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Human Capital, Distance to Frontier, and Technology Diffusion

Master‘s thesis

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Abstract

This thesis analyses how technology diffusion works as the engine of economic growth. Special attention is given to the effects of human capital and the distance to the world technology frontier. The analysis compares models that assume technology to be a public good to models that assume technology transfer is slow and costly because knowledge is tacit and imbedded in the heads of people. The models with a globally identical technology attribute income differences to factor endowments, technology inappropriateness, and barriers to technology adoption. Human capital growth is directly responsible for technological progress and the country with the highest human capital level is generally the technology leader. These models do often imply conditional convergence, though not necessarily. Models that allow for technology differences are more successful at empirically explaining the observed differences. They assume that human capital is an input in the process of innovation of new technologies and adoption of existing technologies. As such the stock of human capital determines the level of growth (through either innovation or adoption). The two channels allow for an important role for human capital composition. Lagging countries should not look to imitate advanced economies and instead exploit the possibilities of technology adoption first.

CONTENT

Figures

Abbreviations

DTF – Distance to Frontier

PGK – Public Good Knowledge

R&D – Research and Development

TFP – Total Factor Productivity

TK – Tacit Knowledge

UK – United Kingdom

US – United States

1 INTRODUCTION

In modern history, there are examples of countries successfully catching up to the world technology frontier and even becoming world technology leaders in some fields such as post-war Germany, Japan or later the East Asian countries, and today China or India. Other countries have been less successful at catching up or have even fallen behind farther. In some cases the reason is political instability or non-growth-oriented leadership, but in some cases the explanation lies elsewhere. One possible source of the different growth rates observed is that some countries were able to draw from the world technology frontier and some were not. Continuing this line of thought, this thesis is focused on the question: How does technology diffusion work?

When a new technology is invented and applied this is referred to as *innovation*. Innovation is what drives growth on a global perspective – the perspective of the world technology frontier. A useful technology that enhances the global technology frontier then spreads throughout the economy and around the world. There are two distinctively different approaches to the question "why are there productivity differences": The first group postulates that all countries have access to the same global technology level. The innovation mentioned above thus instantly and at no cost becomes available to everyone. The second group assumes that each country only has access to some technologies. The first case will be referred to as the *public good knowledge* (PGK) case, the second as the *tacit knowledge* (TK) case. Both groups have to explain the same empirical facts observed in the world and mentioned in the introduction. It is interesting to see, however, how their mechanisms differ and if they have different policy implications.

As will be shown, human capital plays an important part in the diffusion process. Education and experience help countries innovate and grow, but also enables countries to acquire technologies that were developed elsewhere. With PGK these two processes are identical. At the core of the Distance to Frontier (DTF) research in the TK case lies the idea that an increase in productivity is different for countries which enhance the world technology frontier with new innovations, and countries which merely adopt, copy, or imitate innovations that already have taken place elsewhere. These models argue that it should be simpler to adopt a technology that is known to work and where there might even be blueprints or prototypes available than to figure out a truly new process. Even more than how new technologies are developed, how they are diffused from advanced economies towards a poor country is what is of interest for this thesis – the technology of technology diffusion, so to speak. The major influences come from the characteristics of the technology at hand, the country's distance to the world technology frontier and the country's human capital level and composition. The idea is to give general answers from a macroeconomic perspective and the reference to individual technologies will be scarce.

This thesis will therefore strive to answer the following main questions:

- What approaches exist that link technology diffusion to human capital and the DTF?
- How do they model the diffusion of technology, is it the transfer of technology that is costly? Or is it the human capital accumulation that is necessary to gain access to technologies, which would otherwise be free?
- Do the models have different implication based on these differences?
- Does the effect of human capital change with the DTF?
- Does the composition of human capital matter and does its effect depend on the DTF?

The whole thesis is divided into three parts. Chapter 2 sheds some further light on the main concepts and terms used in this thesis: Technology, human capital, distance to frontier, public good knowledge and tacit knowledge. Chapter 3 discusses different technology diffusion models in three steps: First models that treat knowledge as a public good are discussed and in a second step the focus is on models that assume technology differences based on the (partial) tacitness of knowledge. Chapter 4 then analyses the role of human capital, distance to frontier, and the main diffusion channels in empirical research. Chapter 5 draws conclusions – what can we learn from theory and empirics, and which open questions remain?

2 CONCEPTS AND DEFINITIONS

The main concepts and terms have already been introduced in the first section. First of all it is important to clarify what is meant by technology, and how this relates to the terms idea and knowledge. Secondly the important terms of human capital and distance to (world technology) frontier will be explained in the context of this research. Lastly two different approaches or types of knowledge will be discussed: Public good knowledge and tacit knowledge.

2.1 TECHNOLOGY AND KNOWLEDGE

The two terms technology and knowledge are closely related. In this thesis it is understood that technologies are part of human knowledge. But the two terms are not identical, it is not necessarily assumed that all knowledge can be seen or used as a technology.

Technology is a key component of the aggregate production functions many neo-classical macro-economic models are built around. It models in a simplified way the transformation of different inputs (traditionally capital and labour) into an end product, the output. However, the same amount of inputs does not yield the same output in different situations. This is due to *productivity* differences. Productivity can be split into two terms: *technology* and *efficiency*. Technology refers to the technical and organizational aspects of production. Efficiency can for instance refer to the productiveness of activities, utilization of resources, and factor allocation between sectors or firms. But often both combined are referred to as technology as the two cannot easily be separated both conceptually and empirically. In this thesis the focus will not lie on the efficiency aspect but instead on the more layman understanding of technology – how something is done technically.

Measures of technology

Measuring technology for empirical research is quite difficult due to the concept's intangible nature. Keller (2004) distinguishes three main approaches of what to measure: 1) inputs (R&D expenditures), 2) outputs (patents), or (3) effects (productivity).

Keller further states that data on *inputs* in terms of R&D expenditures are available only for relatively recent time periods and for richer countries. It is also questionable whether it is comparable across sectors, research areas, and country borders, since expenditures only make sense as a measure of technology growth if they are equally productive everywhere. In comparison Keller finds that the analysis of technology output data via *patents* has the advantage that it is available for a longer time period (up to 150 years) and for more countries, since patents are also filed in significant numbers in poorer countries. There are also three clear disadvantages that he mentions: Firstly, patents differ strongly in their value, and a small number of patents accounts for almost all of the total value of patents. Comparing the number of patents is therefore not equal to the value of innovations.[1] Secondly, not all innovations are patented since firms do regularly choose trade secrecy over the publication via a patent. The third issue is that of the tacit knowledge dimension which cannot be patented. The third measure of technology comes closest to that described in the introductory part to this chapter. It's the measure of *effects* via total factor productivity (TFP). The measure is the residual that is calculated from measures of economic outputs (e.g. production) and after subtracting the effects of inputs (capital, labour, etc.). As such it relies on the availability, unbiasedness and accurateness of multiple data sources, about which Keller rightfully has serious concerns. Since it is calculated as a residual it is also prone to capturing non-technological effects and labelling them as technology.[2]

Measures of technology transfers and diffusion

As we have seen the measures of technology are imperfect. As Radosevic (1999) states, different forms of technology can be transferred through different channels. And because technology has no unique form in which it is embodied and transferred, there are severe limitations for quantifying it and for studying its effects. For the market-transaction technology transfers actual data sources exist. The OECD collects and publishes data on royalty payments made by firms for licences, patents and copyrights. Radosevic estimates these technology transfers to account for only a small portion of the total international technology diffusion. Most technology diffusion is believed to happen via unintentional spillovers, imitation and research externalities. These can of course only indirectly be measured or rather estimated. One approach is to link new patents to old patents via their citations. The new patent is then assumed to have benefitted from the previous patent. But most researchers choose a different way. According to Keller (2004) the largest set of papers estimate international knowledge spillovers via regressions of technology measures.[3]

Future use of terms

The exact specifications will be of a larger importance in Chapter 4 where empirical data is discussed. For the theoretical part technology will refer to technology in a total factor

[1] There are ideas how to adjust for this problem. For instance Jaffe and Trajtenberg (2005) weight the patent data with the number of citations as a proxy for their importance.
[2] Keller lists institutional and cultural changes, demand fluctuations, changes in factor shares, omitted variables, and measurement errors as possible factors that can get confused with technical change.
[3] See Keller (2004) for a more discussion of the approaches.

productivity sense, but it will be abstracted from the potential effects of cultural, political or institutional origin. Knowledge and ideas are used as a term that includes technology, but also other things not necessarily associated with productivity. Technology diffusion shall refer to the same concept of technology of any form (codified or non-codified) that increases productivity.

2.2 HUMAN CAPITAL

Human capital is the attempt to measure a person's individual skills and abilities in an economic sense. Any stock of knowledge, skills, or characteristics a worker has that contribute to his productivity can be called human capital. In the most basic economic models goods are produced using labour as an input. However, not all labour measured in hours worked is equally effective and thus not equal. An economist attributes this to their different levels of human capital. Such human capital differences can have different origins. They are usually differences in innate talent, level of education, or experience.[4]

Measurement of human capital in empirical studies

Data scarcity dictates that human capital measures for broad empirical studies need to be simplified quite strongly. Early measures for human capital were school enrolment and literacy rates. The problem with school enrolment rates is that they measure the flow of new human capital, rather than the stock of existing human capital in the economy. Literacy rates on the other hand measure only a part of human capital, and neglect what is learned after primary schooling. Later measures have then focused on years of schooling, highest educational attainment, or a mix of the two. The question then becomes, what is the relevant sample covered with the measure? The discussions and data limitation concerns revolve around what age cutoffs to use, whether to use the general population or the working force, and in some cases whether to include women's education or not. While refining the measurements more and more has benefits on the theoretical accuracy of human capital measurements, it brings along more and more measurement problems, especially when one wants to compare the data internationally and across nations at different developmental stage using different measurement approaches for their national statistics. In an important early

[4] Another question is whether human capital as such is bounded. There is no indication that science or technology is reaching its limit. If human capital is responsible for technological progress, it cannot be bounded. Lucas (1988) shares this view of human capital. Romer (1990) sees human capital as a bounded variable. An individual can only dedicate a fixed amount of time in his lifetime to studying. He also claims that it is reasonable to assume that – at least primary and secondary –schooling goals have not significantly changed in the relevant timeframe. They focus on teaching basic cognitive skills like reading and math. Since this thesis looks more at technology diffusion than the process of innovation, this does not lie at the centre of attention. However it is an interesting thought to keep in mind when thinking about human capital and tacit knowledge.

contribution, Barro and Lee (1994) stated that the human capital measure most significantly correlated with growth is the measure created by them in their earlier work: Average years of schooling in the population above 25 years of age (Barro and Lee, 1993).[5]

None of these measures reflect much on the quality of education. Hanushek and Kimko (2000) have tried to adjust human capital measurements for schooling quality. Messinis and Ahmed (2013) even use a latent index of cognitive skills with four components as a measure of human capital: Formal education, scientific research output, life expectancy (proxy for health), and the current application of IT educational equipment by the working force. Madsen (2014) constructs a dataset that focuses on making human capital estimates more comparable across different nations and provides an overview over the different possible measurements.

2.3 DISTANCE TO FRONTIER

The concept of *Distance to Frontier* (DTF) dependence arises from the thought that there are two types of technological growth, namely innovation and adoption as explained in chapter on technology. When these two processes are different the respective country's lag behind the world technology frontier can severely impact the effects of human capital or political measures. The idea is that the process of *adoption* of technologies already developed elsewhere is simpler and thus cheaper than cutting-edge technology development, i.e. *innovation*. Lagging, poorer countries can opt to pursue an adoption strategy which would allow them to converge to the slower-growing world technology frontier. There are historical examples of countries successfully doing that, e.g. the TIGER countries of East Asia. With adoption as the cheaper option to innovation, convergence is possible. The DTF research focuses on the question of whether the basic assumptions hold true, through what mechanisms adoption works and under what conditions. Especially interesting is the role of human capital in the process. Nelson and Phelps (1966) argue that education helps countries adopt technologies already developed. Vandenbussche, Aghion and Meghir (2006) analyse how the composition of human capital determines the impact of the education level in relation the DTF. Researchers such as Acemoglu, Aghion, and Zilibotti (2006) and Acemoglu, Gancia and Zilibotti (2012) focus on possible mechanisms through which the distance to frontier mechanism could work other than the simple notion of "there is more technology to choose from".

[5] This dataset has been updated and revised multiple times. A recent version is available from Barro and Lee (2013).

Measures of distance to frontier

The distance to frontier is usually measured by the ratio or difference between a country's productivity measure (usually TFP) and that of the world technology leader, usually the US or a group of countries including the US. A smaller country (even if it is richer than the US like Norway or Switzerland) cannot credibly be the world technology leader due to its size. If nothing else is stated, this is the understanding of the DTF here. For models that assume that all countries have access to the same technology the measure is usually not TFP but rather income. The DTF term gets slightly complicated if we allow for capital-specific technologies as discussed by Basu and Weil (1998), but usually it's just a one-dimensional variable.

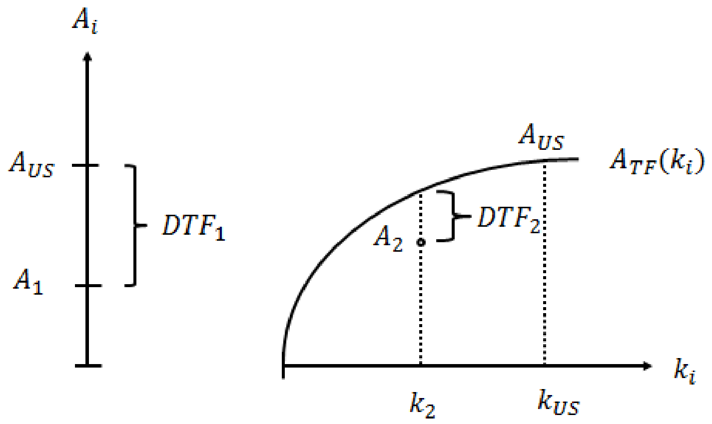

Figure 1: The distance to frontier for capital-neutral (left) and capital-biased (right) technological progress.

The DTF_1 displays the normal measurement of the DTF as used in this thesis. On the right the DTF_2 measures the distance to the frontier level of technology for the country 2's capital intensity. This is used in some appropriate technology models where technological progress is not uniform across capital intensities (see chapter 3.1.2). The world technology frontier curve A_{TF} consists of the highest achieved productivity by any country for each capital intensity k. Lagging countries have a lower capital intensity than frontier economies, but they can also fail to achieve the productivity precedent set by other economies when they had the same capital intensity. This is can be due to inefficiency, imperfect imitation or factor composition effects. But as stated, this view is very specific to these models and in general the DTF means just the total productivity lag or sometimes the income difference.

2.4 PUBLIC GOOD KNOWLEDGE

A public good is a good that fulfils two criteria: It is non-rivalrous in consumption and non-exclusive.[6] For a good that is non-rivalrous in consumption, an individual that has the good is

[6] See for instance Hirshleifer, Glazer and Hirshleifer (2005, p. 518).

not directly affected by another individual also consuming the same good. Non-excludability means that it is impossible or very difficult to exclude someone from consuming the good.

Non-rivalrousness: Ideas and knowledge do by their nature qualify as non-rivalrous. To illustrate this, Stiglitz (1999) quotes Thomas Jefferson: "He who receives an idea from me, receives instruction himself without lessening mine; as he who lights his taper at mine, receives light without darkening me." As Stiglitz explains, when people share an idea nothing is lost to the person that passes it on in that moment. The marginal cost of reproduction is effectively zero, which takes away the incentive to innovate anything at a cost greater than the free market price zero. What this does not mean is that the transfer of knowledge is necessarily free. Just like with other public goods such as a beautiful poem – or an equally beautiful mathematical theorem – there can be some costs associated with distributing (printing, reciting) it but the good itself is still non-rivalrous by nature and can remain free.

