LIBERA UNIVERSITÀ INTERNAZIONALE DEGLI STUDI SOCIALI

Dipartimento di Impresa e Management

Cattedra di Economic Growth and Development

Technological Progress, Spillovers and Economic Growth: An Empirical Analysis

Relatore:

Prof. Gianfranco DI VAIO

Candidato:

Alfredo SILVESTRI

Matr.: 162881

Anno Accademico

2012/2013

Table of Contents

Introduction

Ever since the effects of the industrial revolution have become clear on the world's economies, the difference of wealth between countries has risen drastically (Studymode, 2006). The motives for this particular phenomenon and the reasons why industrial economy, while making some countries richer and richer in a relatively short time, has made little or no difference in other countries' living conditions are still to be found. Nowadays, tons of paper and ink and the some of the most brilliant minds of the academic world have been put to work in order to find out just what is the engine of economy and the explanations that they have found are so many that it's almost impossible to name them all. Among those factors, technology is without a doubt the one that makes everyone agree: there is indeed a correlation between technological e and economic progress (Grilli, 2005). There is no accurate way to measure technology; we can describe it as "The purposeful application of information in the design, production, and utilization of goods and services, and in the organization of human activities." (Business Dictionary); in other words, a particular process or idea (or the available stock of processes and ideas) that is somehow involved in economic production and helps making it easier, cheaper, faster or better, thus raising it without changing the amount of labor and capital involved (personal contribution). Technology is not entirely definable, as it can appear as a tangible object (a blueprint, a manual, a prototype) or be transferred without leaving a material trace (consultancy, training). Different technologies can also be divided by their level of intelligence and automation (high, intermediate or low); of course, technology of a higher level requires more specialized work and training to be used properly (Business Dictionary).

My aim in this work is to analyze empirically the way technology and innovation have an influence on output, why technological differences between countries are so important in determining their income and how is it possible to enhance technology diffusion and spillovers in order for poorer countries to raise their technology level.

In this first section, I will present the phenomenon of technological progress: how it happens and what are its determinants. Furthermore, I will make a brief historical digression on it, from the Industrial Revolution to the present days.

In the second section, I am going to explain why and how technological progress had an increasing impact on theoretical work over the years and I will analyze the principal models of economic growth that involve productivity growth, confronting them briefly with their critics and the historical data and explaining what made the theory evolve.

In the third section, I will survey the main empirical research of the past years in order to explain what is happening in the real world and how the theory meets reality. I will also consider the actual data, examining the principal indicators of economic and technological growth and relating them. My focus will be especially on technology diffusion and spillovers in order to find a recognizable pattern in the relationship between advanced and laggard countries.

Section 1

1.1 – History of Technological Progress

The difference in technological progress among countries is significant: not everyone has the capability or the financial availability to come up with innovations on a regular basis and to keep up with the most advanced countries. In fact, for those countries technological progress is a business itself, with its own kind of labor force (R&D workers), its capital (research facilities, labs, machinery and so on) its productivity (the previous knowledge, training and experience) its reward (royalties) and of course its result (the improvement in productivity). However, there is one fundamental difference between technology and any other product: in this case, increasing investments does not necessarily lead to an increase of output. Over the years, governments and firms have been spending increasing amounts of money and energy in research and development, while productivity growth has been quite inconstant (Weil, 2013).

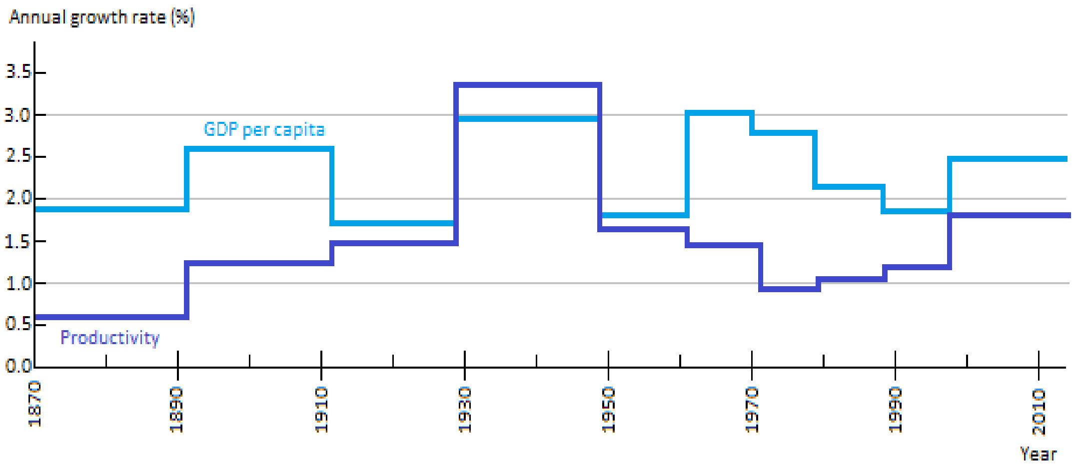
During the First Industrial Revolution, giant steps forward in terms of technology have been made, but economic growth has not been as fast as it is nowadays. The reason for this phenomenon is easy to explain. The innovations that date during this period (like the mechanization of the textile industry, the steam engine or the use of coal as the main combustible material in metallurgy) caused a fracture in industrial production as it was until then. Worker had to change their habits, learning new techniques, even change their home and their way of life, not to mention being replaced by machines and losing their job. Entrepreneurs had their worries too: the new technologies required new long-term investments that not everyone was willing to make, especially since their efficiency had not been proved yet. Productivity and GDP per capita did not grow much during that time, but everyone refers to this period as the moment when economy changed its course forever (Mokyr, 1999).

Once everyone learned how to deal with these innovations and to put them to work in an effective way, they started to prove beneficial for the whole economy. Moreover, they inspired other groundbreaking innovations that were even more useful, for example, the steam engine is no longer in use today, but it inspired the creation of electric power, which is the main source of energy for current industrial machinery (Weil, 2013). When this process started to take off, economy started to experience a "new kind" of growth that classic economists did not foresee: productivity started to grow along with population (Mokyr, 1999). Humanity (at least in advanced countries) was experiencing a continuous renovation in its life conditions: things that until a few years before were unimaginable, like electric light, telephones, air travel, cars, radio and so on, became an every-day reality. Industry had of course a huge role in this: economic growth and the continuous increase of income per capita made people richer, and the decreasing costs of production that the new technologies granted made everything cheaper, so everyone could afford the new sensational products and economic progress started to "feed" itself. This happened thanks to some particular innovations that proved capable of changing almost every industrial sector, such as network electricity, railroads and (later) semi-conductors (Weil, 2013).

After almost a century of constant technological progress, which had its peak during World War II, during the 70s and 80s productivity growth started to slow down. The reasons for this phenomenon are still matter of debate today. The dynamics of this slowdown are shown in the graph (see Figure 1.1).

The first thing we need to know is that productivity slowdown doesn't necessarily mean technological progress slowdown: as I said, technology is only a part of productivity and any other component may have played a major role. For example, those were the years of the oil crisis, in 1973 and 1979. In those years the OPEC forced a dramatic increase in the price of oil, the most widely used fuel at the time (and still today) that caused a big economic meltdown, one of the worst since the 1929 crisis. The suddenly heavier cost of a material on whom the whole industry relied may have caused the productivity slowdown, especially since it was followed by a big recession that prevented the economy from using all the available resources (Weil, 2013). However, someone else had a different vision about it: many

Figure 1.1 - Annual GDP per capita and productivity growth rate in the U.S.:



(Weil, 2013)

economists look back at that period as the true beginning of the age of information technology, or the Third Industrial Revolution (Bessen, 2010).

The first transistor had been created in 1947 while ARPANET, the precursor of the Internet, saw the light in 1969, but it wasn't until the 80s that those technologies were made available to the public. During this decade, the first personal computers and cellular phones started to come out and someone began thinking about something that we call now the World Wide Web (Technopedia). The innovations that allegedly led to the digital revolution had some similarities with the ones that came out during the first industrial revolution. The first resemblance that we notice is that these technologies, like those invented in the late 18th century, are no longer in use, but served as inspiration and basis for technology as we know it now (Bessen, 2010). The first example that comes to mind is ARPANET: it was a structure built to facilitate military communications, which is very far from the current idea of Internet (personal contribution). The second similarity is their effects of productivity the new technology introduced in the 80s fell into a productivity paradox. The majority of economists believed that the automation of the production methods were boosting productivity, but growth accounting was showing no such effect. This caused the famous Robert Solow quote: "*You can see the* *computer age everywhere but in the productivity statistics*" (Solow 1987). The possible explanations for this modern productivity paradox are roughly the same as before: it takes time for people using new technology to actually learn how to use it in an efficient way and investments are heavy and potentially leading nowhere. We also need to take into account all the companies and workers who couldn't or wouldn't adopt these new technologies, perhaps not considering them to be beneficial: those subjects were "left behind" and eventually succumbed to those who moved on with innovations. They indeed represent a loss for economy in its entirety and until everyone realized that not only information technologies were useful, but they were essential to remain in the market, many industries fell apart and their workers remained without a job (Goodwin, 2013). If we mention the enormous adoption costs that those companies sustained we have a full picture of how the digital revolution affected economy. Those costs obviously had a big influence not only on the fall of productivity growth, but also on the bonuses for skilled workers, thus on wage inequality and on the relative employment of skilled and unskilled workers and on stock prices. When economy went through those changes, instability and uncertainty in investments were the cause of a temporary economic decline (Bessen, 2010).

The benefits of information technology eventually showed in the statistics and we are still enjoying them today, in spite of the recession in which the world has been for a few years having slowed down productivity (Bessen, 2010). As we can see from the previous graph, productivity growth had a new acceleration during the mid-90s. This is when many economists started to see the true beginning of the Third Industrial Revolution (Weil, 2013). We can see the evolution of productivity in the United States in the following graphs (see Figure 1.2 and Figure 1.3).

As we can see, after the slowdown in the 70s and in the 80s, productivity started to feel the effects of the digital revolutions in the mid-90s and productivity growth has been quite constant ever since. We have to consider that the 2000s have

Figure 1.2 – Productivity in the U.S. (logarithm) dynamics:

Figure 1.3 – Productivity rate of growth in the U.S. dynamics:

(Personal research, data on GDP per hour worked taken from the Conference Board's Total Economy Database; measured in 1990 Geary-Khamis dollars)

been a period of decline for economy in its entirety. With the first half of the decade being characterized by 9/11 and the subsequent disorders in the Middle East and the second half struck by the economic meltdown, in my personal opinion productivity should have dropped like it did in the 70s and 80s and it would have if it wasn't still being affected by the benefits provided by information technology (personal contribution).

The dynamics of technological and productivity growth during the past decades has been raising many questions and many researchers analyzed them deeply; I will take some of them into account, but first I will explain what makes this technological progress possible.

1.2 – The Two Faces of Technological Progress

The main way to increase a country's productivity and consequently its output level is to acquire new technology to put to work, improve the production method and obtain better results with the same effort in terms of capital and labor. There are two ways to do this: we can create new technology on our own or we can purchase it from another country. The process of creating new technology is called innovation or invention, while the implementation of a technology invented by someone else is called adoption. These two are the only ways to obtain it and this is why we can say that technological progress has two faces, and it can be done both ways, even at the same time. Of course, those two methods are very different in terms of availability, risk and quality of technology produced, and they lead to different results. (Weil, 2013)

1.2.1 – Innovation and Patenting

Either way, technology improvement has its costs, much like capital and labor, but sometimes little or no economic effort led to groundbreaking inventions that raised productivity dramatically. This is the case of many 19th century discoveries like the steam engine or electric light, but nowadays this is no longer the case. Many of the most important discoveries of the past centuries were made by a handful of inventors working in their own houses in their spare time, while now the majority of the inventions (but not all of them) are the result of a systematic financial effort by huge enterprises or even the public authority itself. Those subjects devote much of their earnings to big Research and Development teams in well-equipped facilities for the only purpose of creating new technology. In the richest countries, as much as 2.5-3% of the total GDP is spent on R&D and a little less than 1% of the population is employed in the sector (Weil, 2013).

Venture capital funds also made even more money flow into R&D, with big companies financing small start-ups with good ideas of whom they want to take advantage. In this case, while promoting technological progress and helping a small firm with relatively small effort, the big company exploits the fact that the capital and stock market tends to have an eye for companies with big R&D expenditures (Meyer and Ehmer, 2011). Of course, firms will choose if and how much to invest in R&D only if they see a solid opportunity of enhancing their profits. They will consider if the new technology is going to give them substantial advantage, the size of the market in which the new technology's product will be sold and how long that advantage is going to last. It is also important to see if the innovation is easily replicable by the competitors and if the investment is too risky: a large R&D investment can make or break a company's fortune. Bad or too little R&D investments may make a market-dominating company fall apart (Weil, 2013). High-tech markets are a good example: Motorola was the market leader and principal innovator of the cellular phone market during the 90s, but other companies like Nokia proved to be more innovative and Motorola lost its leadership to them in the early 2000s. Right now Nokia lost its market leader spot to Samsung and is losing ground to other companies (namely HTC and Apple), while Motorola has lost much of his economic value and has been purchased by Google in 2012 (Strategy Analytics, 2013). Now other enterprises like Canonical are rising with new ideas that may (or may not) revolutionize the mobile device market, making it one of the most competitive, especially when it comes to innovation (Mobility, 2013).

When we consider technology as a product, we see another fundamental problem: since other industrial products are tangible, they are rival in use: no one can use an object that someone else is using. Even the service market is structured in a way that allows the provider to know who is using the service; this way, the user is easily chargeable. Technology, on the other hand, is a mere idea and therefore, non-rival in its use, and the impossibility of charging who is using an idea means no profit for the people who work in the R&D sector, hence no people working in the R&D sector at all. The legal protection for the inventor against any unauthorized use of his idea is represented by the patent, which grants the creator the sole property of his invention for a determined amount of time, usually 20 years.

Although the patent proved to be quite effective in protecting the rights of inventors, it has a number of downsides. First, it causes all the inefficiencies connected with monopolies (the patent generates, in fact, a monopoly). Second, it is only valid in a single country, and the inventor has to request it in every country where he wants to protect his intellectual property (Weil, 2013). Third, there is no clear idea of what can be patented; according to the United States Patent and Trademark Office, the only restrictions for an invention to be patented is that it has to be novel, non-obvious and "useful" (however objective "useful" can be). Those "restrictions" didn't turn out to be very "restrictive", as the examiners that have to approve each patent application find themselves overwhelmed by applications for inventions that can never work or by requests that can be considered questionable or even ridiculous, and some of them were even granted a patent (Weil, 2013). For example, in 1999 someone successfully patented a stick as an animal toy (United States Patent no. 6360693), while the Walt Disney company submitted an application for a "Marine mammal communication device" that allows dolphins to communicate with humans and with each other (United States Patent no. 5392735) (USPTO).

The main issue with patents is deciding which inventor has to be granted the patent itself. At first, the problem was addressed with a "first to invent" system in which whoever proved to be the first person to come up with the idea became the owner of its rights. However, since investigations and litigations proved to be too long and difficult and the patent, once conceded, was always jeopardized by someone else claiming to be the original inventor, the U.S. government later changed its approach to a "first to file" system. This method gives the patent to the first who requests it, making it more secure, but there are some downsides here too. With this solution, the real inventor may not be granted the patent and someone can always request a patent for an idea before it has even been invented. These deficiencies led to the rise of the so-called "patent trolls", companies that buy stocks of patents they do not even intend to use in order to receive payments from those who intend to put them to work. They also try to obtain patents for obvious technologies or for inventions that are not even been made yet in order to sue the creators once they introduce them. These companies are of course a big obstacle to technological progress, since they make it more difficult for inventors to receive their benefits (Weil, 2013). The vicious mechanism that patent trolls exploit reached his acme when the Halliburton Company requested a patent for "Patent Acquisition and Assertion by a (Non-Inventor) First Party against a Second Party", which is basically a patent for patent trolling (United States Patent Application no. 20080270152) (USPTO). Of course, there is always the possibility to try to keep your idea secret to everyone else, but this also proves to be expensive, especially if that idea is the basis for a multibillion-dollar business, like Coca-Cola. The lack of credit and fair financial profit that inventors get from their creations may hold technological research back, and this is why we cannot completely rely on the fact that the number of people employed in the R&D sector will continue to grow over time, as we will see later (Weil, 2013). Here is an example: H. Tracy Hall invented the process to obtain synthetic diamonds, which are used in multibillion-dollar industries today. General Electric, the company for whom Hall worked, rewarded him with a 10-dollar U.S. Savings Bond (Maugh, LA Times, 2008).

1.2.2 – Adoption, Diffusion and Spillovers

We have seen that obtaining new technology, however important for economic growth, is not a simple task; it takes huge investments in R&D, and those cannot even be consider proper investments, as they don't necessarily correspond to new factors of production. In fact, they can yield to nothing but a deficit on the balance sheet. However, investing a lot of money in R&D is not the only way to have access to innovation: a country can always obtain new technology from someone else rather than creating it. Of course, if one country is already at the top of a particular sector and already possesses all the available technology, innovation becomes the only way to improve productivity. but adoption seems a very good option for the vast majority of countries. Of course, there is not only one technology leader; although there could have been at some points in history, today technology leadership is more diffuse and shared among some countries. However, those countries are just a few, so adoption seems to be a very good option for a vast part of the world: innovation becomes a matter for a few rich countries, the others will follow the technology leader and absorb its innovations. Unfortunately for the latter, this doesn't happen. Technology adoption seems to have its costs and sometimes they are unbearable for a small economy. This is why adoption happens slowly and the gap between rich and poor countries continues to widen instead of disappearing instantaneously every time a new discovery is made (Weil, 2013).

