-house research and secondary education in US, continuation vocational training in UK	Institutional research and rise higher education in US, institutional rigidity in UK	Rigid government policy in UK, later on more investment in formal education
Difference in innovation systems	Surpassing of UK by US	Establishment of US leadership	Further widening of UK gap	Some delayed catch up by UK
Capital intensity	UK gap from 1850, rapidly increasing in all sectors	Increasing UK gap in machinery from 1870s	UK gap relatively stable with some temporary shocks	Constant UK gap in machinery and equipment
Joint factor productivity	UK gap disappears in total economy, UK gap fluctuates in manufacturing (without trend)	US and UK at par in total economy, UK gap fluctuates in manufacturing (without trend)	UK gap fluctuating in all sectors (without trend)	Delayed catch up by UK in all sectors
Labour productivity	UK at par with US in total economy, UK gap fluctuates in manufacturing	Increasing UK gap in total economy from 1890s, UK gap remains large in manufacturing	Some further increase of UK gap in all sectors	Delayed catch up by UK in all sectors

The conceptual framework sketched in the current section is the guide through the evidence in the following sections on long run comparative Anglo-American performance in technology systems, institutions, productivity and capital intensity between 1840 and 1990. Table 3.1 summarizes this evidence. The main conclusion from the evidence is that changes in the innovation system Z_{2t} due to international transfer of institutions might have been more important to economic growth than technology diffusion absorbed by the technology system Z_{1t}. The evidence also suggests that the transfer of innovation-related institutions takes more time to diffuse than direct technology transfer.

3.3 Productivity and capital intensity

The current section presents time series on capital intensity, joint factor productivity and labour productivity for the US and the UK between 1840 and 1990.[9] The development in these economic variables are (partially) the outcomes of underlying changes in technology, the technology system and the innovation system. Assuming that technology is embodied in machinery and equipment, changes in the capital intensity may indicate changes in the underlying technology system of the two countries. Furthermore, changes in joint factor productivity may be assumed to partially capture knowledge spillovers via e.g. research and human capital accumulation, possibly giving an indication of changes in the innovation system.

First I describe the data sources and calculation methods underpinning the new time series in Section 3.3.1. In Section 3.3.2, I sketch the developments of these time series. Finally I test for trend breaks on the basis of the properties of the time series (Section 3.3.3).

3.3.1 Technical discussion of the estimates

The time series on capital intensity, labour productivity and joint factor productivity for both the total economy and manufacturing are constructed by Albers et al. (1997). They estimate capital stocks for the US and UK by following a middle track between estimates directly based on national accounts and estimates constructed on an internationally comparable basis. Joint factor productivity is estimated using a Tornqvist index of a translog production function allowing for annual changes in

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[9] These data were developed in Albers et al. (1997).

factor weights. Time series for the total economy and the manufacturing sector are presented, as a sectoral view is crucial for explaining aggregate growth differences.[10] At least until the Second World War, major technological innovations originated from the manufacturing sector. Below, the estimation methods and data sources are sketched. Appendix B.1 provides more detail.

Labour productivity Labour productivity is calculated as GDP or value added per person employed. GDP figures are mainly from Maddison (1993, 1995a), interpolated with estimates from various primary sources. The main datasources for value added in manufacturing are Van Ark (1996) for the period 1950-1990 and Broadberry (1993, 1994b) for the earlier period. UK estimates were converted to 1990 US dollars with binary ICP Fisher PPPs for GDP and value added. Employment data are from Van Ark (1996) for 1950-1990. Pre-war employment data were linked to Maddison's estimates for key years, with intervals mostly interpolated with series from Kendrick (1961), Feinstein (1972), and the US Bureau of the Census (1975).

A complication for the analysis of long run time series is that the quality of the estimates is subject to discussion, particularly those for the period before the First World War. This is due to a lack of consistent time series and low international comparability. For instance, there is still an on-going debate on comparative UK/US labour productivity levels, and at what time the US passed the UK in overall productivity leadership (Ward and Devereux, 2003, 2004; Broadberry, 2003b). Broadberry applies time series projections from a benchmark year comparison of productivity levels, while Ward and Devereux use direct benchmark estimates for earlier years. According to Broadberry's estimates, the US surpassed the UK by the late 1890s in terms of overall labour productivity, while Ward and Devereux calculated that around 1870, the US were already the productivity leader. Albers et al. (1997) provide estimates which are somewhere between these two alternatives.

Capital intensity Capital intensity is calculated as capital per person employed. Estimates of capital stocks over long periods are usually based on the perpetual inventory method (PIM). According to the PIM, the stock is constructed by cumulation of investment derived from national account statistics, with assumptions on the lives of individual

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[10] The total economy estimates include the government sector.

assets and their scrapping pattern. Albers et al. (1997) follow a middle track between two approaches in assumptions on asset lives. One approach uses stock estimates obtained from official and historical national accounts, with country-specific asset lives. But asset lives differ substantially between national estimates, making international comparison difficult. Another approach is to construct so-called standardized stock estimates assuming one common scrapping pattern across countries with the same asset life assumptions, usually that of the presumed technology leader. It is assumed that fixed assets that are regarded as technically obsolete in the leading country due to technological progress, should also be given a zero value in follower countries. However, to the follower country, the 'obsolete' assets could still be of economic value exactly because it is not on the technology frontier. Furthermore, asset lives can also differ internationally because of other reasons, such as differences in industrial structure, relative prices, and investment tax.

Albers et al. (1997) assume that before the Second World War, asset lives in the UK were longer than in the US. This assumption is based on evidence in the economic-historical literature of rapid capital accumulation in the American manufacturing sector in the 19th and early 20th century, and that labour-intensive production methods prevailed in the UK, involving slower replacement of capital goods. Hence, for the prewar period, stock estimates are directly obtained from national accounts (Feinstein (1972, 1988) for the UK; Gallman (1987) and BEA (1993) for the US). For the period after the Second World War, Albers et al. (1997) assume that British asset lives converge gradually to the shorter American asset lives because of greater technology diffusion during this period. Hence BEA data (1993) are used for the US. For the UK, Albers et al. apply their own perpetual inventory method, gradually shortening UK asset lives to those of the US.

Albers et al. (1997) estimate the total stock of fixed reproducible non-residential capital, and its two parts, non-residential structures and machinery and equipment.[11] According to the Habakkuk literature, the comparative development in machinery intensity explains much of the growth differences between the US and the UK in the 19th century. For international comparison, ICP 1990 US PPP dollars for investment are applied.

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[11] Non-reproducible components of wealth are thus excluded, such as land and mineral resources, inventories, work in progress, monetary assets and consumer durables. Residential capital and intangible capital assets are also not included.

Joint factor productivity Applying the growth accounting method, joint factor productivity (JFP) represents the impact of differences in capital intensity on relative labour productivity performance. JFP growth is no measure for 'technical change'. At best it measures disembodied technological change.[12] JFP is calculated on the basis of a Cobb-Douglas production function with constant returns to scale. In this framework, knowledge spillovers cannot be modelled and technology is exogenous. This is of course a gross simplification of the production function in Equation (3.1). However, JFP growth can be calculated on the basis of a Tornqvist index, that allows annual changes in relative shares v_L of labour compensation in output,

$$\Delta \ln A_t = \Delta \ln y_t - (1 - v_L) \Delta \ln k_t \qquad (3.2)$$

where A is the joint productivity of inputs, y output per employee and k capital per employee, and v_L is the unweighted average of the share of labour compensation in output (GDP) at time t and $t-1$. The comparative levels of JFP are estimated with the same equation, replacing time notations for country notations.

With the Tornqvist index, changes due to disembodied technology progress, knowledge spillovers from research, human capital accumulation and the like, are absorbed via the changes in factor shares, leading to changes in JFP. This does not imply that technology does not become embodied in capital (rent spillovers). However, within this framework, it is not possible to unambiguously distinguish embodied and disembodied technological progress. I cannot ascribe relative price changes of investment goods to technology embodied in capital or to disembodied technological change (Ho and Stiroh, 2001). In this chapter, capital per worker is a measure for the nature of the technology system under the assumption that technology is embodied in machinery. This shifts the composition of capital stock from non-residential structures in favor of machinery and equipment. Furthermore, joint factor productivity growth may be assumed to partially capture knowledge spillovers via e.g. research and human capital accumulation. This may possibly give an indication of changes in the innovation system.