Non-Excludability: This property says that one cannot exclude someone else from the consumption of the good in question. Again following the argument made by Stiglitz, the fact that the consumption of a good is non-rivalrous is not to say that that the initial owner has nothing to lose. Just the opposite is the case: For an inventor this can mean that he loses the opportunity to make money off his innovation. If he anticipates this he has little financial motivation to invest time and money into his innovative activities. Patents ensure the exclusiveness of a technology in a legal and somewhat artificial way. As mentioned before this can be desirable since it allows producers or innovators to charge a price, make a profit and thus have an incentive to innovate at a cost. Also, when ideas are made public they enable others to be inspired by, imitate them, or work with and build upon them. Innovators know this and so some choose to go the other way: The alternative to exclude others from using your idea is to keep it secret. This is an option because ideas and knowledge are not all completely non-excludable.

For these reasons knowledge, ideas and hence technology cannot be considered a public good in general, but are often referred to as an *impure* public good.[7] In this thesis models that assume technology to be freely and instantly available to everyone are regarded as public good knowledge (PGK) models.

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[7] Examples of ideas, knowledge, or technology that are (almost) pure public goods, i.e. that are both non-rivalrous in consumption and non-excludable are found in art, design, software, simple manufacturing or chemical products, agriculture and most service-based industries that are very transparent. In all those cases it is almost impossible to bring the product to the market without making it very easy to copy.

2.5 TACIT KNOWLEDGE

At the opposite end of the spectrum lies *tacit knowledge*. It is imbedded in the heads of people and, as Spender (1996) defines it, “not yet explicated”. The polymath Polanyi (1966) even specified tacit knowledge to include semiconscious and unconscious knowledge, imbedded in the head, and/or the body of people. But in his understanding, all knowledge has tacit dimensions. There is a gradual scale for knowledge from tacit knowledge to the other extreme with knowledge that is explicit, or codified, structured, and accessible to other people. It is important to know that in Spender’s (1996) understanding tacit knowledge can be codified and thereby be made explicit, but it is not at the moment. Evenson and Westphal (1995, p. 2213) think that knowledge necessarily has a tacit component since it cannot be perfectly codified and state: “… though two producers in the same circumstances may use identical material inputs in conjunction with equal information, they may nonetheless employ what are really two distinct techniques owing to differences in understanding of the tacit elements.“ Leonard and Sensiper (1998) see tacit knowledge where someone cannot simply and completely articulate all that he knows. Tacit knowledge of this kind is gained through practice and experience. It manifests itself in the form of insight, intuition, and what is often referred to as gut feeling. In another form tacit knowledge exists on a group scale, in organizational forms and routines.

Transferring tacit knowledge is a difficult process. One can think of coaching and seminars as attempts to transfer tacit knowledge between people and organizations. To some extent such knowledge indeed seems to be explicable and transferable, to some extent it can be experienced, practiced and learned, and to some extent it is innate talent. The distinction between tacit knowledge and individual human capital becomes difficult here. On an individual level we could view tacit knowledge as a component of a person’s human capital, together with his physical capabilities, and his acquired transferable knowledge, among other characteristics. However, this is not how it is treated in empirical research or the following models.

When abstracting from the idea of tacit knowledge on an individual scale to thinking of ideas as being tacit knowledge we get closer to the point of this thesis. When an idea or a technology is indeed tacit knowledge there is little reason to assume that its invention in one place benefits its adoption elsewhere without a significant cost or time lag. Thus models that include such costs or lags are treated as tacit knowledge models.

3 Technology Diffusion – Theoretical Review

The central question is how does technology diffusion work: What is necessary for technology to transfer? Does it take time, resources, or interaction? Or is technology freely available but it takes some human capital level to gain access? The analysis will be divided into these two parts: Models that assume technology diffusion to be free and instantaneous as it is a public good (yet not unconditionally useful) and models that assume that there is a cost (money or time) associated with the transfer due to its tacit components. The focus will lie on models that relate technology diffusion to human capital and the distance to frontier.

The whole topic of technology diffusion is closely related to the question of what drives growth: Factor accumulation or technological progress? If technological progress happens because of individual people's human capital accumulation, others can be excluded. Knowledge thus has a strong tacit dimension. This is what neoclassical growth models such as the one by Lucas (1988) base their level of productivity on. The new growth theories built on the model by Romer (1990) on the other hand treats human capital as an input in the R&D process that leads to technological progress. Romer focuses his model more on the innovation process; it is primarily a model for a frontier economy. Lucas' model was developed with the international productivity disparities in mind. While in the Lucas approach frontier technology is theoretically available to everyone (if their level of human capital permits) other researchers following the idea of Nelson and Phelps (1966) have emphasized a second role of human capital: As a catalyst in the process of technology adoption from more advanced countries.

3.1 Knowledge as a Public Good and Free Technology Diffusion

In the most extreme case an innovation is instantly and freely available to everyone. In the simplest neoclassical growth models this is actually what is assumed: Countries have the same production function (with exogenous technological progress), no increasing returns to scale, and produce the same goods. Differences in productivity per worker must come from different levels of human or physical capital employed in production.[8] When diminishing returns to capital are assumed, this means that capital would be more productive if employed in the currently less productive country and free capital or labour markets would lead to convergence in productivity until all marginal productivities are equalized. Lucas (1990) explains as much and shows that the capital flows observed are not as large as predicted.

[8] Models in the spirit of Solow (1956) focus on the savings rate as a driver of capital accumulation and its role in cross-country growth and income differences.

Mankiw, Romer and Weil (1992) enhance the Solow (1956) model with human capital that depreciates just like physical capital.[9] They, along with Galor (1996), postulate *conditional convergence*: Countries with the same characteristics converge to the same growth path. Prescott (1998) identifies total factor productivity differences as the major source of differences in output per worker on a global scale, which strongly collides with the idea of identical technology in all countries. Prescott and Lucas make it evident that the idea of public good knowledge cannot work without additional factors besides physical and human capital employed taken into consideration. The question is: What prevents capital from flowing to these places where it should in theory be more productive? Is it barriers to technology diffusion like Prescott suggests? Or is it barriers to capital flow? Some sort of bias? Are there other factors affecting the capital returns that are not taken into consideration in these simple models?

Lucas (1990) proposes external benefits to human capital as a potential solution to this problem. Other human capital accumulation based models are also discussed, especially learning-by-doing models.

Basu and Weil (1998) argue that technological progress in advanced countries is not appropriate for the lagging economies. Since innovation is almost exclusively done in a few advanced economies these innovations are also tailored to the needs of these capital-rich and labour-scarce economies. Parente and Prescott (1994) come to the conclusion that technology adoption is hindered by barriers to technology diffusion. Factors other than capital endowments and technology, but of social or political nature distort the incentives of people that could potentially adopt or invent a new technology and raise productivity. This last approach is discussed only shortly since it does not directly relate to human capital or distance to frontier.[10] It is also interesting to analyse the case where technology is a(n) (almost) perfect public good and freely available to all. While not being realistic to an economy as a whole it is an interesting benchmark case to consider and might not be that far from the truth in some special cases. Some innovations are impossible to be kept a secret but also not possible to patent. Boldrine and Levine (2008) study the incentive to innovate in such an environment.

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[9] The model implies slower convergence than the Solow model into country-specific steady states defined by the capital accumulation and population growth parameters. The model implies convergence only if these are equal – thus it implies *conditional convergence*.

[10] This is not to say that there are no indirect links between human capital and technological development and the technology-friendliness and political stability of a country, for example.

3.1.1 Brains and Gains – Human Capital Driving Growth

In the first section the role of human capital in the process of innovation by human capital accumulation is discussed. This corresponds to the diffusion of knowledge towards a country from a common technology frontier or "idea space".[11]

3.1.1.1 Human capital accumulation and external benefits of human capital

The classical accumulation based models go back to Solow (1956). As explained in Mankiw et al. (1992) Solow's model assumes diminishing returns to factor accumulation and therefore convergence to a steady state with constant growth. These steady states depend on savings rates and population growth. They find that the model needs more variables to credibly explain the data and include human capital accumulation like a regular production factor. Lucas (1988, 1990) takes a similar path when he makes a couple of rough estimates to try and explain the observed remaining productivity differences without directly adding country-specific production technology levels. He argues that when each country has a different technology level this has little intuitive value. His solution is to add more country-specific variables into the production equation, but requires them to have intuitive value. A large portion of the cross-country differences can be explained by just adding a rough human capital estimate. In this important model outlined in his paper (1988) human capital accumulation drives sustainable growth as its accumulation is linear in the effort put in and unbounded. Human capital accumulation is determined by the efficiency of the accumulation process and the time preference of individuals in the economy. If those are equal across countries, they converge to the same growth rates but richer countries permanently stay richer.

Motivated by his empirical work and the existence of innovation centres (cities) Lucas includes *external benefits of human capital* to the production function. This is essentially a country-specific technology level but based on the average level of human capital h in the country:

$$y = Ak^{\beta}h^{\gamma}$$

The new term h^{γ} is the new additional beneficial external effect of human capital.[12] The factor γ measures by what factor an increase in the human capital of one's co-workers increases his own productivity. With the addition of this factor and some plausible estimates

[11] This idea space can either be seen as the world technology frontier, a public good that can be accessed given a sufficient level of human capital, or something outside of this world and the average level of human capital in the economy itself actually constituting the technology level and being completely tacit. Since Lucas' growth models fit international data reasonably well (as will be showed in chapter 4) it is reasonable to look at it as a public good technology level where other countries define the world technology frontier.

[12] γ: income per effective worker, k: capital per effective worker (x in the paper), h: human capital per worker

for the parameters of his model Lucas (1990) is able to explain cross-country productivity differences surprisingly well. However this assumes that this external effect is entirely constrained to the country itself with zero spillovers to other countries. In this model human capital accumulation is the sole driver of economic growth. The initial conditions then persist since only the long-term growth rates equalize across countries. The external benefits to human capital would lead to significant migration pressure, since there is an incentive to move to a country where the average level of human capital is higher, which increases wages for all skill levels.

Many other researchers have reworked the neoclassical growth models and its measures of human capital. Without international spillovers however its implications for technology diffusion and how human capital and the distance to frontier impact it are very simple: Human capital determines growth and technology diffusion towards a country. Economic growth is the result of factor accumulation.

Howitt and Aghion (1998) argue that the common view, which says that human capital or technological progress are determining long-run growth, while physical capital has only a passive effect, is wrong. They see both physical and human capital as two state variables that determine the output of an economy at any time and which, when influenced, will affect the state and growth of an economy. Aghion and Howitt (1992) introduce the idea that innovators might anticipate the creative destruction that follows their innovation and that affects the expected payoffs from their innovation, since they will be driven out of the market by better quality products. They combine this idea with a neoclassical Solow model resulting in "Schumpeterian" growth models. They find that the stock of capital can affect innovation because it induces a "scale effect" by raising the overall output and thus the potential profits from R&D. Secondly the increase in capital will lower the cost of capital, and thus lower the capital cost of R&D. The first important takeaway from their model is that human capital's role in technological growth might be a bit overestimated. Even more importantly, it might be more effective to subsidize capital accumulation, since R&D subsidies can exhibit hard-to-control agency problems.

3.1.1.2 Threshold Externalities and the Underdevelopment Trap

Azariadis and Drazen (1990) study the functional form of the human capital to growth relation. They, too, looked at the puzzle that some countries were able to rapidly catch up to the technology frontier while other countries were not able to. Like Lucas (1988) they want to provide an alternative explanation than the one about these differences being due to structural differences in social institutions. Instead they assume identical structures. The non-convergence is then attributed to different growth paths, which follow from the threshold property of technological externalities in their model. If such a threshold is reached it allows returns to scale to grow rapidly. This corresponds to a “take-off” of growth. Countries that fall below this threshold are in a so called “underdevelopment trap”. Azariadis and Drazen mention possible explanations for a situation with two steady states (one with no education and one with high education). In the first the return to education depends on the aggregate level of human capital.[13] In that case the private return to education is much lower than the social one, and a country can get trapped in a situation where nobody is willing to invest in education if the initial level of human capital is too low. Other researchers have looked for other explanations for two steady states, another paper focusing on the human capital channel was written by Galor and Zeira (1993) who find that wealth inequality paired with credit market imperfections and indivisibilities in human capital investments can lead to poor people being trapped in a low-education steady state. The other possibility Azariadis and Drazen mention is a critical level of human capital. If this level is surpassed, productivity could increase sharply (a “take-off” effect). This could be the case because adoption of frontier technology requires some basic level of human capital (reading or computer skills come to mind), which in turn makes a large set of technologies available. Another possibility is that it would facilitate the diffusion of frontier technology to the country significantly (for instance basic engineering skills) as discussed in later chapters.

3.1.1.3 Learning-by-doing human capital accumulation

As mentioned before it is not simple to separate human capital and tacit knowledge. In the neoclassical growth models with human capital accumulation as the driving factor of growth the stock of human capital determines the level of development of a country. Now there are two ways to interpret this with regard to public good or tacit knowledge: Either technology “is just there” and human capital is needed to access it – that’s the public good view – or technology is itself not something that is available to everyone and is imbedded in the heads of people – that’s the tacit knowledge view. In the models here the human capital accumulated within people’s heads takes an even more prominent role as the human capital necessary to profit from these innovations is gained through learning-by-using. Since these models still assume the exogenous and instant arrival of new technologies they are discussed in this section.

[13] As with externalities to human capital like in Lucas (1988).

Lucas (1988) also creates a model of his human capital accumulation based growth model where human capital is accumulated “on the job”. In a stable two-good environment where the goods are substitutes the implication of his theory of capital accumulation is that of specialization. Countries with high initial human capital specialize in the production of the skill-intensive good and countries with low in the low-skilled good. This implies that the growth rates are stable for each country but different between countries, divergence is a very real option. The structure of demand can offset some of this effect as demand shifts with rising income (e.g. away from food production). This model can also be used as an argument for inhibiting imports of goods, so your own country can improve its skills in the sector with higher growth potential and only open it up to the world market once it is competitive.

Vintage human capital with exogenous innovations

Chari and Hopenhayn (1991) develop a model where human capital is not an index but is split into vintages. Each vintage relates to a specific year’s new technology. New and old human capital are complementary inputs in production, and new technologies arrive exogenously and continually. Human capital is acquired through learning-by-doing only. Their model is an overlapping generations model with agents living for two periods. They can work in a specific technology vintage for one period as an unskilled worker and will then be a skilled worker for that vintage in the second period. They can also choose to work as unskilled workers in the second period as well. Unskilled and skilled workers are complementary inputs in the production function. The production function has constant returns to scale for unskilled labour, and diminishing returns to scale for skilled labour. Because of these features there is continued investment in old technologies, even if they are already outdated because the skilled workers in these vintages complement the unskilled labour of the young workers. This increasing investment after the arrival corresponds to the diffusion of the technology in their terminology.

The authors then analyse the properties of the stationary equilibrium of their model. In the stationary equilibrium there are only a finite number of technologies in use, meaning that for each new technology arriving an old one is discarded. The distribution among the technologies in use does not change if there are no exogenous changes, meaning that the technology that is one year old always employs the same amount of workers, even if each year a new technology is one year old. The distribution of workers is single-peaked and log-concave. The rate of diffusion depends on the current distribution of vintage human capital, the relative superiority of the new technology and the expected quality of future innovations. If the new technologies start to arrive in shorter intervals, the diffusion also increases. This resolves the question that Rosenberg (1976) posed when he pointed out that an increase in the expected quality of future innovations has two effects: A higher incentive to adopt them, but also a higher incentive to wait for the even better innovations arriving thereafter. According to Chari and Hopenhayn the first effect is dominant and diffusion is accelerated.

For the analysis of technology diffusion an interesting takeaway is that technology diffusion is a slow process, if technology-specific human capital is important. The exogenous arrival of new technologies can be viewed as innovation done in an advanced country from which the lagging country cannot be excluded. The model then implies a technology lag stemming from the learning time required. There is a steady state distance to frontier when the human capital distributions are locally stable.[14] Thus the model implies convergence only to this degree. Technology is assumed to spread faster if growth is high. The role of human capital in this model is very specific, one could extend it so that a general education would lower the learning costs needed for new technologies and thereby make new technologies more interesting, and reduce the technology gap.