Royalty costs are certainly a part of it: companies promoting and financing R&D expect an adequate profit, and secure their ideas, making sure that they are not usable without permission and relative payment. There is no way to obtain an innovation legally from outside but to pay the royalty costs in full, which is usually a share of the profits around 25%. This 25% rule has established itself as the most common way to compute royalty charge, even though it has its critics. Nevertheless, using an innovation owned by someone else cuts out a big piece of profits (Goldscheider, 2011). That 25% is not the only cost of absorption: there are many more and some are possibly heavier, even if they don't show as clearly as royalty costs.

It is a common opinion that researching, developing and applying an innovation for the first time is much more costly and difficult than transferring it to someone else: everything is easier when it has been done before. However, like Berrill pointed out: "only the broad outlines of technical knowledge are codified by non-personal means of intellectual communication, or communication by teaching outside the production process itself" (Berrill, 1964). In other words, technology cannot be reduced to a bunch of papers and blueprints: there is a lot of learning-by-doing and training that is not easily transferrable, and of course, it is not cheap either. There is indeed a "hardware" component of a new technology: this is represented by plants, structures, machinery, blueprints and so on, which are a big investment themselves, especially if, once acquired, they prove useless. This happens if they are not sufficiently supported by a set of non-material factors, which have their own costs, but if machinery can be sold in case of failure, those factors cannot, hence they represent a much more risky investment. We divide them into four groups. The first group includes the basis of the technology and the theory on which it stands. The second group is formed by the engineering costs, which cover the knowledge of how the innovation works and the details of the process that it produces. The third group includes the R&D costs, which are not for the people who develop the technology (as someone else already paid them), but for those who adjust it and adapt it to the new owner's necessities, which are almost never the same as the old one, especially if we are considering it at an international level. The fourth group is the pre-start-up costs, which cover all the losses that may occur during the first installments of the new technology: of course, every worker will need a period of training and learning-by-doing during which the innovation won't be exploited at its full potential (Teece, 1977). Those costs can be heavy, but there is another consideration to make before even thinking of adopt a new technology.

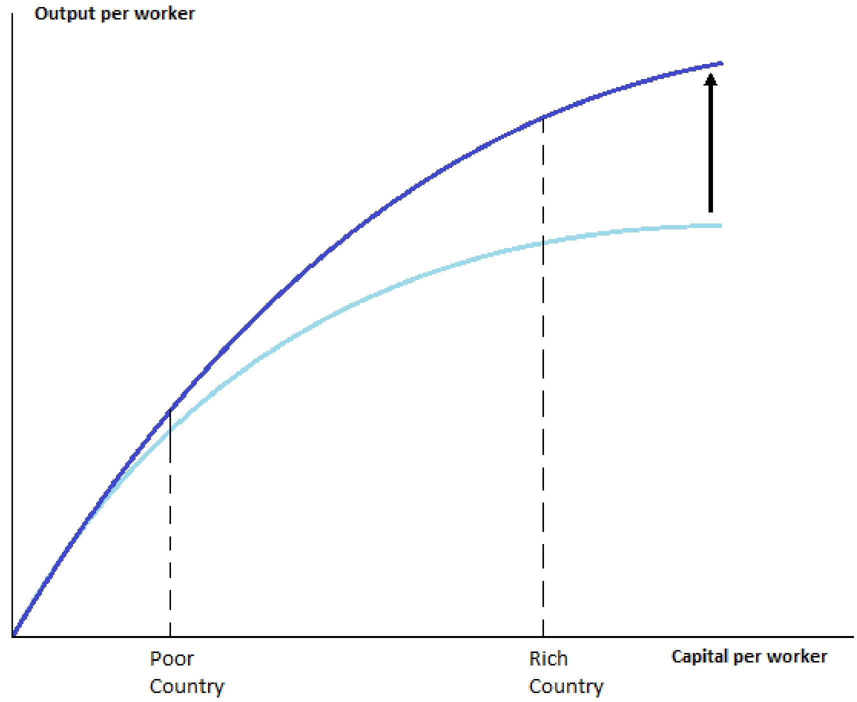
The adopting country may not have the right characteristics to make the innovation work efficiently: that innovation may be "inappropriate". Over 90% of R&D work is done in OECD countries, so we can expect innovations to work better if connected to the characteristics of those countries (Acemoglu, 2007). For example, technologically advanced countries tend to have a temperate climate; therefore, their inventions may not work in warmer zones, especially when it comes to agriculture (Weil, 2013). We also have to consider the intellectual property protection's ineffectiveness at an international level: big companies will only develop technologies for their home market, where the innovation can be more efficiently patented. In order to do so, they can associate their technology with a specific set of skills that are common in their home country or with a singular kind of production organization that cannot be replicated abroad (skill-biased and organization-biased technologies). It is easy to understand that those two strategies work much better on poorer countries (Acemoglu, 2007).

Moreover, some technology may need adequate levels of capital per worker in order to originate a relevant increase in output. This may happen because that particular technology works on an exponential scale in order to allow each worker to put more capital to use and produce more output. Inventions like this are very common in developed countries, where there is a large availability of capital, but in poorer countries it may not work just as fine. In the graph below, we can see a schematic representation of the phenomenon, relating capital per worker and output per worker and representing the effect of an innovation for both poor and rich countries (see Figure 1.4):

As we can see, in a standard production function, a raise in Total Factor Productivity leads to an irrelevant increase in GDP if not sustained by an appropriate amount of capital per worker. This is why rich countries with high levels of capital per worker can get a huge benefit from a technology that is almost useless to poor countries (capital-biased technology). Spending a lot of money on an innovation that might prove useless due to different characteristics from the inventor or to the lack of capital accumulation and can be an economic disaster for a small economy, this is why technological convergence is slow and, for some countries, going backwards (Weil, 2013). Of course, technological diffusion and adoption has its good sides. Some innovations prove to be cheap and useful for many countries and their invention alone contributes to boost economy not only in the country in which they are invented, but also in countries that are close or have partnerships with it, and sometimes in the whole world. Those positive effects are called Spillovers.

As we said before, technology is non-rival in its use, which means that even if the inventor protects it with every legal way or keeps it as hidden as possible from imitators, he will never be able to take all the benefits from it. We call spillovers those beneficial effects that a new invention has on entities other than the inventor.

Figure 1.4 – Effects of innovation on a standard production function for rich and poor countries:



(Weil, 2013)

Spillovers can be a huge gain for society in its entirety to the point that a new invention may be more beneficial to the community than to the inventor (Peri, 2012).

The diffusion of technology happens through trade, migration, technological licensing (which is the permission to use a patented technology) and foreign direct investment (FDI) (Peri, 2012). Many theorists assert that technological spillovers are the most valuable engines of growth for relatively small economies along with physical and human capital investment, and those theories are generally supported by research on actual data. Right now, technological spillovers are amongst the main issues for developing countries, focusing on establishing new trade partnerships and trying to draw foreign investment, not only to obtain financial availability, but also to be granted access to new technology (Grilli, 2005).

Technological spillovers work on two main channels: on one hand, the absorption of new technology improves productivity; on the other hand, it boosts significantly the adopter's own R&D sector with new ideas and methods that make it more effective. The first channel is dominated by market: this is where trade, FDI and royalties come along: an innovation has its price and the inventor has to get at least a part of the profit. The second channel is more subtle, it is often a consequence of the first: a new technology necessarily has to come with a trace of how it has been created, allowing the adopter to discover some R&D mechanisms that can prove useful in the future (Peri, 2012).

Of course, the benefits that a firm or a country gets from those spillovers does not depend on the spillover itself, nor on the entity of the technology, nor on how much the inventor is willing to give away: it also depends on how the receptor deals with it. Absorptive capacity a reality among researchers who are currently trying to estimate it, stating that it can be a serious obstacle to technological convergence. The general opinion is that, in order to take advantage of a new invention in full, the adopter must have a good level of human capital and R&D investment itself: that is the only way to understand every aspect of the new technology and the process behind it (Peri, 2012).

The issue of technology spillovers is one of the greatest in economy today and the obstacles to technological diffusion and convergence seem to stand in the way of generalized economic progress, especially in poorer countries, whose economic data generally show low levels of physical and human capital per worker (Grilli, 2005). Can those barriers be torn down? I will get back to this issue with empirical evidence and research to show the real extent of the phenomenon (and the possible solutions), but first I am going to analyze how the economic theory has been dealing with technological progress, the models that described it and characterized it as one of the most important (if not the most important) determinant of economic growth.

Section 2

2.1 – Technology and the Theory of Economic Growth

Lionel Robbins asserted that the principal objectives of the economic growth theory the understanding of the fundamental causes of development and the path that it follows (Robbins, 1968). Theory offers the basis for every economic policy and the various approaches that have characterized the academic mainstream (but also some "underground" theories) contributed orienting many countries' decisions on the matter. This strong correlation between theory and politics is even stronger when economic growth is involved, as it is the main objective that policy makers try to accomplish. In fact, the first theories that have been created on the matter were the result of efforts driven by the purpose of finding the right economic policy to use. It is no wonder that technology has always been one of the main focuses of those theories in order to grant intensive growth, along with physical and human capital accumulation (Grilli, 2005).

At first, technology was not considered as an important factor of growth in theory: the main concern of those studies was capital, as the majority of economies during the 19th century were under-capitalized. Once the neoclassical theory of economic growth started to emerge, technology (as a part of the so-called Solow residual) came to be one of the main issues. The new theories made clear that the economic world was moving towards a steady state, which meant that increasing capital and labor wasn't enough to make economic growth last forever (Grilli, 2005).

Since then, theorists' attention on technology and human capital has been increasing. They began studying models that could outline the invention of new technology in a closed economy through research and development, thus introducing the concept of endogenous growth. This is the first milestone of a series of technology-based models and every one of them has introduced and analyzed a new aspect of the phenomenon. Some of those key aspects of technological progress that offer a real challenge to theorists are the decreasing marginal returns to technology (the so-called "fishing out effect"), the extent of technology's scale effect, the exact mechanisms of adoption of foreign technology and why it is slower than expected (Zeira, 2013).

Let us analyze some of the most important theoretical contributions on the matter.

2.2 – Technology in the Classical Economic Theory

Technology has not always been the corner stone of economic growth models, especially in the past. Classical economists like Adam Smith tended to focus more on capital accumulation and investment. Of course, Smith was aware of the fact that innovation could lead to better organization of the factors and improve production, but he thought that new techniques and products were available at all times, and they were useless without an appropriate amount of capital. In other words, technology is a result of investments and is nothing without capital accumulation (Smith, 1776).

John Keynes did not give technology much attention, as he was more concerned with short-term growth, but other Keynesian authors like Harrod and Domar tried to extend his theory, finding the principal engine of growth in savings and investment. In fact, an important assumption in their model it that technology is fixed. They characterize the long-term income per capita growth as it follows:

$$\gamma_Y = \frac{(s + s')}{v}$$

In this equation, γ_Y represents the rate of growth of income per capita. This value is determined by s, which is the internal savings ratio, s', which is the foreign investment in the country, and v, which represents the technology level in the form of units of capital per units of output and, as I said, it is assumed as fixed (Harrod, 1939; Domar, 1946; cited in Grilli, 2005).

Theory has then evolved, introduced some further dynamics and analyzing economic growth with a closer attention to the long term.

2.3 – The Neoclassical Theory

The neoclassical theory of economic growth started with Solow and Swan, who introduced a new way to elaborate the interaction between capital and growth (Grilli, 2005). The model that I am going to introduce is a good characterization of the economic dynamics and widely regarded as one of the most (if not the most) important model in economic growth theory. It has been for years the starting point for many students of economic growth in general, including myself.

The first thing we need to do is quantifying output as a function of two factors: Capital (***K***) and Labor (***L***):

$$Y = F(K, L)$$

We know that, by applying a certain amount of these two factors to the function, we obtain a certain amount of output, but the function is not the same for everyone, as we observe that equal amounts of capital and labor generate different amounts of output for different countries. Let us stylize the production function as a Cobb-Douglas function, which is the most widely used:

$$Y = AK^{\alpha}L^{1-\alpha}$$

As we can see, this function introduces a new factor (***A***), which is called Total Factor Productivity. TFP explains the way ***K*** and ***L*** combine to generate output and explains all of the aforementioned output differences between countries when the other factors are fixed. On the other hand, $\boldsymbol{\alpha}$ indicates the share of capital in the Gross Domestic Product (the datum used to measure output) and it is similar for every country, generally around 1/3.

This function explains that there are three ways to raise the level of output (thus generating growth): increasing the labor force, increasing the amount of capital or increasing the TFP. Let us assume that the first scenario comes up: population increases and we find ourselves with a larger labor force: ***L*** increases. One of the assumptions of the production function is that it has constant returns to scale, so an increase in ***L*** makes *Y* go up, so in this scenario total production is increased, but let us look at the Marginal Productivity of Labor:

$$MPL = \frac{\delta F(K,L)}{\delta L} = (1-\alpha)A\left(\frac{K}{L}\right)^{\alpha}$$

From this equation, we derive another assumption of the production function: the Marginal Productivity of Labor is decreasing, so let us rewrite the production function dividing everything by ***L***:

$$\frac{Y}{L} = A\left(\frac{K}{L}\right)^{\alpha}$$

Y/L is output per capita, which we can rewrite as ***y*** and ***K/L*** is the capital/labor ratio (***k***):

$$y = f(k) = Ak^{\alpha}$$

In order to have economic growth and improved life conditions, output per capita (which is also income per capita) must increase, and we see that this is not the case when a raise in ***L*** occurs. In fact, total production will rise, but at some point, it will not be enough for everyone and production per capita will fall. Since this does not happen, the reasons for growth have to be found somewhere else.

In order to increase both ***Y*** and ***Y/L*** capital has to grow as well, and it has to grow more than ***L***, which means that we need to raise the capital/labor ratio, a process we call "capital deepening". Robert M. Solow explains the relationship between capital deepening and economic growth in his famous model, published in 1956. The creation of new capital is investment, which is accomplished by saving some of the income without consuming it. The inclination to consumption is measured by ***c***, which means that every year a portion ***c*** of total income is consumed. This means that ***cY*** is total consumption and ***(1-c)Y*** is total saving. We also consider that a portion ***d*** of the physical capital deteriorates over the year and is no longer usable (depreciation), so it needs to be replaced. Net investment is total investment minus the portion of it that is dedicated to replace depreciated capital:

$$Net\ Investment = (1 - c)F(K, L) - dK$$

If we express the same equation in per-capita terms, we obtain net capital deepening:

$$Net\ Capital\ Deepening = (1 - c)f(k) - dk$$

Let us consider population growth: as we have seen, more population needs more capital to work with, so we need to take it into account. We assume that population grows at a constant ratio ***n***.

$$Net\ Capital\ Deepening = (1 - c)f(k) - (d + n)k$$

Solow considered the steady state of his model the point in which investment is just enough to cover for population growth and depreciation and net investment is zero:

$$(1 - c)f(k) = (d + n)k$$

Every economy will keep on accumulating capital until they reach the steady state, and the further away the country is from the steady state, the faster it grows (see Figure 2.1).

Now, let us assume that everyone can borrow the money that they need to invest at an interest rate ***r***. It is clear that if there is a chance to make a profit everyone will keep on investing, therefore at the steady state (where there is no net investment) capital has to be only productive enough to repay interests and depreciation. This means that the Marginal Productivity of Capital has to be equal to ***r+d***. In a Cobb-Douglas function, we obtain the following results:

$$MPK = \frac{\delta F(K, L)}{\delta k} = \alpha A \left(\frac{K}{L}\right)^{\alpha - 1}$$

$$MPK = r + d$$

$$\alpha A \left(\frac{K}{L}\right)^{\alpha - 1} = r + d$$

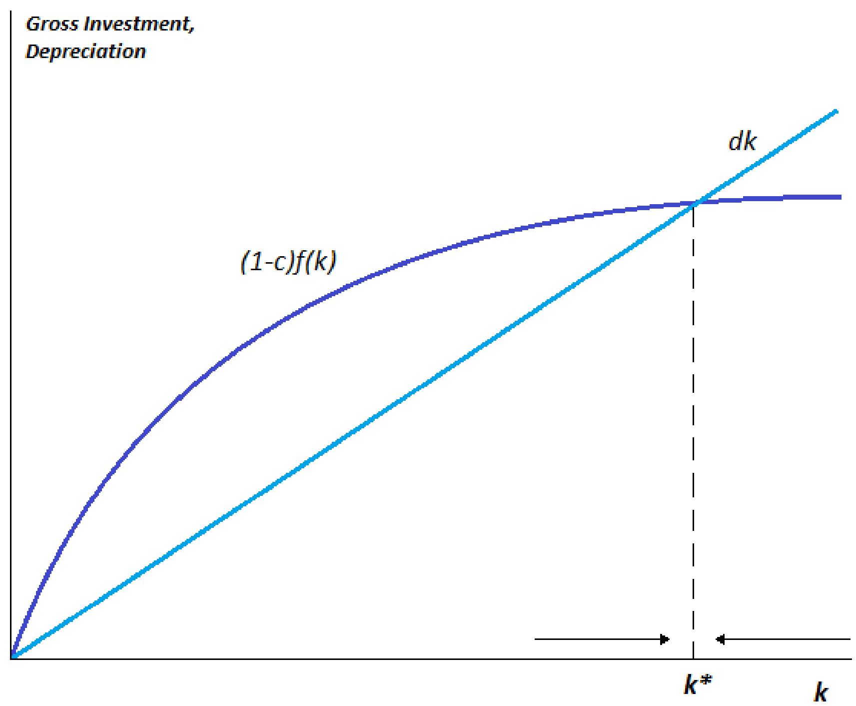
From this equation, we derive the steady state levels of output and capital per person:

$$k^* = \left(\frac{\alpha A}{r+d}\right)^{\frac{1}{1-\alpha}} \quad ; \qquad\qquad y^* = A\left(\frac{\alpha A}{r+d}\right)^{\frac{\alpha}{1-\alpha}}$$

(Solow, 1956; cited in Zeira, 2013)

Those results that are incompatible with the actual data. Given that both ***r*** and ***d*** are roughly the same all over the word (and this is true even in the real world), many countries have been investing far less than they should have according to the Solow model. Besides, the actual data shows that MPK has not fallen over time. The only explanation is that growth does not depend only on investment and capital deepening. Total factor productivity has to have a role in this as well (Zeira, 2013).