The time series for labour productivity, capital intensity and joint factor productivity for the US and UK, and for total economy and manufac-

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[12] See Section 2.3.4 on the decomposition of the residual.

turing, are displayed in Figure 3.3 to 3.7.[13]

3.3.2 Comparative developments, 1840-1990

When did the US catch up with and surpass the UK in labour productivity? Which inputs determined the moment of catching up of the UK by the US: capital, technology or other factors? Below I sketch the comparative UK/US developments in labour productivity, capital intensity and joint factor productivity for three subperiods.

The nineteenth century In 1840, the labour productivity level of the aggregate UK economy was somewhat lower than in the US (Figure 3.3). After a period in which the UK was more productive than the US, the US definitively surpassed the UK as economic leader in the early 1890s. However, in manufacturing, the UK was already far below the US productivity level in 1840. On the average, the UK level was about 60% of the US level between 1840 and 1900. The comparative UK/US agricultural productivity level did not change much during the 19th century, according to Broadberry and Irwin (2004). They suggest that it was probably a rapid shift of employment out of agriculture to the service sector with relatively high productivity levels, that explains the US overtaking in overall labour productivity.[14] The UK probably always had a relatively large share of the service sector in total economy.

Total capital assets per employee in the UK rapidly fell behind the US level from 1840 onwards (Figure 3.4).[15] By 1900, the UK capital intensity level was only 40% of the US level in both non-manufacturing and manufacturing sectors. In machinery and equipment, the UK initially had a comparatively large head start(Figure 3.5). But the US came on par with UK manufacturing in 1870, and eventually with the UK economy as a whole in 1880. Broadberry (1997b) argues that the US mass production system which emerged in the second half of the 19th century was saving skilled labour and therefore more machinery intensive. According to Figure 3.5, this is valid for the total manufacturing sector only in the period after 1870. But Broadberry (1997b) also admits

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[13] In Appendix B.1, the time series for the US and the UK are displayed separately, in (natural) log-levels.

[14] Although the current evidence shows that the role of the service sector is probably not as large as the data of Broadberry and Irwin (2004) suggest.

[15] This contrasts the calculations of Field (1985), see Section 2.2.

that mass production techniques could not be immediately successfully applied in all industries in the US.

The comparative UK/US joint factor productivity level rose in the total economy as well as in manufacturing (Figure 3.7). In 1840, the comparative UK/US levels were the same for the total economy and manufacturing. By 1900, the UK joint factor productivity level in non-manufacturing sectors was considerably higher than in the US, but at 80% of the US level in manufacturing. Moreover, the comparative UK/US joint factor productivity level fluctuated more strongly in manufacturing than in total economy. This might be explained by the role of the service sector. The UK still had a comparative advantage in some service industries where mass production systems were not appropriate (yet), such as distribution, banking and finance (Broadberry and Ghosal, 2002).

The early twentieth century The labour productivity gap of the UK with respect to the US rapidly widened until 1920. Part of the decline was caused by the economic consequences of the First World War for the UK. The gap narrowed somewhat during the 1920s and 1930s. In manufacturing, comparative labour productivity remained relatively stable, with a dip in the 1920s.

