Technology Transfer Through Trade

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Technology Transfer as an Additional Benefit from Trade – A Theoretical and Empirical Assessment

Summary

This paper examines the role that trade plays in economic development through the channel of technology transfer, approximated by total factor productivity. Three strains of factors influence the process of technology transfer; direct effort that is taken to transfer technologies, the capacity to adopt technologies, and differences in the underlying conditions between donor- and receiving countries. In this context, trade in (capital) goods allows technology import and improved input decisions. Second, trade opens export markets, allowing learning-by-doing. Third and most importantly, trade increases the set of accessible technologies, increasing the scope for imitation. The theoretical insights are compared to the empirical literature that deals with trade and technology transfer. Not surprisingly, it turns out that openness and human capital have a positive influence on the transfer of technology. Yet methodological problems with the data weaken the practical significance of the results, especially as the precise and fundamental mechanism of spillovers and the factors that condition the degree of technology transfer are not profoundly illuminated. These underlying processes have to be better understood in order to be able to give valuable policy recommendations that will go beyond the general advice of increasing openness and human capital formation.

Keywords: Technology transfer, Trade, Economic growth, Total factor productivity

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The text represents the author's personal views and is not to be seen as an official position of the Institution.

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1 Introduction

This paper defines technology transfer as technology diffusion between economies. While Vernon (1966) and Krugman (1979) simply assumed technology transfer in their articles, this paper focuses on the factors that influence it. Taking the importance of technology for economic growth into consideration,[1] technology transfer is of utmost importance for output growth and the catching-up process of developing countries, especially as nearly all R&D activity takes place in industrialised countries.

Technology transfer refers to the arrival or the transfer of a certain technology to a country, where it has not been used before.[2] In most cases, this process will be intertwined with a process of adaptation due to different demands on the produced good and/or the production environment, such as input prices and existing ways of problem-solving. Also the utilisation of a certain technology in a similar context for the production of another good is regarded as a transfer of technology with adoptive action. Together with subsequent national diffusion and wider utilisation of this technology, technology transfer works in increasing a country's Total Factor Productivity (TFP). It will be difficult to distinguish the two mechanisms within the data, as their effects are identical. Technology transfer in this context describes both transfer to countries that did not use that technology before and subsequent diffusion within that country, therefore, the terms technology transfer and technology diffusion will be used as interchangeable terms in the following. This paper will commence with defining some important terms before turning to the factors that determine technology transfer. Next, the theoretical mechanisms of technology transfer will be described. Subsequently, the results of empirical studies on technology transfer will be summarised while the concluding section will compare the theoretical to the empirical results and evaluate them.

2 Some Central Terms and Concepts

Technology and techniques

Technology is created by controlled inventive action following profit incentives and is used as an input into production. It is in general a public good but the degree of complexity and practicalities of its use as well as patent rights increase its degree of excludability largely. First, technology is never fully expressed by the descriptions about the needed material inputs, as Pietrobelli (2000) argues. Technology contains a tacit element, knowledge that is not readily describable or codifiable such as the way how to use a certain equipment efficiently. These tacit elements can not easily be transferred but are of crucial importance to the proper functioning of the technology and the choice of the used techniques. With regard to patent rights, Eaton and Kortum (1999), argue that protection takes mainly place in the inventor's home country and to a much smaller degree in foreign countries. Under these circumstances, technology transfer of good designs can take place legally as long as the transferred technology is only used in the imitating country. As markets in developing countries are generally larger for low-tech goods, this might lead to more imitation of less sophisticated technologies.

Every technology can be operated with a wide range of techniques. While technology refers to the general idea, machinery or blueprint, techniques refer to the way this technology is actually used. The choice of the appropriate techniques can depend on factor prices and differing needs of output. Even though a technology might be existing in a country, it is not necessarily the case that users of this technology are aware of the technique that is appropriate in their special position due to the tacit knowledge that forms part of the technology. As a result, technology might not be used effectively, as Clark and Feenstra (2001) point out. The process of acquiring the appropriate techniques forms the second important step in technology transfer after the basic technology has been transferred. Technology and human capital both increase the effective use of capital and labour inputs. To the degree that increases in human capital are not observable or measurable, such as learning-by-doing and experience, its effects will most likely be picked up by TFP. As a result, this element of human capital is analysed as part of technology transfer, an idea that is also implicitly contained in Bernanke and Gürkaynak (2001) and that is in line with the argument of Lloyd-Ellis and Roberts (2002) who emphasise the interactive working of technology and skills.

Inventing activity does not only take place in research labs or as a controlled and planned action (primary inventions described by Young (1991)). A second set of inventions exists, being equally important in the determination of TFP. These so-called secondary inventions can be described in various ways and they include the concept of learning-by doing (Arrow, 1962), dynamic learning (Radosevic, 1999) or learning-to-learn (Connolly, 1997). Secondary inventions relate to primary inventions as do techniques to technologies. While the primary invention describes the conceptual technology, secondary inventions refine this technology and improve its efficiency. Secondary inventions are based on experience and are a by-product of final goods production. Their effects on TFP are nevertheless substantial and we will assess their importance in technology transfer. There exist three kinds of inventive activity. One is of quality-improving nature, the second deals with the invention of new goods and the third form is of cost-reducing nature.

Human capital

Human capital is used as an input into production but also fulfils a crucial task in the creation and adoption of technologies. The stock of human capital is influenced by primary, secondary and tertiary education, vocational education, on-the-job-training and by work-experience but also social capabilities and health aspects of the workers can influence the efficiency of the workers. In a recent attempt to better and more accurately quantify human capital stocks in different countries, Barro and Lee (2000) take the completion of "education-levels" as well as average schooling years as the central indicators of human capital. They also correct for quality while leaving out other factors such as on-the-job-training and work-experience, which increase human capital, as for example Lucas (1988) argues.

Measurement of absorption and quality of education (see Lloyd-Ellis and Roberts, 2002) is difficult and human capital estimation using wage as done by Gollop and Jorgenson (1980) and Mulligan and Sala-I-Martin (1995) (cited in: Barro and Lee (2000:16-17)) is difficult and can conceptually run into problems (see e.g. Muysken, Rieder and Hoppe (2002)).

Conceptually, it can be said that human capital includes all knowledge that is embodied in human beings and that is relevant for production and technology creation. In this light, the paper by Barro and Lee (2000) leaves the reader with a greatly improved measure of human capital. Work-experience and on-the-job-training, however, are hard to include and it will therefore be likely that these improvements of human capacity will be rather accrued to TFP when output growth is analysed. This has to be taken into account, however, when analysing the effect of technology transfer on TFP growth.

Models of knowledge creation acknowledge the importance of human capital, either directly (Romer (1990) or through intermediate inputs (Rivera-Batiz and Romer (1991)). Aghion and Howitt (1998) point towards the fact that more sophisticated intermediate inputs into knowledge production increases research efficiency. Eaton and Kortum (2001a) indicate that it is the amount of researchers and the research efficiency of a country that is of crucial importance for knowledge production. The role of human capital in technology adoption will be dealt with in the section dealing with "technological capabilities".

Total Factor Productivity

The effects of technology are usually captured in the applied literature by total factor productivity. This measure captures the effectiveness of all used inputs and comprises technology and other unobserved factors such as institutional structures. Technology increases the output that can be generated with a given set of inputs. The empirical literature usually analyses TFP as measure for the level of technology within a country, its distribution varies widely between industrialised and developing countries.

It is difficult to make general statements about the development of TFP-levels in developing countries. Calculating them as a residual as in the growth accounting approach, Hall and Jones (1999) report productivity levels for 127 countries in relation to the productivity of the United States using data from 1988. They find that the average productivity of these countries equals 51.6 percent of the US-value with a reported standard deviation of 32.5. The values range from 120.7 percent for Italy and 112.6 percent for France to values as low as 10.6 percent for China and 16 percent for Zaire. These numbers show the huge disparities of TFP between countries.

Coe, Helpman and Hoffmaister (1997) report the development of TFP levels for 77, showing that large differences in development exist. While ten countries experienced an increase of more than 50 percent of their TFP from 1971-1990, another set of twelve countries saw their TFP fall by 20 percent and more. In total, TFP decreased for 37 out of the 77 countries during this time period. Regional differences in TFP development are clearly visible. While the Middle Eastern and European countries experienced an average productivity growth of 46 percent during these 19 years, the countries in the Western Hemisphere actually lost 5 percent of their productivity on average. Without surprise, also the dynamic East Asian economies experienced strong TFP growth of 58 percent over 19 years, representing an average productivity growth rate of 2.4 percent, a figure roughly in line with the analysis of Young (1995). Klenow and Rodríguez-Clare (1997) find similar results.

Measurement

Technology is difficult to measure as the process of technology production is not linear. Inputs do not directly translate into technology and not all outputs are observable (secondary inventions, production processes, non patenting), constraining both methods of assessing the stock and creation of technology. Moreover, the rate of knowledge decay is difficult to assess and unobserved factors might blur the picture. Usually, a growth-accounting approach is used when assessing national technology stocks. In this case, the productivity effect of changes in the input-composition as well as the effects of all non-described inputs or effects of external changes will accrue to TFP. While producing some comparative explanatory potential, not only changes in the underlying productivity are reflected. There exists no generally satisfactory measure.[3] Changes in the exchange rate, oil-prices, positive or negative output-shocks, the rates of capital- or labour utilisation all can have an effect on the TFP-measure without reflecting any underlying change in real productivity in case these changes are not taken care of. Especially for developing countries the stock of human capital is likely to be overestimated, when enrolment rates are used as Islam (1995:1153) points out. Lastly, the labour market structure of many developing countries is characterised by a large informal sector (Allen and Thomas, 2000), leaving the TFP-measure represent the productivity of the formal sectors. Under these circumstances, the precise measurement of output and inputs becomes more difficult and measurement errors in TFP-values are to be expected such that they do not necessarily reflect the precise underlying theoretical value.

3 Theoretical aspects of technology transfer

The incentives for technology transfer lie, in parallel to technology creation, in competitive rewards while lacking the uncertainty aspect of technology creation. An adopter knows before imitating a technology that it is viable, while this is never clear a priori in the process of technology creation. Moreover, the costs are generally much lower (see e.g. Grossman and Helpman (1991a)). As long as the marginal costs of adapting another technological innovation are smaller than the expected marginal (monopoly) profits, inward technology transfer of this particular innovation will be worthwhile and firms will try to gain access and implement foreign technologies. The degree of product market integration and the size of transport costs influence the amount of technology transfer.[4]

Active efforts and inputs are needed for technology to be transferred.[5] Being closely related to technology creation (e.g. Teece (1976), cited in Wang (1989)), the same factors work also in technology transfer. R&D spending can be seen as an investment in the special form of human capacity to adopt technological knowledge and the amount of researchers increases the set of possible ideas, a fact that Eaton and Kortum (2001a) point towards in the context of knowledge production. As in the model of Wang (1989), R&D can interact with the size of the technology gap in increasing the amount of transferred technology. The effectiveness is also influenced by other important factors.

Technology's property of being largely non-excludable makes it prone to diffusion. When a design is not very different from an existing one, copying might not need many resources for being successful. This sort of knowledge diffusion stands central to the paper. Evenson and Westphal (1995) present a general form of a national diffusion model, based on Mansfield (1961). Diffusion takes place without underlying explanation but with a certain pace and it is precisely this lack of underlying reasoning that can be found back in most of the diffusion literature. While the gros of the literature takes spillovers to be automatic, Grossman and Helpman (1990) point out that the mechanisms by which these spillovers take place have been generally ignored. A precise model of the phenomenon lacks, even though some factors such as labour movements and vertical relationships might give some explanation (see Teece (1976), or Saggi (2000)).