Figure 2.1 – Dynamics and steady state in the Solow model:



(Zeira, 2013)

2.3.1 – Total Factor Productivity

The first thing to know about total factor productivity is that it is not a measurable quantity like capital and labor. Instead, it comprehends everything that has an effect on production and cannot be described as physical capital or labor. This particular nature has made it possible to measure total factor productivity only as a residual: given total GDP, population and amount of physical capital, we apply them to the production function and obtain our results. In fact, in the aforementioned production function, $\boldsymbol{A}$ is called "Solow Residual". We can analyze the effects of TFP on economic growth by taking the previous equation:

$$y = A\left(\frac{\alpha A}{r+d}\right)^{\frac{\alpha}{1-\alpha}}$$

We know that expressing economic measures in logarithms makes a good approximation of the measure's growth rate, so let us apply this to our case:

$$\ln y = \ln A + \frac{\alpha}{1-\alpha}\ln\alpha + \frac{\alpha}{1-\alpha}\ln A - \frac{\alpha}{1-\alpha}\ln(r+d)$$

Since we are talking about growth, hence variations, we can exclude $\boldsymbol{r}$, $\boldsymbol{d}$ and $\boldsymbol{\alpha}$ from the equation: they remain fixed over time. In growth rate terms, the result that we obtain is:

$$\frac{\Delta y}{y} = \frac{1}{1-\alpha}\frac{\Delta A}{A}$$

This explains the dramatic impact of TFP growth on output growth: if total factor productivity changes, output changes even more. This means that, if we consider total factor productivity as a measurable production factor, it does not have decreasing marginal productivity like capital and labor (Zeira, 2013).

TFP has two main components, technology and efficiency. We already know what technology basically is, while we can describe efficiency as a compound of every other aspect that affects production. In fact, efficiency has countless components that involve almost every economic, political, social and geographical characteristic of the country, the most important of which is human capital and schooling. Some other examples: the country's form of government, the degree of freedom that people (and firms) have, the way the government interacts with economy, health care, housing, income distribution, the effort that people put into work, the opportunity cost of free time versus work time, climate, morphology, latitude, neighbor countries, proximity to navigable rivers and seas and so on. The debate is still on about which is more important, but efficiency seems to be the most inscrutable of the things that concur to economic production, or at least the most difficult to put a finger on. On the other hand, we have technology (Weil, 2013).

2.4 – Endogenous Growth

As we know, the production function as Solow described it failed to justify economic growth as we observe it and the way it happens. During the 80s, the economic growth theory started contemplating the phenomenon of technological progress as one of the engines that allowed a country to grow continuously without any external support, hence the term "endogenous growth".

Paul Romer was one of the very first researchers to develop a model in which innovation was the main focus, explaining the way it interacts with production. After trying to include this new "factor" in the production function, he realized that the best thing to do was to separate production and innovation, making technology the product of the R&D sector, distinguishing it from the production sector. The R&D sector must have increasing returns to scale, so that the innovations created in the R&D sector improve production and the more innovations the higher the improvement (Zeira, 2013). Let us assume that we have a production function in which the only factor is labor:

$$Y = aL$$

The total amount of working people is $\boldsymbol{N}$, but only some of them work in the production sector (workers); the others work in the R&D sector (innovators). We call the people working in the two sectors $\boldsymbol{L}$ and $\boldsymbol{R}$ respectively. The productivity of a single worker is $\boldsymbol{a}$, and we assume that every new innovator will improve each worker's productivity from $\boldsymbol{a}$ to $\boldsymbol{a + b}$. Since technology is non-rival, everyone will be able to use the innovator's work, therefore, each innovator will raise production by $\boldsymbol{bL}$. This means that, if we had 200 workers and then we add 2 innovators, total output will increase from $\boldsymbol{200a}$ to $\boldsymbol{200a + 400b}$: increasing returns to scale. The production function is now:

$$Y = aL + bRL$$

The output growth is entirely due to the new technology, and the rate of growth we obtain is:

$$g = \frac{(aL + bRL) - aL}{aL}$$

Which is:

$$g = R \times \frac{b}{a}$$

As we can see, $\boldsymbol{a}$ represents the stock of technology available at the beginning of the period of time that we are considering, while $\boldsymbol{b}$ is the new technology. Romer assumed the $\boldsymbol{b/a}$ ratio as fixed:

$$\frac{b}{a} = \theta$$

Therefore, this model suggests that as long as there are researchers, growth will continue endlessly. But why would people choose to work in the R&D sector? In this particular model, the innovator is a monopolist who gets full and maximum profit from his idea, and that profit is equal to the entire benefit that the economy has, which is $\boldsymbol{bL}$. The worker, on the other hand, will have the same profit he had before, which coincides with his productivity, $\boldsymbol{a}$. People will move to the R&D sector as long as $\boldsymbol{bL \geq a}$, or $\boldsymbol{\theta L \geq 1}$. Therefore, the starting point of innovations is when the economy reached the point where:

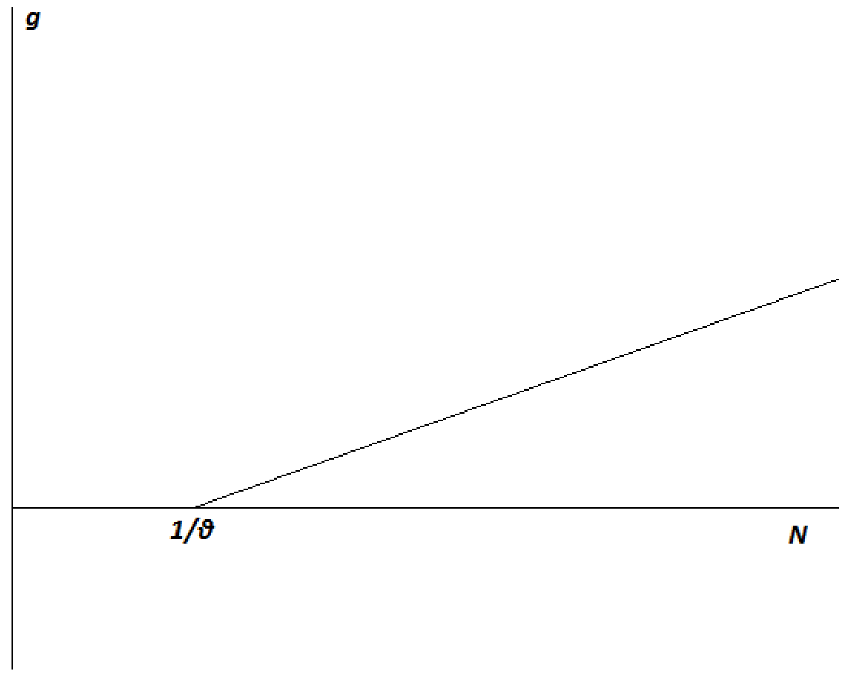
$$L = \frac{1}{\theta}$$

From that point, the more people moves to the innovation sector, the more economic growth we obtain (see Figure 2.2).

(Romer, 1986; cited in Zeira, 2013)

The fact that the $\boldsymbol{b/a}$ ratio is fixed means that the amount of new technology produced in a determined period directly correlates to the technology already

Figure 2.2 – Dynamics in the Romer model:



(Zeira, 2013)

available. This is called "spillover assumption" or, as Sir Isaac Newton would put it, "Standing on the shoulders of giants": the more knowledge is already available, the easier it is to come up with new groundbreaking innovations. Unfortunately, as Charles Jones explained in his critique to the model, this assumption is very strong and not verified in the real world: the scale effect has to be reduced somehow (Zeira, 2013).

The interpretation that the Romer model provided about the scale effect of innovation proved to be ineffective: the effect was too strong and had no connection with reality. This is a consequence of the fact that having a strong knowledge and background makes innovation easier in a way, but harder in another way: you might be standing on the shoulders of giants, but those giants left you with less yet to be invented. Therefore, as technology moves forward, R&D and innovation require new people and new funds; we can say that technology balances its increasing returns with increasing costs (Weil, 2013). Just like before, we divide our population (***N***) between researchers (***R***) and manufacturers (***L***) we define the fraction of people working in R&D as:

$$\gamma = \frac{R}{N}$$

Therefore, the amount of manufacturers is:

$$L = (1 - \gamma)N$$

We maintain the production function as it is, with the only factor being labor. Now we can rewrite it as:

$$Y = a(1 - \gamma)N$$

Alternatively, in per capita terms:

$$y = a(1 - \gamma)$$

Output per capita depends on productivity and on the number of people working in the production sector. The reason for it is easy to understand. If more and more people work in the R&D sector, they will come up with new technology, thus raising productivity and improving the output, but new techniques are not put to work instantaneously: workers need some time to develop their effects. On the other hand, there is less people working in the production sector and manufacturing the real output. Technological progress itself is not as easy as it was in the previous model: we add another factor, which is the cost of the innovation, called $\boldsymbol{\mu}$. The rate of growth of productivity can be determined as:

$$\frac{\Delta a}{a} = \frac{R}{\mu}$$

Which can be written as:

$$\frac{\Delta a}{a} = \frac{\gamma}{\mu} N$$

If we assume $\boldsymbol{\gamma}$ as fixed, output per capita growth will be equal to productivity growth:

$$g = \frac{\Delta a}{a} = \frac{\gamma}{\mu} N$$

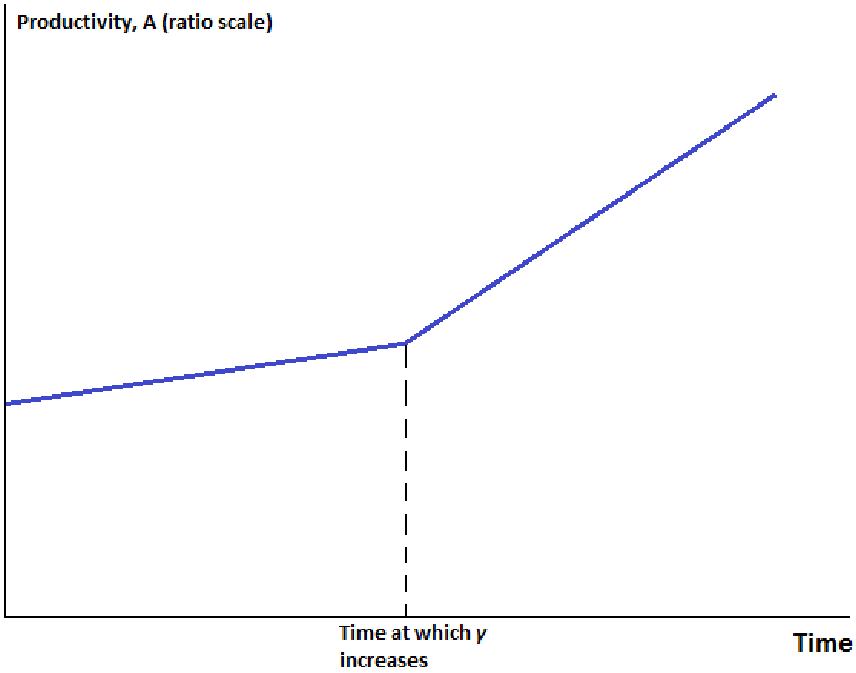
Since there is no trade-off between the two sectors (we assume that the income is the same), manufacturers will produce the amount of output that they are supposed to, while every year innovators will produce new technology, improve production and make output grow at the exact same rate at whom they create innovations. Now, let us assume that the remuneration for the inventors suddenly grows, making some people decide to change their field of work. The ratio of researchers over total population (γ) grows and we find ourselves with more inventors and less manufacturers. Productivity will grow at a faster pace, but, as I said before, the remaining number of producers will not be able to generate the same amount of output they did previously, not until the innovations will grant a new boost in economy, making it grow even faster than before.

Productivity and output growth will follow the paths shown on the following graphs (see Figure 2.3 and Figure 2.4):

(Lucas, 1989; Mankiw, 1995; cited in Weil, 2013; notations modified to my purposes).

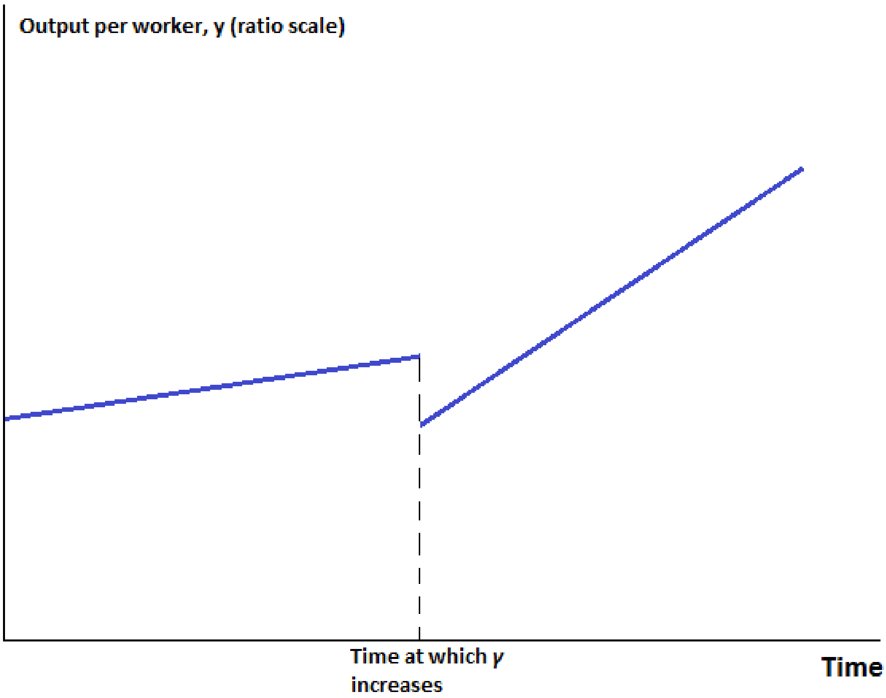
This model, however very simple, makes a good compromise between the models by Solow and Romer: it adds the scale effect of technology that moves the steady state forward and makes economy grow at a fast pace, but this effect is significantly less strong than in the Romer model as a result of the introduction of the innovation cost. However, something still does not add up: according to this model, more population means more researchers and more manufacturers, hence more output. The model tells us that not only aggregate output depends on population, but also output per capita does: if a country is more populated, it should have more researchers and a higher productivity (Weil, 2013). The following graphs show the relationship between population and productivity and between population and GDP per capita (see Figure 2.5 and Figure 2.6):

Figure 2.3 – Dynamics of productivity over time in the Lucas/Mankiw model:



(Weil, 2013)

Figure 2.4 – Dynamics of output per worker in the Lucas/Mankiw model:



(Weil, 2013)

Figure 2.5 – Relationship between population and productivity in 20 countries:

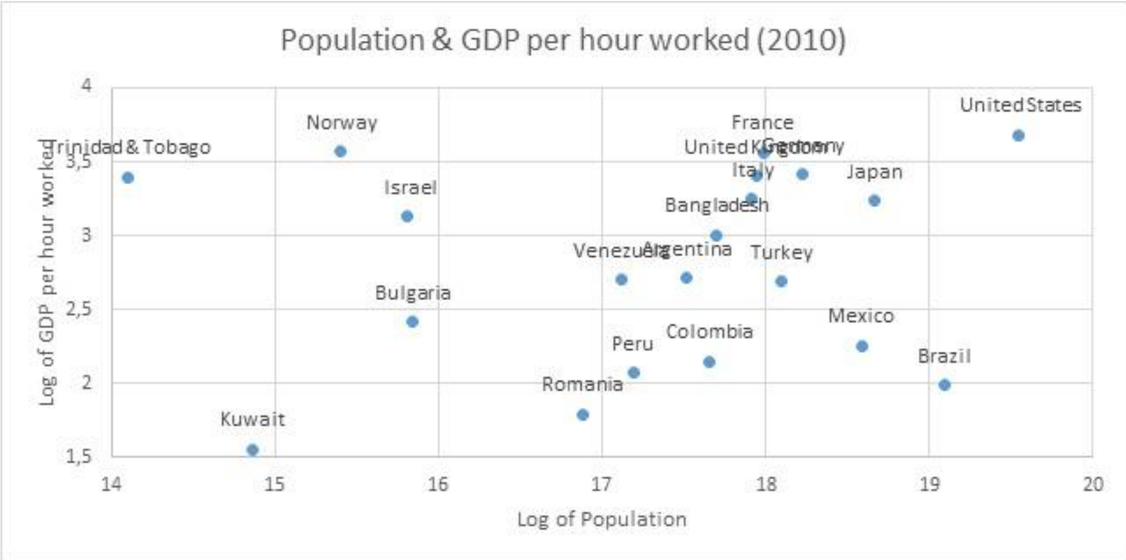
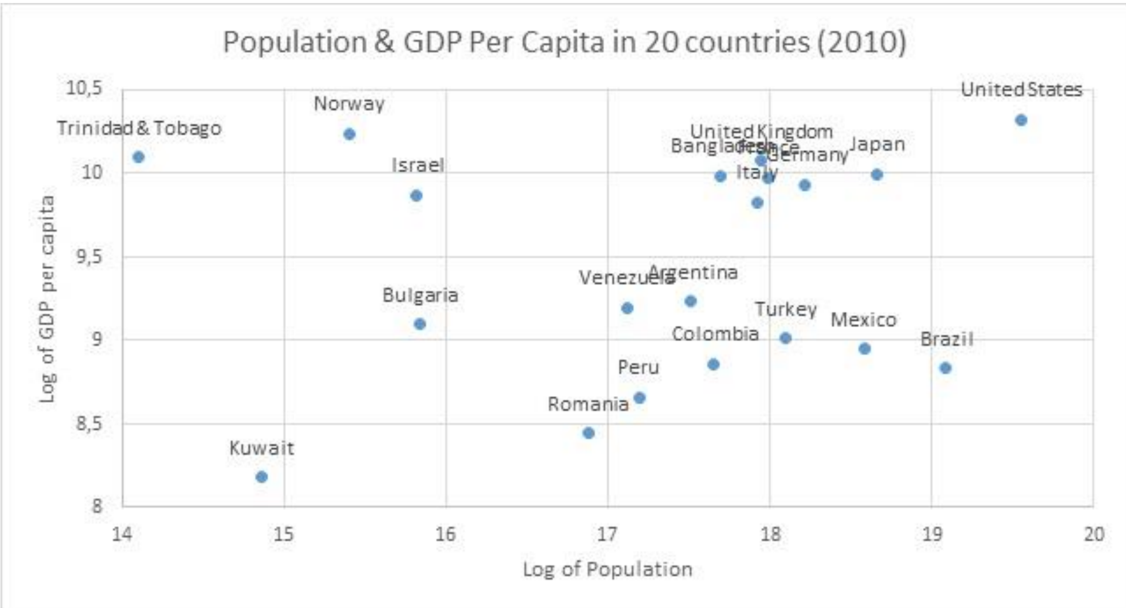


Figure 2.6 – Relationship between population and GDP per capita in 20 countries:



(Personal research, data on GDP per hour worked and on mid-year population taken from the Conference Board's Total Economy Database, data on GDP per capita taken from the Maddison Project Dataset, GDP per hour worked and GDP per capita are measured in 1990 Geary-Khamis dollars)

What we can see from the two graphs is that they look very much alike and that they show no correlation between the values whatsoever. This tells us that the relationship between population and both output per capita and productivity has no validation in the real world data. As I said, innovation is not the only source of new technology; a country can always adopt foreign technology. Therefore, it seems useful to the purpose of our analysis to expand the model in order to include another country that imitates technology instead of creating it (personal contribution).