Figure 3.3: Output per employee (US=100), 1840-1990

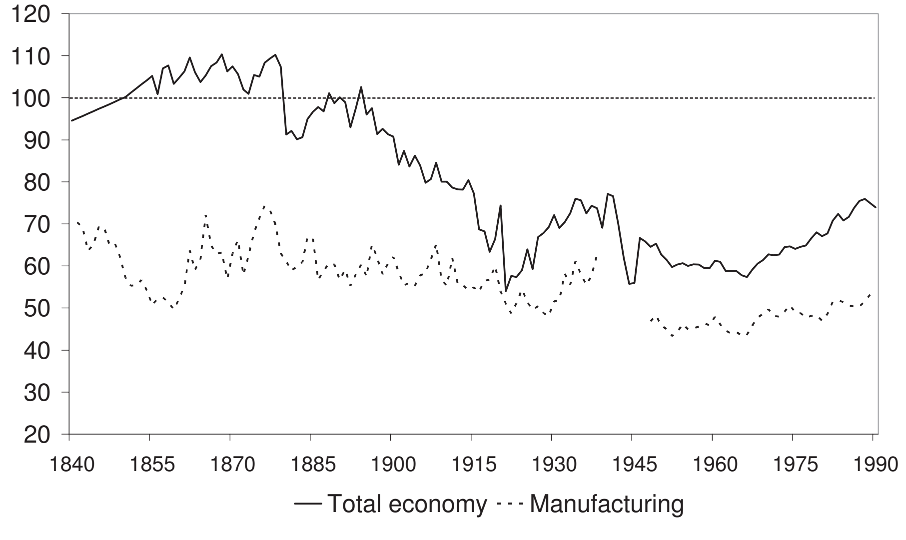


Figure 3.4: Capital assets per employee (US=100), 1840-1990

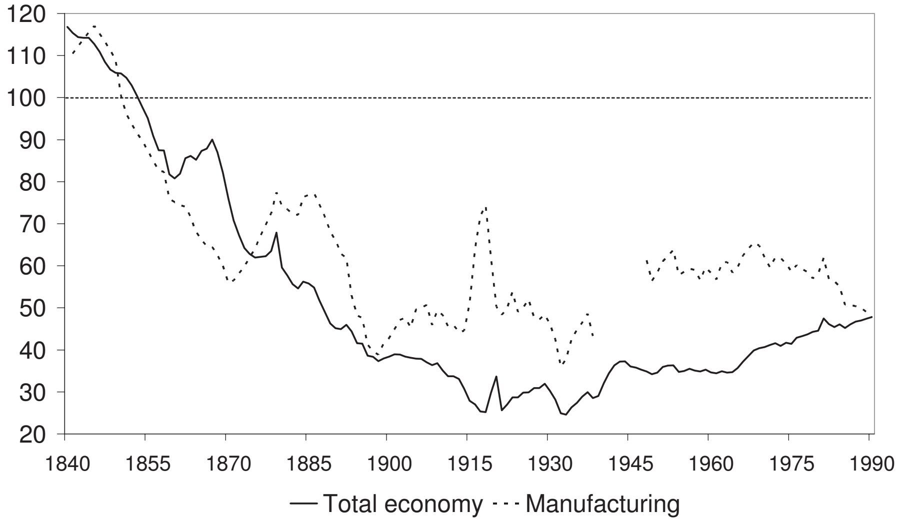


Figure 3.5: Machinery and equipment per employee (US=100), 1840-1990

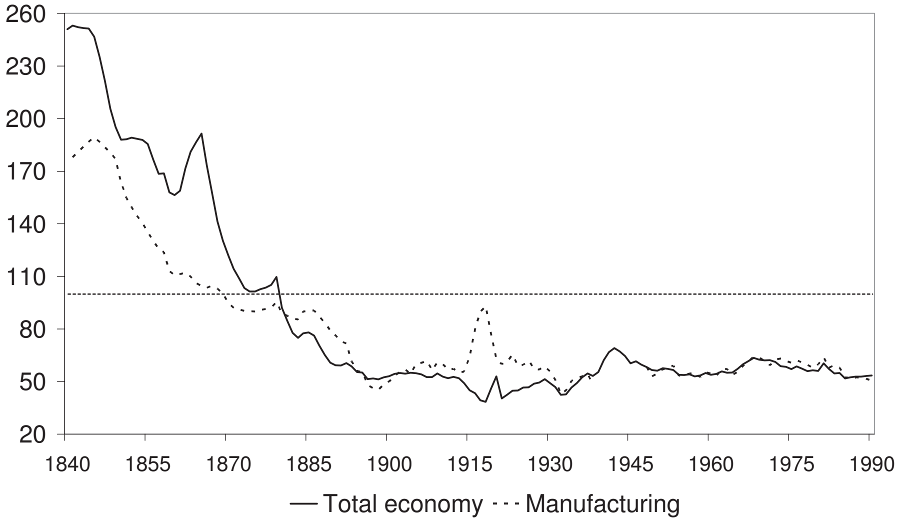


Figure 3.6: Non-residential structures per employee (US=100), 1840-1990

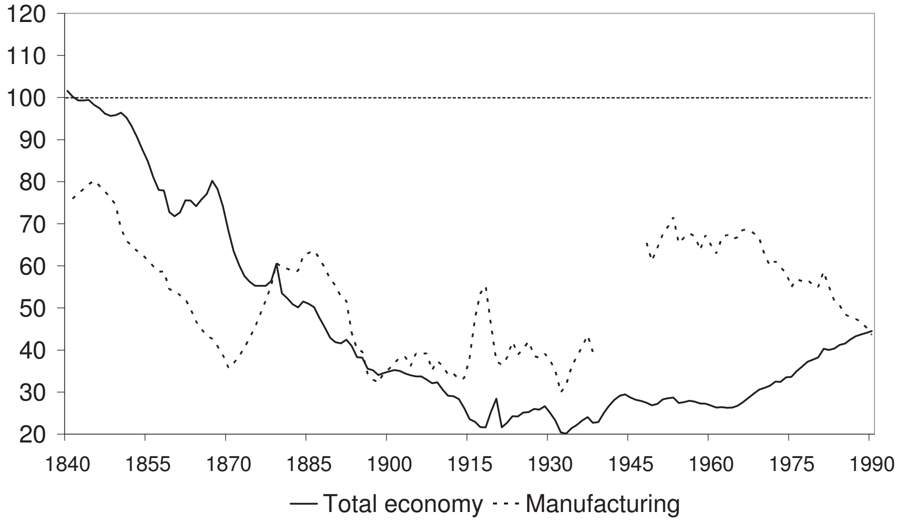
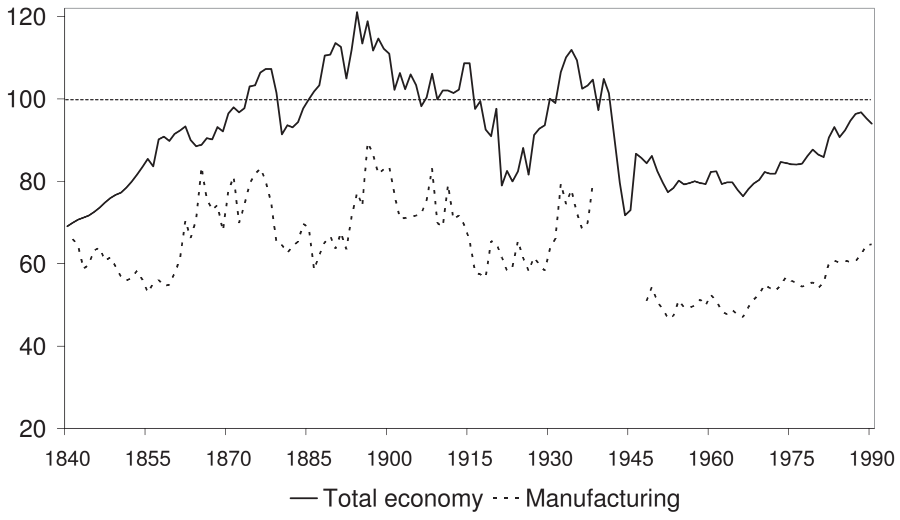


Figure 3.7: Joint factor productivity (US=100), 1840-1990



Following the rapid decline in comparative capital intensity in the 19th century, the UK experienced a relative stabilization of its capital intensity level with respect to the US in the interbellum, although the aftermath of the First World War and the Depression caused fluctuations. The difference between total economy and manufacturing in the comparative machinery intensity level is fairly small. On the other hand, the comparative UK/US joint factor productivity level continued to fluctuate strongly. In both total economy and manufacturing, joint factor productivity increased faster in the US than in the UK, and the UK lagged behind the US. The interbellum appears to be a period of both divergence and convergence movements; one cannot easily detect a long run trend at sight.

The late twentieth century The Second World War put the UK economy on a comparatively lower labour productivity level, 60% of the US level, and even less than 50% in manufacturing. It did not succeed to start to converge towards the US until the late 1960s in both total economy and manufacturing. After then, the UK non-manufacturing sectors converged relatively more quickly towards the US level than the manufacturing sector. But by 1990, the UK was still far behind in both non-manufacturing and manufacturing sectors.

Because the comparative UK level in non-residential structures per employee in the aggregate economy was comparatively low and the development in machinery intensity was relatively flat, these variables did not seem to drive the comparative UK labour productivity development. Rather, as joint factor productivity steadily increased, this suggest a larger role for other forces than capital accumulation. One potential force is new knowledge not embodied in machinery and equipment.

Conclusions Comparative UK/US labour productivity and capital intensity developed more gradually than comparative joint factor productivity. During the course of the 19th century, the UK overall labour productivity gap widened relative to the US in particular for total economy. But it widened also in manufacturing since the early 20th century. Subsequently, these gaps gradually narrowed. The developments in comparative UK/US capital intensity are explained by very rapid accumulation in the US up to 1900 and relative stabilization after that period. The increasing difference in the capital intensity level, particularly in machinery and equipment, suggests that the technology systems of the

UK and the US became increasingly incongruent in both total economy and manufacturing. The comparative UK/US joint factor productivity level shows an irregular pattern in both total economy and manufacturing during the period 1840-1990. If JFP growth partially reflects changes in the innovation system, then the fact that the UK did not catch up with the US in manufacturing JFP, and that the comparative UK/US JFP level for the total economy fluctuates, gives rise to questions on differences in innovation systems between the two countries.

3.3.3 Trend breaks

In the course of time, economic changes (possibly related to the technology system) or non-economic changes (possibly related to the innovation system) may lead to a change in the trend in the long run growth rate of productivity and capital intensity. If a trend break occurs, the level of productivity or capital intensity shifts, resources are reallocated, and the growth rate is persistently higher or lower than before the trend break. Endogenous growth theory also predicts non-constant growth rates over time. Hence a trend break may signal a change in the technology system or even in the innovation system.

Maddison (2001) divides the past into subperiods or ‘growth epochs’, which are separated by institutional changes. These changes occur around the ‘break years’ 1820, 1870, 1913, 1950 and 1973. His division is useful and commonly used in the analysis of long run growth, but is intuitive. A formal test on a break in the trend of time series might confirm this division or reveal more trend break years within these subperiods.

Technical discussion In the applied trend break test (based on Ben-David and Papell, 1995), a regression on the time series under consideration is repeatedly estimated for different potential trend break years. The right-hand variables are a trend variable, two dummies for the periods before and after the potential trend break year, and a number of lags of the variable. The null hypothesis states that there is no trend break, that is, the coefficients of the dummies are zero. This null hypothesis is rejected if the Sup Wald statistic is greater than the critical value.[16]

This critical value, however, depends on whether the time series under consideration is stationary. Therefore, the series are also tested on a

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[16] The Sup Wald statistic is two times the maximum F-value across the repeated estimations.

unit root. In order to account for a potential trend break year, the conventional unit root or ADF test is adjusted by adding the two dummies. This ADF test is estimated sequentially. The null hypothesis of a unit root against the alternative hypothesis of trend stationarity with one break is rejected if the Dickey-Fuller statistic is larger than the critical value.[17] Appendix C describes both the sequential ADF test and the trend break test, and gives the critical values up to a 10% significance level.

The trend break test and sequential ADF test are applied on the time series. The assumptions underlying the estimates of these time series (described in Section 3.3.1) may influence the trend break test results, such as the assumptions on asset lives in constructing the capital stock. However, the effect of these assumptions on the test results remains unknown. Hence the trend break test results have to be interpreted with some caution.

Although the test results point to specific years as a trend break year, this should not conflict with historical observations that important changes occurred in other years. The break test only makes use of the statistical properties of the time series, so that more subtle, long run changes may not be unveiled by the test. Moreover, if a break is detected for a war year, one should not attach too much importance to it as data for war years are relatively less accurate. In such a case the break is related to the war period as a whole rather than to precise years (Ben-David and Papell, 1995). Furthermore, the test results are sensitive to the choice and length of the period. Also, the number of observations is reduced because of first-differencing and lag length. Finally, the trend break test method is still subject of discussion in the literature. Nevertheless, the test is an analytical tool which may signal trend breaks, or at least confirm break years as used by Maddison (2001).

The tests are applied on the whole period 1840-1990, but also on various subperiods in order to show the sensitivity of the test. Of course there might be more than one trend break in the series.[18] To some extent, I account for more than one break year in the series by testing on various

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[17] The Dickey Fuller-statistic is the maximum value of the t-statistic of the coefficient of the one-lagged variable.