The capacity to adopt

The capacity to adopt depends on a set of factors and is often referred to by termes such as "technological capabilities" (Wang, 1989; Lall, 1992) or "national absorptive capacity" (Movery and Oxley, 1995). It is normally assumed to be influenced by certain form of human capital, and experience with imitation. Human capital and particularly tertiary education is central in technology transfer. Trained workers largely influence the adoptive capacity of firms, reducing the costs of technological imitation or adoption. Gruber and Marquis (1969:268) also point out the importance of the kind of highly trained human capital and in particular the workers' experience and motivation.

In his influential paper, Sanjaya Lall (1992) describes the technological capabilities at the firm level as composed of three factors. Investment capabilities, production capabilities and linkage capabilities. He describes investment capabilities as the skills that determine the capital costs and allow the appropriate selection of projects, a sort of experience in investing. Production capabilities then describe the skills such as quality control or knowledge on how to adapt machinery that function in an efficient utilisation of the technology. The last set of capabilities as described by Lall includes the capabilities to transfer skills and technology from other actors in the economy. While these factors explain the degree of technology transfer by capacity, determination of these capacities is not clarified. Lall's argumentation should therefore be rather seen as supporting the importance of adoptive capacity in the process of technology transfer. All of these factors, however, are rather difficult to measure and to integrate into one coherent measure of human capital or adoptive capacity, as was already indicated. Human capital, in particular secondary and tertiary education, directly influences the adoptive capacity of workers, reducing the costs of adoption. This "adoptive" element of human capital is also influenced by the amount of experience with technology adoption.

In their analysis of the functioning of human capital in the growth process, Benhabib and Spiegel (1994) point towards the indirect effects of human capital on growth. In their eyes, the major contribution of human capital lies precisely in its strength to make workers better at "creating, implementing and adopting new technologies". They draw on the theoretical model by Nelson and Phelps (1966) who formalised the effect of human capital on technology transfer. Human capital, however, forms only one factor in this model, interacting with the technology gap.

While R&D spending directly affects the amount of technology transferred, it also works in increasing the absorptive capacity of a firm. Wang (1989:78) points out that firms use R&D not only to create new inventions themselves but also to increase their capacity to recognise, to understand and to use technologies developed abroad. This is also contained in Wang's model of technological capability where the change in technological capability, is determined by the resources that are devoted to transfer activity. While Wang sees investment as directly influencing the technological capability of a firm, Lall (1992) argues that national adoptive capacity is directly influenced by both the amount of research experience and the amount of technological success. Griffith et al. (2000) find empirical support for these factors, using industry-level data of 12 OECD countries.

As Pietrobelli (1998) and Lall (1992) argue, the national sum of technological capabilities exceeds the sum of firm-level capabilities due to interlinkages and externalities that arise from the accumulation of these technological capabilities such as scale and synergy effects. As firms most likely do not take this positive externality into account, a state can be active in investing in human capital formation, increasing productivity through the direct effect of human capital on output and indirectly via lower technology transfer costs and the resulting increased technology transfer.

Differences in the underlying conditions of countries

Countries that are "leaders" and "followers" differ in their level of technological development, their engineering history and the kinds of technology that are appropriate to the existing factor endowments. Of importance is the technology gap between the technological leader and the country that is trying to adopt technologies. On the one hand, a larger gap between the leader and the follower gives rise to more technologies that can be transferred (e.g. Wang (1989), Findley (1978), or Griffith et al. (2000)). However, these technologies must be accessible by the country that wants to imitate them. Trade acts in making formerly unknown designs available to actors in other countries. Due to the embodied nature of technology, this leads to the accessibility of more technologies to potential imitating firms.

On the other hand, the larger the gap, the more difficult the leading technologies are to be understood as for example Blomström and Sjöholm (1998) argue. If in this case adoption of older technologies takes place to a large degree as these technologies are closer to the level of technological development of the adopting nation, it depends on the speed of invention and adaptation whether the technology gap will actually in- or decrease. The two opposing views have some truth to it and it is difficult to decide which factor dominates. It can be said, though, that at least some technology transfer will take place. When the technologies transferred become older and older, the imitating country will never catch up in terms of technological development and due to the crucial role of technology for income per capita neither in terms of income. Taking the large correlation between income per capita and the technology level into account, Navaretti and Soloaga (2002) show that this scenario actually represents what can be observed in reality, using a sample of developing Central-Eastern European and Southern Mediterranean countries. The unit value of machinery (and therefore the complexity) imported by the developing countries constantly lags behind the unit value of machinery that the United States are importing, leading to a consistent and increasing technology gap.

As e.g. Eaton and Kortum, (1995) argue, distance has a large influence on technology transfer. Taking account of trade intensity should remove this factor as the increase of the knowledge pool through trade should not depend on geographical distance. Still, the compatibility of culture or machinery of the receiving and the transferring country can be important. Technologies must be compatible and different approaches to the same problem might exist in different cultural backgrounds. Therefore, imports from culturally distinct origins might increase the knowledge pool with technologies which are more difficult to adopt within a certain technological background as compared to ideas that were developed in countries belonging to the same cultural background. Long-during trade relations lead to an equalisation of existing sets of technology. While geographic distance can explain some of these intense trade relations also historical relations with certain nations can be seen as determining factor. This idea gains some support when analysing the rates of return of industrial countries' R&D spending to developing nations (see Coe, Helpman and Hoffmaister, 1995). While the United States as technological leader have a very important influence on nearly all developing countries, the relative importance of other countries for certain nations differs. Comparing the effect of Japanese R&D on different countries, it can be seen that its effect is larger for China, Korea, Singapore, Hong Kong, and Kenya when compared to other countries. While the first four countries lie in the proximity of Japan, Kenya is a very important trade partner of Japan and receives large assistance from Japan.[6] This indicates that Japanese R&D has a relatively larger effect on culturally and historically related countries.

A similar pattern can be found, when analysing the former British Colonies. While British R&D spending in general has a lower rate of return to African countries then does German or French R&D spending, Zimbabwe, Uganda, and Kenya benefit clearly more from British than from the former' spending. India also benefits strongly from British R&D spending. The same sort of colonial ties can still be observed in the return of French R&D spending on Cameroon's output. While cultural closeness does not fully explain the observed pattern, it nevertheless helps in intuitively explaining large parts of it.

Complexity of technology and skill-levels

This section deals with the complexity of technology and the (in)compatibility of different skill-levels with a certain technology that Acemoglu and Zilibotti point out in their (1998) seminar paper. Here, they construct a model of two regions, one being rich in skills (the North) with the other (the South) lagging behind and being poor in skills. Only the North is investing in R&D and they can develop machineries to their needs. The authors assume that the utilisation of skill-intensive machinery with unskilled labour leads to lower productivity (see also Lall, 1992:168). This means that machinery might be so complex that imitating firms cannot reap profits from using them as the labour input they have at their disposition is lacking the appropriate skills. Therefore, less technology will be transferred. Moreover, the technology that is transferred and operated with sub-optimal labour input will lead to a lower TFP increase than an identical transference with qualified labour input would generate. Basu and Weil (1998) point to the importance of the appropriateness (in terms of capital-labour ratios) of the existing technology. In line with Acemoglu and Zilbotti (1998), this leaves most high-quality technology inappropriate for utilisation in developing countries. Their idea is supported by the arguments of Evenson and Westphal (1995), arguing that not only differences in factor endowment but also differences in physical, economic and social conditions affect the value of technologies and therefore its appropriateness. While this effect is not empirically quantified, the idea of appropriateness should be kept in mind, when analysing technology transfer.

As Lall (1992) points out, firms have knowledge of the technologies they are actually using. He argues that this knowledge decreases for similar technologies that other firms use and decreases further for dissimilar alternatives. As a result, technological progress is expected to appear in the surrounding of already existing technologies. When technological improvements are seen as consisting of a spectrum of small improvements, a larger complexity difference or an upgrading of larger scale become increasingly different. Following Lall's argumentation, these technologies will be less known to firms and will therefore be more difficult to implement, when large changes are supposed to take place at the same time. In investment theory, a very similar concept exists. Installation costs are supposed to increase with the size of an investment but are expected to be transitory. Based on the increased complexity of technology and the decreasing knowledge of technologies that are farther away from the ones that are used, the same can be argued for technology transfer. It should become clear that the technological distance between the actually used and the potentially transferred technology has a positive impact on transfer costs and technology transfer will therefore be likely to take place in small steps. It will equally be more costly between than within sectors.

Competition is of large importance for multinational corporations as Blomström et al. (1992), and Blomström and Wang (1992) argue. The underlying idea can also be applied to the case of spillovers. The technological advantage of an affiliate translates into better quality products and resulting higher mark-ups and profits. Similar to the argumentation in the case of technology creation, the aggregate effect of increased competition on technology transfer is difficult to assess. The role of ownership has not been answered sufficiently clear to my knowledge (see also Blomström and Sjöholm (1998)).

Summarising, the marginal revenue of technology adoption depends ambiguously on the level of competition. The costs of adoption are negatively influenced by the existing and accessible technology pool, the quality of the researchers, best approximated by the tertiary education rate, the amount of cumulative past R&D spending, the appropriateness of the accessible technologies, and a measure of cultural or engineering closeness, as described above. The working of the different factors that influence marginal revenue and marginal costs of technology transfer have been analysed and their effect on the speed of technology transfer has been pointed out. Of these factors, the accessible set of technology will be central in the subsequent analysis as this is the factor that is most strongly influenced through trade.

National diffusion succeeds technology transfer

Diffusion within a recipient country follows its transfer International technology diffusion [technology transfer] appears to be slower than national technology diffusion. This is due to the differences in the underlying conceptions, the lower degree of communication and the differences in the functioning of firms. The more widely used a technology becomes, the more will this technology be adopted by different firms. The awareness of an existing technology is greatly improved when it is geographically close not only with respect to its productive output but also with respect to its productive processes. Personal contacts, news and especially labour movements play a crucial role in the diffusion of technology once it has reached a certain geographical location (Saggi, 2000). Once a technology is employed in one firm of a less developed country, labour mobility between firms and also between sectors can be central in further diffusion. Transfer might take place in an unchanged way from one firm to another within the same economic sector, or might be adjusted to different sectors, where adoption of the technology might take place. Larger (or more advanced) firms that start acquiring foreign technologies will be able to pay skilled labour a large wage premium in developing countries. It remains highly doubtful, whether small or young firms will have the financial means to compete the qualified (and technologically advanced) labour away from the large or adoptive enterprises. This would lead to a slower triple-down effect within the country than it could be hoped. On the other hand, this worker-rigidity will lead to higher profits and the forces pulling technology towards the developing countries will be larger. An overall evaluation of the two opposing forces is not possible with the data at hand.

4 Trade and Technology Transfer

While many approaches point to static gains from trade, this paper points to other, dynamic mechanism that works through trade. Through trade, product designs and product characteristics spread to developing countries in the sense that they are widely available and accessible by firms in these countries. The more contact points exist (the larger the trade volume is), the larger is the assumed effect. This section will present the three core mechanisms/variables that help transfer technology and increase TFP in turn. First, imports of capital goods and the effects of an increased set of intermediate goods will be described, as these are the most direct effects. Next, trade can lead to a dynamic effect in production and to the learning of techniques, increasing TFP. Last and most important, trade increases the amount of accessible technology and the knowledge stock. As a result, knowledge (re)production in developing countries is likely to increase.