2.5 – Theory of Technological Adoption

The strategy that countries adopt when it comes to technology is different, as every one of them has a choice: trying to create its own innovations or import them from abroad. Of course, the most technologically advanced country has no choice but to innovate. This is simply because it already has in stock the whole available amount of knowledge. Innovation has its costs and as I said before, a huge investment can yield to nothing at all. On the other hand, imitation is far less risky: we are talking about technology that has already been created and tested and the benefits it brings are proved. So why don't all the followers absorb all the available technology? It seems the most proper thing to do in order to induce a significant boost in terms of production, and at the same time we wouldn't have the technology and wealth gap between north and south of the world that we are witnessing today (Zeira, 2013).

Unfortunately, as I said before, technology adoption has a number of downsides; it is not easy to import a production method in another country, especially if the two differ so much between each other: different climate, capital accumulation, experience and training can make a new technology beneficial for a country and worthless for another. This is why a country, especially if we are talking about a poor country, will not import every technology available, since adoption has its costs too. We can identify adoption costs as the price that the inventor has to perceive according to its patent: if there were no such thing, the inventor would not have begun working on it in the first place (Weil, 2013). The interaction between north and south of the world when it comes to technology adoption is analyzed by Paul Krugman, who proposed a simple model to explain it.

Let us suppose that the world is divided in two parts: the North and the South. The North is the technology leader and the South is the follower. The North makes its own innovations, so it is granted a constant economic growth: let us call the North's output per worker $\boldsymbol{F}$ and its rate of growth $\boldsymbol{g}$. Since we maintain the same production function that we have seen in the previous models (no capital), $\boldsymbol{F}$

will also be each worker's productivity. On the other hand, the South has a productivity and output per capita called $\boldsymbol{A}$. The only way for the South to increase its productivity, hence its output per capita, is to adopt technology from the north. This doesn't happen instantaneously: the growth that the South will experience depends on its distance from the North's productivity, which is the frontier we want to reach:

$$A - A_{-1} = a(F_{-1} - A_{-1})$$

We are of course talking about the previous year's frontier: this is the stock of available technology since the South is the follower; in the meantime, the North has grown to:

$$F = F_{-1}(1 + g)$$

Therefore, the South will only adopt a portion $\boldsymbol{a}$ of the technology gap. This is due to all the reasons that I mentioned in the previous section: costs, nature of the innovations and so on; for these reasons, the South is only able to adopt a portion $\boldsymbol{a}$ of the available technology. Its rate of growth will be:

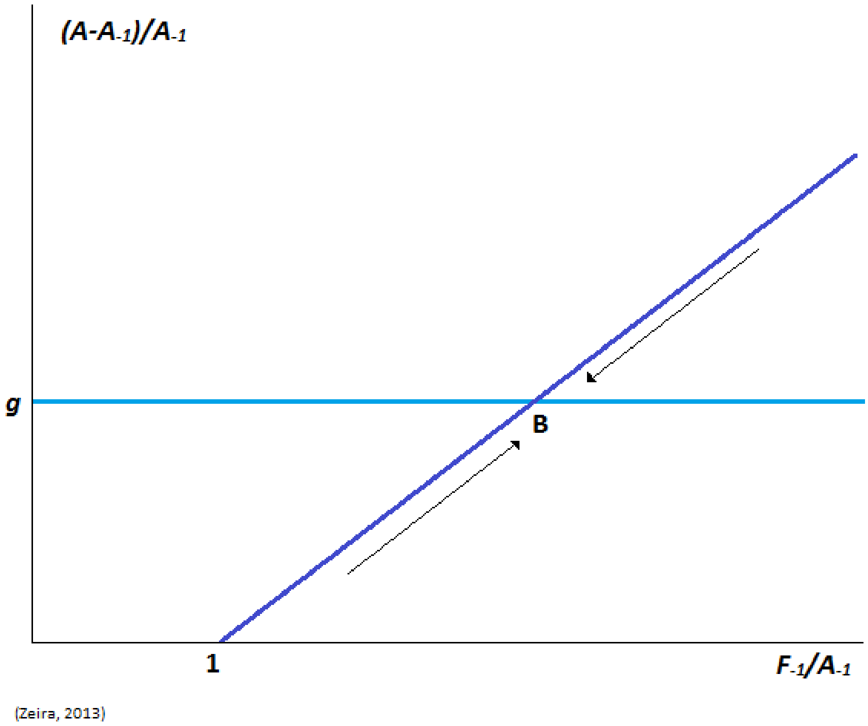
$$\frac{A - A_{-1}}{A_{-1}} = a\left(\frac{F_{-1}}{A_{-1}} - 1\right)$$

The dynamics of growth in the South are shown in the graph (see Figure 2.7):

The horizontal line in the graph is the growth rate of the North, which is fixed at level $\boldsymbol{g}$, while the line that represents the growth of the south is upward sloped: the growth rate will increase more as the gap widens, and the slope of the line is $\boldsymbol{a}$, which is a positive number but it's smaller than 1. As shown in the graph, the steady state in this model is represented by the point in which the South grows at the same rate ($\boldsymbol{g}$) as the North. At this point, while the growth rate is the same, the south will not have adopted all the available technology, so the gap will still exist. At the steady state, it will be:

$$\frac{F}{A} = \frac{g + a}{a}$$

Figure 2.7 – Dynamics of growth and steady state in the Krugman model:



It can still be very large if ***a*** is small, but if we assume that for some reason ***a*** rises, the steady state will change to a point where the gap is much smaller.

(Krugman, 1979; cited in Zeira, 2013)

Let us see how this model faces the facts. We know that in terms of total factor productivity, the North of the world is approximately six times ahead of the South, so:

$$\frac{F}{A} = 6$$

The North grows at an approximate annual rate of 1.8 percent, so:

$$g = 0.018$$

Given those data and assuming that we are in the steady state right now, we calculate that:

$$a = 0.004$$

This means that the South catches up about 0.4 percent of the gap each year. As usual, something does not add up. The math seems to be about right, but the North and the South have not been growing at the same rate, so we are definitely not at the steady state right now (Zeira, 2013).

The problem of the slowness of adoption by poorer countries remains unsolved in the Krugman model. It introduces the concept of imitation in the economic theory about technology and it provides a good explanation of how it works, but it leaves some questions unanswered. Why exactly does the South adopt only a portion of the available technology? Is there a way to represent the cost that adoption has for each worker? What is the precise relationship between the South's gap from the frontier and its growth and why is it much slower than predicted by the model? To answer some of these questions, Stephen Parente and Edward Prescott developed a new theory, which introduces some changes in the previously analyzed model (Zeira, 2013).

The model by Parente and Prescott highlights the cost of innovations in a deeper way. We are aware that besides the cost of the innovation itself, the introduction of a new technology comes with more expense in terms of conversion of the production methods, training and so on. The assumptions we make are the same as before, but now we also assume that the cost that each worker has for the implementation of a new technology is:

$$COST = \frac{1}{2a} \frac{(A - A_{-1})^2}{F_{-1}}$$

As we can see, this is a quadratic function, which means that the marginal cost of technology is increasing: adopting a technology will be more expensive for every leap forward. In this case, $\boldsymbol{a}$ is a quantification of the speed or ability of a country to adopt innovations and it is specific for each country. Since every worker gets a benefit ***A*** from the innovation, his or her profits will be:

$$PROFITS = A - \frac{1}{2a}\frac{(A - A_{-1})^2}{F_{-1}}$$

Every worker wants to maximize his profits and we can obtain this condition by making a simple derivative, which has to be equal to 0:

$$\frac{\delta PROFITS}{\delta A} = 1 - \frac{(A - A_{-1})}{aF_{-1}} = 0$$

Which means that:

$$\frac{(A - A_{-1})}{aF_{-1}} = 1$$

In this equation, the first part represents the marginal costs and the second part is the marginal profit. We derive that:

$$(A - A_{-1}) = aF_{-1}$$

Therefore, the growth rate is:

$$\frac{(A - A_{-1})}{A_{-1}} = a\frac{F_{-1}}{A_{-1}}$$

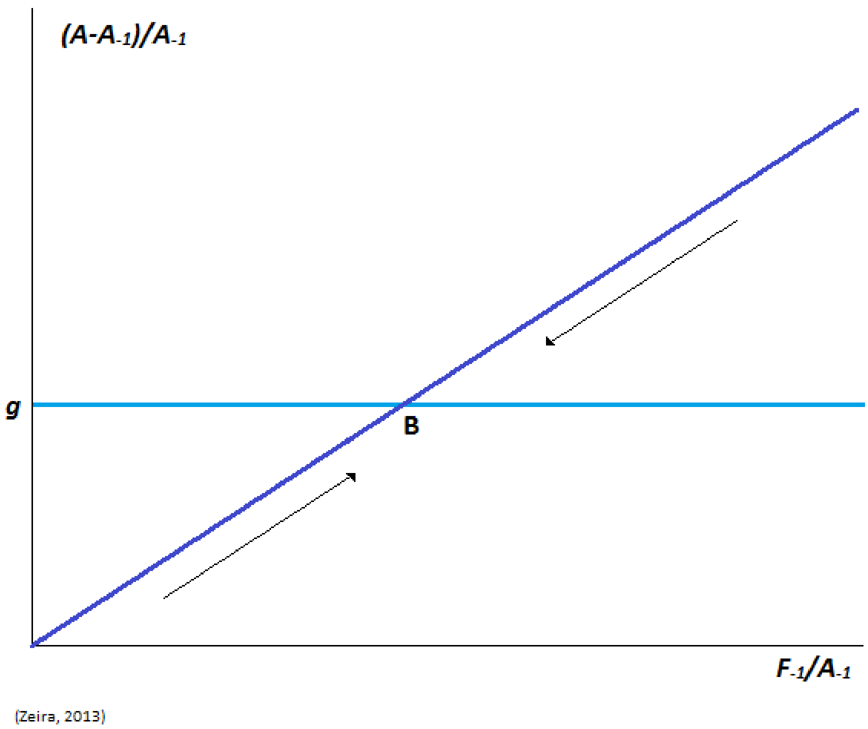
As we can see, ***a*** plays a great role in this model: countries that for one reason or another are slow or less able to adopt foreign technology will get nowhere near the frontier set by the technology leader. The dynamics of this model are shown in the following graph (see Figure 2.8).

The long-term gap is now:

$$\frac{A}{F} = \frac{a}{g}$$

As we can see, much of it depends on ***a***. As I said, the smaller the ***a***, the poorer the country.

Figure 2.8 – Dynamics of growth and steady state in the Parente/Prescott model:



(Parente & Prescott, 1994; cited in Zeira, 2013)

This model helps expanding the Krugman theory by giving more attention to some characteristics that were not taken care of enough. Once again, there are still many important questions to be answered. For example, what it is that makes a country faster or more capable of adopting new technology? Moreover, what are exactly those costs that come with adoption? And what is their influence in a country's ability to import technology? In my opinion, these questions cannot be answered with theory: only an extended empirical analysis of the phenomenon has a chance of getting to the core of the problem, which is to find the components of the coefficient ***a***. However, this model introduces the concept that ties us to the facts we analyzed before: the marginal cost of technology. Since every country has to spend more and more in order to innovate, is it possible to compute its status simply by analyzing its R&D spending? Moreover, since the theory asserts that in the future innovation costs will reach inestimable sums, is it possible that technological progress will eventually come to an end? (personal contribution)

In the next section, I will analyze closely the empirical evidence and the related research, particularly focusing on technological barriers and spillovers, trying to understand why and how technologically laggard countries remain stuck in their position, what is keeping them from technological convergence and how the academic world proposes to find a solution to this issue.

Section 3

3.1 – Technology Gap and Technology Clubs

Technological progress has been recognized by both empirical and theoretical research as one of the dominant factors of economic growth. It comes as no surprise that, much like economic growth itself, convergence has not been stable over the years. In fact, some countries experienced it, while others have seen their technology gap widen due to crucial defects that have compromised their path to progress and independence. This process, both in economic and in technological terms, seems to have become more intense after World War II in spite of (or maybe because of) globalization and trade openness (Di Vaio and Enflo, 2011). Let us analyze some of the main empirical works on the matter in order to better comprehend what the tendencies in technological convergence have been.

An important work about technological convergence and divergence has been published by Fulvio Castellacci in 2006. In his research, Castellacci discusses convergence and the concept of "technology clubs", which are an evolution of the twenty-year old concept of convergence clubs. Those groups of countries follow diverging growth paths due to their initial differences and are the cause of the initial skepticism towards neoclassical theory. This led to the introduction of the concept of relative convergence: every country converges to his own club's steady state, which can be very different from another country's steady state (Baumol, 1986). Studies have been conflicting about the number of clubs that can be distinguished and about what are those differences that make their growth path so different: some think that it is a matter of capital stock (physical, human or both), some think it is about technology. This is Castellacci's approach: he collected data and observed the existence of three technology clubs. Of course, the act of measuring technology is a complicate task, due the variety of its nature, and the standard approach was always indirect, as it involved the Solow residual. Castellacci's method is much different: he uses a number of direct indicators that attempt to measure the technological activity within the country. Those indicators, collected for as much as 131 countries through the ArCo database by Archibugi and Coco, are the following: the number of patents, scientific publications, internet users, telephone users, electricity consumption, science and engineering schools enrolment, years of schooling and literacy rate (all in per capita terms). Those values are strictly correlated, so the author tried to restrict them into two macro-factors that are distinct and take all of those values into account. Factor 1 measures "technological infrastructures and human skills" (gathering telephones, electricity consumption, science students, schooling and literacy), while Factor 2 measures the "creation and diffusion of codified knowledge" (patents, scientific articles and internet penetration). Castellacci collected these data for the years 1990 and 2000 and obtained some interesting results about the pattern that have been followed during those years.

Using various clustering algorithms in order to obtain a result that is statistically robust and effective in highlighting the existence of separate clusters of countries. All of the algorithms pointed to the existence of three distinct groups:

- Advanced cluster: It is a small group of 15 to 20 technologically advanced countries holding 40% of the world GDP. Obviously, this set is formed by European countries and Western offshoots, with some highly productive Asian economies (Hong Kong, Singapore, South Korea) becoming members of the club during the 90s. Of course, those have the highest values in all of the previously mentioned factors and impressive growth rates for all of them during the 90s.
- Follower cluster: A large group of about 70 countries holding 36% of the world GDP. This set includes catching-up economies from South-East Asia, Southern Europe, Middle East and South America. Between 1990 and 2000 the members have been quite stable, with only a few European and South-East Asian countries moving upwards to the Advanced cluster and fewer entering from the lower group. This group shows a smaller capacity of technology creation and absorption as measured by patents, scientific publications and internet users (Factor 2). In fact, those values are much lower in the follower set and the gap is bigger than we may expect (the advanced/follower ratio is 16:1 for patents, 9:1 for publications and 11:1 for

internet users in 1990), even though this gap has decreased over the 90s. The gap in technology infrastructures and skills was much lower in 1990 (almost nonexistent) and remained quite stable over time.