[18] The F-values across the repeated estimations for some time series show more than one peak, suggesting more than one trend break. A multi-break test might be preferred, such as the two-break test of Ben-David and Papell (1996). However, my aim is to find relatively important shifts rather than a series of subsequent, probably minor, trend breaks.

subperiods. I imposed the two World Wars and Depression as exogenous shocks to define these subperiods. Table 3.2 presents the resulting trend break years for the comparative series and for the US and UK series separately.[19]

Table 3.2: Trend break years, 1840-1990

		Total economy			Manufacturing		
	Test Period	UK/US	US	UK	UK/US	US	UK
Production per employee	1840-1990		1940			1919	
	1840-1913					1860	1869
	1840-1939			1924			
	1919-1990	1941		1945			
	1904-1947		1942		'38-'45		'40-'45
Capital per employee	1840-1990	1921		1945			
	1840-1913		1932				1886
	1840-1939	1918	1932				
	1919-1990	1932	1933		1932	1938	
	1904-1947		1929		'38-'45	1929	'40-'45
	1946-1990						1982
Machinery and equipment per employee	1840-1913		1865				1886
	1919-1990	1932	1931		1932	1938	
	1904-1947		1933		'38-'45		'40-'45
	1946-1990	1965					1983
Non-residential structures per employee	1840-1990		1932	1945			
	1840-1913						1886
	1840-1939	1865					
	1919-1990		1933	1945		1943	
	1904-1947		1929		'38-'45	1929	'40-'45
	1946-1990	1965			1966		1980
Joint factor productivity	1840-1990		1938				
	1840-1939						1915
	1919-1990	1945	1940	1945		1932	
	1904-1947		1941		'38-'45		'38-'45
	1946-1990	1964					1979

See Appendix C for the underlying test results.

The nineteenth century In the aggregate economy, no trend breaks seem to have occurred in labour productivity during the second half of the 19th century. The economic-historical literature also states the US surpassed the UK in productivity terms only by the turn to the 20th century. In contrast, the 1860s appear to be a break period in labour

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[19] Only the statistically signficant test results are presented.

productivity in both American and British manufacturing. Probably the break for the US is due to the Civil War rather than to a fundamental economic change. US manufacturing was already on a high-productivity growth path by 1840. Moreover, the sector was still quite small at that time. The break year 1869 in British manufacturing also seems to have been only a temporary shock.

The shock of the Civil War may also apply to the trend in American machinery and equipment per employee, which seems to show a trend break in 1865. The year 1886 represents a trend break year for British manufacturing capital intensity, in both machinery and equipment and non-residential structures. From this time on, UK capital intensity growth decelerated until the turn of the century.

During the 19th century, no trend breaks occurred in joint factor productivity, neither in the US nor in the UK. The development of the joint factor productivity time series in Figure 3.7 also do not suggest a break in the long run trend, but only a temporary shock.

The early twentieth century During the 1930s, the Depression years, capital assets per employee and joint factor productivity in the American economy and manufacturing underwent various fundamental changes, while for the UK no break is detected. The comparative developments in capital intensity, particularly machinery and equipment, differ during this period. The changes in the American economy probably lead to a shift in its aggregate labour productivity around 1940, affecting comparative performance.

The trend in British aggregate labour productivity shifts in 1924, but this is probably more related to the recovery from the First World War than to fundamental change in capital or technology.[20] In 1919 American manufacturing labour productivity shifts to another path with a somewhat higher growth rate. This may be the result of earlier, 19th century accumulation of capital.

The late twentieth century The Second World War forms a clear watershed in the comparative development of US and UK, because the UK experienced various changes after this war. This is particularly the case for UK manufacturing. In labour productivity, no trend breaks are

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[20] This is also the case for the shift in 1915 in British joint factor productivity in manufacturing.

detected after 1945. However, capital and technology underwent changes, with potential effects on labour productivity at a later stage.

In terms of comparative capital intensity of the aggregate and total economy, a break seems to occur in the 1960s. For the total economy, UK non-residential structure intensity seems to converge to the US level after 1965. However in manufacturing, a divergence occurred. Divergence is also observed in machinery and equipment intensity. Furthermore, capital accumulation per employee slowed down in British manufacturing during the early 1980s.

During the 1960s, comparative joint factor productivity in total economy also showed a trend break. Joint factor productivity growth seems to decelerate in the US economy. Since the late 1970s, it has accelerated in British manufacturing. This suggests structural changes in institutions and organisation of production in both countries, if one assumes that JFP partially captures such changes.

Conclusions The trend break tests indicate that in the nineteenth century, no real trend breaks seems to have occurred. This suggests that both the US and the UK did not deviate from their growth path between 1840 and 1900, and that they continued to develop their own technology system. This would confirm the finding of economic-historical studies on 19th century US and UK, and the David-Broadberry model that the technology systems of both countries could co-exist, as long as both were technologically progressing and adapting each others technologies.

In contrast, the twentieth century is marked by important trend breaks, signalling fundamental changes in technology systems and probably also innovation systems. The 1930s were a period of changes in US capital stocks, mainly because of the Depression. However, this probably accelerated the development of the US technology system in manufacturing. The end of the Second World War started fundamental changes in international relations, and European countries were supported by the US in their restoration. This was likely to affect the post-war UK technology system and even its innovation system. The 1960s and 1980s seem to have been periods of trend breaks in capital and joint factor productivity.

However, the developments in capital and productivity and the trend break test results miss the story on the underlying developments of the technology systems and innovation systems of the two countries, and how these have affected international technology diffusion between the countries. Does the increasing gap in capital intensity indicate that increasingly less international technology diffusion took place between the countries in the 19th century? Did a large disembodied technology transfer take place after 1950 from the US tot the UK, as the UK level of joint factor productivity increased relative to the US? In the next section, I discuss the changes in technology systems and innovation systems such as they emerge from the largely dispersed and qualitative evidence in the economic-historical literature, and what role international technology diffusion plays in these developments.

3.4 Changes in technology and institutions

The current section focuses on how technology congruence between the US and the UK and their innovation systems changed over the long run, with a focus on the impact of congruence and institutions on international technology diffusion in space, over time and between sectors. Technology diffusion may occur via various channels. Technology flows may be embodied in international flows of trade goods, capital, and labour. The more congruent the US and UK are, the easier technology flows via these channels. But if the countries are incongruent, appropriate institutions are needed to adapt each other's technologies. Technology may also be channelled via more disembodied flows, particularly via research and human capital. The latter may change the innovation system.

3.4.1 Localized developments, 1840-1870

Around 1850, technology was primarily transferred from the technology leader UK to the developing US economy. But the US was technologically incongruent to the UK, with quite different factor proportions and market conditions. This incongruence increased as the US effectively absorbed UK technology and institutions, and adjusted them to its own technology system and innovation system.

Changes in technology systems By 1840, the first industrializer UK was still the world technology leader (Crafts, 1998). During a large part of the 19th century, technology was primarily transferred from the UK to the developing US agriculture and manufacturing.[21] This technology was adapted to the very different US technology system by means

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[21] Up to the late 19th century, the US economy had a relatively small service sector.

of learning. The Habakkuk literature points at three characteristics of this system: relative abundance of land and natural resources, relative labour scarcity and a large-scale homogenous market.

The abundance of land in the US attracted many immigrants and capital from the UK (O'Rourke and Williamson, 2000). In the early 19th century, engineers introduced transport equipment from the UK. The subsequent extension of water-ways and railways and declining transport costs reinforced the westward movement, and attracted more, mainly young, immigrants. A large geographical market was created with a well-developed infrastructure, and high population growth with a relatively equal income distribution and homogenous demand (Abramovitz and David, 1996).

These developments stimulated US agricultural and manufacturing production and exports, thereby shifting trade patterns (Fremdling, 1999).[22] Moreover, because these US sectors felt the pressure of relative labour scarcity, production methods that saved on labour were favoured, particularly those that could exploit natural resources. Therefore mechanization and capital deepening started early. This was fostered by absorption of UK technology, such as tillage machinery and seeds (Hayami and Ruttan, 1985), and water and steam power technology (Atack et al., 2005; Rosenberg and Trajtenberg, 2004).