In the above model agents live only for two periods and there are always enough workers interested in switching to the new technologies available. Parente (1994) builds a similar model where firms, not workers, gain experience from using a certain technology. In contrast to workers, these firms live forever. It is the firms deciding which technologies to adopt and which not to. They continuously have the choice between different technology vintages. The learning by doing effect for each vintage shows diminishing returns to scale. To have perpetual productivity growth the firm thus needs to switch technologies from time to time. The expertise gained is not specific to one technology, but its value diminishes with an increasing "distance" between the old technology used and the newly adopted one. The optimal path for each firm is to regularly switch between technologies. This means that the productivity path at the individual level is not smooth, but because of the large amount of firms, it is in the aggregate.

Uncertainty and the specific human capital underdevelopment trap

Jovanovic and Nyarko (1996) expand the model of Chari and Hopenhayn (1991) based on the ideas introduced by Parente (1994). Workers also have access to all technologies, and technologies come in vintages. However workers live forever in this setting, i.e. they can be looked at as small firm. When a worker uses a technology he gains experience (human capital) through learning by doing. This experience increases his productivity for the given

[14] Chari and Hopenhayn found that for the parametrizations discussed in their paper these distributions are indeed locally stable.

technology. Each technology has a productivity limit, thus this effect will stop at some point. At all times the worker faces the choice of continuing to use the old technology where he benefits from his experience, or switch to a newer, better technology with a higher productivity limit. Since the model assumes knowledge to be a public good, there is no direct cost for switching to a new technology. The worker however does not know his exact productivity with the new technology. This uncertainty can cause some workers to refuse to switch to new technologies. Others can in that case overtake them if they had less incentive to stick to the old technology in the early periods. Depending on the parameters, however, it is also possible that all workers switch technologies from time to time. The first case is more likely if human capital is highly technology-specific (thus more like tacit knowledge of the technology), while the second case is more likely if human capital is more general (the educational understanding of human capital). This model thus shows that there can be a development trap not stemming from a lack of human capital as discussed in chapter 3.1.1.2.

Heterogeneously skilled workers

In further research on the topic Jovanovic (1998, 2009) and Jovanovic and Yatsenko (2012) analyse vintage human capital models with heterogeneous workers. The workers are not heterogeneous in their productivity ex ante but they use different technologies and this accumulation of specific human capital leads to inequality. The workers do not take multiple periods to switch between technologies like the firms did in Parente (1994). Instead the best learning workers continuously adopt the latest technology, the second best the second vintage, and so on. In Jovanovic (1998) it is a capacity constraint in the physical capital market, in Jovanovic (2009) it is the competitive pricing of innovations, and in Jovanovic and Yatsenko (2012) it is the intra-firm diffusion lag, which cause the fastest learning to adopt first.

All these models explain how technology lags can occur even if the knowledge of the technology spreads instantaneously. The positive sorting effects of the most skilled workers on the most productive technologies also have international effects. If the skills are unevenly distributed internationally then the newest (intermediate) goods are produced in the most advanced country, and the older goods in the lagging countries. The low-skilled agents' skills do not justify the use of frontier technology.[15]

3.1.2 Appropriate Technology

The idea of a single technology measure that can be used anywhere worldwide is very abstract and not intuitive when we look at the realities in the world. A public good knowledge based

[15] Jovanovic (2009) estimates fairly long technology cycles of 68 to 124 years.

model must provide an explanation for the observation that around the world many different technologies are used to produce the same goods. The human capital models where human capital was necessary to use the technologies available offer such an explanation. Another approach is called *appropriate technology*, as discussed for instance in the works of Basu and Weil (1998) or Acemoglu and Zilibotti (2001). A technology can be inappropriate for an economy's endowments for many reasons. If we think of very specific technological advancements, this becomes evident quickly: A new ski lift design might be an opportunity in countries like Switzerland, but a country in a subtropical climate in all likelihood will not benefit from this innovation. Basu and Weil (1998) point out the differences using the starkly contrasting image of an American farmer harvesting a field in his air-conditioned combine and a group of sweating Indian farmers doing the same work using scythes on the other side of the planet. Now the question is why does the technological advancement not have an impact in far-away India? The answer they are shooting for is that while the Indian farmers have access to the same technology, that technology is not appropriate to India's (human and physical) capital intensity.[16] The capital intensity is their "convenient shortcut" to model the notion of *appropriateness*. Acemoglu and Zilibotti (2001) suggest that technologies might not be appropriate for poor countries reasons such as institutions, taste, culture, and climate (think of the ski lift). However the better studied inappropriateness of technology comes from the differences in factor prices in poorer countries, where we normally observe cheap unskilled labour in abundance, and scarcity in the skilled labour and capital markets.

3.1.2.1 Capital Intensity and Appropriate Technology

Basu and Weil (1998) build a model that works with innovation that is inappropriate for some countries. Technology usage diffuses slowly throughout all countries, whereas knowledge of said technologies spreads instantaneously and without cost associated. In their model an innovation is also localized to a certain capital intensity. This corresponds to the notion of localised technical progress as described by Atkinson and Stiglitz (1969). They pointed out that the neoclassical growth models seemed to have abstracted to far from the actual characteristic of an innovative blue print that improves one production technique. Such an innovation shifts the production function only for one specific capital intensity (on the right) and not generally upwards as implied by many neoclassical production functions (on the left).

[16] They deem it implausible that technology does not flow across national borders, which is what country-specific technology indexes assume.

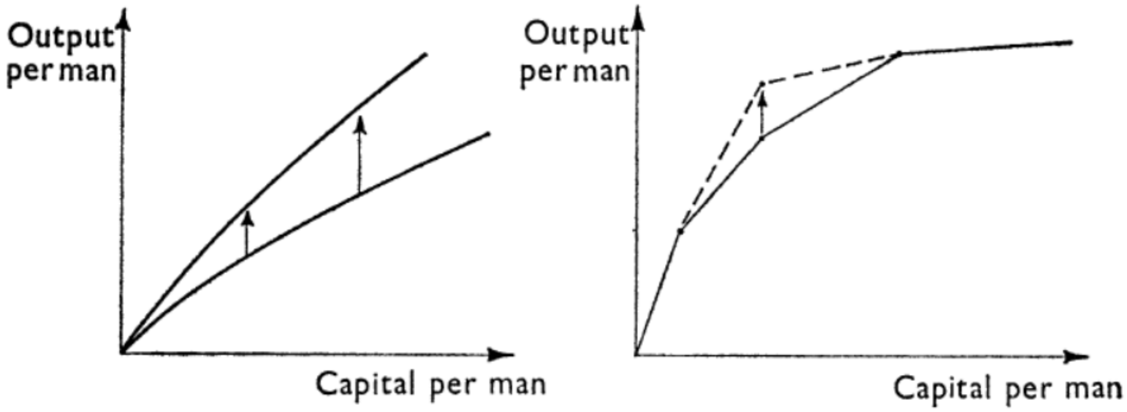

Figure 2: Localised technical progress by Atkinson and Stiglitz (1969, p. 573): On the left the neoclassical approach, on the right the localised technical progress.

Basu and Weil's model is a less extreme version of Aktinson and Stiglitz' model. Since it is very likely that the technological progress is not completely localised but instead affects similar capital intensities as well to some extent, they assume technological progress to be imperfectly localised. Their model uses a combined capital measure including both human and physical capital. For each capital-labour ratio there is one appropriate technology (or multiple technologies with the same productivity). According to the authors this understanding of technology is reasonable if one thinks of innovations as a consequence of learning by doing and can also work for the R&D investment approach when thinking of a new machine blueprint as mentioned before. Their model combines elements from both endogenous and neoclassical growth models. As the only exogenous variable in their model they take the savings rate that determines the long-term growth rate (as in endogenous growth models). A growth rate is not uniquely linked to a savings rate. Since lagging countries can still benefit from the spillovers of technology leaders, multiple countries can have the same growth rate in their steady state despite differing in their savings rate and having different outputs (as in neoclassical models). Due to the localised technological change however, a lagging country can benefit from the technology leader only if it is sufficiently close. This distance to frontier effect means that the relationship between growth and the savings rate can be highly nonlinear.

They specify their model with one country, two countries with free technology transfer, more than two countries, and finally two countries with imperfect or perfect capital mobility. Their models generally find *conditional convergence*. They find that there can indeed be convergence and in the multi-country model there can be "convergence clubs" of some countries growing at the same rate in steady state. The model generally has more realistic predictions for convergence than standard growth models or simple endogenous growth models. In a Solow (1956) model a country's catching up or even passing of a more developed nation has no effect on the country's own growth rate which moves unaffectedly towards its steady state. In their model however the former technology leader benefits from the following country's passing and subsequent knowledge spillovers.[17] Poor countries can become an economic miracle if they successfully increase the savings rate and thus their capital intensity. Through this process they can access the many technologies already available and quickly catch up.[18]

3.1.2.2 Skill-appropriateness of technologies

Acemoglu and Zilibotti (2001) assume public good knowledge for new technologies. In their model all countries have access to the same technologies. They adhere to the very primal concept that ideas are the most important ingredient of technologies and are easily transferable. They calculate that over 90% of the world's R&D expenditure takes place in the OECD countries. This research is assumingly targeted at the industries in these advanced economies and then imported by less developed economies. A lack of intellectual property rights in lagging countries and unspecified other barriers to technology transfer make it unattractive for these R&D firms to target innovations at the conditions present in less developed countries. Instead they focus on the situation in advanced economies. The core of their argument is that the differences in economic conditions and factor prices mean that the new technologies are *not appropriate* for the less developed economies, as a consequence of a conscious decision by R&D firms. Their main focus lies on the differences in *skill scarcity*, thus the relative supply of skilled versus unskilled labour. As skilled labour is relatively more abundant in more advanced countries, innovation is targeted at substituting unskilled labour with skilled labour (and capital). This is referred to as *skill-biased technological change*. When using technologies developed in other countries, lagging economies must employ unskilled workers in positions that would require a skilled employee due to their scarcity in the labour market. Thus the new technologies are not used to their full productivity potential. Even in their most extreme model with no barriers to technological transfer Acemoglu and Zilibotti can replicate vast differences in productivity levels with this mechanism.

Acemoglu and Zilibotti's model implies sectoral productivity differences within the poor countries. In advanced and lagging countries there are sectors which use the unskilled

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[17] An observation also made by Barro and Sala-i-Martin (1997) in their model.

[18] Los and Timmer (2005) build on their model and dissect technological advance into three distinct processes for their empirical analysis as discussed later: Assimilation (getting more productive at a given capital intensity), creating potential (increasing the capital intensity), and localized innovation (increasing productivity at a given capital intensity). Jerzmanowski (2007) drops the Cobb-Douglas production function assumption for the appropriate technology model and makes technology depend on the capital intensity, i.e. $A=A(k,h)$.

technology, but there will be more such sectors in the poorer country. This goes along with higher relative prices for skill-intensive goods (possible due to a lack of trade) and a higher wage-premium, both due to skill scarcity. With a lack of international trade and a lack of intellectual property rights protection across boarders the small markets in poorer countries give no incentive for local firms to invest in their own R&D which would be directed at the unskilled technology, instead they import the skill-intensive technology from the more advanced economies. This is reinforced by the scarcity of skilled workers which would assumingly be needed for R&D in the poorer countries. When copying a technology the local company incurs a small fixed cost. This assumption makes sure that each technology, figuratively a *machine* in this model, is supplied to producers by a local monopolist since the alternative would be Bertrand competition with negative profits. At a global level there is a unique and stable *Balanced Growth Path* with a growth level g for GDP, consumption, N_L (supply of unskilled-labour-compatible machines) and N_H (supply of skilled-labour-compatible machines). An increase in skilled labour leads to skill-biased technological change. Net output and consumption are maximized for the advanced economy (since the R&D choice is made with its endowments in mind) and not at the global level. The situation is not optimal for the poorer countries with the possibility to import technology from the advanced economies and no own R&D. The model implies divergence as long as technological progress favours the skill-rich North. The natural remedy would thus be to enhance the skill base in poor countries.

This model does abstract from international trade in goods or machines. Acemoglu and Zilibotti themselves show that if trade were included, we would see *convergence in productivity* but *divergence in output per worker*. Since the balanced growth equilibrium condition remains unchanged and with unenforced patent protection the R&D firms would continue to only consider the North's endowment for their R&D decisions. Due to the law of one price countries will now adopt the same technology in all sectors. The "machines" will be supplied globally. Since prices for products in the skill-intensive sector rise in the North, skill-heavy innovations get more profitable (the market stays the North), and trade induces an even stronger skill-complimentary technological change. This leads to lower productivity in the unskilled sector, and since this sector makes for a larger share of the South's economy, the South's relative income deteriorates even further than in the model without trade. TFP differences however disappear since unskilled and skilled workers in the North and South now perform the same tasks.

Acemoglu and Zilibotti's model also assumes that there is no intellectual property protection in poor countries, which is certainly not realistic. With some sort of protection, R&D firms are more likely to develop technologies suited to the South's labour endowment. The market size would then dictate where the R&D efforts would be directed. Here the poorer countries are in an advantage due to their population size but still put at a disadvantage by distortionary factors such as relative capital prices, new goods markets, credit market problems, or general technology adaption delay problems. Whether better suited innovation through appropriate R&D would benefit the South is not clear, since prices would also rise accordingly. Additionally they mention the prisoner's dilemma that occurs because all poor countries would benefit from the technological change directed at them, but they would benefit even more if that were due to other poor countries enforcing intellectual property rights and themselves free-riding.[19] Gancia and Zilibotti (2009) build a model that combines this model of inappropriate technologies with barriers to technology adoption that are discussed in the next chapter in an attempt to build a workhorse model. Gancia, Müller, and Zilibotti (2011) combined this together with the missing capital accumulation. Both however do not rely on public good technology and instead use an innovation-and-adoption mechanism as discussed in chapter 3.2.2.

Caselli and Coleman (2006) expand on the idea of imperfect skill substitutability in a model closely related to Acemoglu and Zilibotti. However, they also assume that advanced and lagging countries have a relative advantage in skilled and unskilled labour productivity respectively.[20] They build on the idea of skill-biased and de-skilling technological change as in Caselli (1999), explained later. They emphasize that when developing poor countries, the goal should not be to copy potentially inappropriate technologies from advanced countries, but instead to make more technologies available to them so that they can choose appropriate technologies.

3.1.3 Barriers To Technology Adoption

According to Parente and Prescott (1994) the problem with technology diffusion does not lie within the characteristics of technology itself or government policies such as taxation and intellectual property rights protection. They think that technology would indeed spread

[19] Acemoglu and Zilibotti also don't allow for the use of non-frontier-technology by poorer countries. When assuming that these technologies improve slower than the frontier technology however, these will all be phased out eventually and all countries switch to the frontier technologies at some point. However convergence would be higher until that point since the technologies used would be more appropriate to the available skill endowment.

[20] The advantage of lagging countries in unskilled labour productivity is a possibility in the model; the advantage of skilled labour in advanced economies a key component.

relatively quickly, but is inhibited from doing so by barriers to technology adoption. These barriers impose high costs on firms that are looking to transfer technology. These barriers have the form of regulatory and legal constraints, corruption and bribes, political instability and violence, insecure property rights, threats and sabotages, or strikes. These factors can be seen as increasing the cost of technology adoption far above levels that would result from the difficulties of transferring knowledge and technology.[21] The model is thus not actually a model based on the assumption of public good knowledge, since it assumes that the transfer of technology is costly and affected by the DTF. It is shortly summarized in chapter 3.2.1.2.

Many economists have followed the same line of logic. It is not technology diffusion that doesn't happen. The problem merely lies in the incentives of individuals within a political, social, or cultural system that doesn't encourage or allow them to exploit their full potential and all available technologies and innovation opportunities. Acemoglu and Robinson (2000), and Krusell and Ríos-Rull (2006) for instance argue that technological shifts cause shifts in political power, which are opposed by people who currently hold the power. Parente and Prescott (1999) find that the monopolistic structure in many sectors in lagging economies could prevent the entry of adopters of superior technology firms contrasting the view that monopolies are needed for innovation. Acemoglu (2012) famously followed the same logic in his book on "why nations fail". He argues that a society needs to be inclusive and give a broad group of people incentives and assured property rights. This is the key to long-term growth and prosperity since it lowers barriers to innovation and technology adoption.