- Marginalized cluster: This is the largest group, as it holds 60% of the world population, but only 23% of GDP. This cluster is formed by the majority of Asian economies (including the biggest, although China has moved up during the 90s) and almost all of Africa. The gap between followers and marginalized in technology creation and adoption was incredibly huge in 1990: ratios are 190:1 for patents, 14:1 for articles and 270:1 for internet. The internet gap has been decreasing rapidly in the following ten years, but the other two increased. The gap in terms of technological infrastructures and human skills has shown equally striking gaps which decreased slowly over time, but remained remarkable in 2000.

The distinction in three clusters and the existence of two large gaps seems to be confirmed by the data (see Table 3.1).

In order to define the dynamics of catch-up in these groups, Castellacci proposes a renovation in the concepts of β-convergence and σ-convergence, which are the most widely used in growth accounting. The assertion of β-convergence in its technological meaning is that less developed countries tend to have faster technological progress than advanced countries, while σ-convergence happens when the dispersion of the values of GDP per capita across countries tends to decrease.

Castellacci introduces the concept of Q-convergence as an evolution of β-convergence, dividing the general tendency to convergence in four quartiles, thus highlighting the gaps between more dynamic economies (such as China, who has grown the most in terms of technology and is in the 4th quartile) and slower economies. This leads to a deeper understanding tendency of the world technological dynamics, which may seem positive and uniform from β-convergence, but, when analyzed through Q-convergence, appear as the result of a few very dynamic countries' efforts, while others remain inactive.

Table 3.1 – Data on technology in the three clusters as reported by Castellacci (2006):

	Cluster 1: Advanced		**Cluster 2: Followers**		**Cluster 3: Marginalized**	
	1990	**2000**	**1990**	**2000**	**1990**	**2000**
Patents granted in USPTO (per million people)	69.45	97.37	4.29	6.81	0.02	0.03
Scientific articles (for million people)	627.36	670.65	68.56	90.54	4.94	5.63
Internet users (1994 & 2000) (per thousand people)	26.67	289.77	2.48	57.32	0.01	3.51
Fixed and mobile telephones (per thousand people)	516.78	1055.92	163.07	404.72	13.36	47.14
Electricity consumption (kWh per capita)	9411.5	10450.9	2584.1	2989.4	265.8	318.5
Science and engineering enrolment ratio	10.87	17.31	6.68	9.33	1.28	2.06
Mean years of schooling (population over 14)	9.91	10.44	6.56	7.06	3.42	3.93
Literacy rate (population over 14)	98.66	98.80	91.29	93.86	58.01	67.57

(Data on patents provided by the USPTO. Data on scientific articles provided by the Science Citation Index generated by the Institute for Scientific Information. Other data provided by Archibugi and Coco's ArCo Database).

On the other hand, Castellacci evolves the notion of σ-convergence with Cluster convergence, which happens when the center of the distribution in a cluster (for example, the Follower cluster) approaches the center of the top cluster (in this case, the Advanced cluster).

The analysis of technological convergence during the 90s has shown that the general tendency has been towards convergence, but there are different dynamics for the three clusters. The Follower group has reduced its gap in every factor, except for scientific and engineering tertiary school enrolment, which has consistently increased in advanced countries. The tendency is quite different for the Marginalized group: in this cluster, there has been rapid convergence only in terms of telephony and internet, while we observe a rather slow catch-up for the remaining factors. The most shocking result is the one regarding patents and scientific publication, which are a good measure for a country's tendency to create new technology and innovate. In these cases, the gap has widened: marginalized countries have not been innovating and this tendency is worsening, against every theoretical odd. This means that technological infrastructures and human skills are improving in the developing world, but we cannot tell the same for innovation capabilities (Castellacci, 2006).

A research similar to Castellacci's was conducted by Ewa Lechman in 2012, who extended the analysis to the following decade, which goes from 2000 to 2010. This research focuses on information and communication technologies and their adoption by a total of 145 economies. The aim is to find technology convergence patterns in today's economy. The author uses the concepts of β-convergence and Q-convergence that we have already seen in Castellacci's work, which means that she analyzes convergence both in absolute terms and in quantiles, trying to have a better understanding of the direction that technology adoption is taking.

The indicators that Lechman used are the following:

- Fixed telephone lines (per 100 people)
- Fixed internet subscriptions (per 100 people)
- Fixed broadband subscriptions (per 100 people)
- Internet users (per 100 people)
- Mobile phone subscriptions (per 100 people)

All according to the International Telecommunication Union statistical database.

Although not very sophisticated, those indicators provide a good approximation on where a country stands on ICTs, if its population has a good access to them and if they are providing the country with significant help towards economic progress. Lechman collected the data for both 2000 and 2010 in order to observe the tendency in this period, which is widely regarded as the one of fast and dynamic diffusion of new technology, especially ICTs. Some of the statistical data are summarized in the Table 3.2.

As we can see from the data, means seem to have raised dramatically in ten years, as it is for minimums and maximums, which indicates that there has been a worldwide tendency towards the increase of ICTs implementation. This is a proof of the fact that technology diffusion and implementation has been very strong in this decade. The only indicator that has a decrease (however not remarkable) is the fixed telephone subscriptions count, probably a consequence of the “advanced” countries switching to cellular phones. All other means tend to grow: for example, the broadband subscriptions mean in 2010 was almost ten times as much as it was in 2000.

Table 3.2: Statistical data on ICTs as reported by Lechmann (2012):

Variable	No. of Obs.	Mean	Std. Dev.	Variance	Min	Max
Fixed Phones (2000)	145	23.6	21.9	483.63	0.019	86.07
Fixed Phones (2010)	145	22.6	18.7	351.86	0.063	82.06
Fixed Internet Subscr. (2000)	145	4.71	7.6	58.95	0.0037	39.30
Fixed Internet Subscr. (2010)	145	12.0	12.5	156.89	0.010	47.35
Fixed Broadband Subscr. (2000)	145	1.3	3.12	9.75	0	22.58
Fixed Broadband Subscr. (2010)	145	11.1	12.2	150.35	0	63.83
Internet Users (2000)	145	10.03	13.7	189.18	0.0059	51.3
Internet Users (2010)	145	39.7	27.4	753.82	0.72	95
Mobile Phones (2000)	145	20.2	24.29	590.32	0	81.48
Mobile Phones (2010)	145	96.5	39.3	1547.66	3.526	206.42

(Calculated by Lechman using Stata 11.0. Data provided by the International Telecommunication Union statistical database).

An important thing that is not shown in the table is that not only worldwide means have grown, but also differences between countries did. In fact, technology diffusion and implementation is highly uneven, as it is strong in richer countries, but very slow and poor in low-income countries.

Let us try to look for convergence in this scenario. Lechman ran a regression to prove β-convergence, trying to see if the actual data show a negative correlation between implementation growth and the original stock of technology. The results are statistically significant and show that the negative correlation exists, so β-convergence is a fact, at least as far as ICTs are concerned: countries that had a weaker information and communication technology set in 2000 are generally catching up. The indicator in which poorer countries are catching up faster is the mobile phone users count, as the negative coefficient reached -8.14, while the fixed telephone lines' coefficient showed the weakest correlation with -1.96. This tendency is called "technology leapfrogging", which we will analyze later in this work.

On the other hand, the Q-convergence regressions (dividing the set of countries in quantiles) offers us a different point of view. When Lechman ran separate regressions for four increasingly rich groups of countries, she found that richer countries tend to have stronger regression coefficients, showing that low-income countries are a generally less predisposed to adopt technologies, or at least a lower ability to acquire those tools. However, they are catching up as well and, even if their growth is not as fast as expected, it is, in fact, happening (Lechman, 2012).

It may be interesting to analyze the similarities and differences between Castellacci's and Lechman's works. In Castellacci, we find a perhaps deeper empirical analysis, with the author trying to measure the ability to adopt new technological structures as well as the instruction level and the predisposition to innovate endogenously. On the other hand, Lechman's focus is on ICTs, analyzing these data with more attention than Castellacci, but she does not consider instruction and academic work. We can say that this research is more about technological structure than knowledge, and does not try to measure the innovating potential of a country. With these specifications made, we can say that in their point of encounter (information and communication technology) these works complete each other and show roughly the same result. In fact, for both of them poorer countries are catching up the internet gap, they have been doing so for the past 20 years and they are continuing to do so even today. But does this mean that they have now more real chances of catching up in economic growth rate terms or that they just have more internet? Is this change influential for economic growth?

Castellacci tries to answer all of our questions about technological convergence in his 2011 research. In this work, he investigates the distinction between absorptive capacity and innovative capability. This difference emerged in the same author's 2006 work, which showed that the implementation of internet, cellular phones and other economic structures did not help low-income countries' general lack of capability to innovate. In other words, poorer coutries are reducing the gap in terms of adoption of foreign technology, but they are not developing their capability to generate technological progress from within.

First, Castellacci creates a simple model, contemplating the dynamics in question and providing a theoretical basis for his analysis. Let us consider the productivity growth rate of a country ($\boldsymbol{\Delta A/A}$) as the sum of technology imitation (***KC***) and invention (***KI***):

$$\Delta A/A = KC + KI$$

We assume that imitation depends on the distance from the technology frontier (***GAP***) and the absorptive capacity ($\boldsymbol{\delta}$), which represents the portion of this gap that the country is able to imitate:

$$KI = GAP^{\beta} \times \delta$$

Absorptive capacity can be described as a measure of how dynamic the country is and how fast and effective their implementation is. In Castellacci's opinion, this capability depends on human capital (***HK***) and technological infrastructures (***TI***):

$$\delta = TI^{\delta_1} \times HK^{\delta_2}$$

The other determinant for technological progress is innovation, which increases with instruction (**INN**). However, only a portion (***θ***) of this knowledge can be put to work effectively due to other restrictions and limitations:

$$KC = INN^{\alpha} \times \theta$$

Once again, this portion depends on human capital and technological infrastructures:

$$\theta = TI^{\theta_1} \times HK^{\theta_2}$$

Technological infrastructures and human capital are determinant factors for both innovation and imitation. If we combine all of the previous equations and take logs to describe growth rates, we obtain that the growth rate of productivity is structured as it follows:

$$\Delta A/A = \alpha \log INN + (\theta_1 + \delta_1) \log TI + (\theta_2 + \delta_2) \log HK + \beta \log GAP$$

This simple equation highlights the main components of technological progress and catch-up: the innovative effort by the country, the level of technological infrastructures and human capital (which have an effect on both innovation and adoption) and the technology gap. These factors, combined with physical capital investment, generate economic growth and increase production.

Now it is time to see how this equation goes along with the data. Every determinant analyzed in the previous equation is considered as a combination of a series of indicators that synthesize it:

Indicators of innovative intensity (***INN***):

- Patents (registered patents per million people)
- Scientific publications (scientific articles per million people)

Indicators of technological infrastructures (***TI***):

- Internet penetration (internet users per thousand people)
- Mobile telephony (mobile phone users per thousand people)
- Fixed telephony (fixed phone users per thousand people)
- Electricity (kWh consumed per capita)

Indicators for human capital (***HK***):

- Tertiary enrolment ratio (share of university students)
- Years of higher schooling (average years of higher education in the population over 15)
- Secondary enrolment ratio (share of secondary students)
- Years of total schooling (average total years of schooling in the population over 15)
- Primary enrolment ratio (share of primary students)
- Literacy rate (for people over 14)

When we look at the data, we can recognize the same three clusters that we have seen in the previous research by Castellacci (2006). This time, the data is collected for 1985 and 2004. We can see the average results in Table 3.3.

As we can see, the gap between advanced and followers is very pronounced when it comes to innovative intensity, but much lower in terms of technological infrastructures and human capital. The gap between followers and marginalized, on the other hand, is far bigger, not only in terms in innovative intensity, but also in the other two macro-factors, although it has decreased over the years in the latter.

In order to analyze these data and the way they evolved over the period, Castellacci uses the previously analyzed concepts of β-convergence, σ-convergence, Q-convergence and cluster convergence. In this case, the absolute tendency shows a negative correlation between the initial level of an indicator and its growth rate, which means that β-convergence is generally happening, but the dynamics are very different for each indicator and each quantile. The negative correlation is particularly strong when it comes to internet and mobile phones (a tendency that we have seen in both Castellacci, 2006 and Lechman, 2012) and rather weak if we consider scientific articles and patents. In fact, if we look at the Q-convergence data, these two indicators show a positive correlation between initial stock and growth rate for the first quantile (the indicator of scientific articles shows a positive correlation in the second quantile as well). This means that in less dynamics countries, convergence for innovation intensity is not happening. For the first quantile, there is no catch up for tertiary and total schooling as well, which means that those countries are not experiencing a significant and sufficiently pronounced increase of human capital as well. We have seen this result before, but now we can analyze this phenomenon in a deeper way and with a theoretical basis, but first we need to expand this analysis and consider clusters.

Table 3.3 – Data on the three technology clusters as reported by Castellacci (2011):

		Cluster 1 - Advanced		**Cluster 2 - Followers**		**Cluster 3 - Marginalized**	
		1985	**2004**	**1985**	**2004**	**1985**	**2004**
INN	**Patents**	61.89	116.12	3.90	9.16	0.01	0.02
	Scientific articles	644.8	791.4	67.6	110.4	3.6	5.3
TI	**Internet users**	51.9	613.8	4.7	225.1	0.0	32.1
	Mobile telephony	49.0	799.2	6.5	444.5	0.2	70.2
	Fixed telephony	429.4	597.1	123.7	262.7	8.3	38.2
	Electricity	9290.6	12107.9	2626.8	3672.9	223. 7	395. 8
HK	**Tertiary enrolment ratio**	42.2	66.5	24.4	40.8		
	Years of higher schooling	0.46	0.75	0.17	0.40	4.2	8.2
	Secondary enrolment ratio	98.3	119.1	75.4	90.3	0.03	0.08
	Years of total schooling	9.3	10.4	6.1	7.1	29.7	45.1
	Primary enrolment ratio	5.63	5.87	4.04	4.64	2.5	3.5
	Literacy rate	98.5	98.9	91.3	94.3	1.95	2.81
						51.6	63.3

(Calculated by Castellacci. Data provided by the Barro and Lee dataset on education, the World Bank database and the USPTO).

As we said earlier, σ-convergence happens when the dispersion of a technological indicator's values across the world tends to decrease in average, while cluster convergence happens when the center of the distribution for a cluster tends to approach the center for the upper cluster' distribution. The σ-convergence data's results are in line with the β- and Q- convergence analysis: there is a general catch-up, but it has been weak, as the gap is still large. In this case, the dispersion has not sufficiently decreased over time. If we extend the analysis to cluster convergence, we see every group's performance for each indicator. The technological distance between followers and advanced has generally diminished, especially in mobile telephony and internet, a consequence of the rapid worldwide diffusion of ICTs that we have discussed earlier, but also in terms of scientific articles and patents, which were the factors that showed the widest gaps. The distance between followers and marginalized has decreased as well, but here the significant implementation of ICTs has not been accompanied by a consistent growth in innovative intensity; in fact, the gap in terms of scientific publications and patents has widened and the lower cluster's performance in terms of human capital has been poor as well.

The dynamics described here show a substantial convergence to the advanced cluster for follower countries, while the gap between them and the marginalized widens. If we represent this tendency on an income distribution chart, we can see that two "twin-peaks" are emerging, both technologically and, consequently, economically speaking. This means that in the past years two different set of countries have formed, and while the countries inside a group are converging, the two sets are diverging from one another. The twin-peaks pattern has been analyzed by Quah (1997) for the 1961-1988 period and Castellacci observes that this pattern is continuing in the present (Castellacci, 2011).

We have seen in those three empirical works that convergence, which is a staple in technology and economic growth theory, is a much more complicate matter than expected. Poorer countries do not seem to experience it and they are moving further away from the technological frontier as opposed to follower countries that are catching up quickly. The main reason for this is their lack in innovative intensity: they simply do not seem to have the right incentives or the capability to create new technology for themselves. As we know, adoption does not work in certain cases because imported technologies do not always adapt to another country's social, economic and geographic conditions (Weil, 2013). When we get to that point, innovation (and therefore research and development) becomes essential for a developing country. Let us see how R&D can produce a significant boost in economic growth.

3.2 – R&D: The Engine of Progress

Research and Development can be described as the sector of economy that is devoted to the production of new technology, and therefore it has been recognized as one of the main factors for economic growth. We have seen how innovation, which was often the result of a few bright minds' unremunerated work in the past, recently became the product of huge investments by big companies with groups of scientists working with advanced equipment, but the result of these investments is not certain to obtain nor easy to calculate. However, since patenting is the main way to profit from inventions, the number of patents per million residents may be a good measure of what the innovative performance of a country is. In Table 3.4 we can see the number of patents registered in the United States per million residents for a set of countries (all countries with 30 or more patents in the U.S. are included) and their respective GDP per capita in 2010. We are only going to use the number of patents registered in the United States because patenting rules are different for each country and this kind of data is generally not easy to find for other countries. We omit the United States in order for the data to be accurate and not distorted by the presence of an outlier (Weil, 2013).

As we can see, the relationship between patenting and GDP per capita is positive and strong: countries that innovate more tend to have higher income. However, the relationship may be distorted by the fact that in many industrial sectors patenting is not regarded as the main way to protect intellectual property (many companies choose to keep their innovations' specifics secret), while in other sectors (pharmaceuticals is a good example) patenting remains the most widely used intellectual property protection method. A country that is at the technology frontier may be specialized in other industrial sectors and consequently be technologically advanced without having many patents registered (Weil, 2013). Therefore, we can consider another measure of innovation intensity: the amount of money invested in R&D each year.