Direct effects

Import of capital goods

The most direct relation between trade and technology transfer remains in the direct imports of machinery goods (a very obvious but often neglected form of technology transfer via trade, see Eaton and Kortum (2001b) and the criticism by Navaretti and Soloaga (2001)). Machines are imported and they have an immediate impact on productivity through the technology that is embodied in them. The pure import of capital goods does not necessarily lead to an appropriate use of the machinery, indicating that also disembodied or tacit knowledge must be transferred.[7]

The effects of machinery import on TFP are difficult to separate from the effects of other channels. Moreover, the "pure" productivity of imported machinery is hard to evaluate as the technical and knowledge aspects only together result in the observed productivity gains. The amount and quality of imported capital goods and the underlying efficiency of the machinery is difficult to assess even when capital imports are disaggregated in import data. Navaretti and Soloaga (2001) argue that more complex production goods will increase productivity by a larger degree than older and less complex technologies. They find for the European countries that there does exist a positive correlation between income per-capita and the complexity of imported capital goods: more backward countries import less advanced technologies.

Quantity aspects of intermediates

International trade consists to the largest extent of trade in producer rather than consumer goods (Ethier, 1982; Coe and Helpman, 1995). Consequently, the range of inputs that can be used by producers in every country is increased through trade, a point that is used by Keller (1999) in his model. The theoretical foundation for this lies in the models of Ethier (1982) and Grossman and Helpman (Grossman and Helpman, 1991a). Here, the production of the final good depends on the amount of intermediate inputs (goods and services) that are used in the production process. The production function that Grossman and Helpman (1991:47) present exhibits constant returns to scale in the production of the final good and is based on a model by Dixit and Stiglitz (1977).

(4.1) $$D = \left[\int_0^n x(j)^{\alpha} \, dj \right]^{\frac{1}{\alpha}}, \text{ for } 0 < \alpha < 1,$$

where $x(j)$ is the amount of intermediate product j used and α represents a parameter that allows to calculate the elasticity of substitution between the different intermediate inputs which equals $\varepsilon = \frac{1}{1-\alpha}$. Differentiated inputs are the result of inventive activity and it is assumed that all intermediate inputs are produced with the same constant-returns-to-scale production function. As Ethier (1982) argues, all $x(j)$ will be equal in equilibrium and the resources that are used therefore equal nx. As nx represents total inputs, TFP can be written as

(4.2) $$TFP = \frac{D}{nx} = n^{\frac{1-\alpha}{\alpha}}, \text{ with } \frac{\partial TFP}{\partial n} > 0 \text{ for } 0 < \alpha < 1.$$

In this model for a closed and small economy output therefore increases with the amount of available and used intermediate goods. With the non-existence of obsolescence in this model, and with profit-maximising agents, all available goods will also be used. This property is explained by Ethier (1982) with an ever increasing division of labour into separate production processes. When moving from this closed economy to an open economy model, trade will increase the amount of available intermediates and will therefore increase TFP.

Quality aspect of intermediates

Next to the issue of a wider variety of intermediate inputs into production, also the effects of quality improvements through technology have been discussed (e.g. Grossman and Helpman (1991a; 1991b)). Quality improvements are of large importance as they include the concept of obsolescence, meaning that new generations of products (and intermediate inputs) replace older versions. This is also valid in a developing country context. Quality ladder models (e.g. see Connolly 1997, p.6) state that inputs of higher quality that are invented are more productive and therefore raise total output, while keeping input prices constant (equally, production costs of intermediate goods might fall, lowering input prices while keeping output constant, again raising TFP). A certain number of intermediate products (J) exists whose quality is improved by invention or imitation (denoted by k). Quality improvement are assumed to be of a constant factor q>1 making it q times more effective than the older version. If the knowledge how to produce a certain intermediate good is available, the good can be produced at marginal costs which are independent of the quality level of this good due to perfect competition in the final goods market as Connolly (1997) points out. Production of final goods can be described as follows (Connolly 1997, citing Barro and Sala-i-Martin (1995))

$$(4.3) \quad Y_i = A_i L_i^{\alpha} \sum_{j=1}^{J} (q^{k_{ij}} x_{ik_j})^{1-\alpha}$$

Here, the parameter A describes the effectiveness of institutions in country i. This variable will also include the amount of human capital and probably the capital stock which is not taken care of in this model. The factor $q^{k_{ij}} x_{ik_j}$ describes a quality adjusted measure of inputs into production. Connolly argues that firms will use limit pricing to capture the entire market and push older products out of the market and concludes that assuming A_i and L_i as given, output solely depends on the quality measure of intermediate products that are used in a country. For a developing country this means that under an open trade-regime, it can use intermediate inputs of supposedly higher quality that are imported from developed countries in their own production process. Hereby, the quality and value of the final goods increases directly through the intermediate input of higher quality.

A wider set of inputs to choose from

When producers have to chose from a discrete rather than a continuous set of inputs, their input decisions most likely are less than optimal as some needed intermediate products or intermediate inputs of a certain desired quality or quantity are not available. With trade, both the quantity and the set of quality of intermediate inputs that producers can choose from rises and access to them becomes easier. Trade therefore allows producers to improve their input decisions, thereby reducing the amount of inputs needed for the desired level of output.

Dynamic gains from trade – learning-by-doing

While technology is transferred via direct imports and intermediate goods, techniques are improved through better input decisions as indicated above and due to learning-by-doing. This process of market integration also allows the production of goods that are not demanded in the developing country's market (e.g. because they are based on a General Purpose Technology that is not widely used yet in that country).

The concept of learning-by-doing as formulated by Arrow (1962), aims at the efficiency gains of repeated production, increasing TFP. Aghion and Howitt (1998) present a model with internalised learning-by-doing. In their model, workers can use their human capital in the R&D sector to perform basic research or they can use their human capital in production. In this case, learning-by-doing will take place and secondary inventions can be made. While R&D focuses on the creation of new products, secondary inventions only deal with the improvement of already existing goods and processes. In correspondence to the existing models of product variety and product quality, R&D relates to the former, while learning-by-doing relates to the latter. The initial quality of intermediate goods depends on the moment of time in which they were invented; that is they depend on the amount of general knowledge that was available when they were invented. In the second stage, learning-by-doing and the resulting secondary inventions increase the quality of these goods. Both aspects therefore work together and both raise TFP. While the innovation of new intermediate goods depends on the Poisson-arrival rate of each researcher, the quality-evolution depends only on the rate of learning-by-doing within each firm and not on the general stock of knowledge that increases with primary and secondary innovations. This rate is determined by the amount of labour used in the production process and by a parameter determining the productivity of learning by doing. Both parameters are exogenously determined and as they largely determine the growth rate, the basic reasoning for an increased growth rate still remains with the factors influencing these exogenous factors. In both cases they should be related to education with the Poisson-arrival rate of each researcher related to higher education (as well as experience in imitating), and the productivity of learning by doing related to primary, secondary, and vocational education, as well as work-experience. Aghion and Howitt argue that the stock of general knowledge depends on both sorts of innovation, basic and secondary ones. This way of interpreting learning-by-doing will be used in the remainder of this paper.

Production of final output leads also to an externality through learning-by-doing. Consequently, more production will lead to a larger increase in the knowledge stock, increasing TFP.[8] Market integration and trade increase the incentives to transfer also more advanced technologies to developing countries, giving rise to learning possibilities. Foreign Direct Investment (FDI), sourcing relationships and import/export competing industries give rise to these learning possibilities.

Foreign Direct Investment (FDI) and Joint Ventures

In the context of learning-by-doing and an increasingly integrated world economy, FDI and Joint Ventures are important for the transfer of technology to developing countries. Often, re-imports based on low labour costs are an important reason to invest in a country with low labour costs. Integrated markets can lead to an increase in production in less developed countries increasing TFP directly through the used capital goods as well as through the learning effects of workers. Moreover, the larger the responsibility and control of the domestic firm, the better also the understanding is expected to be as involvement is higher. A better understanding gives a higher incentive for workers to defect and to found independent firms. Therefore, Joint Ventures, which leave more control and more responsibility to the domestic firm will give more incentives for workers to learn and might lead to a more rapid technology diffusion within the host country. Still, sourcing and import- or export-competition give again stronger incentives to domestic firms to innovate and to learn.

Sourcing and subcontracting

While world markets are ever more integrating, the production of goods becomes more and more specialised and therefore dispersed. Multinational enterprises outsource the production of intermediate products or parts of products to other markets, mainly due to geographical reasons or cost-considerations. In contrast to international production such as FDI or Joint Ventures, being characterised by a centralised system of ownership and control, subcontracting or sourcing deals with the relation between independent firms. International subcontracting can be distinguished from normal import/export relationships through the existence of a stable contract. This contract establishes either a commitment to buy a certain amount of specific goods over an agreed time-horizon, allowing the subcontractor to function as a second-source for supplying customers, or leaves the subcontractor produce final goods which will be labelled as the principal's goods. Also other steps of the production process such as assembly, testing, or marketing can be outsourced. The subcontractor will be given certain requirements, giving scope for understanding and learning. In a second step, a development from an "economic" subcontractor (based on cost-reduction considerations) to a "specialised" subcontractor can take place through dynamic learning (Radosevic, 1999). The subcontractor will gain more knowledge in the production of "its" good, and will gain a higher position on the "value ladder" of goods. This, however, is not easily and especially not automatically accomplished. The critical factors determining the successful dynamic learning still remain unidentified. It appears, however, that they also depend on the stock of human capital, absorptive capacity and profit incentives of the sub-contractor. The increase in sourcing activity can be recognised by the increases in intra-industry trade between developing and developed nations. Again, the precise transfer process remains unidentified.

In the case of FDI, competition between firms might lead to higher technology transfer towards subsidiaries in developing countries, but the threat of spillovers might as well lead to the transfer of older or less technology. When dealing with sourcing, inventive capacity is needed to defend the technological advantage that might exist from entering the industry first or to gain a qualitative advantage. Next to competition with foreign based or sourcing firms, also competition with domestic firms that are extracting monopoly profits can exist. While these positive dissemination effects can lead to virtuous circles, the opposing process of trapping sourcing-firms in low value processes and the possibility of driving out local competition due to high cost, technology and capacity advantages can form a vicious circle (Radosevic, 1999). Again, this will greatly depend on firm-level capacities of sourcing-firms and (potential) competitors.

Having become a 'specialised' supplier in a sourcing relationship, also the industrial countries' markets start to present profit opportunities to developing countries' firms, as their labour costs remain lower than in developed countries. Exporting to developed countries, however, increases the competitive pressure on developing countries' firms as they must compete with all firms and not only with selected firms in their market. This increases the set of inventions that a firm is exposed to and gives rise to further incentives and possibilities for innovation. This paper will turn back shortly to this problem later when discussing models of knowledge transfer.

Access to technology

The knowledge pool or the set of accessible technologies

Having analysed the direct and dynamic effects of trade on TFP, the effect of an increased knowledge pool remains to be analysed. This channel is of utmost importance when analysing the role that trade plays in technology transfer. As was already stated, trade increases the number of designs and production mechanisms that are accessible within a certain country. While it could be argued that controlled imports of products and technology can do the same trick, it has to be taken into account that a wider exposure to technology gives rise to more possible and potential points of transfer. This point is explained by Connolly (1997) who argues that importing firms are responsible for distributing goods and therefore have more knowledge concerning them, reducing the costs of adoption. The more goods are imported, the larger supposedly the number of firms for which adoption costs are reduced, as long as imports are not monopolised. The remainder of this section will present the theoretical approaches that support the assumption that more trade leads through a wider accessibility of technology to more technology transfer. It will start with the mechanism of reverse engineering before turning towards models of technology diffusion. Subsequently, the empirical literature will be compared to this section.