3.1.4 Perfectly Competitive Innovation

Boldrine and Levine (2008) argue that even with no intellectual property protection, innovation could still be worthwhile for entrepreneurs. This is already happening for some products. They name the example of the Travelpro, the modern wheeled suitcase with the retractable handle, as an example for this. It is simply too easy to imitate the idea once you see one in action. Another example for a public good innovation are products that work as a "seed" for future copies on their own, for instance in agriculture with crops or animals. This is not desirable from an innovator's point of view since he loses the option of protecting his innovation by maintaining it a trade secret and has to rely on a patent and intellectual property right enforcement, which is a sensitive issue on a global scale. In the extreme case with no additional cost required, no benefits from production experience and no intellectual property

[21] The costs of transferring knowledge are in themselves non-negligible as for instance Teece (1977) has shown when he estimated that the cost of within-firm transfers of know-how lie between 20 and 40 percent for many investment projects.

protection possibilities, the innovator faces a very difficult situation. He has incurred a cost C during the innovation period and this has left him with one initial prototype – the seed. After this he faces the threat of competition without profits as with every sale he creates a potential competitor since any buyer can use the exact same technology to make the products as the innovator himself. This potentially destroys the financial incentive to innovate since profits are necessary to fund any incurred costs of innovation, as the classical argument for patents goes.

To still make a profit in production the innovator can make use of the capacity constraints which occur during the early stages of production when the production capacity is lower than the saturation demand (where the price is equal to the marginal cost of production). Boldrin and Levine explore this possibility. They refer to this case as the trees and fruits case. They try to estimate a lower bound for the competitive rents to be expected by innovators. In the first case there is no marginal cost to production and even with very unfavourable assumptions[22] they show that there is a competitive rent to be earned by the innovator unless the fruits produced by the initial prototype tree saturate the markets already. They enhance the model with more conventional specifications such as productive inputs (physical and human capital) and a trade-off between consumption and the use as a seed. The result however does not differ substantially from the reduced case explained before. The innovator can attract a positive rent whenever there is a demand larger than the productive capacity in the launch period. They modify the model in multiple ways: A case with imitation without a seed (think of Travelpro), one with costly reverse-engineering (pharmaceutical products), one with a trade-off between consumption and further production. The main result holds for all these cases.

The result that innovative rents can exist even without any form of intellectual property protection and complete knowledge spillovers comes as somewhat a surprise. The key finding is that with some (not even perpetual) capacity limit competitive rents can exist and make some innovations viable. The rent is lower than the potential rent with full intellectual property protection, which might affect the rate of innovation as some innovations are no longer profitable.

[22] Firstly, they assume that each seed sold reprocesses itself whether it is consumed or not. This is clearly unfavourable to the producers since there is no trade-off between consumption and production for the buyers, and thus a generally faster growing capacity. They refer to this as the 24/7 case, since all seeds produce new seeds regardless of the use their fruits are put to. Secondly, they assume that the externality of a consumer being able to start selling fruits after the purchase of one is not priced in.

3.2 Technology Transfer with Tacit Knowledge

The cases discussed so far have assumed that knowledge is freely and instantly available to all upon discovery at no cost – albeit with some conditions. In this chapter an innovation is not easily passed on with a blueprint, a manual or a piece of software, but is instead (to a good part) imbedded in people's heads.

The transfer of tacit knowledge is slow and costly, even if all parties involved have an interest in the free transfer, for instance within a multinational corporation. Teece (1977) estimated that the costs of within-firm transfers of know-how from parent to subsidiary were responsible for as much as 36 percent for machinery equipment and on average 20 percent of total project costs. Evenson and Westphal (1995) state that investments in learning, paired with practical experience, are necessary to achieve *mastery* of a tacit technique. This touches upon the interesting question of how tacit knowledge can be passed on. This is a key to the analysis of how technology diffusion works with tacit knowledge, and what role human capital (obviously a key) and the DTF play. Polanyi (1958) argues that tacit knowledge be passed only by example from master to apprentice. And as anyone who has taught or trained in a position in his life knows, even then it is a hard and time-consuming process and there's no guarantee of success. Koskinen and Vanharanta (2002) discuss the multiple ways through which tacit knowledge can be acquired and transferred. The first way is action learning. This is learning by doing combined with seeking help from instruction manuals and critical questioning and reflection. In practice this also includes seeking help from capable colleagues. This all takes time and is costly, especially if workers are not in the same place.

This chapter will point out three groups of interesting models that do not assume free and instantaneous technology diffusion. In chapter 3.2.1 models that assume that there are different types of costs associated with the transfer of technology are discussed, chapter 3.2.2 is about models that relate the cost or speed of technology diffusion to human capital and the DTF, and chapter 3.2.3 is about selected issues associated with tacit knowledge diffusion.

3.2.1 Technology Diffusion with Transfer Costs

Because of the problems associated with uncodified and uncodifiable tacit knowledge it is plausible that technology diffusion is not instantaneous and free of cost. In this chapter different cost types are discussed. The simplest cost imaginable is a fixed set-up or adoption cost which enables you to use an innovation developed elsewhere. This could either reflect a payment to the innovators (for a blue-print), a replication effort cost or the acquisition cost of required know-how relating to the tacit components of the technology knowledge. The set-up cost can be looked at from the perspective of how Romer (1990) modelled (national) technology diffusion when he introduced the new growth theory. In these models human capital was explicitly modelled as affecting technological change, and education became an important determinant of growth. Technological progress is modelled by expanding the variety of intermediate goods that can be used in the production of the final consumption good. Using human capital as an input blueprints for intermediate goods are developed, which entitle a firm to patent an innovation and monopolize it. Technology in the form of intermediate goods is thus non-rival – all intermediate goods are available to everyone – but exclusive – intermediate goods have to be bought at a price. This allows innovators to recoup their incurred costs and encourages innovation and technological progress.

3.2.1.1 Constant and fixed costs of innovation

Barro and Sala-i-Martin (1997) build a model that combines elements from said endogenous growth models with the convergence aspect of neoclassical growth models. The long-term growth rate is determined by an endogenous growth process in a few leading countries as described by Romer (1990). Lagging countries can benefit from the technology developed by these technology leaders. Imitation takes place in the intermediate goods sector (the other sector being the final goods production). The copying and adaption coincides with a fixed cost for the firm in the following country. Barro and Sala-i-Martin (2004) analyse multiple variations of this model. One specification assumes that the imitation costs are constant and low compared to the cost of innovation. The cost of imitation v_2 is lower than the fixed cost of innovation η_2.[23]

Under this assumption the model implies convergence, since the lagging country can copy innovations cheaper than the advanced country can develop new ones. The advanced country is in its steady state and grows at a constant rate. For the lagging country the growth rate depends linearly on the rate of return, which in turn depends on the cost of imitation and the constant flow of profits in the economy. This higher growth rate is sustainable until the lagging country has caught up in technology. At this point it will copy all the new technology developed in the leading country, but the infusion of technology cannot exceed the amount of new technology. In the steady state there is an excess demand for goods to imitate. They solve this problem by assuming that the monopoly rights to an imitated good are allocated randomly, but in proportion to the resources spent on acquiring the monopoly rights from successful imitation. This mechanism drives down the rate of return in the (formerly) lagging

[23] The lagging country is country 2, thus the subscript 2.

country and convergence is achieved with both countries growing at the rate of innovation of the (formerly) leading country. Technology diffuses instantly.[24] Thus this model implies full convergence in the market for intermediate goods ("technology"), rates of return, and growth rates.

The effects are basically identical if there is a global capital market. With a globalized capital market investors will jump at the opportunity to adapt a technology for the use in the lagging country, as long as the cost is low enough to make it more profitable than innovation.

They also analyse the same model with the assumption of perfect international intellectual property right protection. In this setting the innovating firms have a perpetual monopoly on the intermediate good they developed for both countries. The diffusion of technology still works through the availability of these goods. The cost of adapting is still assumed to be a onetime fixed cost and lower than the cost of innovation itself. They assume that there are no entrepreneurs innovating in the lagging country. They also assume that both countries have a specific technology parameter A_i which represents political and institutional differences between the countries. The cost of adapting or transferring it to the lagging country is then carried by the innovating firm, which in turn also gets the profits. In the beginning firms from the advanced country would focus on bringing their existing technology to the lagging country. The innovator then takes the profits from both countries into consideration, and compares them to the total cost of innovation plus adaption. If the cost of adaptation is low enough, it will be done immediately. The technology level will then be equalized and the overall growth rate is higher, since innovation has become more lucrative (due to the profitable adaption to the second market).

In all three cases convergence in growth rates is achieved, because the growth rate is higher for countries further away from the technology frontier. This convergence occurs despite the countries having different R&D costs, productivity levels, and saving propensities. The highest steady state growth rates for both countries are achieved if intellectual property rights are ensured internationally. The countries converge in level terms until the steady state distance is reached.

3.2.1.2 Cheaper by the minute – sinking adoption costs

The cost of imitation could sink when the technology is more and more common and well documented. This can depend on a technology's age or its general prevalence in the world

[24] If a time lag for the imitation process is incorporated into the model, a steady state gap between the two countries would persist. They quote Caballero and Jaffe (1993) and Mansfield (1985) who estimate these time lags to be around one or two years for the majority of innovations.

economy. If you encounter a problem in your specialized mathematical analysis software it might be rather hard to find solutions to your problem on the internet, as there are relatively few users and little active problem solvers. However if you encounter a problem in a very common software such as Microsoft Excel you can google almost any problem and you will find that someone else has already encountered your problem, asked the question, and had it answered, all easily accessible to you. There is little reason to assume that this should work differently for more physical or industrial technologies such as cars or machines. Through such a mechanism it could be imaginable that adoption costs for older technologies are actually lower than more recent ones. Therefore a higher distance to frontier might actually increase technology diffusion towards your country. Another implication is that there should be considerable heterogeneity in transfer costs in general.

As explained before, Barro and Sala-i-Martin (1997) build a model that combines elements from endogenous growth models with the convergence aspect of neoclassical growth models. The imitation costs are a fixed cost for the firm in the following country. The cost is specific but not necessarily identical for each technology and because of this the cost of imitation is likely to be lower far away from the technology frontier, as there are more still unadapted innovations to choose from. Close to the technology frontier, only the expensive ones would remain. Intellectual property rights can also affect this cost.

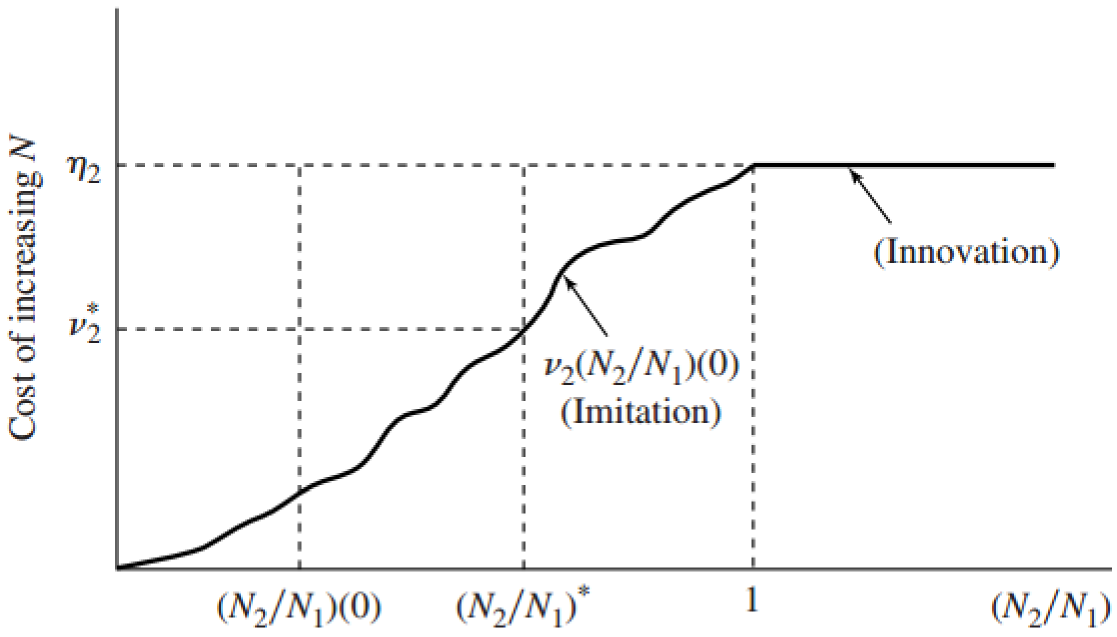

Figure 3: Cost of technological adoption in the lagging country by Barro and Sala-i-Martin (2004, p. 354).

The ratio N_2/N_1 is the ratio of technologies adopted or developed in the lagging country N_2 and the number of technologies N_1 developed in the leading country. The cost of imitation ν_2

will get closer and closer to the fixed cost of innovation η_2. The case depicted above does not include the possibility of innovations where the imitation is more expensive than the original innovation, which is possible in theory.

In their baseline case the following country is structurally inferior to the leading country in terms of its productivity, labour endowment, or cost of innovating parameters. Thus it never chooses to innovate and instead follows at a perpetual lag at its steady state distance to frontier. In this framework imitation does not imply full convergence.

The leader-follower positions and the level of output and innovation however are determined by underlying structural parameters for the cost of innovation η_i, and government policies A_i. If the following country (country 2 in the below diagram) has lower innovation costs η_2 than steady state imitation costs ν_2^*, it can overtake the former leader:[25]

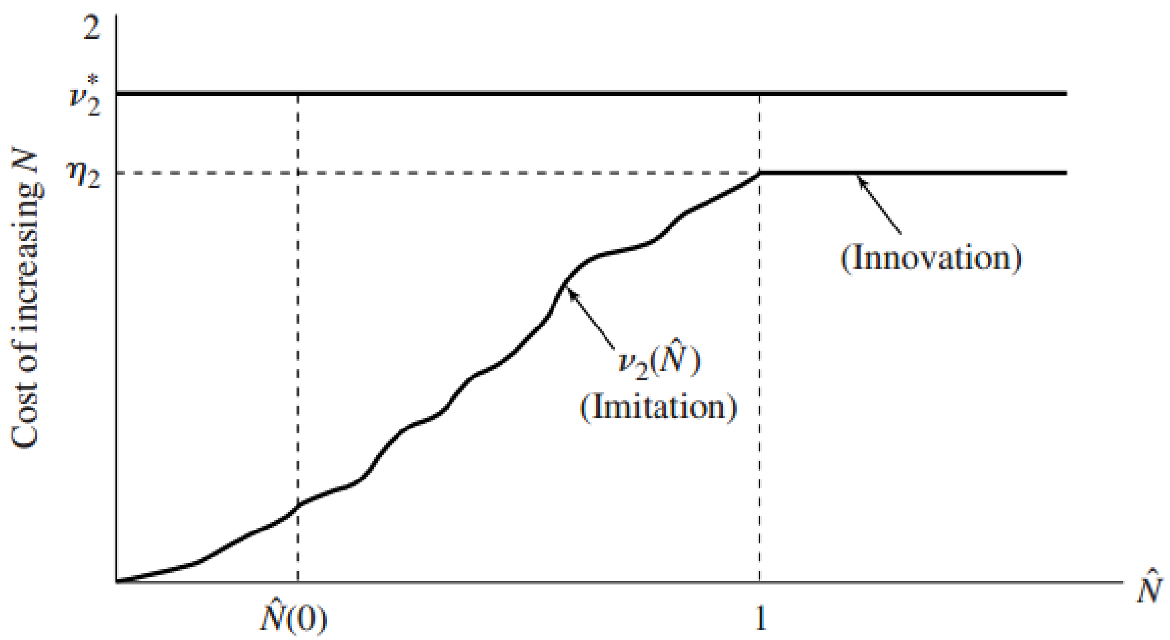

Figure 4: Costs of technological change if the following country has lower innovation costs by Barro and Sala-i-Martin (2004, p. 374)

The following country will only pursue the imitation strategy for as long as innovation is not cheaper. Once this point is reached the roles are reversed and there is a new technology leader. There is no mechanism that causes a lagging country to leapfrog and overtake the

[25] The cost of technology imitation is a key variable in this setting and it can vary substantially. An interesting question is whether this cost can be influenced. Barro and Sala-i-Martin identify human capital as a very likely candidate for such an influence. Human capital has the potential to lower the costs of adaption for sophisticated technologies significantly. Higher education at the secondary at tertiary level should be especially important. This links it to the models discussed in chapter 3.2.2 where human capital affects the speed of technology diffusion.

current technology leader.[26] Such a change has to happen exogenously, for instance through the political process, and would take a long time to fully come into effect. This means that it is unlikely for an individual country to become the technology leader, however it is also unlikely that the same country will stay technology leader forever.