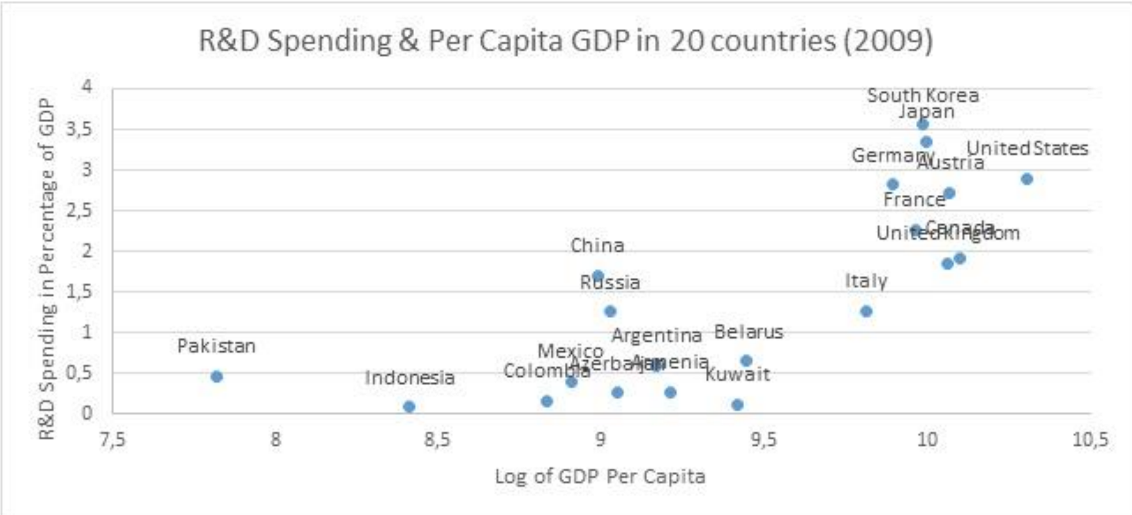
Table 3.4 – Patents per million residents registered in the U.S.A. and GDP per capita in 2010 as reported by Weil (2013):

	Patents per Million Residents	GDP per capita
Taiwan	418.5	23 292
Japan	368.2	21 935
Israel	260.7	19 171
Finland	324.4	23 290
Switzerland	247.8	25 033
Sweden	175.7	25 306
South Korea	257.2	21 701
Germany	167.0	20 661
Canada	163.3	24 941
Hong Kong	101.0	30 725
Singapore	123.2	29 038
Luxembourg	88.4	37 843
Denmark	138.9	23 513
Netherlands	115.8	24 303
Iceland	80.9	23 749
Austria	110.2	24 096
Australia	96.6	25 584
Belgium	86.0	23 557
France	77.8	21 477
Norway	95.8	27 987
United Kingdom	80.8	23 777
Ireland	59.5	22 013
New Zealand	54.6	18 886
Italy	37.1	18 520

(Data on patenting provided by the USPTO. Data on GDP per capita provided by the Conference Board's Total Economy Database and from the Maddison dataset. All measured in 1990 Geary-Khamis dollars).

Figure 3.1 illustrates the relationship between R&D spending and GDP per capita. There seems to be a positive relationship between the two, but it is not perfect: countries with low GDP per capita tend to have low R&D investments, and the picture does not seem to change even for higher values. However, when we get to the richest countries in the world, R&D spending tends to increase dramatically. The reason for this phenomenon is imitation: a country can always obtain new technology from someone else rather than creating it. Of course, if one country is already at the top of a particular sector and possesses all the available technology, innovation becomes the only way to improve productivity, hence the increase of R&D spending. The other countries will follow the technology leader and absorb its innovations. Of course, there is not only one technology leader; although there

Figure 3.1 – Relationship between R&D spending as a percentage of GDP (1999-2009) and GDP per capita (2009) in 20 countries:



(Personal research. Data on GDP per capita provided by the Maddison dataset and measured in 1990 Geary-Khamis dollars. Data on R&D spending provided by the WorldBank dataset).

could have been at some points in history, today technology leadership is more diffuse and shared among some countries (but not many) (Weil, 2013). We can see this in Figure 3.1: some of the sectors in which technological progress is more rapid and sharp are the electronics, mechanical and chemical markets. Japan, United States, Germany and South Korea are leaders in those markets and as we can see, they have the highest R&D spending (personal contribution). Those researches lead us to think that R&D is indeed the engine of growth: innovation does lead to economic progress. However, these data are not conclusive: in order to analyze and understand the full dynamics of the relationship between innovation and growth we need to examine an empirical research that takes all the possible measures of technological innovation into account and analyzes the relationships between them in a deeper way.

Ulku's 2004 work is purposeful for this matter. She develops the discussion from Romer's assumption about increasing marginal returns to R&D investment and confronts this theory with the real-life experience of 20 OECD countries and 10 non-OECD countries. The OECD countries that we consider are Australia, Austria, Belgium, Canada, Denmark, Finland, Greece, Iceland, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden and the United Kingdom. On the other hand, the non-OECD countries are Argentina, Brazil, Hong Kong, India, Indonesia, Malaysia, Philippines, Singapore, South Africa and Venezuela. The period in question is between 1981 and 1997 and the measures for R&D that Ulku takes into account are the following:

- <u>Patent applications</u>: Those data consist in the number of patent applications per capita requested in the United States by inventors of different countries, divided into five categories: chemical, computers and communication, drugs and medical, electrical and electronic and others.
- <u>Gross R&D expenditure</u>: Total expenditure on research and development in each country's national territory (even if funded from abroad). The sums are deflated using the 1995 price deflator and converted to U.S. dollars.
- <u>Other data</u>: including GDP (in 1995 U.S. dollars), gross fixed investments (in 1995 U.S. dollars), secondary school enrolment (share of population that belongs to the age group that corresponds to secondary school), labor population, import share in trade of manufacturing goods (sum of imports over total of imports and exports in 1995 U.S. dollars), openness in current prices, expropriation risk (on a scale from 1 to 10) and U.S. trade share (the total amout of commercial transaction between the country and the U.S., divided by the country's GDP).

If we take a first look at the data, we find that for OECD countries those variables are roughly all correlated: in fact, the countries that show the highest values are more or less all the same for every variable. For example, of the top ten countries for patents in the sample, eight rank high in R&D expenditure and seven in GDP per capita as well. Namely, Switzerland is at the top of the list for all of the above with Japan and Scandinavian countries (Sweden, Norway, Finland and Denmark) showing also strong relationships, while for other countries performances are slightly more varied. Market openness also shows this kind of relationships. Income and market width seem to be positively correlated with R&D expenditure growth, but they are negatively correlated with patent applications growth. If we divide the sample into categories like high and low income OECD countries, large and small market OECD countries, G-7, non-G7 and non-OECD we see that some of the dynamics change.

The first thing noticed is that market size, income and patents per capita are correlated for all of those groups, but patents growth rates seem to be negatively correlated with the level of GDP per capita and the market size. This leads us to think that patents in low income countries are growing faster than in richer countries even if their stock is still lower: some kind of patent-convergence phenomenon is happening. However, both levels and growth rates are roughly positively correlated across country groups. In Figure 3.2 we can see how patents and GDP per capita seem to move the same way for most of the countries.

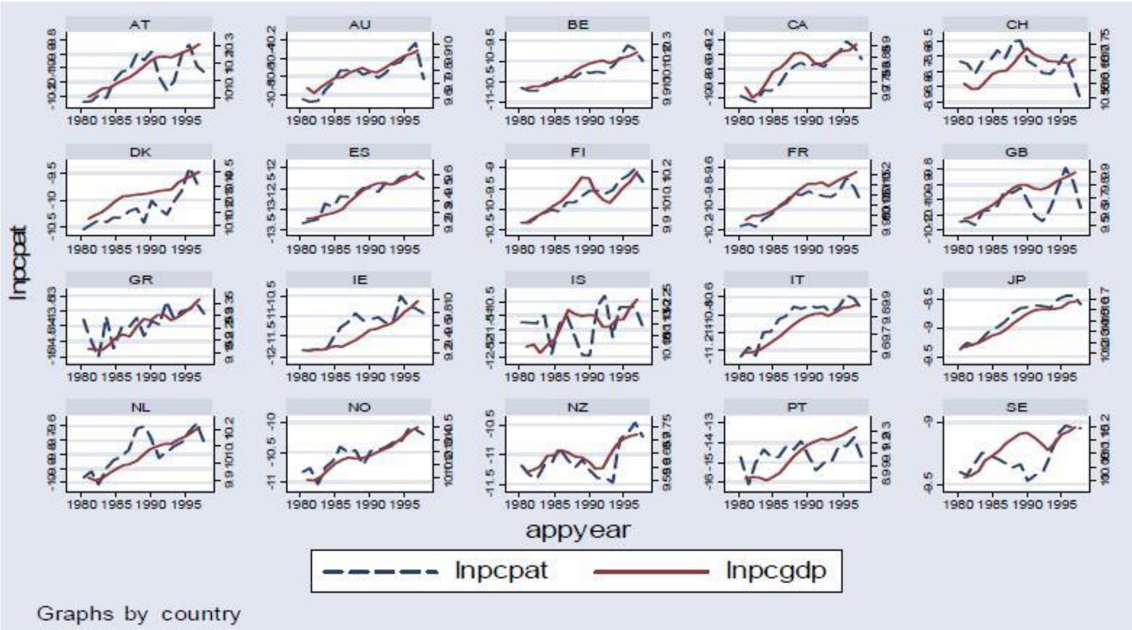
In her analysis, Ulku approximates the productivity growth function as it follows:

$$\Delta A = AH^{\theta}$$

In this equation, $\boldsymbol{\Delta A}$ indicates the productivity growth, $\boldsymbol{A}$ is the stock of previous innovation (which is measured by patent applications) and $\boldsymbol{H}$ is the human capital devoted to R&D (which is measured by the stock of R&D expenditure). The data about import share of trade, openness, U.S. share of trade, secondary school and expropriation risk are used as control variables and the flow of innovations in the previous period is also included. The purpose of the research is to determine the value of $\boldsymbol{\theta}$, which has to be equal to 1 in order for output to grow continuously, as theorized by Romer, so we need to compute the effect of R&D investment on innovation, hence the number of patents. The analysis has only 19 OECD countries as objects because data for other countries are not available.

The results of the regression show that the coefficient of R&D stock is positive and significant for large market OECD economies, which include low income and G-7 countries. According to this result, a 1% enlargement of the R&D stock increases innovation by 0.2% in the G-7 and large market countries, and by

Figure 3.2 – Relationship between patents and per capita GDP growth in the 20 countries as reported by Ulku (2004):



0.3 in low income countries. If we analyze the data in a deeper way, we see that low income economies with large markets (U.K., Canada, Italy, Australia, Spain) have a significant coefficient, while low income economies with small markets (New Zealand, Ireland and Portugal) don't. The conclusion is that the effectiveness of R&D investment is in fact influenced by a country's market size.

Another important result is that countries with ineffective R&D stock (non-significant coefficient) have significant coefficients on the import share of trade, which suggests that countries with ineffective R&D stock import innovations from abroad. The previous period's innovation flow has an important effect for every country: countries with 1% more patents in the previous year seem to have an average 0.3% more innovations. This result means that previous knowledge does have a positive effect on innovation, as theorized by Romer.

Secondary school enrolment seems to matter only in the G-7 countries; institutional quality (measured by the expropriation risk) has an effect in large market countries only; while economic alliance with the U.S. and openness do not seem to have an effect on any economy's innovation flows.

From this first part of the analysis, the results are:

- R&D intensity changes across countries.
- Only large market OECD countries (which include the G-7 and some low-income economies) seem to increase their innovation flows with R&D investment.
- There are no constant returns to innovation. However, this result might depend on the data not being able to provide a full measure of innovation: as we have seen, patenting is not the only way to protect an invention, so the analysis may be incomplete.
- Technology spillovers have large effects on countries that do not have an effective R&D stock.

The full results of Ulku's research are shown in Table 3.5.

If we analyze the effect of patent stock on GDP per capita, the results are equally important (this time the analysis is also on non-OECD countries). We notice that the coefficient of patent stock is positive and significant for all the countries, except for the G-7, but this effect may be due to the sample being too small. High income and large market OECD countries have the largest effect, with 0.60% of GDP per capita growth for every 1% patent stock increase, while the other samples have a 0.40% effect. Investment (0.10%), Expropriation risk (between 0.20% and 0.11%), Openness (between 0.09% and 0.14%, except for G-7, large market and non-OECD countries) have also a positive and significant effect, while schooling does not, maybe due to the small variation that it has had over time. The full results are shown in Table 3.5 and 3.6 (Ulku, 2004).

This research shows that while the returns to innovation in terms of GDP are positive and proved, the returns to R&D investment in terms of innovation intensity are much less so, especially for low income and small market economies.

Another important conclusion is that countries with ineffective R&D structures tend to "import" innovations from abroad, thus using technologies that were invented somewhere else. The positive effects that an innovation has on foreign countries are called technological spillovers. Let us analyze empirically how they work and what their effects are.

Table 3.5 – Results of the regression analysis of Per Worker Patent Flows, as reported by Ulku (2004):

	Full	Non- G-7	G-7	Large Market	Small Market	High Income	Low Income
R&D stock	0.080 (0.94)	0.015 (0.14)	0.162 (2.52)	0.231 (3.44)	0.073 (0.53)	0.130 (1.06)	0.298 (3.09)
Secondary school	0.039 (0.17)	-0.012 (0.04)	0.184 (1.84)	0.104 (1.06)	-0.169 (0.35)	0.362 (0.83)	0.047 (0.20)
Expropriation risk	-0.314 (0.63)	-0.522 (0.89)	0.297 (1.02)	0.455 (1.90)	-0.715 (0.72)	-0.289 (0.29)	0.356 (0.71)
Import/trade share	1.844 (2.89)	1.761 (2.17)	-0.315 (1.04)	0.178 (0.81)	2.633 (2.29)	4.226 (3.72)	0.057 (0.09)
U.S. trade share	-0.066 (0.38)	-0.164 (0.80)	0.340 (3.77)	0.154 (1.75)	-0.095 (0.32)	-0.650 (2.28)	0.339 (1.96)
Openness	-0.169 (0.52)	0.034 (0.08)	-0.171 (1.42)	0.046 (0.43)	-0.323 (0.51)	0.583 (1.17)	-0.697 (2.05)
Patent flows in t-1	0.297 (4.26)	0.304 (3.72)	0.309 (2.42)	0.576 (6.99)	0.228 (2.36)	0.191 (1.94)	0.317 (3.89)

Table 3.6 – Results of the regression analysis of Per Worker GDP, as reported by Ulku (2004):

	Full	Non-OECD	OECD	Non-G-7	G-7	Large Market	Small Market	High Income	Low Income
Investment	0.312 (24.46)	0.365 (17.72)	0.274 (16.79)	0.268 (14.49)	0.296 (7.39)	0.288 (8.30)	0.262 (9.86)	0.239 (9.29)	0.254 (8.86)
Patent stock	0.104 (9.18)	0.111 (6.44)	0.076 (4.94)	0.074 (4.16)	0.023 (0.87)	0.071 (2.86)	0.044 (1.70)	0.059 (2.63)	0.098 (3.47)
Secondary school	0.009 (0.41)	-0.198 (2.91)	0.010 (0.53)	0.012 (0.51)	0.016 (0.54)	0.018 (0.73)	0.032 (0.99)	-0.025 (0.60)	0.084 (3.47)
Openness	0.025 (1.43)	-0.034 (1.39)	0.071 (2.90)	0.111 (3.43)	-0.040 (1.58)	-0.026 (0.96)	0.133 (3.01)	0.009 (0.24)	0.127 (3.50)
Expr. risk	-0.025 (1.72)	-0.025 (1.04)	0.131 (4.66)	0.144 (4.76)	0.174 (2.09)	0.097 (1.63)	0.063 (1.75)	0.196 (2.42)	0.140 (4.80)

(Calculated by Ulku. Data on GDP, investment and secondary school enrolments provided by the World Bank's World Development Indicators database. Data on employment provided by the IMF's World Economic Outlook database. Data on patent applications provided by the NBER Patent Citation Database. Data on openness provided by the Penn World Table 6. Data on expropriation risk index provided by the World Bank's International Country Risk Guide. Data on import/trade in manufacturing sector provided by the OECD. All measured in 1995 dollars).

3.3 – Vehicles and Dynamics of Technology Spillovers and Diffusion

During my analysis, we have often come across the concept of technology spillovers, which we described as the positive effects that new technologies, often created in rich and developed countries, have on other countries' productivity (Weil, 2013). Of course, those spillovers are not automatically transmitted to poorer countries: there are many factors that make this knowledge easier to transfer. The country's capability to "receive" this information and to put it to work effectively is essential, but there are other "physical" factors that are essential, such as being close to a developed country or to the sea (the main channel of trade) (Weil, 2013).

It has been observed that countries that have developed an economic policy that is more "open" to the outside world have largely taken advantage of foreign technology, while those who have chosen to protect their economy have been left behind. This is the case of South America: in the 19th century, this region was one of the most developed in the world (right after Europe, Australia and North America) and experiencing fast economic growth. This performance was mainly a result of the tight commercial bonds that tied this particular region to the developed world. However, during World War II, those "advanced" countries put a limitation on commerce and South America suffered a sudden stop in terms of growth. Blaming this slowdown on the extreme dependence on other countries, many South American governments decided to adopt a different policy: they ignored the economic theory of comparative advantage and imposed taxes on raw material export and finished products import, trying to develop their own industrial sector. This strategy eventually backfired and South American countries never returned on their previous growth standards. On the other hand, South-East Asian governments supported commerce and eventually obtained their reward: they acquired new knowledge and technology and developed their industrial sector without sacrificing trade, entering the "club" of the most developed countries. Those countries (South

Korea, Singapore, Taiwan and so on) have now values of output per capita that are comparable to those of European countries and Japan (Grilli, 2005).