Reverse engineering and imitation

Reverse engineering aims at strapping products, understanding them and to rebuilt them afterwards. This means that existing products, designs or methods are copied and adopted towards local needs. For the imitating country this process functions as a kind of invention, with the difference that this sort of imitative invention demands less labour than inventing goods from a set of unknown possibilities, as Grossman and Helpman (1991a) argue. In the case of imitation, this uncertainty does not exist, as a functioning product with the desired characteristics is already existing and “only” has to be copied. Assuming that a technology can be mastered by pure physical reverse engineering and without the participation in the actual production process or direct communication between scientists of the producing and the imitating firm, reverse engineering becomes possible through the exposure to goods.

The costs of adoption are influenced by the set of technologies that is accessible in a country. Two opposing factors exist. On the one hand, the more technologies are available in an economy but have not yet been adopted by the economy, the larger is the set that firms can choose from when copying, increasing the possibilities for imitation. On the other hand, the large set of technologies might result from large differences in the technology level between the importing and the exporting country. More complicated technologies are more difficult to copy, as Connolly (2001) argues. Still, ceteris paribus, more trade leads to a larger available variety of designs and goods to copy, increasing the probability of imitation.

The larger the level of technology that is existent in an economy, the closer is that country to the Technological Frontier Area (TFA). This implies that, generally, the gap between the existing knowledge and the knowledge that has to be acquired through reverse engineering is smaller. As a smaller technological gap between existing knowledge and desired knowledge should make it easier for an engineer to understand and copy the technology at hand, the stock of existing knowledge will have a positive effect on knowledge imitation. In this context, reverse engineering functions as "knowledge production" for the developing country as the transferred knowledge is new to the developing economy and raises the parameter of the technology stock, A, in the developing country. Yet, a higher level of technological development reduces the scope of copying, as the imitating country comes closer and closer to the TFA. The set of technologies to copy is reduced and the total effect on imitative activity is likely to be negative. Besides, the higher the intensity with which a country is exposed to a certain technology, the more actors have the possibility to imitate the technology. Analysing the determinants of innovation and imitation, Connolly (2001) argues that the probability of successful imitation is positively influenced by the resources that are used in the imitative process and past imitating experience, while the complexity of the good that is to be imitated has a negative effect on the probability of imitation. This section will now turn towards its central point, the effects of an enlarged and more widely accessible set of technologies on technology transfer. As technology transfer functions as knowledge production for the imitating country, this paper will turn to describing models of technology transfer. These models are often based on models of knowledge production and are related to an increase in the set of accessible technologies through trade, leading to technology transfer. Increased access to unknown technologies increases the rate of technology growth in imitating countries as long as the accessible technologies are not too complex to be understood.

Models of knowledge transfer

Grossman and Helpman (1990) argue, that not only domestic R&D spending but also foreign R&D spending add to a "stock of knowledge capital" that reflects the local understanding of technology, engineering, and industrial know-how. Foreign R&D-spending, so their argumentation, lets the local knowledge stock grow if and to the degree that there exist contacts between the two countries. Trade, in this line of argumentation, increases the number of contacts greatly and therefore increases the local stock of knowledge capital and therefore the effectiveness of research or imitating activity. They do not point out, however, in which ways this process works precisely. This section will present different models of technology diffusion or will relate already presented models to the effects of an increased knowledge stock through trade.

Nelson and Phelps (1966) present a model of technological implementation. They formulate the change in the level of applied technology:

(4.4) $$\frac{\dot{A}}{A} = \phi(H)\frac{T(t) - A(t)}{A(t)}.$$

Nelson and Phelps use this model to describe the rate of implementation of technology into practice. They try to express the importance of human capital for knowledge diffusion. Applying the model to the concept of technology transfer, we have to focus on the technology gap, which is the second determining factor in the rate of technology implementation. The authors assume that the theoretical level of technology, $T(t)$, grows exogenously at a constant exponential rate. In the context of this paper, however, $T(t)$ for a developing country depends on the amount of technologies that are accessible. This understanding mirrors the concept of the theoretical level of technology in a country that is developing its own technologies. The growth rate of the level of technology in practice in a developing country can therefore be described with the model of Nelson and Phelps, taking $T(t)$ as the set of technologies that is accessible by most actors in the developing country. Arguing that more imports increase the spread of a certain technology within a country, more imports also increase the set of technologies that are widely accessible (depending on the technologies that are used in the exporting country). By widening the technology gap, this leads to a higher growth rate of technology in practice.

The model of knowledge creation that is presented by Rivera-Batiz and Romer (1991) (see also Romer (1990)) described knowledge production as depending on the human capital stock and the already existing knowledge stock.

(4.5) $$\dot{A} = \delta HA$$

This specification, however, relates to the knowledge production of one country. In the framework at hand that analyses technology transfer from developed to developing countries, the knowledge stock of the developing country can be expected to be smaller than the knowledge stock of the developed country and it can be expected to be a subset of the developed countries knowledge stock. While this might not be completely true due to adaptations that are made in receiving countries, this assumption can be used as an approximation. For the trade context, Rivera-Batiz and Romer assume that knowledge stocks between countries do not overlap, an assumption that is not fulfilled in this paper's context. Therefore, to take the specific knowledge distribution into account, I propose to adopt the model in the following way:

(4.6) $\dot{A}_H = \delta_1 H_A A_H + \delta_2 H_B A_F(A_H)$,

where A_H and A_F represent the knowledge stock in the developing and industrialised country, respectively, H_A human capital used for domestic innovation, H_B human capital used in imitative research, and δ_1 and δ_2 two productivity parameters. All information that is used in the developing country is also known in the developed country. As $A_H \in A_F$, the measure $A_F(A_H)$ must be introduced, representing the knowledge stock of the developed country to which scientists of the developing country have access and which does not form part of A_H yet. Considering only the portion of foreign knowledge that scientists have access to lies in line with a comment made by Romer's (1990) presentation of this model of knowledge creation. He points out that only the knowledge that scientists have access to must be considered (p.83). In this context, it has to be stated that also disembodied spillovers might take place, as Grossman and Helpman (1991a) argue. They claim that the general knowledge stock is not only influenced by the number of technologies that the developing country has already acquired but also by the number of technologies that only the developed country's firms can produce. In this case, some information can nevertheless have spilled over to the developing country, through contacts, blueprints or imported goods, increasing the factor $A_F(A_H)$ in the adopted Rivera-Batiz-Romer model, as this factor is determined exogenously.

Under this setting, trade constantly increases the set of accessible technologies of the developing country because technologies that are newly invented also become accessible by the imitating country. The effect is a rise in the stock variable $A_F(A_H)$, as the foreign accessible knowledge increases while it is not immediately imitated and therefore A_H does not change. Knowledge creation is greater than under autarky as Rivera-Batiz and Romer

(1993) point also out in an addendum to their 1991 article, stating that trade policies which increase the available stock of knowledge increase growth in the economy. The factors δ_1 and δ_2 were included to allow that domestic and foreign knowledge influence domestic knowledge production to differing degrees. As imitation is assumed to be easier than own knowledge production, it should be expected that $\delta_2 > \delta_1$. Summarising, it can be said that A_H rises due to two mechanisms. First, trade leads to a continuous increase in the accessible knowledge, increasing the imitation of knowledge through the wider set of available ideas. Second, this increased knowledge production increases the factor A_H, leading to more own knowledge production given that human capital is used for own knowledge production. At the same time, this increase in A_H, ceteris paribus, leads to a reduction in $A_F(A_H)$, the accessible knowledge stock which does not form part of A_H yet, reducing the scope for imitation.

Following Connolly (2001), the concept of learning-to-learn could be included in this specification. Learning-to-learn in knowledge production is a concept similar to learning-by-doing in the production of goods. Experience in imitating technologies that is gained through the process of reverse engineering will lead to a more thorough understanding of the general technological concept and will increase the likeliness of both further reverse engineering (imitation) as well as the probability of creating new technology in the future. This insight is also described by Teece (1976, cited in Wang (1989)) who finds that transfer costs fall for every subsequent application of an existing innovation. This means that once a new strand of innovation has been transferred, new versions of this strand are transferred at lower costs (i.e. imitation experience has increased and the imitation efficiency δ_2 would increase). I will not further follow the effects of introducing such a fundamental change to the Rivera-Batiz and Romer model.

In the lab equipment model of Rivera-Batiz and Romer (1991), knowledge only has an influence on the production of knowledge through the use of more sophisticated intermediate goods. Nevertheless, trade in goods has an effect on the production of knowledge. Similar to the model of increasing varieties, also the knowledge production function as presented by Rivera-Batiz and Romer depends on the set of inputs. As long as trade brings such inputs into a developing country that are used in knowledge production, trade will also in this model have a positive effect on knowledge production, as Aghion and Howitt (1998:374) argue.

This model, however, appears ill suited for developing countries. Their specification of knowledge production might have some justification for countries that are similar to the technological frontier area, but it appears less appropriate when analysing countries that are distant to it and which use mainly reverse engineering in order to transfer technology.

This section shortly addresses the working of Manfield's (1961) model, as presented by Evenson and Westphal (1995), of knowledge diffusion in an international context. In his model, the speed of diffusion depends on an external factor, b, describing the degree to which the benefits and costs of adoption influence the diffusion rate.

(4.8) $$p(t) = \frac{1}{1 + ae^{-bt}}$$

Here, $p(t)$ describes the fraction of firms that have adopted the new invention at time t and the factor a represents a constant. This model, however, depends on the underlying costs and benefits of adoption, without explicitly analysing these two factors itself. In his influential article, Teece (1977) analyses the factors that influenced transfer costs for multinational enterprises. It can be said that the same factors apply also to the transfer outside these enterprises even though their effects might be larger or smaller. The three main factors he finds are i) the age of the technology, ii) the number of manufacturing experience of the receiving firm, and iii) the number of firms that use a similar or identical technology. Teece then further analyses the international aspect of the transfer costs and comes to the conclusion that for machinery transfer the level of host country development play a significant role in the determination of the transfer costs. In this context, trade can help making a technology accessible or known and therefore initiate the subsequent process of diffusion.

Wang (1989) presents a model of firm-level knowledge stock growth. In this model, both the effect of R&D spending and the effect of imitation play a role. He argues that a portion z of the foreign existing knowledge, A^*, is available in a country that is participating in international trade. This size of this portion, $\bar{z}$, is determined by the size of A^* and a factor that summarises other factors influencing knowledge transmission (e.g. the degree of economic integration).[9] The knowledge stock of a developing countries' firm, z_t, then develops as follows:

(4.9) $$z_{t+1} = z_t + I_t + \tau(I_t, g_t)\bar{z}_t,$$

where I_t represents the amount of R&D spending, g_t the technology gap, $\tau(I_t, g_t)$ a function that represents the capability of absorption, depending on both I_t and g_t, and t a time index. The absorptive capacity increases with the amount of own research and the effect of own research increases with the size of the technology gap, $\frac{\partial\tau}{\partial I_t} > 0$ and $\frac{\partial\partial\tau}{\partial\partial I_t g_t} > 0$. When the gap vanishes, so does the possibility of imitation. In this formulation, however, some additional thoughts have to be incorporated. First, the effect of R&D depends on the existing knowledge stock and on the quality of the researchers as indicated above. Second, the absorptive capacity should also depend on the quality of the researchers and on the cumulative experience in imitating. In order to take these two points into account, it should be considered to adopt the model to:

(4.9‘) $$z_{t+1} = z_t + \delta I_t H_t z_t + \bar{z}_t \tau(I_t, g_t, H_t, \sum_{i=0}^{t} \tau(I_t, g_t)\bar{z}_i),$$

where H represents the firm's human capital stock in period t, δ a parameter indicating research efficiency of the particular firm, and $\sum_{i=0}^{t} \tau(I_t, g_t)\bar{z}_i$ cumulative experience of imitation. This result, however, is valid for the individual firm and difficult to test for due to data constraints. Assuming that all n firms are equal in the economy, total technology stock growth equals $\dot{A} = n\dot{z}$ and also equals TFP growth.