Parente and Prescott (1994) build a model where the world technology frontier W_t grows exogenously and the cost of technology adoption for advancing from technology level A_t to the level A_{t+1} falls with the DTF (W_t relative to the firm's technology level S). Barriers to technology diffusion measured by the parameter π also affect the cost of adoption X_{A_t} (as explained in chapter 3.1.3):

$$X_{A_t} = \pi \int_{A_t}^{A_{t+1}} \left(\frac{S}{W_t}\right)^{\alpha} dS$$

This represents the observed fact that development rates increase over time when development rates and barrier to technology diffusion are held constant. Their model finds that structural differences in a country's growth rates (relative to the US as the world technology leader) and changes in the trend can be explained well by the barrier to technology diffusion variable. These barriers to technology adoption prevent some countries from converging. The authors conclude that there must be large unmeasured investment in the business sector that drives growth in countries that catch up to the world technology frontier. They call it is a *technology adoption investment* made possible by low barriers to technology diffusion compared to other countries. Their understanding of this measure is very broad: It includes human capital acquired by learning on the job, investments undertaken by entrepreneurs, and also foregone wages during education. To summarize they argue that political and social factors can affect the potential productivity of human capital and transferred technology strongly enough so that technology diffusion happens much slower than theoretically possible.

In Caselli's (1999) model technology diffusion is not affected by political circumstances but instead by the nature of technological change which is either skill-biased or de-skilling. In a skill-biased technological change the new machines require higher learning investments than the old ones did. The cost of technology adoption is sinking relatively for older technologies. Fast-learning workers are more likely to switch to the new technology, since their opportunity

[26] In that regard it differs from models of leapfrogging, e.g. by Brezis, Krugman, and Tsiddon (1993), or Jovanovic and Nyarko (1996). Brezis et al. propose that leapfrogging occurs when a major change in technology happens and the incumbent technology leader has a lot of experience in the current technology, while a lagging country has more incentive to invest in the new, superior technology. This can lead to a change in technology leadership. Jovanovic and Nyarko argue via vintage human capital.

cost (during the learning period) is smaller. Since they are more productive at the new machines than the slow-learners who still use the old technology, the innovation triggers a capital reallocation towards the new technology and the fast-learning workers. Since technologies are assumed to have diminishing marginal returns to capital this eliminates arbitrage opportunities. The different endowment of capital and the different technologies used causes large relative wage differentials, which is the main focus of his paper. Through the increasing wage differentials it becomes profitable for more and more slow-learning workers to learn and use the new technology. One possibility is that this leads to universal adoption of the new technology. However a steady state with both technologies in use is also possible.[27]

It is interesting to link Caselli's approach to the idea of human capital and technology diffusion. It is very plausible that the learning costs of workers can be influenced via state policy (be it by raising the overall base education level or by giving people better "tools" to learn new technologies). Furthermore one can extend his approach from the national view of his paper to an international context. The differences in learning cost might very well be different between a technology leader and lagging countries' citizens. In such a framework, lagging countries can have access to newer technologies than they currently use, but their workers (or enough of their workers) lack a sufficiently high incentive (or possibilities) to shoulder the high learning investment necessary to learn the new technology. In such a framework we would expect de-skilling innovations to spread more easily to poorer regions, i.e. manufacturing to move to poorer countries, and this is indeed a key component of the globalization the world has experienced. However there seem to be limits to this.

3.2.1.3 Rising costs of technology diffusion

There is also a case to be made that costs of adopting technologies are increasing with their age. Grant and Gregory (1997) document cases where the transferability of older technology was significantly reduced because in more mature process, workers relied more and more on experience, routine and colleagues. The process documentations thus did not reflect the more mature processes anymore. Such effects could lower the diffusion-enhancing effects of a higher distance to frontier, because these countries would have higher transfer costs if the older technologies that are appropriate for them (e.g. because of their capital-intensity) might

[27] As examples for this skill-biased technological change Caselli lists the steam engine, the dynamo, and more recently information technology. He also lists the example of a de-skilling innovation, where the necessary learning cost investment for a new technology is lower than the investment for the technology previously used. The example he provides for a de-skilling innovation is the assembly line which allowed more people than ever to take part in the manufacturing of goods because the now simpler tasks could be learned by many people for which the previous process knowledge was too difficult to acquire.

fall exactly into this realm of poorly codified (routine tasks) or hardly-codifiable tacit knowledge (problem solving techniques). However this case seems less relevant in practice.

3.2.2 *THE DISTANCE TO FRONTIER AND HUMAN CAPITAL*

In Lucas' (1990) model growth comes from the accumulation of human capital. The productivity parameter A does not change and is the same for all countries. This assumption is dropped by models in this chapter. They study the dynamics of technology diffusion across borders, and how it is affected by the human capital level and composition in relation to the distance to frontier. The diffusion happens at a time lag that is affected by the variables mentioned. This chapter studies the joint interaction of the DTF and human capital.

3.2.2.1 Distance to Frontier and Average Human Capital

The idea that the level of human capital has an effect on innovation and technology adoption goes back to the paper of Nelson and Phelps (1966). They discuss the example that farmers with a higher educational attainment are more likely to quickly adopt a new technology than farmers with low educational attainment. In principle all farmers have access to the same technology. However the speed of technology adoption depends on the human capital of the farmer and thus not all use the same technology *de facto*. This can easily be adopted as a model for international technology diffusion from technology leaders to followers. From a lagging country's point of view the world technology frontier can be seen as an exogenously growing theoretically possible technology level. What they introduce into their production function is a difference between the theoretically available best technology T and the actual technology used A:

$$A(t) = T\left(t - w(h)\right) \, with \, w'(h) < 0$$

The function $w(h)$ is a time lag of technology adoption that depends negatively on the educational attainment or human capital h. The technology actually used is thus the technology that became available w years ago. In this model technology diffusion is no longer instantaneous.

Based on the same thought they introduced a second view in that technological advance in practice depends on the level of human capital available. The rate of realization of the technology in practice $A(t)$depends positively on the human capital level h and proportional to the distance to the frontier technology level $T(t)$:

$$A'(t) = \phi(h)\,[T(t) - A(t)]$$

The function $\phi(h)$ measures how the human capital level affects technological growth. It suffices $\phi'(h) > 0 \; and \; \phi(0) = 0$. In the long run the theoretical technology level T is assumed to grow at an exogenous constant rate λ, and consequentially so will A, as long as $h > 0$. The steady state implies a constant technology gap $T(t) - A^{*}(t)$ at which the following country follows the technology leader. If in the beginning the country is farther away from the technology frontier than this, technology diffusion towards this country will be higher and the country will catch up until the steady state is reached.[28] The gap can be closed by increasing human capital:

$$\frac{T(t) - A^{*}(t)}{A^{*(t)}} = \frac{\lambda}{\phi(h)}$$

The payoff of human capital investments is larger if long-term growth is higher. This model already includes the main implications for the role of human capital in models which assume that the speed of technology diffusion is affected by human capital: If imitation is possible, education has positive externalities, since it has a positive effect on the process of imitation. Due to this mechanisms just including human capital as another factor in the production function might wrongly specify the relationship. It is notable that in this model human capital affects the speed of technology diffusion towards the lagging country, and the steady state distance to technology frontier, but has no effect on the steady state growth rate which will be identical to the exogenous growth rate. Also, both human capital and distance to frontier fuel technology diffusion towards the country. However the model does not imply full convergence to the technology frontier *T*.

Benhabib and Spiegel (1994) expand on the same idea and model. In their model educational attainment of the labour force is not an ordinary input in the production function, but has two effects instead: A direct one as an input needed for innovation, and an indirect one in interaction with the distance to frontier to model the catch-up effects. The new aspect is that the catch-up effect is not towards some theoretical technology or growth level, but instead to the country which is the technology leader. This country exclusively makes use of human capital as an input in the innovation process. In the lagging country human capital is also used for imitation. They work with an endogenous growth model and have a technological progress formula that differentiates between innovation and adoption and links it to human capital H:

$$A_{i,t} - A_{i,j-1} = c(H_i)\,(\bar{A}_{t-1} - A_{t-1}) + g(H_i)\,A_{t-1}$$

[28] The same goes for the other direction. If the country is closer to the world technology frontier initially, the term $T(t) - A(t)$ will be very low (potentially even 0 or negative) and cause the country to fall back to the "natural" distance to frontier.

In contrast to Nelson and Phelps they split technological growth into adoption depending on the distance to the world technology level $(\bar{A} - A)$ and genuine innovation depending on the country, sector or firm's own prior technology level A. What Benhabib and Spiegel keep is a link to the local aggregate human capital level H_i (modified by the functions $c(\cdot)$ for adoption and $g(\cdot)$ for innovation) for both types of technological advancement.

The innovation effect of human capital means that now the leader is not an exogenously given theoretical frontier but instead will in the end be the country that manages to achieve the highest level of innovation, which it does by having the highest level of human capital. The steady state distance to frontier implied by the model is lower, since the following country will do some genuine innovation as well, adding to the technology level within the country. The graphic below shows the two models' implied steady state distance to frontier (on the x-Axis) compared for the case of the following country with a leader that grows at rate ω (previously λ in the Nelson-Phelps model). The Nelson-Phelps equilibrium is a special case where the innovation for the follower is 0 and the leader grows exogenously.

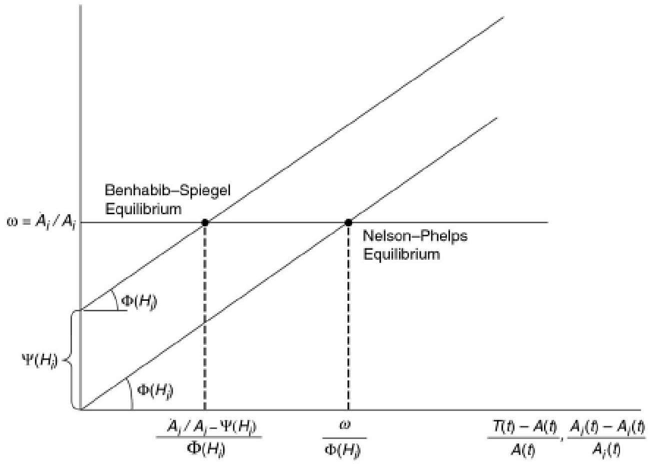

Figure 5: Nelson-Phelps and Benhabib-Spiegel long-run equilbria by Savvides and Stengos (2009, p. 71)

In this model, technology diffusion again takes time. Human capital is both a catalyst in the catch-up process and a driver of innovation.

The similarities to the model of Acemoglu, Aghion and Zilibotti (2006) are evident. There, $\gamma_{i,t}$ is managerial skill (which affects the efficiency of the innovation process but has no effect on adoption) and η is a constant that measures the relative efficiency of adoption of the world technology level from last period $\bar{A}_{i,t-1}$:

$$A_{i,t} = s_{i,t}(\eta\, \bar{A}_{i,t-1} + \gamma_{i,t}\, A_{t-1})^{29}$$

[29] The variable $s_{i,t}$ denotes the size of the project managed and is not relevant for the discussion here.

This model relies on the same technology diffusion mechanism, but looks at the individual skill of a manager and not at the aggregate human capital level that affects the evolution and diffusion of technology. It can be seen as a specification of the diffusion process that leads to the aggregate conclusions reached from the models discussed before. The mechanism introduced is *manager selection*. In their model firms face the choice whether to employ a new manager or keep their existing one. Managers can have different skill levels and the manager's skill level is crucial for firms engaging in innovation activities (*innovation-based strategy*), and not as important for firms carrying out adoption activities (*investment-based strategy*). Pursuing and politically supporting an investment-based strategy while catching up to the world technology frontier is beneficial in their model in the short term (and catching up is possible), however it might be detrimental in the long run due to possible economic and political trap mechanisms which make the switch out of this strategy increasingly less likely. The trap mechanism – somewhat simplified – works as follows: Firms tend to grow very large when the focus of companies is to invest and grow, and not hire the best talent and innovate. The larger size comes with greater political and economic power. This adds an interesting long-run perspective to the role of the distance to frontier and related policy implications. What their model also includes is the possibility of *leapfrogging*, meaning that economies can overtake the original technology leaders. In their model this can occur between an economy that initially benefits from choosing the investment-based strategy but then gets stuck in this strategy for too long. An initial laggard that invests more resources to an innovation-based industry can then leapfrog ahead.

3.2.2.2 Looking at the Composition of Human Capital

Following the idea of Grossman and Helpman (1991a) who point out that the composition of human capital affects innovation, Vandenbussche, Aghion and Meghir (2006) further break down the human capital variable into skilled labour s and unskilled labour u:

$$A_t = A_{t-1} + \lambda\left[u_{m,t}^{\sigma}\, s_{m,t}^{1-\sigma}\, (\bar{A}_{t-1} - A_{t-1}) \;+\; \gamma\, u_{n,t}^{\phi}\, s_{n,t}^{1-\phi}\, A_{t-1}\right]$$

They also specify the human capital dependency functions (unspecified $c(\cdot)$ and $g(\cdot)$ above) using the σ (resp. ϕ) parameters for the elasticity of unskilled labour in adoption (resp. innovation). $\gamma > 0$ measures the relative efficiency of innovation compared to adoption in generating productivity growth, and $\lambda > 0$ measures the efficiency of the technological advancement process in general. The elasticity of skilled labour is expected to be higher in innovation activities than in adoption, thus $\phi > \sigma$.

Their model yields two effects of change in human capital: a *composition* and a *level* effect. The level effect is always positive, as it is the effect caused by an overall increase in human capital while holding the composition of human capital constant. The composition effect is what happens when the composition of skilled vs. unskilled labour is shifted holding the overall human capital level constant. It is shown that the growth-enhancing effect of skilled labour is stronger close to the technology frontier. This is because an increase in skilled labour triggers a reallocation of both unskilled and skilled labour to innovation activities (due to the fixed proportion of labour needed in their model), which is more growth-enhancing where innovation is more profitable than adoption. A model or empirical analysis that simply relies on total human capital in an economy misses this effect. Their model even implies that far away from the technology frontier an increase in skilled labour can have a decreasing effect on growth, if the increase in innovation triggered by the reallocation of workers cannot compensate for the loss in imitation.

Krueger and Kumar (2004) analyse the different education systems that are observed in the US and Europe also with the idea of a distance to frontier based effect that is affected by the composition of human capital in the economy. They do not differentiate between skilled and unskilled labour explicitly, and talk of a general education and vocational training instead.[30] Low-tech firms use the common-practice technology A_t, and high-tech firms adopt a technology between A_t and the frontier technology $A_{f,t}$. The introduce technology diffusion at a cost, which becomes increasingly high towards the frontier technology. This can be thought of as expenditure for training people and fixing bugs, which are generally high with cutting-edge technologies.[31] Krueger and Kumar assume that the general education is advantageous in the new information technology era with high growth rates of the technology frontier. High growth rates make the adopting sector and thus the general education more attractive. The country with the higher stock of general human capital can profit more from this. In a slow growing environment both economies are closer to the technology frontier – possibly even at the same balanced growth path distance – and the effect of the different subsidies is smaller (or zero), which is why there was no divergence before the information technology age. They theorize that the lower European subsidy to general education was optimal from a welfare

[30] A general education is received at a college or university, which was more strongly encouraged and subsidized in the US according to the authors.