One of the basic works about international technology spillovers has been published by Coe and Helpman in 1995. Their basic assumption is that R&D investments have a considerable effect on output per capita for both the country where the investment takes place and the other countries. The more "open" a country is to the outside, the more benefits it gets from foreign technology. The question they try to answer is what exactly the extent of foreign R&D investment's effect on TFP is. Coe and Helpman start by estimating their regression equation as it follows:

$$\log F = \alpha^0 + \alpha^d \log S^d + \alpha^f m \log S^f$$

In this equation, $\boldsymbol{F}$ indicates the country's TFP, α^0, α^d and α^f are the parameters to be determined, $\boldsymbol{S^d}$ is the internal R&D investment, $\boldsymbol{S^f}$ is the foreign R&D investment and m is the incidence of import on GDP. This last factor is a part of the equation because Coe and Helpman assert that countries with larger import relatively to their GDP have the best chances to absorb external spillovers.

Coe and Helpman consider data for 22 developed countries (availability issues make this analysis impossible for poorer economies) in the period 1971-1990. We can see a summary of the data about TFP, domestic and foreign R&D and import incidence on GDP in Table 3.7. We can see that all of the analyzed countries have increased their TFP except for New Zealand, but this tendency has not been uniform for everyone, with Japan and Norway leading the group, having improved their productivity by 70% and 50% respectively. Domestic R&D capital stock has increased substantially in all of the countries, with Greece increasing it almost 19 fold; Israel is a distant second having increased it by 730%, while the U.K. has the worst performance with a dull 20% improvement. On the other hand, foreign R&D capital stock does not have such big numbers, even if there has been an increase for everyone, with the U.S.A. experiencing the largest growth with 300% and Spain being the slowest with 20%. As far as import shares are concerned, there has been an increase for everyone (this indicator has more than doubled in the U.S.A.) except for Japan, Finland, New Zealand, Norway and Switzerland: those countries have decreased their import share on GDP. The cross-country dynamics are also interesting because values for this variable tend to vary by a large scale from a country to another. For example, Belgium has by far the largest import share (88.2%), while Japan has the smallest (only 9.3%).

Table 3.7 – Statistics about TFP, domestic and foreign R&D and import share, as reported by Coe and Helpman (1995):

	F_{1990}/F_{1971}	S^d_{1990}/S^d_{1971}	S^f_{1990}/S^d_{1971}	m (in percent)	
				1971	**1990**
United States	1.1	2.0	3.4	5.5	11.2
Japan	1.7	4.2	1.7	9.6	9.3
West Germany	1.2	2.6	1.6	19.1	26.1
France	1.4	1.8	1.7	15.3	22.8
Italy	1.4	2.8	1.4	15.6	19.6
United Kingdom	1.3	1.3	1.8	21.4	27.7
Canada	1.1	2.7	1.9	20.0	25.5
Australia	1.1	4.9	2.0	14.7	18.6
Austria	1.2	3.6	2.3	30.8	38.9
Belgium	1.4	2.3	1.5	43.9	88.2
Denmark	1.2	2.3	1.9	30.9	31.1
Finland	1.4	4.5	2.2	26.8	25.4
Greece	1.2	18.7	1.7	17.0	32.0
Ireland	1.3	3.7	2.3	42.1	56.1
Israel	1.3	7.3	1.6	50.0	52.0
Netherlands	1.2	1.5	1.9	45.1	53.9
New Zealand	0.9	2.1	2.2	25.5	22.6
Norway	1.5	4.0	2.0	45.3	37.7
Portugal	1.3	2.0	1.4	33.6	44.9
Spain	1.2	7.0	1.2	14.7	21.4
Sweden	1.1	3.5	1.9	22.8	31.6
Switzerland	1.1	1.3	1.9	39.1	38.3

(Calculated by Coe and Helpmann. Data on GDP per capita provided by the OECD Analytical Database, the Monthly Labor Review, the Monthly Labor Survey, the Monthly Bulletin on Statistics and the Bank of Israel. Data on R&D expenditure provided by the OECD Main Science and Technology Indicators Database and from the Monthly Bulletin of Statistics. Data on trade provided by the IMF's Direction of Trade Database. All measured in 1985 dollars).

The aim for Coe and Helpman was to find long-run tendencies and relationships between those variables and total factor productivity for every country. Having TFP elasticity to foreign R&D adjusted for import shares is important to see if spillovers have more or less the same effect everywhere in the world regardless of international trade policies. We find that foreign R&D elasticity is larger for United States and Japan: a 1% increase of R&D capital stock in those countries gives an average of 0.0422 and 0.0138 percent benefit to their trade partners respectively. The same value is 0.0091 for Germany, 0.0032 for France, 0.0010 for Italy, 0.0033 for the U.K. and 0.0011 for Canada. Moreover, the benefit that the whole set of countries put together gets from a 1% R&D capital increase in the U.S. is 0.1211% and in Japan it is 0.0446%. The same value is 0.0266 for Germany, 0.0180 for France, 0.0154 for Italy, 0.0179 for the U.K. and 0.0103 for Canada. Of course, these results are adjusted for every country's openness, which means that the recipient country has to have constant trade relationships with the inventor in order to take advantage of those spillovers. Nevertheless, those results are very encouraging: this research was one of the first to show that R&D does have very high rates of return, not only for the country in which technology is created, but also, in some measure, for the whole world (Coe and Helpman, 1995). In this work like in many others, commerce is regarded as the main vehicle of technology spillovers and it is indeed, but there are at least two other vehicles to technology diffusion.

In his 2001 work, Keller analyzes the main vehicles of spillovers, the way they work, their consequences and what makes them spread faster. He notices that there are three main vehicles for spillovers: three factors that can make a difference between convergence and divergence. Those vehicles are international trade, foreign direct investments and communication flows. Those are all influenced by distance, which is the main factor that Keller takes into account, trying to understand how it affects spillovers.

Using data about the G-7 countries (Canada, France, Germany, Japan, Italy, U.K. and U.S.A.) for the period 1970-1995, Keller examines their relationship and the way they share their knowledge, focusing on how R&D investments, productivity, geography, trade, FDI and communication are linked. Looking at the data, we notice that there is disparity between those countries, even if they are the most developed in the world. For example, the U.S.A. alone contributes about 33% of the G-7 club's total manufacturing and they spend on R&D about twice as much as Japan, four times as much as Germany and even forty times as much as Canada. However, Germany has the highest growth rate for R&D stock with 11.82% while in the U.S. this rate is 7.36%. We have to notice that almost 90% of all R&D expenditure is done in just a few sectors, which are chemicals, machinery, electronics and transportation. The data on FDI are also interesting: we can see that German multinationals employ 2.40% of total manufacturers in France, while American multinationals employ 4.72% of French workers. Keller also offers data in bilateral language skills, trying to understand which paths are made easier by the recipient's knowledge of the inventor's language, even if many of those communications are conducted in third-country languages such as English. TFP for each country depends on the industrial sector, as one country may be at the top for a sector and at the bottom for another. Overall, the U.S. have always been the productivity leaders for the considered period, but there has been convergence over time, which represents a strong proof that effective knowledge spillovers exist among this club of countries. Keller estimates a statistical regression that can exemplify the relationship between a country's productivity and the factors that tie it to the other countries. This regression is based on the following equation:

$$\ln F_{cit} = \alpha_{ci} + \alpha_t + \beta \ln \left[S_{cit} + \sum_{g \neq c} \gamma S_{git} e^{-\delta D_{cg}} \right] + \varepsilon_{cit}$$

In this equation, $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$ and $\boldsymbol{\delta}$ are the parameters to be determined, $\boldsymbol{\varepsilon}$ is the error term, $\boldsymbol{c}$ indicates the country that we are considering, $\boldsymbol{g}$ indicates every other country, $\boldsymbol{i}$ is the industry sector, $\boldsymbol{t}$ indicates the time, $\boldsymbol{F}$ is the TFP, $\boldsymbol{S}$ is the R&D stock and $\boldsymbol{D}$ indicates the distance between the countries.

The first result that Keller wants to obtain is to determine whether spillovers are influenced by distance or not. In his estimates, $\boldsymbol{\beta}$ (which measures R&D's incidence on productivity) is equal to 0.039, which indicates a positive correlation between R&D and productivity, $\boldsymbol{\gamma}$ (the relative potency of foreign R&D assuming that all the countries are equally distant) is 1.111, and $\boldsymbol{\delta}$ (which measures the effectiveness of foreign R&D) is 0.147. Those results suggest that the term $\boldsymbol{\gamma S_{git} e^{-\delta D_{cg}}}$ is falling with distance, which means that R&D work form a distant country has less effect on productivity than R&D from a nearer country. Of course, these results show very low effectiveness for R&D spillovers from and towards Japan. If we analyze the data and consider time, we can see how these R&D spillovers' effectiveness has varied over time. Keller accomplishes this by introducing two parameters that indicate variations in $\boldsymbol{\gamma}$ and $\boldsymbol{\delta}$ respectively. While the former is equal to zero, indicating that overall effectiveness of foreign R&D has not changed over time, the latter is negative. This result means that distance has now a lower effect on spillovers: globalization has led to an easier diffusion of knowledge and localization of technology has fallen of about two thirds in the 1970-1995 period, at least among the G-7 countries (according to Keller's estimates). If these results are true, we can imagine that by now distance is no longer influencing spillovers in the G-7 countries.

Keller then re-writes the equation as it follows, changing the $\boldsymbol{\delta}$ parameter with $\boldsymbol{\tau}$ and $\boldsymbol{D}$ (distance) with $\boldsymbol{M}$ (imports). Of course, trade is positively correlated to productivity, so the minus sign is removed:

$$\ln F_{cit} = \alpha_{ci} + \alpha_t + \beta \ln \left[S_{cit} + \sum_{g \neq c} \gamma S_{git} e^{\tau M_{cg}} \right] + \varepsilon_{cit}$$

Doing the same regression with $\boldsymbol{V}$ (FDI) and $\boldsymbol{B}$ (language skills), Keller finds that all three variables have positive coefficients and when he includes the three factors at once together with distance, he finds that $\boldsymbol{\delta}$ is not significantly different from zero (of course this effect could depend on the fact that the three factors may be correlated with distance). We notice that the U.K. is attracting the most FDI

(36.2%) and that much of the spillovers that the U.K. receives are due to English being spoken by a great share of the G-7 population: 43.4% of the difference between the U.K. and Japan in technology spillovers is a consequence of low Japanese language skills in the G-7 countries. Italy has the lowest language skills: if Germany had the same level of language knowledge as Italy, it would benefit 6% less from spillovers. Canada takes 69.1% of its spillover flows from the U.S.A., which is also the main source for Japan (63%). About a third of the inflows to Italy and France are from Germany, while the U.K.'s flow to Canada only reaches 13.5% of the total (Keller, 2001).

Keller's research suffers the unavailability of data from developing countries: it would have been interesting to see if the tendencies described in this work are also happening for poorer economies. However, it shows the importance of language skills and that the incidence of distance on technology diffusion is decreasing and by now it is potentially almost non-existent, but why is this happening? Keller estimates that trade provides about two thirds of the total effect generating spillovers, with FDI and communication accounting for about one sixth each, but while commerce has remained quite stable in the considered period, enormous changes in FDI and communications have occurred: is it possible that those two factors are the ones causing this dramatic delocalization of knowledge?

According to structuralism and many other schools of thought, this relationship is what is causing technological and economic divergence, together with comparative advantage-based trade policies (Grilli, 2005). We can see from the data that total FDI towards developing countries has increased from 1 billion dollars in 1960 to over 240 in 1998-2000 (in average). Private capital has become more and more important in this computation, as it accounts for 80% of total investment. The effects of foreign capital is largely positive for every recipient, both in direct terms (capital accumulation) and in indirect terms (technology and productivity growth); this phenomenon is true especially for long-term investments. In fact, the correlation between foreign investments and total domestic investments is between 0.5 and 0.7, reaching the unit for long-term capital. This explains how important

FDI is, and if we look at the correlation between FDI and GDP per capita growth, we see that it is 0.3 for total private capital in the country, 0.7 for long-term capital and over 1 for foreign direct private investment. This correlation is however much lower when it comes to public foreign funding: empirical data has shown how it is not effective in helping the economic performance of developing countries. This fact is due to public investment not having economic purpose and thus not helping the local economy, as it is often addressed to purposes that are not driven by profits, but rather non-efficient or even damaging. For example, public capital given to a developing country's government can be used to fund a war. This is why public donations do not really work and a developing country should to its best to attract profitable private capital in order to enhance its economic performance. Eliminating lobbying, corruption and political and social instability may be a good way to go (Grilli, 2005).

However, technological diffusion may have other determinants. This aspect is analyzed in another important analysis about technology diffusion, conducted by Comin and Hobijn in 2003. Using data taken from the Historical Cross-Country Technology Adoption Dataset, which they have created, they intend to explain the dynamics of diffusion in a deeper way, analyzing different technologies in order to recognize the different patterns that have characterized diffusion for each of them. As it has been for the previously analyzed works, Comin and Hobijn's analysis only involves advanced countries, due to the difficulty of gathering reliable information about poorer countries. However, this research is very vast in time, as it takes a 215-year period into account, from 1788 to 2001.

The large set of data has been divided into eight industrial categories and each of those groups contains data about the diffusion of related technologies. Each of these categories contains the main technologies that have been used in each field over the years. These categories are:

1. Textiles production technologies
2. Steel production technologies
3. Telecommunication
4. Mass communication
5. Information technology
6. Transportation (rail-, road-, and airways)
7. Transportation (shipping)
8. Electricity

This analysis uses a different indicator depending on the technology that we are considering, the one that better represents the level of adoption. For example, the diffusion of cars (category 6) is measured by calculating the number of cars per capita, while the adoption methods for steel production (category 2) is measured by looking at the share of the total production that is generated with a certain method. Those are all proxies of how much a technology is used in an economy and their behavior over time tells us when those technology had their peak of diffusion and when they became obsolete. If we analyze the dynamics of technology adoption in average, without considering the cross-country dynamics, we see that diffusion has a different pattern depending on the considered technology. For example, the telephone was invented in 1876, but until about 1900, there wasn't any data about it, not even the extent of the telephone line, which gives us a picture on how slow and difficult the diffusion of new technology is, even if this phenomenon has improved over time (ironically, telephone was one of the reasons for this). Of course, we notice that the use of every technology has increased over time, except for those that have been replaced; for example, no one is going to use telegraphs ever again. However, some technologies that became obsolete have been improved and came back in use; this is the case of Electric Arc furnaces in steel production.

As we know, diffusion of technology is not the same all over the world, even if we only consider the most advanced and powerful countries. The general tendency is towards catch-up, at least if we consider the most developed economies, but differences still remain. When Comin and Hobijn relate the percentage of adopted technology (a measure of adoption speed) and GDP per capita, they find out that they are positively correlated and this correlation is stronger for newer technologies. This result suggests an interesting dynamic for technology diffusion: newer technologies are adopted by richer countries first and the others follow; when the technology gets "older", the other countries adopt it. The reasons for this phenomenon are easy to find; as we can see from further data, the vast majority of the analyzed innovations were invented in the leading countries, which are the U.K. in the 19th century and the U.S.A. in the 20th. The only exceptions to this tendency are the OHF and BOF steel production methods, which were invented in Germany; these are the only technologies whose diffusion is negatively correlated with GDP per capita. The available data show a positive correlation between technology adoption and GDP per capita, which seems to confirm the assertion that richer countries not only are the main inventors in the world economy, but they also are the first to adopt innovations, with other economies catching up later. This phenomenon is called trickle-down diffusion. We also notice that the substitution of a technology that has been used for years with a new production method takes time and this is true even for advanced countries, this is called "lock-in effect" as production tends to stay "locked" into an old technology instead of adopting a new one as soon as it is available. Those two circumstances seem to be fairly consistent with the data and robust for every technology that Comin and Hobijn analyzed.

The authors then estimate their regression equation:

$$Y_{ijt} = d_{jt} + \sum_{k=1}^{m} \beta_k X_{ijkt} + e_{ijt}$$

In this equation, ***Y*** indicates the level of adopted technology, ***d*** indicates the world average for that particular technology adoption, ***e*** is the error term, ***β*** indicates the coefficients that we are considering (how the variables affect the country's absorptive capability). The independent variables are embodied by ***X***: there are ***k*** variables, for ***t*** moments in time, ***i*** countries and ***j*** technologies. Comin and Hobijn propose five main variables. The first one (***A***) contains the dummy variables and the logarithm of real GDP per capita; its coefficient will tell us how a country's wealth and endowment influence its adoption pace. The second variable (***B***) is human capital, consisting in enrolment and attainment rates. The third variable (***C***) is trade, measured by openness and level of development of a country's trading partners. The fourth variable (***D***) contains institutional indicators, giving a specific measure to the type of regime and executive authority, party fractionalization and overall effectiveness of the legislative power. The last variable (***E***) considers technology interaction, or the way that the sequential nature of technology interacts with adoption (in other words, the lock-in dynamics).

The variable ***A*** seems to have a rather generalized positive correlation with adoption: as we have seen, richer countries tend to absorb more innovations. Much of the disparity in technological adoption (about 23.7%) depends on this variable, and its coefficient is bigger than 1 for many technologies, which means that having a 1% better GDP per capita raises a countries' adoption ability by more than 1%.

Education (variable ***B***) seems to have a big role as well: an increase of 3% in secondary enrolment produces about 1% more absorptive capacity. Secondary enrolment shows a much more robust correlation with adoption because primary schools do not really provide the right skills that are useful in new technology use; on the other hand, secondary school sees much larger variations in enrolment ratios across countries and teaches much more advanced skills.