5 Empirics of Technology Transfer Through Trade

This section deals with the empirical models and findings at the macro-level, putting emphasis on technology transfer to developing countries. Still, the data situation for developed countries is much better and countries are much more similar in underlying conditions, leaving less "noise" in the models. As a result, the empirical models chosen touch both on technology transfer between industrialised countries and towards developing countries. No models that test for technology transfer between developing countries or from Newly Industrialised Countries (NICs) towards Developing Countries exist to my knowledge. Results are much less clear for models dealing with developing countries, pointing towards the fact that many underlying determinants of technology transfer have not yet been incorporated in the models. This can also be seen in the often significant country-fixed effects.

Models focus normally on embodied technology spillovers, while some also take disembodied spillovers into account. The determination of the level of technology in the donor country stands central to the analysis. Moreover, the correct description and functioning of the level and kind of human capital turns out to be problematic and large differences in results occur, when different measures of human capital are used. We will now turn towards the specifications and results.

The influential article of Coe and Helpman (1995) started the empirical debate on the effects of knowledge-spillovers through trade. Starting from the assumption that a country's productivity depends on both the domestic and the foreign stock of knowledge they use cumulative R&D spending in trying to assess the spillover effects through trade between 21 OECD countries and Israel. Building on Ethier (1982), they assume that the set of horizontally or vertically differentiated available intermediate goods influences factor productivity and proxy this set of inputs by accumulated R&D spending. The central concept of Coe and Helpman is a measure of "foreign R&D stock" for each country. The R&D capital stocks of a country's trade partners are weighted by import shares, reflecting the importance of a trade partner in determining the domestic foreign capital stock, and are summed up, representing the "foreign R&D capital stock". Their specification and basic idea builds the basis for a wide set of models dealing with international knowledge spillovers.[10]

A serious drawback of the Coe and Helpman (1995) model is, that it does not include the theoretically important human capital. This might be valid under the assumption that human capital levels are quite similar between the 15 non-G7 countries of the sample. In contrast to this model, Coe, Helpman and Hoffmaister (1997) (henceforth CHH) include a variable for human capital as they focus on 77 developing countries and the R&D stocks of the same 22 industrial countries Coe and Helpman used. In their analysis, the authors point towards the double importance of human capital that directly influences productivity and increases adoptive capacity. The authors use the secondary school enrolment rate as a proxy for human capital, but being aware of this measure's shortcomings, they also experiment with different constructions of existing data (especially the primary enrolment rate) without a change in results. They start from the assumption that imported products embody foreign technology and other information that otherwise would be costly to acquire. They model is specified first differences:

(5.1)
$$\Delta \log F_{it} = \alpha_i^0 + \alpha_i^S \Delta \log S_{it} + \alpha_i^M \Delta m_{it} + \alpha_i^E \Delta E_{it} + \alpha_i^{SM} \Delta (m_{it} \log S_{it}) + \alpha_i^{SM} \Delta (E_{it} \log S_{it}) + \alpha_{it}^T T_t + \mu_{it} ,$$

where F_i stands for TFP, S_i for the foreign R&D stock, E_i for the secondary school enrolment rate, m_i for the share of imports of machinery and equipment from industrial countries relative to GDP and T is a time trend. The foreign knowledge stock is interacted both with the import share and the level of human capital, in line with the assumption that human capital increases the rate of transfer and openness increases the access to foreign technologies. The foreign R&D capital stock in country i, S_i, is calculated as the bilateral import shares-weighted foreign knowledge stock, $S_i = \sum_{k=1}^{22} \psi_{ik} S_k^d$, where ψ_{ik} represents the bilateral import shares of country i with respect to industrial country k and S_k^d the R&D capital stock of country k.

Their estimation leaves a large and positive coefficient before the E_{it}-term, indicating the importance of human capital for TFP. This is not surprising, however, as the authors calculate TFP as $TFP = \frac{realGDP}{K^{\alpha} L^{(1-\alpha)}}$, thus including human capital in their measure of TFP. A second restriction is the fact that they do not include domestic R&D spending. While this is conceptually problematic, they implicitly justify their decision by the skewed distribution of worldwide R&D expenditures.[11] Still, even though developing countries might conduct R&D at a low level, differences in spending between these countries can be large, having a potentially large effect and should therefore be included.[12]

CHH drop S_{it} and $E_{it} \log S_{it}$ as this term turns out to be statistically insignificant. Still they find both human capital variables jointly significant. While dropping the direct effect of the foreign knowledge stock appears theoretically justifiable, dropping the interaction term stands contrary to the theoretical foundations and calls for the use of different human capital concepts. Neither do they include an interaction term between the three concepts of foreign knowledge stock, the import share and human capital. Human capital therefore influences TFP growth only as independent factor. When including a catch-up variable for the scope of technological learning and fixed effects all coefficients increase. Moreover, the elasticity of TFP with respect to an increase in the level of human capital becomes larger than the elasticity of TFP with respect to an increase in the interaction term between the foreign R&D stock and the import shares. The catch-up variable has the expected positive effect on TFP growth. From their estimations, they concluded that inventive activity in developed countries has a large influence on developing countries through trade, increasing with the ratio of imports to GDP and the foreign R&D capital stock. As a summarising measure, the authors state their quantified conclusion that the spillover effects of R&D spending in industrial countries have increased output of developing countries by US$21 billion, as compared to US$50 billion of official development aid.

Lichtenberg and Pottelsberghe (LP) (1996) attack the setting of the Coe and Helpman (CH) (1995) model from two different angels. First, they point out that other channels of technology transfer such as FDI are not taken into account while they are potentially important. And secondly, they criticise the mechanism by which Coe and Helpman estimate their foreign R&D capital stock and the way they estimate its impact on TFP. Both criticisms apply evenly to the CHH model. This section will deal with the second criticism and its improved estimation results, as in Lichtenberg and Pottelsberghe (1998).
LP argue that CHs specification does not reflect the intensity of research in country j. They therefore propose to include research intensity – a ratio of research to GDP - of the donor country in the measure to avoid an aggregation bias. A potential merger of two countries would increase the foreign R&D stock of the importing country, while this bias is largely reduced in the LP measure. Moreover, LP do not use indexed domestic R&D stocks, arguing that they lead to an incorrect estimation of the elasticity the foreign R&D stocks with respect to domestic TFP in a specific year.[13] Their specification reads:

$$\text{(5.2)} \quad \log F_i = \alpha_i^0 + \alpha^d \log S_i^d + \alpha_7^d G7 \log S_i^d + \alpha^f \left[\frac{M_{it}}{y_{it}}\right]^{\theta 1} \log \sum_{j=1}^{21} \frac{M_{ij}}{M_i^{\theta 2}} \frac{S_j^d}{y_i^{\theta 3}} + \varepsilon_i .$$

The variables reflect the before described values and the three parameters $\theta 1$, $\theta 2$, and $\theta 3$ can be used to reduce the model to the version of CH, when $\theta 1 = \theta 2 = 1$ and $\theta 3 = 0$.
Repeating CH's regression without indexation and using their preferred specification with $\theta 1 = \theta 2 = 0$ and $\theta 3 = 1$, the regression with the LP measure of the foreign R&D stock has a better fit than the CH-specification.[14]
LP include the import-ratio as a measure for openness within their foreign R&D stock measure, but also include the import share independently on the right hand side. The elasticity of TFP with respect to the foreign capital stock interacted with the import share in the LP specification is much larger than without the interaction but the import share has a negative influence. The negative impact of the import share, however, indicates that the foreign R&D capital stock must exceed a certain value for openness to have a positive effect on TFP growth.[15] It remains to be pointed out, that inferences for developing countries are difficult to make, as no human capital is included and developing countries are characterised by much less domestic R&D spending.

Mayer (2001) does not use a foreign R&D capital stock at all in his regression. He rather uses the import to GDP share of machinery imports from countries that have a substantial ratio of R&D to GDP. This is a rather similar construct to the measure proposed by LP. Research intensity is what appears important to Mayer. The LP measure weights imports with precisely this research intensity measure of donor countries. The results of both cannot be compared, however, as LP use developed country data while Mayer uses a set consisting of developing countries.

Wang and Xu (2000) test three different specifications for the foreign R&D capital stock, using data on trade in capital goods for 21 OECD countries. Both the measure presented by Coe and Helpman (1995) including the general import share, S^{f-CH}, and the preferred specification of Lichtenberg and Pottelsberghe, S^{f-LP}, are used. In addition they test a third, unweighted spillover variable that is supposed to pick up disembodied technology transfer. They complete their first model by introducing a human capital variable, H. As they assume the variables to be non-stationary, they construct a second specification. This is based on first differences and includes a variable for the technology gap between the countries' technology level and the world frontier, GAP, that increases with a decrease in the size of the technology gap. It can be seen that their GAP measure and the unweighted spillover variable $S^f(UW)$ both potentially capture disembodied spillovers.

(5.3) $$\Delta \log F_{it} = \Delta\alpha_t + \beta_1 \Delta \log S_{it}^d + \beta_2 G7 \Delta \log S_{it}^d + \beta_3 \Delta \log S_{it}^f + \beta_4 \Delta \log S_{it}^f (UW) + \beta_5 \Delta \log H_{it} + \beta_6 \log GAP + \mu_{it}.$$

Wang and Xu first run two regressions with a reduced model – leaving out the unweighted spillover variable, human capital and the technology gap, and defining the model in levels – first using $m \log S^{f-CH}$ (the foreign R&D capital stock, corrected for the share of imports to GDP, m) and then using $\log S^{f-LP}$. For both, the coefficient for $G7 \Delta \log S_{it}^d$ is positive and statistically significant at the one-percent level, while the coefficient on domestic R&D capital is negative but not statistically significant. The coefficient on the LP-measure is half as large as the coefficient of the CH-measure but the fit of the entire model is superior with the LP-measure.

Next they estimate the complete model with the $m \log S^{f-CH}$ and the $\log S^{f-LP}$ measure. The findings for the coefficients in the reduced model change only minimally, human capital and the unweighed spillover variable are not significant, while the coefficient on $\log GAP$ carries the expected negative sign and is statistically significant at the one-percent level. The similarity of the variables $\Delta \log S^f(UW)$ and $\log GAP$ might result in the statistically insignificance of the coefficient of $\Delta \log S^f(UW)$ in the estimations.[16] Wang and Xu point out that neither of their three measures of the foreign R&D capital stock is derived from theoretical models as they are not specified, and call for theoretical approaches to deriving them.[17]

Engelbrecht (2002) builds on the same framework, focussing on TFP determination in developing countries and using a data set of 22 industrial and 61 developing countries.[18] He tries to establish a more precise picture of human capital effects by using different measures for human capital as well as "policy-conditioned" human capital variables. In his last specification, also a catch-up variable is included in order to test for knowledge spillovers that are not related to R&D. Engelbrecht "conditions" human capital, E, with the import share, m, $E' = mE$, and replaces the individual effect of the foreign R&D capital stock with a "conditioned" foreign R&D capital stock as $\log S' = m \log S$.