[31] There are two types of workers now: People with vocational training and people with general training. They can decide for themselves which education they want, but the cost of a general education is based on their innate ability a, while the cost of a general education is fixed. While the human capital gained by vocational training by someone who works in the non-adopting sector is known, there is uncertainty involved with generalists who work in the adopting sector. This reflects the uncertainty involved regarding whether a general education matches the requirements of a cutting-edge technology.

perspective in the earlier environment, while the US might have been oversubsidizing general education.

In the Krueger and Kumar model both countries have access to the same technology frontier. This frontier grows exogenously. In their model high-skilled, generally educated labour is the key to technology diffusion (especially in a high growth environment). Their model is targeted at frontier economies such as the US and Europe, where technology adoption from the technology frontier is very close to the traditional understanding of innovation. In their model the DTF can be affected via government policy and there is convergence in growth rates if countries use the same policies.

Di Maria and Stryszowski (2009) build on the model of Vandenbussche, Aghion and Meghir (2006). They include migration in a later stage, as discussed in chapter 0. Their worker education is similar to that of Krueger and Kumar, but vocational skills are now called technical. A firm employs workers to increase its productivity through both innovation and imitation according to this equation:

$$A_t = A_{t-1} + A_{t-1} T_{nt}^{\phi} G_{nt}^{1-\phi} + (\bar{A}_{t-1} - A_{t-1})\, T_{mt}^{\sigma} G_{mt}^{1-\sigma}$$

The technology level depends on the old technology level plus the effect of innovative activities (depending on the old technology level and the amount of generally (G) and technically (T) skilled workers employed in innovation, denoted by the subscript *n*) and imitation activities (depending on the distance to the world technology frontier from the prior period and the number of G and T workers employed there, denoted with subscript *m*). G workers are more effective in innovation and T workers in imitation, which corresponds to assuming $0 < \phi < \sigma < 1$. Like the models discussed before, they assume that a larger technology gap makes imitation easier since there are more innovations to draw from, and that a higher technology level promotes innovation since there is a broader base to build on.

Their model includes critical technology levels where either only innovation, only imitation or both occur. This market solution is growth maximizing and the model implies convergence in growth rates, and also in levels up until the steady state level of technological distance, where there is no longer a benefit from imitation and neither country will engage in it. Full specialization in innovation is the consequence.

Howitt and Mayer-Foulkes (2005) build on the model by Aghion and Howitt (1998) discussed in chapter 3.1.1.1.[32] Their model is based on three key ideas: First, technology adoption is

[32] See Howitt (2000) for an earlier version of this model that implies convergence as in Mankiw et al. (1992) and persistent income differences even between countries converging to the same steady state convergence rate.

costly (as in DTF models). Second, a country has a stock of "effective skills" that depends on its DTF. Human capital accumulation is less effective when the DTF is higher (due to human capital externalities), and a country needs to increase its skill as the world technology frontier progresses, or it will not be able to keep up with the increasing complexity. The third and key novelty is that originally (before the revolution of the scientific process in the early modern times) there was only adoption (or "implementation" as they call it), until the modern innovation process suddenly arrived everywhere and instantaneously. Innovation relies much more heavily on high-skilled scientific knowledge (i.e. human capital). In this model countries can then "graduate" from adoption to innovation, if their skill level permits it. They find that this can lead to a "trifurcation" of growth paths into three clubs: Countries of club A start with high enough human capital to immediately switch to innovation. Countries in club B don't have a sufficient human capital level to innovate, and fall behind initially, but their human capital level is high enough so that they can benefit from A's technology level and converge in growth rates (not levels). Countries in club C are too far behind and their skill level cannot keep up with the growth rate of the technology frontier. They grow faster than initially but always slower than the countries in the other two clubs. This already takes away some of the conclusions from models discussed in chapter 3.2.2.2 that look at the DTF and human capital composition and their interaction in the sense that catching up is conditional on the country's endowment. In this model skills are necessary to avoid further divergence, not only to determine the speed of catching up.

Acemoglu, Gancia and Zilibotti (2012) specify the innovation vs. adoption mechanisms that remained fairly abstract in the previous models. They introduce the idea of *standardization*. In their model an innovation process, requiring skilled workers, is followed by a costly process of standardization. Standardization makes the production of the new good or a new process feasible using unskilled instead of skilled labour. The cost of innovation is higher than that of standardization. What they find is that standardization can both promote growth by making production more efficient and hinder growth by slowing down innovation through reduced incentives due to competition. In this regard it touches on the basic question of the right amount of intellectual property rights protection. The model's relationship between standardization and growth is inverse-U-shaped.

They also analyse what happens if such an economy as described above (they label it "the North") comes in contact with a large country that only has unskilled labour and is lagging behind the world technology frontier ("the South"). Without trade and international intellectual property protection they assume that firms in the South can imperfectly copy at no cost. However, because of the imperfect technology transfer (perhaps due to tacit knowledge unavailable in the South), the productivity of (unskilled) labour will be only a fraction $\phi \in (0,1]$ of the productivity in the North. There is no innovation in the South. Once trade is introduced and Northern firms are allowed to invest in the South, they will do so to exploit the cheap labour available. Since standardization allows goods to be produced using unskilled labour only, the wage rates of unskilled workers have to equalize across the two countries. Thus opening up to trade will increase technology diffusion, because the technologies will actually be transferred and not imperfectly imitated.

This model takes human capital in the form of skilled and unskilled labour as a given. As long as there is no skilled labour in the South there cannot be any innovation, and the South will continue to only produce the standardized goods. The authors find trade is growth enhancing if intellectual property protection (reflected in the cost of standardization) is adjusted correctly. There are two opposing effects: The lower relative availability of high-skilled workers calls for stricter intellectual property rights. At the same time the heightened competition in the market of standardized goods calls for a less protection, to compensate for the lowered profit margins. If the South is large and bad at imitation (ϕ is low) then the competitive pressure on standardized producers is low, and the ideal strategy is to heighten the cost of standardization. But this is only true from the point of view of a global planner, since the higher cost of standardization would increase the skill premium which the North reaps.

In a paper more focused on educational effects, Ang, Madsen, and Islam (2011) look at the differing effects of primary and secondary education versus tertiary education on technology diffusion in relation to the distance to frontier in an empirical paper discussed in more detail in chapter 4.2.2.

3.2.3 Channels of Tacit Knowledge Diffusion

As explained in the introduction to chapter 3.2 the diffusion of tacit knowledge is a difficult, time-consuming and expensive process. In this chapter some channels of technology diffusion which give special importance for tacit knowledge are discussed shortly.

3.2.3.1 Foreign Direct Investment

To transfer tacit knowledge to a local subsidiary it is necessary to employ people that have the knowledge in question. If this is truly a new technology it will not be possible to hire such employees in the local labour market. The company will thus have to either "import" people with the knowledge (from the parent company or another subsidiary) or train local people (at another plant, by sending instructors, or setting up tele-instructional programs). There clearly is anecdotal evidence for companies sending their experts to new facilities for instructional purposes.

These new plants and their newly trained employees can have local technological learning externalities through labour turnover. For example, Fosfuri, Motta, and Rønde (2001) analyse a model where a multinational firm needs to train a local worker before being able to employ its superior technology in the local subsidiary. The worker's new knowledge can lead to him being hired by a local competitor, thus causing a technology spillover, or to him receiving a higher wage to prevent him from taking the job offer from a competitor, an effect they call a pecuniary spillover. They theorize that such spillovers might be decreasing with the DTF since the local market is not developed enough to offer opportunities and competitive wages to the newly trained people.

They find that with their model the market structure of the local economy plays a crucial role in determining the mobility of the newly trained workers. Their model implies higher mobility in less competitive markets (where the other firms can make a profit with the hiring of the new worker), and where competitors can use the technology to produce unrelated or complimentary products, or serve a different market (geographically for instance). Things get complicated further when one takes into consideration that firms might choose to export instead of doing a foreign direct investment in order to prevent said technology spillovers. Exporting is the best action when tariffs and transportation costs, the threat of technological spillovers, and competitiveness in the market are low. This makes higher import tariffs a potential instrument in trying to encourage more foreign direct investment and thus inducing more tacit knowledge spillovers from advanced economies.

Acemoglu, Gancia, and Zilibotti (2015) analyse this decision in a model where firms from advanced economies can choose to offshore production to lagging countries with lower wages. They primarily focus on wages, inequality and skill-premia. In an extension they also analyse a model with technology spillovers to firms from the lagging country by giving those firms the possibility to imitate a production process at a fixed cost (as in chapter 3.2.1). What they introduce is that the imitating firm is not able to achieve the same productivity as the innovating firm (domestically or when doing a direct foreign investment). Imitating firms enjoy all the local monopolist privileges that are standard in a Romer innovation framework. There is international trade and in equilibrium the technological disadvantage of the imitating firm is perfectly offset by its advantage in lower wages. In this framework there are no technology spillovers between firms, because monopoly rights in intermediate goods are perfectly enforced. When a lagging country only engages imitation as opposed to offshoring it suffers from a technological disadvantage. Offshoring only occurs when its cost is sufficiently low. The cost of offshoring are determined by a raised cost of unskilled labour (coordination cost) and a fixed cost of the investment. Once the cost of offshoring is low enough imitation becomes unprofitable because the offshoring firms drive up the previously low wages that made low-productivity imitation viable. The result of this process is that both countries specialize in the production of a fraction of the intermediates. Each intermediate good is only produced in one country and these are now the goods being traded. The diffusion of technology is better with more offshoring because imperfect imitation becomes less prevalent.

Keller and Yeaple (2013) also analyse firms that have to decide whether to offshore their intermediate good production. The main trade-off is the shipping cost that is added upon the production cost at home versus the cost of knowledge transfer to foreign managers, who lack the specific tacit knowledge that domestic managers have. This process is subject to communication frictions because technological knowledge is tacit. In their model, trade of intermediate goods is a substitute to knowledge transfer as a solution to this problem.

Domestic and foreign technology – complements or substitutes

There is also criticism of foreign direct investment as a channel of technology diffusion. Evenson and Westphal (1995) discuss the relationship between foreign technology and domestic technology. It is clear that a subsidiary of a firm from an advanced country can import a new technology. They point out that the import of foreign technology could be a substitute for domestic R&D and could in that case harm the local development. However their evidence is not conclusive. The import of foreign technology can harm the diffusion of foreign technology only if it inhibits the development of local technological capacity and the learning process. According to Radosevic (1999) this was indeed what was feared by politicians in the 1960s and early 1970s.

3.2.3.2 Migration and the Question: Brain Drain, or Brain Gain?

When knowledge is tacit and imbedded in the heads of people it is very straightforward that knowledge goes where the people go. This can be detrimental or beneficial as the following short chapter will show.

Brain Drain

When we look at the migration patterns of the present it is scarcely in the direction from more advanced countries to developing countries. Since it is often easier for well-educated persons to migrate to an advanced country (due to their financial means or preferred status in the visa process) an actual *brain drain* can occur. This means that the developing country loses some of its best brains, and all the human capital and technological knowledge that it may have subsidized during their education. This is the classical view.[33]

Di Maria and Stryszowski (2009) focus on the role that the composition of human capital plays in the economic development of a country, as discussed in chapter 3.2.2.2, and consider the effects of migration in that framework. They build on the model by Vandenbussche, Aghion and Meghir (2006) as discussed in chapter 3.2.2.2. Di Maria and Strszowski then add the possibility of migration for skilled workers. Migration in this model is a one way flow. Workers from the advanced economy face lower wages in the lagging country, and have no incentive to go there. In the lagging country however, workers face a new market demand when choosing their education. The pull effect of a heightened demand for highly educated people distorts the efficient education choice in the lagging country. This distortionary effect of migration increases with the DTF. There is lower growth and thus slower convergence, until the critical point is reached where the lagging country also specializes in innovation. This remains the steady state and the effect vanishes. If the advanced country can discriminate immigrants based on their education the effect is even stronger and additionally it can mean that the lagging country can never reach the original steady state DTF due to a distorted composition of human capital. In both cases subsidies to the appropriate technical education can lead to faster convergence by restoring the optimal T/G-ratios. The East Asian countries (Japan and TIGER) have indeed had success with directing tertiary education towards technical fields. Di Marian and Stryszowski quote the World Bank (1993, p. 15) report: “Public funding of post-secondary education focused on technical skills […] The result of these policies has been a broad, technically inclined human capital base well-suited to rapid economic development.” In that light that does indeed seem like a valid strategy for countries that are further away from the world technology frontier than their steady state distance and suffer from brain drain effects.

Brain Gain

Other researchers have sought to explain the strong convergence observed in these TIGER countries not despite the brain drain effects, but because of the positive effects from migration. Beine, Docquier, and Rapoport (2001) analyse a model where migration prospects affect how people decide to invest in their human capital. They find that ex ante the prospect

[33] See for instance Docquier, and Rapoport (2012) for a summary on brain drain and brain gain literature.

of migration will lead to more people investing in human capital – they call this the *brain effect* – while ex post some of the human capital built is lost when the actual migration occurs – the *drain effect*. When the *brain effect* dominates a beneficial brain drain situation occurs with an overall higher level of human capital than in the closed economy equivalent. This is likely to occur in two cases: if the country initially has low migration probabilities and is stuck in an underdevelopment trap (with little growth and little incentive to invest in human capital), and also if the country is growing fast and has intermediate migration probabilities. This has important policy implications. Implementing barriers to emigration of high-educated individuals might have the opposite effect and inhibit long-term human capital formation. One can also make the case that high subsidies on education are not warranted in such an environment, as the incentive to invest in human capital is already high due to the high wage differentials and the opportunity to emigrate.[34]

Return Migration

But migration is not a one way street. People that go abroad to study or work are likely to learn about new technologies or increase their human capital. If they do this and then return home, they could be very beneficial to their lagging country as they could pass along tacit knowledge gained abroad. The likeliness of people returning to their home country is quite significant, as Dustmann, Fadlon, and Weiss (2011) state. They present a learning-by-doing based model with two different skills (a local and a foreign skill), where people can go abroad to work and learn, but also return home or even stay there in the first place. The idea is that some developed countries function as a learning centre, where skills are learned more effectively. Tacit knowledge could be a possible reason that this discrepancy exists. The authors explain that in this framework, some individuals will indeed choose to emigrate, learn, and then return. The individuals gain from this process and have a higher income this way, but is not clear whether the local economy gains. In theory the worker or the developed country could reimburse the local country with a transfer[35] (and all parties would be better off than in the case without migration), but such a taxation is hard to achieve. A skill standard by the learning centre country has two effects on the home country in this framework: Some people with intermediate skill levels of the foreign skill do stay at home (instead of leaving and not returning) and benefit the local economy, but also some people with low levels of the foreign skill do not emigrate, learn, and return. The second effect is negative for the local

[34] Beine, Docquier, and Rapoport (2001) also test the implications of their model empirically and find that their theory is not rejected and should be considered as more than just a fluke in a model.

[35] As proposed for instance by Bhagwati (1976).

country. It is therefore possible that restrictions on immigration based on skill levels by advanced countries can make developing countries worse off.

3.2.3.3 Non-Financial Development Aid

It is also attempted to transfer technology explicitly to make it accessible in a less developed country. Development aid has included financial and non-financial aid, as well as conditions and requirements targeted at bringing development to poor countries. Easterly (2007) analyses what we have learned from past experiences in development aid. In general he finds that we still don't know how development is achieved and even comes to the harsh conclusion that it was a mistake. In the case of non-financial development aid in the form of technological assistance (financial transfers or political reforms are not of interest here) he finds it hard to find success stories. While Easterly is known for his critical position on development aid, it seems plausible that technological assistance is not a very important channel of technology diffusion.[36]

3.2.3.4 Other Channels

There are other channels that are relatively separate from human capital levels and the DTF but relate to technology diffusion. The common theme is that they emphasize the role of repeated interaction and exposure to new technologies. Keller (2004) and Keller and Yeaple (2013) find that geographical proximity increases interaction and diffusion. Grossman and Helpman (1991b), Coe and Helpman (1995), and Comin and Hobijn (2004) look at trade as a channel of technology diffusion by promoting exposure to new technologies. This mean of technology diffusion mainly works through high-quality intermediate goods and is not technology diffusion related to human capital as discussed here.