In US manufacturing, falling transport costs and the diffusion of water and steam power technology ultimately led to a relatively capital-intensive, de-skilled and large-scale production system with complementarities in natural resources. Between the 1830s and 1880s, US manufacturing experienced a slow transition from the skilled labour-using artisan shop to the capital-intensive factory system (Goldin and Katz, 1998; Atack et al., 2004).[23] The transition was not completely de-skilling for three reasons (Atack et al., 2004). First, by 1870, a large part of manufacturing output was still produced by skilled artisans. Second, new machinery had to be installed by skilled workers such as engineers. Third, large factories require organisational, white collar skill. But the new vintages of capital raised productivity of unskilled labour.[24] The US

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[22] Early US manufacturing industries were supplier industries such as iron and steel for the building of locomotives, and industries exploiting natural resources such as wood and coal as fuel. With ongoing urbanization and industrialization, manufacturing extended its production to other markets.

[23] The de-skilling effect was probably reinforced by the sizeable immigration of unskilled workers from the Old World after 1840 (Habakkuk, 1962).

[24] Atack et al. (2004) find evidence for the period 1850-1880 that, on average, large

ultimately experienced an economy-wide capital deepening (Abramovitz and David, 1996). In contrast, UK manufacturing continued to use its flexible, crafts-based production system with high skill intensity. This system had been successful in the past, and firms in the UK had no incentive to change the production structure by 1850.

Changes in innovation systems The apparently efficient absorption of UK technology by the US and the transition to a technologically progressive production system in US manufacturing may be explained by a relatively large social capability of the US economy. Its innovation system was fostered by the adjustment of various institutions originating from the UK to local circumstances to serve the economic needs of the expanding US economy.

First, institutions had to serve the needs of a young, fast growing and egalitarian population of immigrants. Elitist powers such as in the UK did not exist in the US. Furthermore, the competition for labour led to extension of suffrage and property rights for women, liberal policy in education, democratic access to land, and flexible immigration policy (Engerman and Sokoloff, 2003).

Second, educational institutions borrowed from the UK were transformed to boost the country-wide diffusion of mass education in the US. Around 1850, the US had comparatively high enrolment rates in elementary education, higher than in any other nation (Goldin and Katz, 2003). The ability to read and write was of value in increasing labour mobility in the settlement and industrialization, in contrast to vocational training that makes labour less flexible to adapt. In the UK, firm-specific craft-based training was still generally suitable.

Third, the intellectual property rights system borrowed from the UK was intentionally adjusted to provide broad access to all individuals, also to those with limited resources and education.[25] It also forced the immediate public dissemination of the knowledge encompassed in

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establishments used relatively much unskilled labour. This was partially offset by establishments which were capital intensive and used the new steam power technology, where higher wages were paid. The overall effect, however, was a de-skilling of the manufacturing labour force because relatively more workers were employed in establishments with low wages in 1880 than in 1850, and wage inequality was increased.

[25] The validity of granted patents was ensured by government, thereby supporting inventors with limited capital and resources to patent or to exploit the patent. US inventors born before 1865 appear to be relatively often low educated and self-employed (Khan and Sokoloff, 2004).

the patent (Khan and Sokoloff, 2004).[26] These characteristics lowered transaction cost and information asymmetries. Hence, patent activity responded relatively quickly to major technological and economic changes (Khan, 2004). Inventive activity increased substantially, and patents were granted on a much broader range of inventions than elsewhere. A relatively large technology market for patent rights was created, inducing specialization in innovation across the US economy (Lamoreaux and Sokoloff, 1999). The UK patent system responded only slowly to these changes in the US, and remained relatively biased towards incumbent interests for a long time.[27]

In overall, the US innovation system was efficient compared to that of the UK. The UK remained the technology leader up to the late nineteenth century, but continued to use the technologies of the First Industrial Revolution. Meanwhile, the US technology system in agriculture and manufacturing was dynamic and flexible, progressing rapidly.[28]

3.4.2 Change in leadership, 1870-1913

After 1870, the volume of world trade boomed, accompanied by mass migration and capital flows. Meanwhile, scientific knowledge became increasingly important for industrial product development. In this period, the US surpassed the UK in overall labour productivity levels, mainly because of a shift out of agriculture to services. But the US became the technology leader in manufacturing and its social capability increased in combination with its technological development. Although technology transfer flows were mutual by now, UK/US incongruence increased further. The UK remained oriented towards relatively 'old' industries, which was economically rational given its technology system.

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[26] In contrast to the UK, the US system granted patents only to the first and true inventors anywhere in the world; patenting fees were relatively low (initially 5% of the UK level); technical details of the new knowledge were made public immediately; and, since 1836, it contained an impersonal and routinized examination by independent technological experts (Khan and Sokoloff, 2004).

[27] The impartial examination procedure, for instance, was only introduced by 1905 (Khan and Sokoloff, 2004).

[28] Some US institutions were less flexible. For instance, the US business legal system was more restrictive than in France. Contractual freedom was relatively limited and less flexible to meet the needs of business until the late 20th century, and American business law was slow to respond to economic changes (Lamoreaux and Rosenthal, 2004).

Changes in technology systems In the late 19th and early 20th century, US/UK trade patterns did not shift but even were reinforced, probably reflecting limited absorption of each other's technology. US industries exported goods, such as iron, steel, machinery and automobiles, produced by the mass production system, with a relatively high intensity in non-reproducible natural resources, energy use and capital (Nelson and Wright, 1992). US comparative advantage in these industries was extended between 1880 and 1929 (Wright, 1990). UK export industries were those that could, more or less, beat US productivity in combination with lower wages (Broadberry, 1997b). These were industries where craft-based production was still competitive despite US mass production (e.g., textiles), where mass production was difficult to apply (shipbuilding), and where demand allowed adoption of a mass production system in the UK (sugar refining).

The US absorbed the largest mass of foreign capital that flew from the UK after 1870 (Hall ed., 1968), but the technology brought with this capital only supported the local development of US technology. This is probably reflected in persistent international differences in prices of equipment, buildings and other capital goods, even during periods of globalization (Collins and Williamson, 2001). Financial capital was used for investment in local railroads, mining, cattle ranching, oil wells, and infant industries. Foreign multinationals investing in the US introduced new technology which was absorbed. The US also imported capital goods from the UK, such as textile machinery, railroad equipment and agricultural machinery (Taylor, 1996).

Most labour immigrants from the UK after 1870 were relatively unskilled, but the fast growing capital- and natural resource-using US industries increasingly demanded skilled labour. The low-skilled immigrants crowded out native unskilled workers in low-growing US sectors (O'Rourke and Williamson, 2000). Progressive industries needed engineers for machinery maintenance, managers for professional organisation of larger scale production, and, by the end of the 19th century, also specialized experts who could handle the increasing variety of products (Atack et al., 2004), in combination with advances in capital-intensive technology and science. By 1890, the US mass production system became increasingly dynamic and progressive, inducing the reaping of the potential of latent knowledge (Abramovitz, 1991), leaving the UK further behind at that time. The US became the world technology leader in manufacturing.

Nothwithstanding the overtaking of overall productivity leadership from the UK by the US by the late 19th century, this was mainly due to a shift in the US out of agriculture to the service sector, rather than major changes in manufacturing (Broadberry and Ghosal, 2002). It reflected a transition to standardized, high-volume, low-margin firms with hierarchical management from the 1870s, and was stimulated by office technology in communication and information processing.

International technology diffusion between the US and UK service sectors was probably limited because of differences in demand conditions. Decentralization, customized products, asymmetric information and trust are important elements in industries such as banking and finance. But the forces that were driving the development of mass production in US manufacturing probably also led to large-scale production in some other service sectors in the US. Broadberry and Ghosal (2002) suggest a link between the rise of the US service sector and large-scale advantages in transport and utilities and standardized products in a homogenous market, and the appearance of the modern business enterprise, supported by the diffusion of office technology.

Changes in innovation systems In the late 19th century, in-house research and professional organisation of large scale firms emerged first in the US. Increasingly larger US manufacturing firms with the progressive mass production technology demanded for professional management (Nelson and Wright, 1992). Moreoever, trade in patented inventions expanded further in the US (Lamoreaux and Sokoloff, 1997), and business networks increased (Nelson and Wright, 1992). This information from outside had to be absorbed, and in-house research combined with firm specific skills was the most efficient way to generate successful innovations (Mowery and Rosenberg, 1989).[29] This research became increasingly less experimental and more directed to the needs of industry (Mowery and Rosenberg, 1989). Technological progress was increasingly complex and the interaction between prescriptive and propositional knowledge became tighter and self-reinforcing, stimulated by a growing common knowledge pool (Mokyr, 2002).[30]

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[29] Experimental stations and agricultural machinery produced in industry played an important role in agricultural research in the US (Hayami and Ruttan, 1985).