(5.4) $$\Delta \log F_{it} = \alpha_{it}^{0} + \alpha_i^{M} \Delta m_{it} + \alpha_i^{S'} \Delta \log S'_{it} + \alpha_i^{E'} \Delta E'_{it} + \alpha_i^{S'E'} E'_{it} \Delta \log S'_{it} + \mu_{it},$$

where the variables have already been described. Using different measures for human capital,[19] Engelbrecht finds that the conditioned human capital variable has an significant and positive effect on TFP growth, especially when using secondary schooling in the total population. Differentiating for average male and female human capital, he concluding that female human capital has a stronger effect on TFP growth than male human capital, this finding being even more pronounced when using "average years of primary schooling in the female population". This variable might, however, rather describe the structure of society, pointing towards the importance of female emancipation for TFP growth.[20]
The coefficient of $E'_{it} \Delta \log S'_{it}$ is negative in all estimations, possibly due to the double scaling of the interaction term, indicating the need for another form of foreign R&D absorption.[21] Includes a catch-up variable, an interaction term between the distance of GDP per-capita in the developing country to that of the average OECD country, and using the non-conditioned human capital variable, he finds a positive effect of human capital, in particular of secondary education, in the absorption of international knowledge spillovers other than those associated with R&D. It would be interesting to see whether this finding is also dependent on the degree of openness as could be tested with an interactive term $E_{it} m_{it} \log C_{it}$.

Miller and Upadhyay (2000) use a different framework for 83 countries from 1960-1989. Using two production functions, with and without human capital, they estimate two values for TFP in the sample countries. They then regress these TFP measures on the stock of human capital approximated by the average years of schooling of the adult population, the ratio of exports to GDP, the terms of trade, local price deviations from purchasing power parity (PPP), and the inflation rate as well as the standard deviations of these variables. They do not take the foreign R&D capital stock into account but include an interactive term between exports and human capital. Moreover, they include fixed effects for countries and six time variables in order to account for time specific effects. In general, their setting does less well fit the theoretical analysis.

Their results indicate that that the more open an economy is (and the more stable the openness variable), the higher is its TFP. Human capital, through the interactive term, increases this effect. Upward deviations from the PPP and a higher inflation rate have a negative effect on TFP. The last two factors, however, represent a rather indirect effect on TFP through external demand and investments that are not of direct interest for this paper. Still, they find that human capital only has a positive effect on TFP when the ratio of export/GDP ratio exceeds eleven per cent. Also, time effects for the first four periods are statistically significant. For the TFP2 measure, the results change slightly, indicating a openness threshold of 50 per cent. Their method of deriving the TFP1 measure assigns productive effects of human capital to TFP while this is not the case for TFP2. As can be shown, this largely explains the negative coefficient of human capital in the latter case.

Finally, they divide the countries in the sample into three groups according to their economic development. Correlations between independent variables and the sets of countries, however, might lead to problems when estimating as not the complete relationship is captured within each group. Results are improved for the segregated regressions and the general model appears to describe the TFP level determination of the middle income countries (between $US3000-$US10000 on average in 1960-1964) best.

Falvey, Foster and Greenaway (henceforth FFG) (2002) estimate output growth rather than TFP levels with the help of a static and a dynamic model, using a sample of five OECD donor countries and 52 developing recipient countries. They argue that knowledge spillovers have a short- and a long-run impact on growth and include lagged GDP growth rates. They specify in first differences:

(5.5) $$\Delta \ln y_{it} = \alpha_1 \Delta \ln y_{i,t-1} + \alpha_2 \Delta \ln y_{i,t-2} + \beta_1 \Delta \ln SPILL_{it} + \beta_2 \ln y_{i,65} + \beta_3 \left[\frac{Inv}{GDP}\right]_{it}$$
$$+ \beta_4 \Delta \ln POP_{it} + \beta_5 SEC25_{i,65} + \beta_6 \Delta \ln TTI_{it} + \beta_7 SACHS_{it} + \Delta\varepsilon_{it},$$

where Δ represents a change in a variable, $\ln y_{i,t-1}$ and $\ln y_{i,t-2}$ the lagged values of GDP growth, $\ln y_{i,65}$ the 1965 GDP level, $SPILL_{it}$ a spillover variable, $\left[\frac{Inv}{GDP}\right]_{it}$ the investment to GDP ratio, POP_{it} the population, $SEC25_{i,65}$ the percentage of people over age 25 with secondary education in 1965, TTI_{it} a terms of trade index, and $SACHS_{it}$ the Sachs and Werner (1995, as cited in FFG (2002)) index of openness. The static model is similar to specification (5.5) but does not include the two lagged values of GDP as independent variables.

The authors test different measures of the foreign knowledge stock by substituting them as the $SPILL_{it}$ variable in their model. They distinguish their measures through the degree of "publicness" in the donor- and in the receiving country as well as through the way the imports are weighted in the receiving country. The five specifications are summarised in table (5.1). When technology is a public good in the donor country, the capital stock enters directly in the calculation. Assuming that technology in the donor country is a private good, the capital stock is weighted by the donor country's GDP, giving a measure of knowledge-intensity. All else equal, this means that a larger country (a country whose capital stock is smaller per unit of production) has a smaller effect on the spillover variable in the recipient. For the recipient country, the "imported knowledge" is weighted with either total imports (specifications 1M and 4M) or with GDP (specifications 1Q and 4Q). This leaves, other things equal, the spillover variable of a larger (or more closed) economy smaller, bringing the amount of "imported" foreign knowledge in relation to the country size or its openness.

Both for the static an the dynamic models, including the SACHS openness measure does not change results, being itself significant at the one-percent level. The catch-up variable, the measure for human capital, and the investment-GDP ratio are always of the expected negative sign and significant at the one-percent level. The population variable is mostly insignificant and carries changing signs. The terms of trade index is only significant in some of the specifications of the dynamic model (1Q, 2, 3, 4Q) and has a positive sign. The discussion here focuses on the spillover variable, however, as it represents the effects of trade on growth through knowledge spillovers.

Table (5.1): The five foreign R&D stock specifications of FFG (2002)				
Specifi-cation	**Calculation**	**Characteristic in the donor/recipient country**	**Construct used by**	**Effect in static/ dynamic model**
(1M)	$M\overline{K}S_{rt} = \sum_d \frac{M_{drt}K_{dt}}{M_{rt}} = \sum_d \theta_{drt}K_{dt}$	Public/Private	CH (1995,1997)	-0,06***/ -0,04***
(1Q)	$Q\overline{K}S_{rt} = \sum_d \frac{M_{drt}K_{dt}}{Q_{rt}} = \frac{M_{rt}}{Q_{rt}}\sum_d \theta_{drt}K_{dt}$	Public/Private	CH $m\log S^f$	0,02**/ 0,01
(2)	$\overline{K}S_{rt} = \sum_d \frac{M_{drt}K_{dt}}{Q_{dt}} = M_{rt}\sum_d \theta_{drt}\frac{K_{dt}}{Q_{dt}}$	Private/Public	LP (1998) (0-0-1)	0,07***/ 0,06***
(3)	$\overline{KS}_{rt} = \sum_d M_{drt}K_{dt} = M_{rt}\sum_d \theta_{drt}K_{dt}$	Public/Public		0,05***/ 0,03***
(4M)	$MKS_{rt} = \sum_d \frac{M_{drt}K_{dt}}{M_{rt}Q_{rt}} = \sum_d \theta_{drt}\frac{K_{dt}}{Q_{dt}}$	Private/Private		-0,14***/ -0,17***
(4Q)	$QKS_{rt} = \sum_d \frac{M_{drt}K_{dt}}{Q_{rt}Q_{dt}} = \frac{M_{rt}}{Q_{rt}}\sum_d \theta_{drt}\frac{K_{dt}}{Q_{dt}}$	Private/Private		0,03**/ 0,02

M_{rt} = total imports of country r

M_{drt} = share of r's imports that come from country d

Q_{rt} = country r's GDP

Q_{dt} = country d's GDP

K_{dt} = country d's R&D capital stock

θ_{drt} = share of imports from country d in total imports of country r

r stands for the recipient country and d for the donor country.
CH stands for Coe and Helpman (1995)
LP stands for Lichtenberg and Pottelsberghe (1998)

Note: ***,**,* represent significance of the spillover variables in the regressions including the SACHS-openness measure at the 1, 5, and 10 percent level, respectively
Source: Own summary

Their results find a significant relationship for some but not all of the spillover measures (see table (5.1)). Only the measures that consider spillovers to be of public nature in the receiving country are positive and statistically significant in both models. When spillovers are considered private in the receiving country, the method of deflations has an effect on the results. Total manufacturing imports used as deflator, taking the distribution of imports into account but not the total volume of them, leads to a statistically significant negative sign, contradicting the theoretical concept of spillovers. When GDP is used as a deflator, the coefficients on the spillover measures become positive but remain non-significant in the dynamic model. From the dynamic model, FFG estimate the long-run effect of knowledge spillovers on growth. For the estimations that include the openness measure, an increase of one percent in the spillover variable (the foreign R&D capital stock) increases the long-run growth rate by between 0,011 (specification 1Q) and 0,067 (specification 2) percent. The authors point out that long-run effects might be of a longer time horizon than the two-year lagged variables.

The results for various spillover variables leaves the reader with some doubt. Not all measures are of the correct sign or statistically significant. The assumption on the nature of spillovers in the donor country do not have a large effect on the results. Modelling them as private, and keeping the assumptions on the recipient constant, however, leads to larger values for the coefficients, indicating that their nature is mixed but apparently more private than public. With respect to the nature of the spillovers in the recipient, the same analysis indicates that the "public" assumption performs better in the estimations. While the discussion on the nature of technology in both countries continues, the assumption of private nature in the donor- and public nature in the recipient country is also intuitively appealing, while also the measures of public/public perform well. The first case (specification (2)) leaves us with the measure that is proposed by Lichtenberg and Pottelsberghe (1998) (henceforth LP) for $\theta 1 = \theta 2 = 0$ and $\theta 3 = 1$, while the second (specification (3)) results in a specification with $\theta 1 = \theta 2 = \theta 3 = 0$, for which LP do not test, and for which FFG's results are not appealing. While FFG test for GDP growth, the measures they use are inherently included in the framework of LP and specification (3) of FFG performs also especially well in the LP-framework indicating that knowledge be best considered private in the donor and public in the recipient country.

Keller's (1999; 2002) model, deals with the output effect of R&D stocks on industries' TFP through using intermediate products that come from other sectors and other countries in production using a sample of 13 industries in the G7 and Sweden in the time period of 1970-1991. Four different measures are used, the domestic, own sector R&D stock, the domestic, alien sector R&D, the foreign, own sector R&D stock, and the foreign, alien sector R&D stock. Measures are calculated using import-export weights (IO), in line with Coe and Helpman (1995) and with the help of a technology flow matrix (TM), as described in Evenson et al. (1991). As the first measure performs better, this paper will focus on the corresponding results.

No measure of human capital in these countries is used. Due to the high homogeneity of the sample, this might be justifiable, with respect to technology transfer to developing countries, however, this surely would have to be adjusted. He regresses TFP on the domestic and foreign (weighted with bilateral import shares), own and alien, sector R&D stocks, a time-, and country-fixed effect.

While Keller's model does not take other effects than the R&D stocks into account and deals with a set of developed countries, his basic conclusions are of interest. Under his IO specification, Keller calculates the relative importance of the four stock variables for TFP determination. It turns out that the domestic, own sector R&D stock accounts for 51,1 percent of the total effect, the domestic, alien sector R&D for another 29,2 percent, the foreign, own sector R&D stock for 4,7 percent, leaving 15,0 percent for the foreign, alien sector R&D stock.[22]

Hakura and Jaumotte (1999) analyse the effectiveness of inter- and intra-industry trade on a country's growth rate for a sample of 24 OECD and 63 developing countries. The paper includes only trade between OECD countries (technological leaders) and the developing countries, not touching the issue of trade between Newly-Industrialised countries and developing countries. Assuming that an increasing gap in TFP between leaders and followers reduces the cost of adoption, they test for the effect of the import-adjusted TFP gap and a disembodied convergence factor. This paper strives for quantifying this parameter with the help of the Grubel-Lloyd intra-industry trade index (IIT). This index takes a value of zero if no intra-industry trade exists and a value of one if all trade within a sector is intra-industry. In their regression, sectors are classified as being characterised by intra- and inter-industry trade depending on the value of the IIT. They explore cut-off values ranging from 0,1 to 0,9.