[36] Easterly sees the role of foreign aid not in development assistance through technology transfers but in the form of providing services that are clearly needed such as fighting diseases, financing infrastructure, providing clean water, and investing in human capital formation.

3.3 Comparison of Implications

As shown there are many different models for both public good knowledge and tacit knowledge. The two groups of models are able to explain the lack of general convergence and the few growth miracles observed with different mechanisms. When technology is assumed to be a public good and there are no differences in technology, the keys to prosperity are factor accumulation, the use of appropriate technologies and low barriers to technology diffusion. When technology is tacit and diffusion is slow or costly, poor countries must look to improve the adoption process by lowering the cost or speeding up the process. Human capital and its composition play a key role in building up adoptive capacity.

In the basic PGK models all countries have the same aggregate production function but different stocks of input factors. Generally, the accumulation of human capital does not exhibit diminishing returns. The stock of human capital determines the level of productivity in an economy and the growth of human capital corresponds to growth in technology. As it grows at the steady state growth rate one would therefore not expect the share of human capital in production to change. Although this has been argued, there is little reason to believe that the DTF would directly affect technology diffusion towards a country in that setting, as all countries have access to all technologies. The country with the highest stock of human capital is the world technology leader, all other things equal. There is only conditional convergence for countries that are similar. In some models there is (conditional) club convergence where the initial conditions influence what steady state is reached, see for instance Azariadis and Drazen (1990) or Galor and Zeira (1993). Although they would have access, not all countries will be using the same technologies since the technologies need to match their local relative factor prices and skill-endowments. In all of these models the savings rate is they key driver of economic growth (when it includes human capital). The relationship can be non-linear as Basu and Weil (1998) show. Like Basu and Weil, Acemoglu and Zilibotti (2001) show that productivity differences can be significant even without any barriers to technology diffusion when lagging countries need to employ unskilled people in position that would require a skilled worker. This makes it possible that technology lags persist, or even further increase (if technological growth is sufficiently skill-biased). Poor countries should look to increase their supply of skilled labour as a remedy. Caselli and Coleman (2006) see it more positively and state that the inappropriateness of new technologies is just a “smaller advantage” for lagging countries, and that they can still benefit from the large amount of technologies available if they choose appropriate ones. Models with barriers to technology adoption as for instance Parente and Prescott (1994) introduce barriers to technology adoption. This means that while technology is available to all countries, in some there are political and institutional factors that prevent the adoption of a foreign new technology or lower its productivity significantly, e.g. through credit market distortions favouring (often state-owned) incumbent firms.

A bit of an odd case within the PGK models are the vintage human capital models. Lucas (1988) sees learning-by-doing human capital accumulation as a potential source of divergence as it leads to specialization. In the vintage human capital of Chari and Hopenhayn (1991) it implies long diffusion lags necessary for learning new technologies. Jovanovic and Nyarko (1996) point out the possibility of experienced workers (or firms) refusing to update their technology due to the uncertainty associated with a new technology. These mechanisms can lead to poorer agents, firms, or countries overtaking the former technology leader because the leader has a high incentive not to switch technologies. Other models by Jovanovic (1998, 2009), and Jovanovic and Yatsenko (2012) based on vintage human capital – but with heterogeneous learning costs – on the other hand imply persistent specialization (and thus a lack of convergence) in technology vintages based on talent levels. All of these models can explain slow technology diffusion and persistent investment in older technologies without barriers or other country-specific technology levels.

TK models can explain the same phenomena, but there, lagging countries do in fact not have free access to new technologies, as opposed to choosing not to use them. For the aggregate production function this means that the technology variable is country-specific. Nelson and Phelps (1966) introduced the idea that human capital can speed up the diffusion process. Romer (1990) pioneered the endogenous growth models where human capital is not an input in production but instead an input in the innovation process. The level of human capital determines the growth rate of technology through innovation.[37] Benhabib and Spiegel (1994) combined the two into a single model. Vandenbussche, Aghion, and Meghir (2006) then pointed out that the skill composition of human capital plays a role in the diffusion of technology and innovation at different distances to frontier. According to Romer growth human capital determines the growth rate of an economy, and not the productivity. With the DTF models human capital got the additional role of building up an adoptive capacity and

[37] Ha and Howitt (2007) summarize how second-generation endogenous growth models have addressed the oddity that despite a strong increase in R&D activity in the US the growth rate has not increased accordingly. Some models labelled "semi-endogenous" have assumed that human capital shows diminishing returns due to the increasing complexity of research. "Schumpeterian" models on the other hand in the line of Young (1998) state that the increased profit opportunities of larger markets lead to more variations and higher quality of the same products, but decrease the quantity-wise effectiveness of R&D. These models focus more on R&D and its drivers than technology and are not discussed in more depth here.

fuelling technology diffusion towards a country. In the models that assume that human capital promotes both innovation and adoption it does not determine the level of productivity but the speed of catching up. In some models, e.g. Sala-i-Martin (1997), leapfrogging is possible if the lagging country has an advantage in exogenous parameters on the attractiveness of production and research, e.g. taxation, property rights, and infrastructure. If those parameters are equal the models also imply convergence in growth rates. As adoption generally comes at a cost the technology lags generally persist when both countries have reached their steady state (technology distance). The cost of technology adoption and the speed of diffusion determine this distance, and the research on tacit knowledge diffusion and important channels (migration, foreign direct investment, etc.) could have the potential to improve these. More importantly however, the human capital composition should be the focus of attention as it directly affects the efficiency of adoption and innovation activities here. As Vandenbussche et al. and Di Maria and Stryszowski (2009) show, lagging countries can benefit from promoting human capital accumulation on the primary and secondary level which has the strongest effect on adoption. Only in innovating middle- and high-income countries does the tertiary education becomes of high importance. Acemoglu, Gancia and Zilibotti (2012) point out that this specialization in adoption also carries danger through power-concentration mechanisms, which have be considered.

4 EMPIRICAL STUDIES

The models presented have been studied empirically as well and some noteworthy results are discussed in this section. The chapter follows the same build-up as the last chapter where first some context is given, then models that do not rely on inherently slow or costly technology diffusion are discussed, before turning to models that assume technology diffusion is costly or slow. Throughout this chapter the roles of human capital and the DTF are highlighted.

The main question remains: How do PGK and TK based models differ in their approach and the role of human capital and the DTF in explaining international technology diffusion? Empirically those models are tested against the real world income data observed and the productivity differences implied. What the models need to explain are both widespread and persistent income differences in level terms, growth miracles (as in East Asia), and the Krueger-Lindahl puzzle: The effect of human capital is not always measured to be positive and not uniform across different country samples.[38] Originally this meant testing the different models (usually neoclassical growth versus endogenous growth, however this models have been enhanced significantly now) and comparing their explanatory power. Another approach to decomposing the effects of technology and inputs is to choose a functional form for the aggregate production function, and then decompose the variance in output per worker into a factor accumulation and a technology part. Caselli (2005) provides a good overview over this field of *development accounting*. He himself clearly dismisses factor differences as the main explanation for observed income differences throughout the world. He summarizes the existing empirical literature in the field and shows that the general consensus also favours technology over factor endowments for explanatory power. He attributes about 50% of the differences in income to technology differences. The factor-only models (without technology differences) seem to work best for comparisons between rich countries (up to 50% of log income variation explained) but do not work when poor countries are included. Hsieh and Klenow (2010) find that human capital differences account for 10-30 percent of cross-country income differences, physical capital differences for 20 percent and TFP for the largest part of 50-70 percent. They also point out that much of the TFP differences could be due to inefficiencies (e.g. due to capital misallocation), caused for instance by political effects in credit markets.

[38] Krueger and Lindahl (2001) find a puzzling pattern in their panel analysis of economic growth. In their data they show that education only has a significant positive effect on subsequent growth for the countries with the lowest education levels.

4.1 Public Good Knowledge Based

4.1.1 Human capital Accumulation

As explained the refined neoclassical models imply only conditional convergence in growth rates. This makes them hard to dismiss as they have similar implications as club convergence models or other models with multiple steady states for long-term trends. Mankiw, Romer and Weil (1992) estimate their human-capital-enhanced Solow model with data for a large sample of countries in 1960 and 1985. While overall convergence is not observed in their data, they do find evidence for conditional convergence, i.e. convergence if the differences in their investment rates in physical and human capital and population growth are controlled for. In the OECD sample growth depends negatively on initial income levels. This concurs with the theory that countries converge to different steady states. Islam (1995) studies a large panel of data and finds even stronger evidence for conditional convergence when controlling for more other effects – this counterintuitively hollows out the convergence implication, as more and more countries converge to their own steady state.

However, the evidence on human capital accumulation as the sole driver of economic growth is pretty clear: It cannot explain the vast income differences observed without being enhanced in one of the three ways described in the following chapters. The growth accounting exercises described above make it clear that diffusion lags need to be explained within this framework or through tacit knowledge mechanisms. The evidence on human capital as a driver of economic growth is also somewhat mixed as explained in the following chapters. The considerable opposition to the neoclassical view that differences in schooling and capital accumulation includes these papers: Easterly and Levine (2001) estimate that 60% of cross-country differences in GDP p.c. growth rates are due to productivity growth differences. Klenow and Rodríguz-Clare (1997) even estimate the same ratio at 90%.

Many researchers also suggest that the effect of human capital differs for different types of education and a different DTF, and that these two terms interact (the Krueger-Lindahl puzzle). This lack of robustness is stressed in Madsen's (2014) overview. Sianesi and Van Reenen (2003) also discuss the empirical literature on the impact of human capital on macro-economic performance and find that the evidence that human capital increases a country's productivity is strong, but not necessarily for overall human capital levels and growth rates. Especially for the OECD subsample neoclassical growth struggles to provide meaningful explanatory power. There, only tertiary education levels increase both the productivity level and growth. The first finding they mention, however, is that the effect of education seems to vary depending on the distance to frontier of the country. For the sample of all countries they favour neoclassical Barro (2001) style growth models over endogenous growth models. They find that human capital also seems to have indirect growth effects via innovation and adoption. The DTF models that address these issues are discussed in chapter 4.2.

For all these models the human capital data is of pivotal importance. And its measurement has been discussed and changed countless times. De la Fuente and Doménech (2001) revisit the neoclassical growth models with such a revised human capital dataset. Their dataset includes fewer spikes in human capital growth rates and gets rid of a lot of noise (and negative human capital growth rates). With this data they find that the human capital growth rate no longer has a negative effect on growth. With a slightly different model they also estimate how much of observed differences in growth rates are due to factor and how much are due to TFP differences. They find that the importance of TFP differences as an explanatory variable has increased over time from around 30 percent in 1960 to 50 percent in 1990. With that estimation they lie between the extremes of Mankiw et al. (1992) and Caselli et al. (1996) who estimate a much larger importance of factor endowments and TFP differences, respectively. Hanushek (2013) finds that while school attainment in developing countries has greatly increased, schooling quality is still poor. This results in little difference in cognitive skills compared to the large differences in schooling. Human capital might be overestimated by schooling attainment. This is an effect already mentioned in Barro (2001).

In the end one can also question the direction of the human capital to growth effect: Bils and Klenow (2000) suppose that reverse causality might cause the human capital to growth link found in empirical research. They build a model where anticipated growth reduces the effective discount rate and increases the demand for schooling, since the payoff to education is higher in a growing environment. They estimate that the effect of schooling on growth – even when accounting for technology adoption – cannot explain more than a third of the observed schooling to growth relation.

4.1.2 VINTAGE HUMAN CAPITAL

The vintage human capital theories attribute the slow diffusion of new technologies to the persistence of vintage *human* capital, which often also complements vintage physical capital. Usually such theories assume that the human capital is gained by using the technology through learning-by doing as in Chari and Hopenhayn (1991), Brezis, Krugman, and Tsiddon (1993) or Jovanovic and Nyarko (1996). When updating to a new technology this human capital is (partially) lost. As Comin and Hobijn (2004) state there is evidence supporting these theories in industries with big revolutions such as shipbuilding or textiles. However it is also contradicted by evidence in industries with slight revolutions such as steel production (from Bessemer to BOF steel production) with relatively small innovations that were still not adopted instantly. Klenow and Rodriguez-Clare (1997) analyse whether workers in poor or in rich countries accumulate more experience at work. The longer life speaks for a stronger effect in rich countries, but workers in rich countries also spend more time in school meaning less time to accumulate work experience. They find the second effect to dominate. This means that including work experience in factor accumulation models does not seem promising when trying to explain cross-country income differences. Also one would observe *leapfrogging* by lagging countries that make an earlier switch to a new technology, since they have less human capital to lose, and are then able to overtake a previously leading country. Essentially one would expect a negative correlation between GDP and technology adoption rates of new technologies, which is not the case.

4.1.3 Appropriate Technology

In a different attempt to explain the slow diffusion of technology, Basu and Weil (1998) introduce the idea of technology inappropriateness as a factor that keeps lagging countries from adopting frontier technology that would actually be available to them. Their empirical work is designed as a direct response to the enhanced Solow model by Mankiw, Romer, and Weil (1992). As shown, their model has very similar predictions, but very different mechanisms and policy implications. In their model there is conditional convergence as the lagging country can exploit more technologies than the advanced economy. The savings rate (reflecting overall economic policy) is also still an important positive determinant of growth, since the capital intensity is the key to technology access for poor countries.

Los and Timmer (2005) analyse Basu and Weil's model empirically by decomposing technological advance into three distinct processes: Assimilation (getting more productive at a given capital intensity), creating potential (increasing the capital intensity, or *capital deepening*), and localized innovation (increasing productivity at a given capital intensity). They find that increasing the capital intensity[39] provides you with growth opportunities, but since the cost of assimilation can be high later on it is not clear if that is always beneficial. With these adoption costs, which they find to possibly also depend on human capital, they

[39] As mentioned by Acemoglu and Zilibotti capital intensity is only one possible measure of appropriateness. Interestingly Caselli and Coleman (2001) show that the effect of language compatibility (think of English software for non-English-speaking countries) on the cost of new technologies (in their case computers) is negligible.

closely link their research to the tacit knowledge based DTF research. Kumar and Russell (2002) empirically analysed technological progress in the same way and found evidence that most countries benefit from a catch-up effect towards the productivity frontier. But this does not lead to convergence as this is true for rich as well as for poor countries. Technological advance on the other hand is clearly benefitting capital-intensive economies, countering the catch-up effect as well. Their main conclusion is that increasing the capital intensity was the main contributor to growth and technology diffusion. Jerzmanowski (2007) also confirms the appropriate technology findings proposing that most countries could benefit from increasing their capital-labour ratio and using more modern technologies. He also finds that most countries suffer from inefficiencies and operate well below the best practice world technology frontier at their capital-labour ratio. He finds that overall and at the moment inefficiencies seem more important than technology. In this context an interesting question is also if capital is allocated efficiently around the world, given the local skill endowments. Caselli and Feyrer (2007) analyse cross-country differences in capital-labour ratios and find that the calculated marginal product of capital is relatively constant across countries despite widely different capital labour ratios. This is an indication that capital is allocated efficiently across countries. Caselli (2005) finds that allowing for appropriate technologies decreases the importance of factor endowments significantly, since countries can choose a technology to match their endowment instead of being forced to use frontier technology. This makes it harder to explain the vast income differences observed only through differences in factor endowments.