[30] Propositional knowledge is about why something works (discovery) and prescriptive knowledge is about techniques, how it works (invention) (Mokyr, 2002).

This also explains why mass formal post-elementary education emerged first in the US, rather than in other countries such as the UK (Goldin and Katz, 2003). As the in-house research could only be conducted by scientifically trained personnel, the demand for such personnel increased in the US. Flexible, general, and widely applicable skills as provided by general knowledge of algebra, and mechanical, chemical and electrical engineering, was highly valued by firms (Goldin, 2001). The management of large firms and research required organisational skill. The education system enabled a higher geographical, occupational and intersectoral mobility of labour (Goldin, 2001).[31]

In the UK with its flexible, skilled labour intensive production system and customized products, the job-specific skills of vocationally trained personnel were still highly valued.[32] The UK level of intermediate vocational skills was relatively high compared to the US,[33] except for skills needed in the new industries chemicals and electrical engineering (Wrigley, 1986). The UK also faced a gap in the higher level vocational skills by 1900 (Broadberry, 2003a). Meanwhile, the UK continued to lag behind in post-elementary formal education levels.[34]

However, the UK/US differences in the innovation system were largely the result of rational decisions by entrepreneurs in both countries given their technology systems. There was no massive market failure in the UK (Crafts, 2003a). First, in the late 19th century, technology and institutions were not transferred easily between countries. Second, as the UK was directed towards older industries requiring less scientific knowledge development, there was less perceived need for formal post-elementary education and in-house R&D. Finally, UK formal education and research did expand between 1890 and 1914. It was because major technological progress occurred in the mass production system, that American overtaking was, more or less, unavoidable.

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[31] Broadberry (2003a) argues that the rise of secondary education had more impact on service sectors, as US manufacturing was already forging ahead using unskilled labour. However, the major innovations took place in the mass production system, so skill was also important for manufacturing industries.

[32] In the US, the apprenticeship system and work-study tracks collapsed by the early 20th century (Goldin, 2001; Broadberry, 2003a).

[33] Intermediate level training concerns craft and technical qualification between secondary and degree level, including apprenticeships. Higher level vocational training at university degree level include among other things membership of professional institutions (Broadberry, 2003a, p.61).

[34] Only by 1914, the UK caught up with the US in elementary schooling (Broadberry, 2003a).

3.4.3 Diverging patterns, 1913-1950

The two World Wars and the Depression years, protectionism and financial disruption marked a period of relative stand still in international relations after the large changes around 1900. Comparative UK labour productivity in both non-manufacturing and manufacturing sectors was historically low. Technology transfer was relatively limited, while the US progressed further and the lack of social capability increased in the UK.

Changes in technology systems In the interwar years, there was probably relatively limited technology transfer between the US and the UK (Abramovitz and David, 1996), and they remained persistently incongruent. International relations were broken up, and flows of trade, migration and capital were disrupted. Meanwhile, new industries (chemicals and electricity) emerged, supported by the electrification of industry (David, 1991; Nelson and Wright, 1992), and the US was again the first in exploiting this opportunity.

Technology, capital and skills became complementary in US manufacturing in the early 20th century (Goldin and Katz, 1998). At that time, US manufacturing shifted to the continuous processing system, reinforced by the diffusion of electricity from the late 19th century onwards. This major technology had been imported from Europe. The electrification of US industry reduced the demand for unskilled labour in many assembling tasks. These firms became more skill intensive than factories, although they were much larger.[35] The supply of educated labour responded to and reinforced the skill bias in technological change. This contrasts the developments in the 19th century, when capital intensive technological development was de-skilling on average (Atack et al., 2004). After 1929, the new chemical and electrical industries emerged, probably stimulated by the Depression years which may have induced faster replacement of old technologies (Field, 2003).

The diffusion of electricity was even faster in UK manufacturing, as it started from a backlog position after 1918 (David and Wright, 2003). By the end of the 1930s, it seems to have caught up with US manufacturing in electrification. However, this did not lead to a higher TFP or labour productivity growth than in the US. This indicates that differences in

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[35] Industries with a high level of capital per production workers and a higher energy use of electricity in the period 1909-1929 employed relatively more educated blue-collar workers in 1940 and paid higher wages to white collar workers (Goldin and Katz, 1998).

technology and institutions between the countries were important. By now, growth was enhanced by productivity advances within new industries rather than structural shifts between sectors (Crafts, 2003a). But the UK was lagging behind in these new industries, and the Depression made things worse.

That technology transfer was relatively limited in this period, may be derived from the persistence in comparative advantage in trade and technology, as shown by indices of revealed comparative advantage (RCA) and revealed technology advantage (RTA). The RTA index reflects industrial variation in the propensity to patent, that is, specialization in technology. The UK stuck to more traditional industries such as textiles, shipbuilding and tobacco, while the US strengthened its position in the higher tech industries such as chemicals, electrical and office equipment and automobiles (Tables 3.3 and 3.4).

Table 3.3: RCA rankings by industry, 1899-1950

	UK					US				
	1899	1913	1929	1937	1950	1899	1913	1929	1937	1950
Iron & Steel	2	3	4	9	15	9	9	8	5	9
Non-ferrous metals	13	16	13	15	14	2	1	3	6	15
Chemicals	9	11	10	12	13	10	12	9	8	4
Brick & glass	15	14	12	10	9	14	11	12	10	11
Wood & leather	16	15	15	14	16	6	7	10	11	13
Industrial equipment	4	5	8	7	8	5	3	4	3	3
Electricals	6	8	7	5	4	3	5	5	4	5
Agricult. equipment	5	10	16	16	12	1	2	1	1	1
Rail & ship	1	1	1	3	5	8	8	11	12	7
Cars & aircraft	7	12	14	11	3	4	4	2	2	2
Alcohol & tobacco	12	4	2	1	2	11	15	15	15	14
Textiles	3	2	3	2	7	16	16	16	16	16
Apparel	8	6	9	6	6	15	14	13	14	10
Metal manufacturing	10	7	11	13	11	7	6	7	9	8
Books & film	14	13	6	8	10	13	10	6	7	6
Fancy goods	11	9	5	4	1	12	13	14	13	12

Source: Crafts (1994), Table 1.

Changes in innovation systems In the early 20th century, R&D became more organized and institutionalized, at first in the US due to its larger organisational capability and science-based research (Nelson and Wright, 1992; Chandler, 1992). Meanwhile, secondary and higher education expanded in response to the demand from industry (Goldin,

Table 3.4: RTA rankings by industry, 1920-1939 and 1978-1995

	UK				US			
	1920-1929	1930-1939	1978-1986	1987-1995	1920-1929	1930-1939	1978-1986	1987-1995
Food and drink	8	7	10	10	3	2	2	1
Chemicals	6	5	6	7	13	13	12	13
Pharmaceuticals	13	11	3	3	14	14	12	13
Metal products	9	9	4	4	12	11	15	15
Mechanical engineering	4	8	10	8	10	6	10	12
Electrical equipment	10	10	12	9	5	5	8	11
Office & computing	11	13	13	13	1	1	1	1
Motor vehicles	11	12	5	6	8	3	11	10
Other transport	2	4	7	5	8	7	3	4
Textiles	1	1	1	1	15	15	14	9
Paper	.	.	.	.	2	12	9	8
Rubber & plastic	5	3	8	11	6	9	7	6
Non-metallic minerals	3	6	9	12	7	4	6	5
Coal & petroleum	7	2	2	2	4	8	5	7
Instruments	.	.	.	.	11	10	3	3

Source: Cantwell (2000), Table 1 and 3.

2001; Goldin and Katz, 1999). Higher education was funded at the state level and was open to the needs of industry and agriculture.[36] This generated a form of entrepreneurial scientific research in which curriculum and research were more closely fit to commercial needs of agriculture and industry than was the case in many European countries. The higher education system was a channel of diffusion of scientific knowledge, though it was not the frontier science (Mowery and Rosenberg, 1989).

In contrast, in the UK, much research was outsourced at research associations and consultant engineers, so that industrial research remained relatively modest in scope and effectivity. Company surveys in the interbellum period show that British firms had relatively less often an R&D laboratory than American firms (Table 3.5). Research expenditure and research employment data show also a backlog for the UK in both total economy and manufacturing. This backlog declined a little between the 1930s and 1950s.