Results for TFP-estimations with and without human capital are similar, therefore they only present the estimations based on $TFP = Y / K^{0,4} L^{0,6}$. These estimated TFPs are used to construct the TFP gap which is then used in the regression.

$$\text{(5.6)} \qquad \Delta \ln TFP_i = c + \alpha \Delta \ln TFP_l + \left[\beta \sum_{s \in IR} \frac{m_{ils}}{y_i} + \gamma \sum_{s \in IA} \frac{m_{ils}}{y_i} \right] \ln \frac{TFP_l}{TFP_i} + \varepsilon_i ,$$

where indices i represent a developing country, indices l the leader countries, indices s sectors which might be either inter-industry (IR) or intra-industry (IA) sectors, and m_{ils} / y_i represents the ratio of imports of sector s of country i from country l to country i's GDP, representing a measure of openness.

First, Hakura and Jaumotte do not include a measure of "adoptive capacity" in determination of the TFP growth rate. Moreover, they also assume that TFP growth does depend on foreign TFP growth as a form of disembodied technology spillovers. The coefficient of foreign TFP growth is close to one as the authors expect, but the mechanisms through which this technology growth is transferred to the developing countries, is not explored and remains an open question. They come to the conclusion, however, that intra-industry trade has a much larger effect on TFP growth than does inter-industry trade, even though some of their estimated coefficients for intra-industry sectors, when disaggregating for regions, are negative (e.g. South Asia).[23]

6 Theory, Empirics, and Conclusion

The models presented focus both on embodied and disembodied technology spillovers and on the role that human capital plays in the adoption of technology. They are predominantly defined in growth rates. Generally, it has to be said that the estimations test only for a small amount of the variables that were theoretically presented. While the increase in the accessible knowledge stock is included in nearly all models and turns out to be significant, the interaction with domestic conditions are less frequently tested for and often turn out to be insignificant. Moreover, a long-term effect of openness is never tested for. If one assumes that knowledge diffuses slowly, a longer openness to trade will increase the effect of openness on TFP growth. The tested mechanisms differ considerately from the underlying theory. The concept of the spillover variable and the accessible knowledge relate to the model of Wang and also to the model of Rivera-Batiz and Romer in its adopted form. The idea of the gap-variable is closely related to the model of Nelson and Phelps, even though the interaction term of human capital (or adoptive capacity) that they use is normally not taken into account. Moreover, the gap variable is used representing disembodied spillovers, and does not indicate the channel through which these spillovers reach the country. Besides, the factors that influence the absorptive capacity are not specifically tested for. An analysis of the empirical findings shows that the empirical models that were presented cannot profoundly illuminate the underlying functioning of the true transfer process, but instead rely on the concept of spillovers and catching up. The most important differences and findings are presented in table (6.1).

The specification of spillovers

A central point of discussion relates to the construction of the spillover variable. As Wang and Xu (2000) point out, the theoretical concept does not aid in giving guidance for the empirical construction of this variable. As a result, the precise construction of the embodied spillover variable remains strongly debated. Both Lichtenberg and Pottelsberghe (1998) (LP) and Falvey, Foster and Greenaway (2002) (FFG) present a set of different constructs and test for the one that is most significant. LP state that the foreign R&D stock should take the research intensity of the exporting country into account and weight the foreign R&D stock by foreign GDP. In contrast to LP, FFG approach the problem of the spillover variable from a more holistic point of view. They analyse the nature of spillovers in the donor and the receiving country and construct six variables which they test using an estimation in output growth rates with lagged variables for a set of developing countries. They come to the conclusion that spillovers are best modelled when considered as a private or public good in the donor country and as a public good in the recipient country. Interestingly, LP's and FFG's preferred specifications are similar, even though it is difficult to compare the two sets of regressions of LP and FFG as they use levels for OECD countries and growth rates for developing countries, respectively.[24] Especially the private/public spillover variable that FFG construct mirrors the preferred specification of LP. The public/public spillover variable of FFG is not tested for in any of the other models, but it can also be described in the LP-framework, with all three θ set to zero. While some results are obtained, the actual nature of technology in both donor and receiving countries remains a field for further research.

Related to the construction of the spillover variable is the question of which categories of imports should be taken into account. Conceptually, intermediate good imports have an effect on the accessible knowledge stock, while capital good imports represent the direct channel of technology transfer. Half of the estimations uses trade in intermediate or manufacturing goods, while the other half uses machinery imports for the construction of the spillover variable. Coe et al. (1997), Wang and Xu and Engelbrecht use machinery import data. With respect to this category, Mayer (2001) tests for different kinds of machinery imports on output growth. His results show that the largest impact is derived from general machinery imports that can be used in different sectors, followed by sector-related machinery, while the lowest elasticities of imports on income per-capita growth is found for the general category of machinery and transport equipment that Coe el al. (1997) use. Machinery imports, however, are more related to trade in capital goods and have a different effect on technology transfer than trade in intermediate goods. This understanding is also shown by Coe et al. (1997) who repeat their estimations also with a spillover variable based on trade in manufacturing goods. When doing so, the fit of their model is nearly identical to the one where they use machinery import data.

Following the argumentation of Navaretti and Soloaga (2001) who find that the quality of imported machinery is correlated with a country's GDP, the quality of the imported

machinery goods should also be taken into account. It would be of interest to investigate the effect of the complexity of technology on productivity gains. Incompatibilities of the demanded and existing skill level in a country can reduce the positive effects of machinery imports on TFP growth. This argumentation is founded in the writings of Basu and Weil (1998) and Acemoglu and Zilibotti (1998), claiming that technologies have to be appropriate in order to give rise to the full effect on TFP. Estimation problems are therefore likely to occur when it is neither accounted for quality nor for the skill level of the importing country and a countries' imports are biased towards high-technology. As a result, the estimated coefficients might not appropriately reflect the effect of the foreign R&D technology stock and might be biased downward, if the technology is not fully utilised. For both machinery and intermediate product imports, it would be interesting to test whether the quantity of imports or the quality of imports has a larger influence. While the quantity of imported goods increases the spread of knowledge in a country the quality increases the set of technological knowledge that is accessible by the developing country.
Blyde (2003) includes both a trade and a FDI weighted foreign TFP measure, in order to account for both channels of technology transfer. The effect related to trade in capital goods seems to be stronger as it carries a larger coefficient (his estimation is specified in first differences). Human capital interaction terms are positive and partially statistically significant.

Also disembodied spillovers are taken into account by Wang and Xu (2000), Coe et al. (1997), and Engelbrecht (2002) by means of the technological distance between donor and receiving country. Wang and Xu use the relative TFP level of a country with respect to the United states, while Engelbrecht and Coe et al. use differences in per capita income between developing countries and the average OECD country. Both find that the technology gap variable has a positive and statistically significant effect on the TFP growth rate. Engelbrecht uses the technology gap variable in interaction with the human capital term. He finds that in particular secondary education has a positive effect on the absorption of foreign technology. This finding supports the theoretical approach of Nelson and Phelps. Wang and Xu and Coe et al., however, do not include the interaction term that is seen as crucial by Nelson and Phelps. Whereas this paper pointed out that the technology gap should consist of the difference between applied technology and the set of accessible technology, the factor of accessibility is not taken into account for disembodied spillovers. Testing for an interaction term between the technology gap, the import share and human capital would give further insight into the process of technology transfer. Not taking the import share into account, makes these variables pick up a form of disembodied spillovers that are not related to openness or trade.

The role of human capital

Engelbrecht (2002) finds that the amount of secondary and tertiary school education have a significant positive effect on TFP growth, when interacted with a GDP gap variable. Additionally, he finds that primary education is particularly important in increasing domestic productivity. This single human capital term should theoretically include secondary inventions or learning-by-doing, as was pointed out in the theoretical section. Yet, Engelbrecht does not succeed in modelling both the domestic advancements and the spillovers in one model, without the human capital variable of one of the two effects turning negative. Moreover, he does not take the experience with R&D spending into account when analysing the determinants of the effectiveness of technology transfer in a country, a factor that is seen by Lall (1992) or Wang (1989) as a crucial determinant of absorptive capacity.

Miller and Upadhyay (2000) test for the significance of an interaction term between a human capital variable (average years of schooling of the adult population) and the export share. They find this interactive term to be positive and statistically significant, meaning that a higher human capital stock increases the positive effects of openness on TFP. This finding is very encouraging. Mayer (2001) also finds a positive coefficient for the interaction term between human capital (proxied by overall educational attainment) and the un-weighted share of imports from countries that have a high R&D intensity in relation to total imports. Also Blyde (2003) finds partial evidence for a positive effect of human capital on technology transfer, particularly when interacted with the FDI-flow weighted foreign TFP. Taking the interacted and non-interacted FDI coefficient into account, there appears to be a threshold level of human capital below which positive effects of FDI are no longer present.

CHH find that even though both the single variable of human capital as well as the interacted variable with the foreign R&D stock have insignificant coefficients, the two variables are jointly significant. With respect to their measure of human capital, the enrolment rate, it should be taken into account that especially in countries where the enrolment rate is increasing sharply, lagged values of enrolment would more appropriately reflect the level of human capital for the working population. The positive and statistically significant effect of human capital on output growth that FFG find is not helpful in this context as it does not assess its impact on technology transfer.

It can be said that the interaction of adoptive capacity with the foreign R&D stock or the import level appears to be positive even though the coefficient turns out to be insignificant in some models (Coe et al., 1997). Also in the case of human capital, the precise construction of the variable remains a field of debate. Engelbrecht points towards the importance of tertiary education for the absorptive process, finding this relationship for disembodied spillovers. This follows the model of Nelson and Phelps but does not explain the channel through which technology is transferred, while pointing towards a channel of spillovers that is not related to foreign R&D spending. Research experience is not included in any of the models presented. In their analysis, Crespo, Martín and Velázquez (2002) find, for a set of OECD countries, that a measure of adoptive capacity, defined as a linear combination of the human capital- and the domestic R&D capital stock, has a positive effect on technology transfer. The amount of actual own R&D spending has not been used for sets of countries exceeding the OECD countries, however, leaving open the question what the effect for developing countries is. Even though R&D spending remains low in developing countries, large differences exist. Taking the number of researchers per million people as a proxy-variable for R&D spending, values range from around 20 researchers in various African countries to 200 for many other developing countries (UNDP, 2002). These differences, and also possibly large differences in their experience with adopting technologies, can have a potentially large effect on TFP growth and should be taken into account.[25]

Inter- and Intra-industry trade

Two models that tested for the difference in inter- and intra-industry trade both pointed towards the large importance of intra-industry trade. These findings are in line with the obtained theoretical insights. Increased distance to technologies leads to higher costs of adoption and a lower transfer rate. Secondly, intra-industry trade points towards sourcing relationships and its positive effects on technology transfer have been pointed out. With hindsight to the findings of Hakura and Jaumotte, the scope for learning of countries that do not own certain sectors is reduced while sourcing relationships can help in creating such industries.