4.1.4 BARRIERS TO TECHNOLOGY DIFFUSION

Prescott (1998) identifies total factor productivity differences as the major source of differences in output per worker on a global scale. But he also assumes technology to be (almost) a public good: With some minor adaption costs these innovations are available worldwide. But for some reason not all countries fully exploit the available knowledge. He tests a neoclassical growth model that includes human capital and finds that the differences in savings rates cannot explain the large productivity differences observed today. The same goes if he adds a training sector to the model, because the implied time spent on education is implausibly large. In his view this means that there must be other factors hindering technology adoption. He shows examples where industries had resisted the use of new, more efficient technologies because of opposing incentives (e.g. political, unions) or low competitive pressure to do so. Prescott arrives at the conclusion that there have to be either technological differences between countries or factors negatively affecting the diffusion of technology – barriers to technology diffusion. There are many empirical studies that do not heavily rely on human capital, but instead on politics or institutions: Acemoglu (2012) lists countless examples of political structures that contributed to growth or failure of nations. Restuccia and Rogerson (2013), and Hsieh and Klenow (2010) point to misallocations of factors between sectors and industries potentially caused by political influence as large sources of productivity disparities. Banerjee and Duflo (2005) point to credit market imperfections. Mayer-Foulkes (2015) points to increased market power of globalised firms that spreads into politics.

4.2 Tacit Knowledge and Technology Differences

As mentioned before TFP differences account for the vast majority of income differences between countries. These productivity differences are straightforward to explain if technology diffusion is slow or costly. Countries have access to different sets of technologies and therefore differ in their productivity. Most technology diffusion studies linking technology diffusion to human capital and the DTF analyse TFP or income differences compared to foreign measures of productivity. The most important finding in this relationship is that the effect of human capital is in fact dependent on the DTF of a country. Some models focus on the effect of average human capital, while others put more weight on the composition of human capital. They are discussed in two separate chapters that follow.

First let's recall the sinking adoption costs model by Barro and Sala-i-Martin (1997) or Parente and Prescott (1994) where adoption is cheaper farther away from the frontier because of cost heterogeneity and a larger selection of new technologies to choose from. This model would imply a positive DTF term independent of human capital. This is rejected in by Madsen (2014) in his study. In an interesting paper on the subject of innovation costs that is not looking at adoption for lagging countries but instead at innovation, Ang and Madsen (2015) analyse a Schumpeterian growth model with a large set of panel data, and find that innovation, as in the creation of ideas, is significantly more expensive in countries behind the technology frontier.

Comin and Hobijn (2004) follow a different approach and separate their dataset along two axis: The *cross-sectional variation* (do leading or lagging countries adopt it first) and the *time variation* (does it take the country a long or short time to adopt a new technology). This gives them four distinctive model groups with different predictions that can be checked empirically. They study the diffusion process of 25 technologies across industrialized economies. They find that technology typically originates in frontier countries and then follows a slow trickledown diffusion process to the laggards. They also confirm that human capital has a positive effect on adoption rates, but find a negative effect for the DTF.

Time variation: How long does it take for a new technology to dominate existing ones?	*Cross-sectional variation*: What type of country invents and adopts new technologies first?	
	Rich countries/leaders	Poorer countries/followers
Long/locking	• GPT with complementary innovations (Helpman and Trajtenberg, 1998)	• Vintage human capital (Chari and Hopenhayn, 1991; Brezis et al., 1993)
Short/no locking	• Innovator–imitator models (Barro and Sala-i-Martin, 1997; Eeckhout and Jovanovic, 2002) • Technology choice with technology skill complementarities (Jovanovic, 1998; Hobijn, 2001) • Appropriate technology (Basu and Weil, 1998) • Barriers to riches (Parente and Prescott, 1994,1999)	• Vintage physical capital (Johansen, 1959; Solow, 1960; Gilchrist and Williams, 2001; Laitner and Stolyarov, 2002)

Figure 6: Two main dimensions of growth theories evidence by Comin and Hobijn (2004, p. 44)

Interestingly they find that the diffusion model that fits their findings best is the General-Purpose-Technology (GPT) model as described by Helpman and Trajtenberg (1998). A GPT can be used in many sectors but when arriving exogenously first gets adopted by sectors with low adoption costs and the highest expected rewards from complementary innovations. Other sectors then follow slowly. However this model might be more accurate for the specific technologies analysed than technology on a macroeconomic level. It lacks factors that explain why adoption and convergence is slow on a global scale.

4.2.1 AVERAGE HUMAN CAPITAL AND THE DISTANCE TO FRONTIER

Barro (2001) finds growth to be positively associated with initial levels education, especially when accounting for the quality of education via international test scores. Benhabib and Spiegel (1994) find that when including the initial productivity (here income) lag the sign of human capital turns positive and significant, indicating a role in the catch up process. They use their new model to differentiate between the innovation and the adoption process and do indeed find that for the poorest third of countries the catch-up term (human capital times DTF index) is positive and significant, while the innovation term (human capital) is negative and insignificant. For the middle third they are both insignificant and small. For the rich countries the catch-up term is low and insignificant and the innovation term relatively high and significant at the 6% confidence level. All of this paired with the fact that their findings are robust against the inclusion of the initial income level (measuring a non-human-capital-specific catch-up effect) indicates the importance of these two distinct processes of technological progress based on human capital. Benhabib and Spiegel also find that human capital attracts physical capital (plausible if it increases the productivity of physical capital), and renders political instability and income distribution. Since physical capital accumulation is of high importance for productivity the first finding is of utmost importance. The second finding also makes for an interesting extension. But both are directly related to technology diffusion.

Griffith, Redding, and Van Reenen (2004) study the effect of R&D and human capital on innovation and technology diffusion in OECD countries. They find that human capital is stimulating the absorptive capacity and innovation. They also find that R&D stimulates both of these processes. They suggest that poor countries[40] could have a high social (not private) return from R&D through this mechanism. Acemoglu, Aghion and Zilibotti (2006) analyse the same dataset. They find that industries close to the technology frontier (defined on a sectoral basis here) invest more in R&D and this effect is reinforced if the country is closing in on the frontier. Then they split their dataset into two groups of countries: Low-barrier and high-barrier to competition. The hypothesis they have in mind is that for countries far from the technology frontier selection is unimportant and adoption-based growth is more promising. The catch-up effect is thus stronger in high-barrier countries but it also slows down faster and stronger as the country approaches the frontier, since low-barrier countries benefit from more innovation there. These hypothesises are confirmed in the data they analyse. This thus leaves us with a credible channel of technology diffusion linked to human capital in heterogeneous managers.

4.2.2 Human Capital Composition and the Distance to Frontier

As introduced before, it seems quite plausible that human capital in an economy works as a catalyst for technology diffusion towards a country that is behind the world technology frontier. In their survey of empirical literature Sianesi and Van Reenen (2003) find clear evidence of varying effects from different education levels depending on the country's DTF. In particular they also find that there is a need to differentiate between different levels of education. Primary and secondary education seem to have strong growth effects in the poorest and intermediate developing countries. In developed countries however it is tertiary education that leads to growth.

[40] Keep in mind that these are poor OECD countries, thus middle income countries at minimum on a global scale.

Ang, Madsen, and Islam (2011) empirically test a panel of 87 countries from 1970-2004 for different effects of primary and secondary versus tertiary education. The hypothesis in accordance with the theoretical foundation by Vandenbussche, Aghion, and Meghir (2006) is that tertiary education is more beneficial close to the frontier. While the hypothesis was tested before for high-income countries they expand the horizon to low- and middle-income countries. The hypothesis is confirmed and tertiary education has a positive and significant effect on growth only in middle- and high-income countries, while primary and secondary education do not. For low-income countries the effect of the DTF is positive but no type of education has a significant coefficient. For all countries together only primary and secondary education are positively and significantly associated with growth, and the DTF coefficient (independent of human capital) is still positive and significant. Their conclusion is somewhat pessimistic in that for low-income countries, no kind of education seems to have a positive effect on technology diffusion. They suspect that this is due to the low quality of education provided and the inability of students to profit from classes due to sickness and stress. Islam, Ang, and Madsen (2014) then calculate a similar model again using quality-adjusted measures of human capital instead. They find that the quality-adjusted human capital and its interaction with the DTF are essential for growth. They also find that the social return to quality improvements in education are highest in countries where education is the longest, thus giving way to a development trap mechanism for countries with little average education. Other researchers have analysed the same effects on a single country basis: Pereira and Aubyn (2009) for example find that for Portugal, from 1960 to 2001 only primary and secondary schooling were growth promoting, while tertiary education did not have such an effect.

Krueger and Kumar (2004) test their own model that makes the efficiency of the education level conditional on the growth environment against European and US data and find that tertiary college-oriented education becomes increasingly important in a high-growth environment.

Benhabib and Spiegel (2005) test the functional form of the human capital to growth relation. They find that a logistic form, which allows divergence if the lagging country is below a critical human capital level is favoured over an exponential form that does not allow for this. Their model favours the catch-up channel as a source of this effect over the direct effect of human capital, which shows less robust effects.

It is not clear if the effect of the average human capital in an economy on technology diffusion is linear. Gille (2015) for instance summarizes different studies about the effect of education inequality on growth. She herself analyses data for Indian states and finds that education inequality is positively associated with income per capita. The relationship seems to depend on the DTF.

4.2.3 Channels of Technology Diffusion

Based on the short extension to chapter 3 on important channels of tacit knowledge diffusion or movement of human capital, this chapter will hint at some interesting empirical work in that field as well. For a brief introduction see Keller (2004) for instance. Ang and Madsen (2015) also attribute an interestingly large role to technology spillovers via imports and foreign patenting, in addition to the confirmation of the finding of a human capital to DTF link in technology diffusion. Contrary to Keller and Yeaple (2013) they do not find that geographical proximity is an important determinant of technology diffusion.

4.2.3.1 Foreign Direct Investment

The empirical research on foreign direct investment (FDI) is especially vast. Only some select works are mentioned here. As Radosevic (1999) documents FDI is clearly a very powerful way of intentional technology diffusion. He quotes multiple sources saying that international revenue occurred for the vast majority between subsidiaries and parents of international firms, and not unassociated firms.

The question then is whether local firms can benefit also from the technology imported by the foreign firm, whether the tacitness of foreign technology can be circumvented. Borensztein, De Gregorio, and Lee (1998) find support for that hypothesis in their panel data analysis, but only if the local country has a sufficient level of human capital. Aitken and Harrison (1999) find positive effects on growth but negative effects on local competitors in their panel analysis of Venezuelan firms. Keller and Yeaple (2009) find strong positive effects of FDI from foreign firms in the US. They find that spillovers are strongest in high-tech sectors (bad news for poor countries) and for small, unproductive firms (good news for poor countries). Contrarily, in their analysis Aghion et al. (2009), who analyse a frontier economy (the UK) for the effect of foreign direct investment on the incumbent firms, find that firms in sectors that operate close to the technology frontier (the US equivalent) tend to show productivity growth if entry of foreign firms is high. Firms farther from the technology frontier on the other hand show decreasing productivity growth with higher entry. The rationale behind this is that the firms close to the technology frontier can invest in R&D and beat the international competition by moving close or even beyond the current technology frontier, while unproductive firms “give up” on productivity improvements as they have no chance.

Borensztein, De Gregorio, and Lee (1998) find that FDI is an important and potent channel of technology diffusion, but only works if the host country has a sufficient amount of human capital.[41] The stock of human capital works as a determinant of the *absorptive capability* of the host country for foreign technology. They also find that FDI has a positive effect on domestic investment of other firms, indicating that firms can benefit from working together with the new subsidiary more than they are hurt by its presence. This effect is not very robust, though.

Regarding the model of Fosfuri, Motta, and Rønde (2001) on worker mobility as a channel of FDI spillovers discussed before, Görg and Strobl (2005) find support for this hypothesis in their analysis of manufacturing entrepreneurs in Ghana. Keller and Yeaple (2013) test their hypothesis themselves and find support in US firm-level data.

As we can see it is difficult state whether FDI leads to technology diffusion. Overall the evidence seems rather positive on some growth effects on FDI. However it is not clear if this is due to market incentives or technology spillovers.

4.2.3.2 Migration

Di Maria and Lazarova (2012) find that the recent immigration policy changes in OECD countries – the targeting of the best-educated – negatively affects the sender countries: It distorts the human capital formation incentives as discussed in the theoretical part. Beine, Docquier and Rapoport (2008) study their brain gain hypothesis and find that it holds true only for a small number of countries. Docquier and Rapoport (2012) find contradictory evidence and state that high-skill emigration can generate positive network effects for the home country.

[41] They find that the threshold value of human capital is less than 1 year of post-primary education for the FDI effect to turn "positive" (when the effect of the positive interaction term FDI x Schooling becomes stronger than the negative effect of FDI variable). Around half of the 69 countries in their sample reached that threshold, with the exact figure depending on the exact regression specification. The finding is robust to different control variables, including regional and political dummy variables.

5 CONCLUSION

There exist many credible models that link technology diffusion to human capital and the DTF. Both models that assume knowledge to be a public good and models that assume knowledge to be tacit can explain the income differences and only partial convergence tendencies observed across the world to some extent. PGK models abstain from country-specific technology levels and draw on differences in factor endowments as explanatory variables. Technology diffusion in this view works by accumulating the factors necessary to access and actually use the technology already available. Depending on the assumptions regarding capital accumulation, technological progress and appropriateness of technology these models can imply absolute convergence, conditional convergence or even divergence. The main basic models are the Mankiw-Romer-Weil model and the Lucas model of human capital externalities. Their approach has been further refined by including the notion of technology appropriateness and barriers to technology adoption, as well as the possibility of technology-vintage-specific human capital. With these mechanisms it can be explained why different technologies are used in different countries, although all countries would have access to the same frontier technology. In this framework, all countries should look to increase incentives for factor accumulation (foreign investment, savings, education), encourage the use of appropriate technology, and reduce barriers to technology adoption. The goal has to be to reach the steady state faster and if possible increase the steady state level of growth. Advanced economies can serve as a model for this for the longer term.

The empirical analysis, however, favours models that assume total factor productivity differences between countries. Those are the TK based models with a restricted access to the world technology frontier. Those models attribute only a minor role for factor endowments in explaining current income differences. They assume that technology diffusion is slow and costly. Contrary to PGK models they advocate a different role of human capital in countries that innovate, than in countries that adopt. As a consequence, countries with a high DTF should exploit the advantages of cheap technology adoption and adjust their education policies accordingly. For instance, many of them argue that a basic primary, secondary, or vocational education is very important for building up an absorptive capacity that allows lagging countries to actually adopt technology developed elsewhere, tertiary education is much more relevant for middle- and high-income countries that have a more innovation-oriented economy. Such mechanisms mean that growth-enhancing policies for lagging economies differ substantially from the ones for advanced economies. For instance one could think that it makes sense to subsidize education in accordance with this goal. This recipe is one example of such a policy that seems to have been a success South Korea as discussed. It is certainly an interesting direction to analyse more cases of practical implementation of such policies to gain additional insight.

The growing evidence that technological progress seems to be biased towards capital and high-skilled-labour intensive technologies, raises interesting questions: How can technology advancements be better targeted at non-frontier economies? What role can intellectual property protection play? As Gancia, Müller, and Zilibotti (2011) and others have suggested the lack of IPR protection in lagging countries could actually cause lower technology diffusion since the technology is not appropriate, and technology standardization or adoption is costly.

Policy makers looking to exploit the growth potential of a high DTF paired with an adequate human capital strategy should then also have sufficient foresight to anticipate potential trap mechanisms of a too heavily adoption focused economy when reaching middle income as pointed out by Acemoglu, Gancia and Zilibotti (2012). The two engines of growth: Innovation and standardization (or adoption) are both viable engines of growth, but not at every stage of development.

To conclude it became clear that there are many different ways to model technology diffusion. There is convincing evidence that human capital plays an important role in the catch-up process of lagging countries, and that its composition is also of importance. Recommendations for human capital policies should consider the DTF as an important determinant as well. It would be very interesting to see more case studies and the practical, not necessarily economic, problems associated with the implementation of a growth-maximizing human capital strategy. It will also be interesting to see the further research on the intellectual property rights, innovation and adoption discussion that is currently heating up on an international level.

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