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[36] Federally funded scientific research expanded substantially only after the Second World War. In the interwar years, in the US, there was much resistance against federal power, also in research. If there was any federal funding, it was mainly focussed on agricultural research (Mowery and Rosenberg, 1989).

Table 3.5: Business R&D activity before 1960

	Number of firms with at least 1 laboratory to total of firms		R&D as % of net output Manufacturing		RSE as % of employment Manufacturing		RSE as % of employment Total economy	
	UK	US	UK	US	UK	US	UK	US
1930							0.007	
1931								0.028
1933		116/160			0.03	0.17		0.077
1934			0.43					
1935					0.05		0.01	
1936	20/200							
1937				0.98				
1938			0.43		0.07		0.02	0.099
1940						0.29		0.14
1945							0.04	
1946	40/200				0.07	0.32		
1948		164/200						
1950							0.04	
1959			3.10	5.70	0.52	1.35		

RSE = number of researchers, scientists and engineers. *Sources*: Mowery (1986) on firms with research laboratory; R&D and RSE in manufacturing: Broadberry and Wagner (1996); RSE total economy: Edgerton and Horrocks (1994). 1959: Freeman (1962).

The fact that the UK lagged behind in research effort is consistent with its human capital gap. The gap in mass secondary education between the UK and US increased during the interbellum (Broadberry, 2003a). The spread of higher education was relatively limited. Particularly engineering and chemical training was lacking and of non-academic character. The link between science and industrial research was relatively weak compared to the US. This was reinforced by the lack of support by the government and its conservative attitude (Mowery and Rosenberg, 1989).[37]

Intermediate level vocational training, the original strength of the UK, was directed towards retraining of disabled ex-servicemen after the First World War, and later on towards the unemployed (Broadberry, 2003a). This suggests that government policy on vocational training hampered necessary adjustments to catch up in labour productivity with the US. As percentage of total employment, the UK were not lagging

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[37] Greasley and Oxley (1998) found that US-UK convergence at macro-economic level in the twentieth century could not be explained by industrial technology diffusion, as at industrial level, the Anglo-American gap in output per worker was diverging. They state that differences in returns to higher education explain the disparities.

behind in intermediate level vocational skills (Broadberry, 2003a). However, in higher level vocational training, the US had surpassed the UK. American managers of industrial companies were also more often graduates than British managers, and this gap remained large until after the Second World War. Only the British service sector did not lag much behind the US in comparative vocational skill.

The UK economy was apparently locked in on a growth path where switching costs were perceived as being large, while the Anglo-American gap between their innovation systems widened.[38] Rigid social structures and financial institutions (family capitalism), deterioration in industrial relations and principal agent problems within British firms (Crafts, 2003a): all may have hampered the UK in catching up to the US in a period in which investments in intangible assets for absorption of new technologies became crucial for economic viability.[39] The situation worsened with a government policy oriented towards industrial policy instead of competition, leading to a bad incentive structure.

3.4.4 Post-war catching up, 1950-1990

In the post-war period, Western European countries converged to the US in labor productivity. Technology was actively transferred from the US to the Europe. In first instance, this occurred mainly via capital investments and imports. But the role of own R&D and human capital in the absorption of US technology increased. Compared to the continental European countries, however, the UK was slow to catch up with the US, due to failures in its innovation system.

Changes in innovation systems Although the ravage of the Second World War put the European countries at lower levels, the US economy would likely have been a technology leader without the war. By the 1950s, the US was dominating higher-technology industries, as an outcome of the earlier developments in its technology and institutions. But the war brought in the US a large optimistic belief in the possibilities of technology and science (Nelson and Wright, 1992). Industrial and federal R&D and higher education investments rose substantially. This

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[38] Although not all UK industries were performing poorly.

[39] Abramovitz and David (1996) state that the wars and Depression years inhibited convergence. However, higher investment in R&D and formal human capital training might have prevented the widening gap in innovation systems by shifting to the new industries.

increase was not matched by other countries.[40] A large part of federal research was devoted to defense related technologies. This generated large spillovers to civilian technologies, laying the foundations for American dominance in computer and semiconductor industries. Meanwhile, other countries started to catch up in secondary education (Goldin, 2001). US higher education maintained its position (Goldin and Katz, 1999).

In reconstructing the European economies, US and Western European governments actively transferred technology from the US to Western Europe. At this time, there was no mass migration,[41] but capital flowed from the US to Europe via capital imports and American multinationals in Europe. The capital intensity of many countries increased. Furthermore, trade patterns changed, as the US shifted to the most R&D intensive industries. European countries could increase comparative advantage in industries where the US had been the leader but where technological opportunities seemed to diminish, such as automobiles and consumer electronics (Nelson and Wright, 1992).[42]

But technology was increasingly channelled via R&D and human capital. In the 1950s and early 1960s, the European countries faced a gap in experience with technology, management and organisation (Nelson and Wright, 1992). From the 1960s onwards, European R&D investments and human capital accumulation via formal education rose substantially.[43] These investments increased the capacity to absorb US technology. With increasing economic integration by the 1980s, R&D internationalisation and international mobility of scientists and engineers and higher education students between the US and Europe increased (OECD, 1998b, 2002a).[44]

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[40] By 1969, US expenditure on R&D was more than double that of the UK, Germany, France and Japan together (Nelson and Wright, 1992, p.1952).

[41] Just after the War, many Europeans migrated to the US, but this is not comparable to the mass migration in the late 19th century (Hatton, 2004).

[42] The convergence was also related to other institutional changes (Eichengreen, 1996): an increased welfare state and collaboration between social partners, substantial increases in investment, wage moderation and deregulation, world market integration with declining prices of natural resources, causing a decline in the original comparative advantage of the US (Wright, 1990), and a larger European market due to the establishment of the EU and EFTA. The reconstruction and shift out of agriculture also contributed to the fast growth.

[43] Moreover, they invested mainly in civilian technology while spillovers from military research in the US declined (Nelson and Wright, 1992).

[44] In the 19th century, European universities already received American students. However, the post-1960 mobility of students was relatively larger and more institutionalized.

Meanwhile, the UK was caught up by the continental countries in labour productivity. The UK had less scope for catching up after the Second World War than continental European countries as it started at a higher productivity level than these countries.[45] Nevertheless, the UK was probably growing less fast than it could in the Golden Age (Broadberry and Crafts, 2003). This was largely the consequence of ill-designed government policy and a failure to build appropriate institutions concerning research and human capital.

In the Golden Age, the UK government stuck to an industrial policy with wage moderation and labour protection deregulation (Broadberry and Crafts, 2003), and was less supportive of competition, human capital accumulation and R&D. Even worse, the 1950s and 1960s were a period of uncritically copying of American mass production methods in UK manufacturing (Broadberry, 2004a). The UK apprenticeship system was heavily oriented towards industry (O'Mahony, 2004). The UK succeeded to catch up with the US in engineering apprentices during the 1950s and 1960s. Meanwhile, however, industrial relations deteriorated and competition was weak (Broadberry and Crafts, 2003).[46] In other European countries, such as Germany, the apprenticeship system was extended at large scale to the service sector, which became relatively important after 1950 (O'Mahony, 2004).[47]

In the 1970s, when continental countries increased public spending, taxation and regulation of the labour market, in the UK agressive deregulation and low government support prevailed. Its productivity slowdown after the Golden Age was less severe, but increased macroeconomic instability undermined investment (Crafts, 2004). By the end of the 1970s, the American model was replaced by German and Japanese skill intensive production methods (Broadberry and O'Mahony, 2004). In the 1980s, a strong fall in the cost of information processing made flexible production systems more profitable (Broadberry, 2005). But the British skill gap with continental countries remained relatively large.[48]

Ultimately, UK government policy changed. In the 1980s, education

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[45] Moreover, it had already transferred relatively much labour out of agriculture to services.

[46] Although industry performance varied across manufacturing (Broadberry, 2004a).

[47] Highly skilled professionals in the UK were concentrated in the service sector, but many were not graduated at university (O'Mahony, 2004).