Table (6.1): Summary of spillover variables and human capital effects				
	Countries analysed	**Concept of H and effects**	**Foreign capital stock**	**Trade in which goods?**
Coe, Helpman (1995)	21 OECD +Israel	No H included	$S_i^{f-CH} = \sum_{j=1}^{21} \frac{M_{ij}}{M_i} S_j^d$	For weighting: imported goods and services to GDP
Coe, Helpman, Hoffmaister (1997)	**1971-90.** R&D stocks of 22 industrial countries and 77 developing countries	Secondary school enrolment rate in relation to population of this age positive effect on TFP growth, interaction term with foreign R&D insignificant, jointly significant	$S_i = \sum_{k=1}^{22} \frac{M_{ij}}{M_i} S_k^d$	Average bilateral machinery and equipment import share, total imports from industrial countries to GDP
Lichtenberg, Pottels-berghe (1998)	**1971-90** 21 OECD +Israel	No H included	$S^{f-LP} = \sum_{j=1}^{21} \frac{M_{ij} S_j^d}{Y_i}$	Imports in goods and services
Wang, Xu (2000)	**21 OECD countries** 1971-1990	Average years of total school attainment positive effects but not significant	Both S^{f-CH} and S^{f-LP}	Capital goods trade (SITC7)
Engelbrecht (2002)	**1971-90** 22 developed and 61 developing countries	Total years of schooling, secondary, tertiary. secondary: effect on interaction term with gap primary: effect on own knowledge creation	$S_i = \sum_{k=1}^{22} \frac{M_{ij}}{M_i} S_k^d$	Definitions as in CHH
Miller, Upadhyay, (2000)	**1960-1989** 83 countries, PWT-data	Average years of schooling Positive interaction with the import share, positive impact alone only significant at 20 percent level.	None	Exports to GDP ratio
Falvey, Foster, Greenaway (2002)	**1976-1990** 5 OECD countries and 52 developing countries	Secondary education in 1965 positive effect on output growth	Analysis of public and private nature in donor and recipient. a) public/public $\overline{KS}_r = M_r \sum_d \frac{M_{dr}}{M_r} K_d$ b) private/public $\overline{KS}_r = M_r \sum_d \frac{M_{dr}}{M_r} \frac{K_{dt}}{Y_{dt}}$	Total manufacturing imports
Keller (2002)	**1970-1991** 8 OECD countries	No H included	Trade share weighted R&D capital stocks	Inter and intra-industry trade in intermediate inputs
Hakura, Jaumotte (1999)	**1970-93.** 24 OECD and 63 developing countries	wage weighted schooling levels (none, primary, secondary, tertiary)	TFP-gap to OECD average, weighted with trade shares	Manufacturing trade

Source: Own summary

Conclusion

Theoretically, trade has three types of effects on technology transfer. First, direct effects result from the import of capital goods including modern technology as well as positive output effects due to an increasing variety and quality of intermediate inputs into production. Second, dynamic gains from trade result from an integrated world market that leads to higher production in developing countries due to lower labour costs. This higher production that is triggered by FDI, sourcing contracts and import or export competition leads via learning-by-doing to the mastering of better techniques and therefore to an increase in TFP. Third, trade increases the set of technologies that are available in a country. This allows imitation to an increasing degree, the more exposed to new technologies a country is. Besides, knowledge production becomes more effective due to a broader knowledge base and more experience in imitation and innovation. All channels of technology transfer are heavily dependent on the country's or firm's technological capability, a factor strongly influenced by the amount of human capital that exists and is used in the economy.

This paper has presented the theoretical aspects of technology transfer, without analysing the dynamic economic effects of specialisation in goods. It has focused on the process of technology transfer and not on its economic, social and political effects. Results are rather modest, and much work remains to be done until the precise process of spilling-over will be described correctly. Three basic conclusions remain. First, the degree of openness appears to have a positive effect on TFP, as does, second, the research intensity of the trading partners. Third, human capital helps in increasing TFP growth. Its interaction with imports is theoretically clear but not supported by all empirical studies while some evidence for the importance of human capital in disembodied spillovers can be found. Knowledge in the donor and recipient country appears to be private and public, respectively, and intra-industry spillovers have a larger effect on TFP than inter-industry spillovers. Still, the mechanisms of how these spillovers precisely take place, however, have generally been ignored, as Grossman and Helpman (1990) point out. In this context, the analysis of different empirical estimations leaves many questions unanswered. The consistent usage of country-fixed effects indicates that other, relevant factors have not been taken into account. It would be of large interest to specify them more precisely. In particular, the correct construction of the spillover variable remains a key element for research. While accessibility is often taken into account for embodied spillovers, this is not the case for disembodied spillovers, standing in contrast with the theory. While generally giving support to the assumption that human capital helps in technology adoption, the often low significance of the human capital variable calls for a more precise measurement of the elements of human capital that are important in technology transfer. Technology transfer from newly developed countries to developing countries has not been analysed. While this paper has looked at the absolute performance of TFP growth, also its relative performance is of interest. As long as technology transfer occurs at a higher rate then knowledge creation, convergence should take place. The technology level of the developed countries remains the moving target to aim for and the relative analysis is left for further research.

With regard to further research, some potential improvements to analysing technology transfer have been presented. First, the exact channels of embodied and disembodied spillovers remain undetermined while being crucial for a clearer understanding of technology transfer. In this context, the characteristics of technology as being private or public in both donor and recipient country need further analysis. Second, the quality of imported technology and the existing skill level should be taken into account in order to correct for appropriateness and inefficient technology usage. Long-term effects of trade or stable trade relationships should be tested for as they can increase compatibility of existing and new technologies. Third, the effects of past absorptive capacity and therefore of experience with technology transfer should be assessed as they describe the scope for past learning-to-learn, thereby increasing the efficiency of the imitative process. Last, and more generally, it would be desirable to assess factors in technology transfer at the micro level and to integrate the findings into macro analysis. Available data that would allow to determine factors that influence productivity remains rare at micro level, however, as Hasan (2002) points out. The same is valid for the macro level, calling for the construction of more sophisticated data sets.

One can conclude that openness has a positive influence on TFP-growth. This positive effect might be supported or counteracted by other effects of openness on growth that are not considered here. Moreover, increased emphasis on human capital formation appears to increase the potential for – and the rate of – TFP-growth. Results are more robust for developed countries than for developing countries, while the potential effects of better policy recommendations are far larger for the latter group. Results obtained from the sets of developed countries are not readily transferable to developing countries and should therefore not be used to develop policy recommendations. While productivity levels in the world continue to be unequally distributed, explanations for this phenomenon remain basic and are not very insightful. Many questions have to be answered before the concept of technology transfer will be thoroughly understood and more accurate policy proposals can be made.

Notes

[1] Compared to neoclassical growth theory, models of endogenous technological change are much more appealing in explaining the underlying reasons for economic growth in the long-run. See the "quality-ladder" model, including the concept of obsolescence (Aghion and Howitt (1992), Grossman and Helpman (1991b), Romer's (1990) model of differentiated capital inputs, or the model of Grossman and Helpman (1993), who model economic growth as being based on micro-level inventions. Moreover, endogenous technological progress presents an immediate explanation for differing technology growth rates between nations, a fact that can be observed in the available data and which could not be explained by exogenous growth theory.
[2] Historically, trade was the only way by which ideas could disperse between cultures. While some basic inventions, such as agriculture and cooking, were probably invented independently by different cultures, they were also at least locally diffused. For this form of inter-society diffusion of technology, war and trade have been the basic means, war forming in this respect a particular form of trade (or transfer of ideas). The moulding of iron or bronze, the Arabic sailing boat with triangular sails, gunpowder, coining, the modern banking-system, and cotton spinning present some obvious examples.
[3] For a survey, the reader is referred to Nordhaus (2001). Here, the author stresses the point that none of the normally used measures for TFP growth is consistent with the theoretical foundations. He points towards the importance of differences in productivity levels between sectors, the relative changes of employment between sectors, and changes in relative importance of sectors within the economy which form three distinct elements in determining TFP growth as it is usually measured.
[4] Profits for local firms will also exist when production costs in developed and developing prices are identical. The resulting gap in prices has to be taken into account when analysing the profit opportunities for domestic firms selling their products at home. In the case of export competition, however, their price advantages will have to be even larger than equalising prices as transport costs must be covered as well in order to compete successfully.
[5] This spending might be R&D spending or product development projects as well as be implicit in the salary of a worker who is trying to copy a product. It does not have to be officially termed R&D spending.
[6] See http://www.mofa.go.jp/region/africa/kenya/
[7] Recognising this problem, capital goods were exported in a bundle as early as 1845 in the English textile industry and this form of exports also developed later in other sectors (Clark and Feenstra, 2001), meaning that technical assistance, construction expertise and operating personnel were supplied together with the machinery, a huge success in the particular cases and reducing the risk for the importer.
[8] Lucas (1988) argues that learning-by-doing increases the stock of human capital. Due to the reasons that were given in chapter II, its effects will accrue to TFP within the framework of this paper.
[9] It has to be pointed out that $\bar{z} \leq A^*$ for an import competing firm, with $\bar{z}$ most likely being considerably lower than A^*. In the case of an export competing firm that is selling in foreign markets, the degree of exposition to foreign technology will equal A^*.
[10] Keller (1998) argues that randomly created bilateral import shares actually work better than the original ones, casting doubt on the results of Coe and Helpman (1995). In a reply to Keller, Coe and Helpman (1999), however, argue that the shares created by Keller are rather "simple averages with a random error", performing worse than the actual import shares.
[11] In 1991, the G7 accounted for 92 per cent of all R&D activities.
[12] CHH realise that it could be approximated by the number of scientists that work in a country, for example. They argue, however, that differences are small and that the variable can be ignored. They argue for the exclusion, knowing that the necessary data does not exist.
[13] For a more detailed analysis of the problem, the reader is referred to Lichtenberg and Pottelsberghe (1998).
[14] They find an $\bar{R}^2$ of 0,665 as compared to an $\bar{R}^2$ of 0,600 for CH while the coefficient of $\theta 2$ is found not to be significantly different from zero.
[15] It remains open, however, why LP do not test the specification where $\theta 1 = 1, \theta 2 = 0, \theta 3 = 1$ without including the import share on the right hand side as independent variable as well. The results of this specification would be interesting.
[16] It should be mentioned that in their first regression (which is not described here), the results are basically identical to those of Coe and Helpman (1995), although they exclude Israel from their sample. Including $\log H_{it}$ and $\log S^f(UW)$ in their regression improves the fit of the model from an $\bar{R}^2$ of 0,598 to an $\bar{R}^2$ of 0,674.
[17] Also Crespo, Martin and Velazques (2001) make this point.

[18] Engelbrecht re-estimates Coe et al.'s (1997) estimation with the improved education data as presented by Barro and Lee (1996). Moreover, he drops 16 mainly African countries due to lacking human capital data. It results that this re-estimation doubles the wellness of fit of Coe et al.'s model.
[19] Engelbrecht does not correct for schooling quality differences between countries.
[20] It would also be interesting to include measures of human capital distribution within economies as a variable. A more equal distribution could lead to stronger TFP growth as more people could participate more intensely in the economic process.
[21] Crespo, Martín and Velazquéz (2002) find a significant effect of human capital together with domestic R&D spending in the absorption of foreign technology for a sample of 28 OECD countries. For all their specifications, this linearly computed adoption variable has a significant effect on TFP in interaction with the foreign R&D capital stock.
[22] Braconier and Sjöholm (1997) find only intra- but no inter-industry spillovers for a set of nine manufacturing industries for six large OECD countries.
[23] Here, the text says the opposite but from the data it is clear that intra-industry, not inter-industry trade has the negative effect.
[24] Moreover, LP use a measure for imports that contains goods and services, while FFG use manufacturing imports.
[25] In this context, the finding of Coe et al. (1997) deserves special interest. In one of their specifications, they drop the 15 countries which perform the most R&D among the developing countries, increasing the coefficients of human capital and the interaction term between the import share and the foreign R&D capital stock. This indicates that using the amount of R&D spending in developed countries would influence the estimation results.

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