[48] Though there were successes, such as in pharmaceuticals, food and beverages, and firms which exploited niches in the market such as some firms in the car industry (Broadberry and Crafts, 2003).

and training investment increased substantially (O'Mahony, 2004). Particularly the gap in higher level skills with the US was reduced a little, and also the gap with Germany in intermediate level vocational skills. By 1990, this had not yet led to a full catching up in labour productivity with the US. However, it takes a generation before the newly trained young people enter the labour market (O'Mahony, 2004). Moreover, the US were starting to regain technology leadership in manufacturing in high tech industries and ICT, stimulated by its early lead in institutions (Eichengreen and Vazquez, 2000) and complementarities between general higher education and technology (Broadberry, 2005).[49]

3.5 The mechanism of technology diffusion

The comparative Anglo-American growth and technology performance as discussed in the previous sections shows how international technology diffusion interacted with the technology systems and innovation systems of both countries. In this section, I summarize the evidence on the relationship between technology diffusion and productivity differences.

To begin with, the more a leader and a follower country are technologically congruent, the easier leading technology is absorbed by the follower country in an embodied fashion, through traded goods, capital imports, labour migration, as well as in a disembodied way, through e.g. blueprints, patents, and handbooks. Indeed during the 19th and early 20th centuries, the US and UK were rather incongruent due to large differences in factor endowments and market conditions. As a result these countries developed their own technology systems and exploited technologies that fit into these systems.

Sometimes technology diffusion itself may reduce incongruence, as was the case in the post-war period between the US and Western European countries. Also, the early 19th century US caught up with the UK by adapting UK technology. However, in the late 19th century, the US passed the UK and forged ahead due to local developments. Usually, due to the differences in factor endowments and market conditions, and due to learning around the techniques in use, technological development is local and technology from abroad is adapted to local circumstances.

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[49] General education is presupposed to produce a flexibility needed for exploitation of more radical innovations (Lazear, 2004). European countries generally had a larger focus on vocational training. Krueger and Kumar (2004b) show quantitatively that this apparently explains American-European differences in economic performance.

Technological incongruence does not mean that countries cannot learn from each other. If foreign leader technology is not congruent to the follower country's technology system, capabilities to absorb this technology are necessary. Effective research and human capital institutions provide the capacity to understand foreign technology. Nineteenth century US probably had a relatively high social capability to adopt UK technology due to local circumstances. Although it had no technology lead up to the late nineteenth century, it strengthened broad participation in education and technology absorption by the population. In the twentieth century, the American commitment to science strengthened its leadership in technology. In contrast, for a long time period, the UK could not take advantage of technology related to the Second Industrial Revolution, because of less scientific skills in technological progress and rigidities in industrial relations.

Social capability to adopt technology from the leader partly depends on the diffusion of institutions from the leader country, mainly those concerning research and human capital. But these institutions need to be adapted to serve local needs related to the prevailing economic and technological factors. In the 19th century US, institutions of education and patents from the UK were adapted in order to provide the young population of the expanding economy broad access to education and means to develop new ideas and products. In contrast, the difference in technology system and lack of economic incentives was the reason for late 19th century UK not to absorb the US education system quickly. Slow technology diffusion may be rational, as costs of absorption may be too high. But more likely it was institutional rigidity that prevented the UK from adopting US institutions in the early 20th century. Hence, the Anglo-American case exactly shows that technology and institutions are intertwined, and that technology diffusion is no automatic or inevitable process.

The importance of international diffusion of institutions to adopt foreign technologies to local circumstances increased in course of time. Nineteenth century technology transfer to the US was still largely a matter of trial-and-error on the basis of education and patents which originated from the UK (Crafts, 1998). Nowadays, technology diffusion between advanced countries is more formal and mainly occurs via R&D and human capital. This is because the link between science and research has become tighter and technologies are more complex. In the post-war period, the diffusion of institutions of R&D and education from the US had a major impact on Western European economies.

Still it should be stressed that adoption and adaptation of institutions from the leader country does not necessarily mean that the technology system of the follower country has to become a copy of that of the leader. In terms of the David-Broadberry model, the follower's technology system may continue to co-exist with the leader's technologically more progressive system as long as the follower has sufficient flexibility to adapt to some of the leader's institutions. Without the absorption of these institutions, the follower might ultimately fall further behind. A follower country that effectively absorbs human capital and research institutions from the leader, might also ultimately develop such a large social capability to innovate that it can surpass the technology leader, with a technology system that turns out more progressive. Ultimately, not only technology systems, but also innovation systems of different countries do not need to resemble each other. Rather, institutions from the leader will be adapted and the innovation system of the follower will develop with its own technology system.

3.6 Conclusions

The current chapter investigated how comparative Anglo-American productivity and capital intensity were affected by international technology diffusion between 1840 and 1990, and how this was related to their technology congruence and social capability differences between the two countries. This research question was addressed by means of quantitative evidence on comparative labour productivity, capital intensity and joint factor productivity, complemented by qualitative evidence from the economic-historical literature on international technology diffusion, technology systems and innovation systems. This leads to the following observations, also summed up in Table 3.1:

By 1840, the US was already productivity leader in manufacturing. In the 1890s, the UK was definitely surpassed by the US as the overall labour productivity leader. The US were more capital intensive than the UK by 1850, but American machinery intensity was higher than the British only by the 1870s. This development reflects the transition of US manufacturing to the machinery intensive mass production system, which also spread to other sectors of the economy. Meanwhile, the UK technology system continued to co-exist. Only by the twentieth century some trend breaks occurred in Anglo-American comparative performance. The UK did not catch up in labour productivity and joint factor productivity in both manufacturing and non-manufacturing sectors until after the Second World War. The UK gap has always been larger in manufacturing than in non-manufacturing sectors during the whole period under consideration, reflecting a smaller comparative disadvantage of the UK service sector. This also suggests that technology systems and innovation systems differed between the UK and US.

Technology was transferred between the two economies via various channels. In the 19th century, UK technology flowed to the US mainly via trade, capital and migrants. This technology was absorbed effectively by the US. From the late 19th century until the Second World War, transfer of technology between the US and UK did not shift their long run growth paths. They both continued to exploit their own technology systems, but the US system became increasingly dynamic, forging ahead of the UK. Some UK industries and service sectors remained competitive, but the major advances in technological progress took place in US manufacturing. This technology was not easily transferred to the UK because of incongruence, and later on, because of UK institutional rigidities. Only after the Second World War, and even with some delay compared to continental countries, the UK increased its social capability by investing in human capital and research. International technology diffusion was taking place more and more with help of capabilities created by own human capital and R&D. Skilled people and researchers absorbed the technological knowledge involved in international flows of books, patents, blueprints, foreign multinationals and skilled immigrants.

The Anglo-American experience suggests that transfer of institutions for human capital and research might have been more important for long run comparative economic performance than technology transfer itself. It also suggests that these transfers related to the innovation systems take more time to diffuse than technology transfer itself. The diffusion of these institutions is a necessary, though not sufficient condition for effective and efficient absorption of the leader technology. In the 19th century US, institutions of education and patents from the UK were adapted to serve local needs. The difference in technology system and lack of economic incentives was the reason for late 19th century UK not to absorb the US education system quickly. But it was institutional rigidity that prevented the UK from adopting US institutions in the early 20th century. Because of this intertwinedness of technology and institutions, technology diffusion is no automatic or inevitable process.

Some questions are still open. First, to what extent might the Anglo-American case be generalized to other economies, sectors, and time periods? For instance, continental European countries such as Germany and France followed a growth path that differed in their own way from that of the UK. Germany successfully built a skill-intensive technology system based on vocational training, while France put more emphasis on general education. Furthermore, international differences in the nature of production, the technology systems and innovation systems in similar sectors appear to explain a part of the differences in macro-economic performance. Does this extend to other countries? Growth accounting studies have shown that sectoral differences matter. After 1995, US growth accelerated due to the materialization of ICT. With a major technology like ICT, it is supposed that it is strength in higher education that pays off. The Western European countries were slower and less effective in exploiting the ICT potential. Other observed obstacles are barriers to trade, taxes, weak competition and labour market regulation. But the UK currently seems to be in a better position than the continental European countries because of greater strength in higher education and weaker labour protection regulations (Crafts, 2004).

Second, the analysis of technology diffusion in the current chapter is intuitive on the role of international technology diffusion. The chapter has shown that the impact of technology diffusion depends on innovation systems and changes therein, among others by diffusion of innovation-related institutions. These subtleties of institutional diffusion in the technology transfer mechanism are not easy to model. However, it are exactly these complexities which give rise to the modelling and estimation of the impact of technology diffusion, in order to disentangle technology diffusion from other forces. Conditional on international differences in technology systems and innovation systems, one may attempt to estimate the impact of technology diffusion on economic growth differences. This explicit quantification of the effect of technology diffusion is the subject of the next two chapters.