As we said before, openness to trade (***C***) is also consistently important: countries that are 12-15% more "open" (depending on the technology) raise their adoption capability by 1%. The surprising fact is that having commercial partnerships with technologically advanced countries does not lead to a better absorptive capacity, even though it has a positive effect on TFP. The reason for this phenomenon may be that the improvement in productivity comes through different channels than technology adoption (managerial skills, know-how and so on).

The variable ***D*** (institutions) has qualitative connotations that have to be discussed separately. First, having a military regime and having a non-formally recognized government has disastrous effects on adoption. A well-organized government has of course a good influence on adoption, while an excessively effective legislation has the opposite effect. This happens because the inventors of current technologies might lobby the government in order to pose barriers to the adoption of new technology: an effective executive has the better chances to prevent technology adoption. This is why party fractionalization has a positive effect on adoption, although these conclusions might be distorted by the fact that the analysis mainly refers to the post-WWII period.

The dynamics that relate to the sequential nature of technology (***E***) are conflicting: there is statistical proof that the countries that have intensively adopted the previous technology are faster in absorbing innovations. This seems consistent with those theories that predict decreasing adoption cost with the accumulation of knowledge: countries that absorb less technology have more adoption cost and therefore tend to have longer lock-in dynamics. However, there are some examples of a technology follower experiencing some kind of boost that pushes him ahead of the previous leaders. This process is called "technological leapfrogging" and it happens when a subject chooses not to adopt older technology, moving straight to the most up-to-date instead. The most common example is the rapid adoption of cellular phones in Africa, due to the lack of landlines (Weil, 2013). Other examples are worth being cited, like the diffusion of ethanol fuel in Brazil (ethanol is produced from sugarcane and not gasoline, or the city of Rizhao in China, whose energy supply is largely produced using solar power (Xuemei Bai, 2007).

There also seems to be a positive effect of some technologies on other innovations' diffusion; for example, electricity seems to have a positive correlation with almost all of the other technologies.

Further analysis shows that trade has an effect on the adoption of technologies with a predecessor and almost no effects when it comes to innovations that do not replace an older technology. This happens because the effects of trade depend on competition: international commerce opens to outside competitors and the profits of lobbying to avoid the introduction of new products and productions methods become lower. Furthermore, the adoption of previous technology has a positive effect for every sector, except for steel production, as demonstrated by Germany in the post-WWII period, during which internal production of steel was increased almost four fold without adopting the most recent technology. This is probably due to the high costs of adoption.

If we analyze the data with a reference to time, we see that the picture has substantially changed after WWII. Human capital became far more important than it was before, probably due to the increasing skills needed to use the newest technology. The quality of institutions became a key aspect as well, as many countries lost their previous regime and converted to democracy, causing a new homogeneity that left behind every country that adopted a different government structure. The overall tendency has been towards homogeneity, and this led to a more synchronized technology adoption across the world and lower technological barriers (Comin and Hobijn, 2003).

This tendency of de-localization of knowledge exists, at least in advanced countries, but there still are barriers thwarting technological progress in poorer countries. What is their nature? Is there a way to tear them down?

3.4 – Barriers to Technology Adoption

The reasons for the enormous income disparity among countries has very deep roots and neoclassical theories have failed in predicting the future dynamics of economic convergence. The effects of technology have been too strong to confirm those hypotheses: advanced countries have grown far more than poorer economies and it is probably due to their different technological progress. Parente and Prescott (1994) assert that barriers thwarting technological catch-up exist and they are the reason for this gap growing over time. In their research, they prove that the adoption of new technology requires investments: innovations have costs that firms have to pay and these costs depend on two things, which are the world stock of knowledge (which they assume as available to everyone and growing exogenously) and technological barriers. They characterize technological barriers as a reflex of "the various ways governments and groups of individuals increase the amount of investment a firm must make to adopt a more advanced technology".

An interesting thing about Parente and Prescott's approach is that they assume that knowledge is available to everyone, while previously analyzed researches demonstrate that human capital has indeed a great effect on technology adoption capability. Nevertheless, their research is important to understand the effect of technological barriers on the economic gap. They also assume that world knowledge grows exogenously, which means that even if technological barriers remain fixed over time technological progress should increase. This assumption is consistent with the available data: technological progress has indeed accelerated over time. Prior to 1913, a country that was experiencing catch-up took 45 years on average to go from 10% to 20% of United States GDP per capita in 1985; this average decreased over time and in 1950 it was only 18 years. This result is due to an increase in productivity, hence to technological progress.

These results are consistent with the post-war performances of France, West Germany, South Korea and Taiwan. Those countries experienced a fast catch-up towards the U.S. income level and if we apply Parente and Prescott's theory, we see that those performances are a result of the efforts towards the limitation of those barriers' effects on technological progress. The authors compare the experiences of South Korea and the Philippines: those countries had similar economies, but South Korea witnessed a growth miracle after World War II while the Philippines remained a rather marginalized economy. According to Parente and Prescott, this difference is due to South Korea lowering the technological barriers that prevented progress in this country, while the Philippines failed to do so and therefore obtained much worse results (Parente and Prescott, 1994).

The exact nature of technological barriers is unknown; it's not even possible to make a list of them although we mentioned a few before. We have seen that trade, human capital, communication and FDI are all determinants of technological adoption and lacking some of them can be considered as a barrier and surely acts like one. However, barriers change from one country to another and from a technology to another: this is why a true definition of technological barriers is practically impossible (Parente and Prescott, 1994). Such an analysis requires seeing the exact results of the adoption of a technology in every country to understand how that particular technology "fits" that country. As I said earlier, many characteristics determine how appropriate a technology is for a country; here I intend to analyze the most important characteristics on the matter, which are nothing other than capital and labor.

Technology is by its nature skill- and capital-biased, which means that it behaves differently depending on the level of skill that a worker has (I am not talking about instruction or schooling only, but also training and learning-by-doing), or on the amount of capital that he or she can work with (Weil, 2013). One of the possible reasons for the lack of catch-up, according to Prebisch (1970), is that technological development is produced only in developed countries and is generally oriented towards the maximum exploitation of capital, a factor of whom developing countries are relatively poor. This is also the reason why attempting industrialization in poorer countries produced an insufficient creation of labor demand, resulting in vast unemployment. According to structuralism, this mean cycle is a result of foreign investments, which tend to favor the old production methods and to discourage technological progress and industrialization (Prebisch, 1970).

Of Course, those theories are rather old in relation to the pace at which technological progress has changed its dynamics over time and the course of action that they suggest, which involves import substitution industrialization and a much stricter attitude towards international commerce, has been proved prejudicial by empirical evidence (Grilli, 2005). However, there are researches showing that skill and capital bias are important barriers to technological adoption. Let us see how.

3.4.1 – Skill- and Capital-Biased Technology

Growiec's 2010 analysis contemplates a broad set of data and proposes a new way to measure technological progress implying that a possible barrier to technological progress is the non-equal endowment of production factors, which are labor, physical capital and human capital. This conclusion is even more accurate if we consider skilled and unskilled labor as imperfect substitutes. As we know, the main problem with technological barriers is that they are generally overlooked by economic theory whose growth rates predictions are often overestimated due to existence of those barriers, and this happens particularly for smaller economies. What emerges from this research is that problems in measuring and predicting technological progress and convergence to the frontier find their solution in this imperfect substitution.

Growiec offers four possible measures of technological progress, which are estimated in two versions, one with capital and labor and the other with human capital as well:

1. <u>TFP growth rate (TFP)</u>: one of the most widely used methods in measuring technological progress; it is simply calculated as the Solow residual in a standard Cobb-Douglas production function:

$$\frac{A_t - A_{t-1}}{A_{t-1}} = \frac{y_t}{y_{t-1}} \left(\frac{k_t}{k_{t-1}}\right)^{\alpha} \left(\frac{h_t}{h_{t-1}}\right)^{1-\alpha} - 1$$

2. Potential TFP growth rate (PotTFP): this measure is calculated similarly to the previous one, but instead of actual output per capita, the author used an estimate of the maximum output per capita obtainable given the inputs, calculated with a procedure based on the Data Encryption Algorithm. As far as notation is concerned, $y_t*(x_t)$ indicates the maximum output obtainable ($y*$) in time t with the input (x) available in time t.

$$\frac{A_t - A_{t-1}}{A_{t-1}} = \frac{y_t^*}{y_{t-1}^*} \left(\frac{k_t}{k_{t-1}}\right)^{\alpha} \left(\frac{h_t}{h_{t-1}}\right)^{1-\alpha} - 1$$

3. Rate of technological progress at the world technology frontier (WTF): this measure confronts the rate of growth of the maximum output obtainable with the input available in t and with the input available in $t-1$. This measure isolates the effects of technological progress at the world technology frontier from the effect of factor accumulation. Since we are considering changes at the world technology frontier, we are using the maximum output obtainable.

$$\frac{A_t - A_{t-1}}{A_{t-1}} = \sqrt{\frac{y_t^*(x_t)}{y_{t-1}^*(x_t)} \frac{y_t^*(x_{t-1})}{y_{t-1}^*(x_{t-1})}} - 1$$

4. The Malmquist productivity index (Malm): This measure is similar to the above, but the result is measured by the growth on technical efficiency (E) which is the portion of the maximum output obtainable that is actually produced:

$$\frac{A_t - A_{t-1}}{A_{t-1}} = \frac{E_t}{E_{t-1}} \sqrt{\frac{y_t^*(x_t)}{y_{t-1}^*(x_t)} \frac{y_t^*(x_{t-1})}{y_{t-1}^*(x_{t-1})}} - 1$$

$$y_t = E_t y_t^*$$

The data that Growiec collected is all in per-worker terms and involves 19 developed countries for the period 1970-2000, using production functions that involve a distinction and imperfect substitution between skilled and unskilled labor. This distinction helps making the analysis more precise in estimating the world technology frontier. Once again, the unavailability of data on poorer countries is a big issue, but the dynamics and the results obtained in this research lead us to think that the skilled-unskilled labor imperfect substitution is a good explanation for smaller economies as well. In fact, we know that in those countries there is a smaller skilled-unskilled workers ratio, so the effects should be the same, only much larger.

Looking at the data, we notice that results are different depending on the method used. In fact, since every country has experienced GDP per capita growth in the considered period, if we use the Potential TFP and the WTF measures, negative technological progress is impossible. In those cases, we are considering progress at the frontier, and since we are at the frontier, every possible production method is available depending on what we need according to input, so the only way is up. On the other hand, for the actual TFP and for the Malmquist measures, factor accumulation can be stronger than output growth, thus making technology fall back.

Another fact that the author points out is that technological progress at the WTF is positively correlated with the initial physical capital stock and negatively correlated with the subsequent productivity growth, while technological progress for a single country is positively correlated to human capital and productivity growth. This happens because while the WTF and Potential TFP contemplate only technological growth, the other measures include efficiency growth, which is a country's pace at which it approaches the frontier, so different measures are to be chosen according to the purposes. If we want to consider how a country approaches the WTF, we have to look at TFP growth and the Malmquist index, whereas if we want to focus on absolute technological progress, we should look at Potential TFP growth and WTF progress.

Correlation with production growth is strong for TFP growth, but it still leaves a large fraction of it to factor accumulation. The same correlation is slightly weaker for the Malmquist index and the fraction explained by factor accumulation is larger. Potential TFP growth is very poorly correlated with output growth, but it explains a large part of GDP growth differences across countries. This is a possible proof of the fact that technological growth at the WTF is non-neutral, as it favors only countries with a certain kind of factor accumulation (labor, physical capital and human capital). WTF shift is negatively correlated with productivity growth and this is a consequence of the general tendency to convergence and it also corroborates the hypothesis that technological progress at the WTF is highly non-neutral; moreover, it explains a large share of production differences across countries.

The general tendency is now clear: due to the convergence process, poorer countries (with low factor accumulation) advance towards the technology frontier, which is why the correlation of total technological progress (TFP growth and Malmquist index) are positively correlated with production growth. On the other hand, if we consider technological progress at the frontier (Potential TFP growth and WTF shift) we notice that those are poorly or even negatively correlated with productivity growth, but they explain much of the income differences across countries. This means that when an innovation at the frontier is made, it tends to benefit countries that are richer and have larger capital accumulation. In Table 3.8 we can see the data about the fraction of growth that is explained by factor accumulation (the rest is explained by technology), the correlation between growth and technological progress and the percentage of the variance of productivity growth that it explains, all for each method of measurement. I am reporting the panel data (P), which include the effect of time, and the cross-section averages (C).

Correlations between measures are much different if we use cross-section instead of panel data or vice-versa. For example, WTF shift and Potential TFP have a correlation of -0.38 for cross-sectional data, while the same correlation is 0.55 for panel data. This is because all of those measurements are different if taken at a specific moment, but tend to move in parallel. A possible explanation for this is

Table 3.8: Statistical data on technologic growth measures as reported by Growiec (2010):

	Percentage of growth explained by factor accumulation		Correlation between growth and technological progress		Percentage of variance in cross-country growth explained by technology
	Cross-section	Panel	Cross-section	Panel	
TFP	71.27%	65.38%	0.752	0.912	18.40%
PotTFP	45.32%	46.17%	0.474	0.128	112.36%
WTF	61.09%	50.86%	-0.478	0.140	106.43%
Malm	85.40%	70.04%	0.235	0.879	11.38%

(Calculated by Growiec. Data on GDP, investment shares and government shares provided by the Penn World Table 6.2. Data on human capital provided by de la Fuente and Doménech (2006). Other data extrapolated by Growiec. All measured in 2000 dollars).

that WTF technological progress gradually trickles down to poorer countries, balancing the first negative effect with time.

Growiec finds that the endowment of capital has a great effect on the diffusion of new technologies, even if poorer country eventually adopt them with time. Another important finding in this work is that imperfect substitution between skilled and unskilled workers has also an effect. Growiec takes this assumption from Caselli and Coleman's 2000 and 2006 researches, which give empirical evidence on this matter (Growiec, 2010). Let us see how they came to his conclusion.

Caselli and Coleman's empirical analysis on the matter of skill and capital bias in technology starts from the assumption that not only skilled and unskilled workers are imperfect substitutes, but also that unskilled worker's efficiency is negatively correlated with that of skilled workers and capital. Every country has a frontier, which is the maximum level of technology that it can adopt, and each will choose the point of the frontier that fits it the best according to its factor endowment. How a country's frontier will look like depends on its specific characteristics. Adoption barriers can make a poor country's technological frontier lie way beneath a rich country's frontier.

They back their assumption with a regression based on the following data, collected for a set of countries:

- Output per worker (***Y***).
- Capital per worker (***K***).
- Skilled and unskilled workers (L_s and L_u): In this case, they used the data on schooling collected by Barro and Lee, which divides the population in seven categories according to their education level, and then labeled the first two categories as "unskilled" and the others as "skilled".
- Skilled and unskilled workers salaries (w_s and w_u): here they used the Mincerian coefficients collected by Bils and Klenow, who regressed log wages on schooling years.
- They assumed the remuneration of capital (r) as fixed at 0.12.

According to the cross-country data, the L_s / L_u rate goes from a minimum of .32 to a maximum of 36.11, while the w_s / w_u rate goes from 1.10 to 3.16, which means that in some countries skilled workers are paid over 3 times as much as the unskilled, while in other places they only get 10% more. The countries in which skilled workers are the most are also the ones in which they are paid less relatively to unskilled workers. Those countries also tend to have a higher income per capita.

Then they designed a new production function:

$$Y = \left\{(A_u L_u)^\sigma + [(A_s L_s)^\rho + (A_k K)^\rho]^{\frac{\sigma}{\rho}}\right\}^{\frac{1}{\sigma}}$$

Using this function and equalizing the remuneration with the related marginal productivity, they estimate the most likely values of (σ) and (ϱ). Every country's efficiency has to be within its frontier, which represents the available set of technology that each country has, and moving along this frontier causes a trade-off between skilled and unskilled workers efficiency:

$$(A_s)^\omega \leq a_0 - a_1 (A_u)^\omega$$

$$(A_u)^\omega \leq a_0 - a_1 (A_s)^\omega$$

Given these data, Caselli and Coleman were able to estimate the average World Technology Frontier and then, confronting it with the previous procedure's results, the deviation of each country's frontier from the average, making some interesting findings. We can see the results in Figures 3.3, 3.4 and 3.5

In Figure 3.3 we can see that unskilled workers' efficiency is in fact negatively correlated with both skilled workers' and capital's efficiency. Plus, if we assume that the United States Frontier applies for every other country, none of them has the same optimum point as the U.S., and if we make the country use the same technology used in the U.S., their output will decrease, except for Canada; the same thing happens using the average frontier. We can see this effect in Figure 3.4.

This means that each country has a unique set of skilled and unskilled workers, and this makes them have a different optimum point even if they had the same frontier. This is a big setback for innovation: each country will ignore every new technology that, however available, would not be useful given the ability of that country's workers. However, this does not mean that a different technology frontier does not affect a country's output. In Figure 3.5 we can see is the gain in output that every country would have if we assume it having the same frontier as the U.S., but choosing its own optimum point.

We notice that the majority of countries (especially the poorest ones) would benefit from having the same frontier as the U.S. or even the average frontier. This happens because the U.S., despite choosing a combination of technologies that favors skilled workers, have a larger set of technology for unskilled workers than almost anyone. This is why technological adoption barriers are so important: if technology could spread without limits, some countries would see their GDP per capita increased over seven fold, and if everyone were at least allowed access to the technology included in the average world frontier, the increase would still be over 400% for some countries. The whole set of technologies available all over the world is the World Technology Frontier, and if there was no barrier to hinder technology adoption, that would be every country's frontier. Such a scenario is not likely to

Figure 3.3 – Relationship between capital/skilled labor efficiency and unskilled labor efficiency:

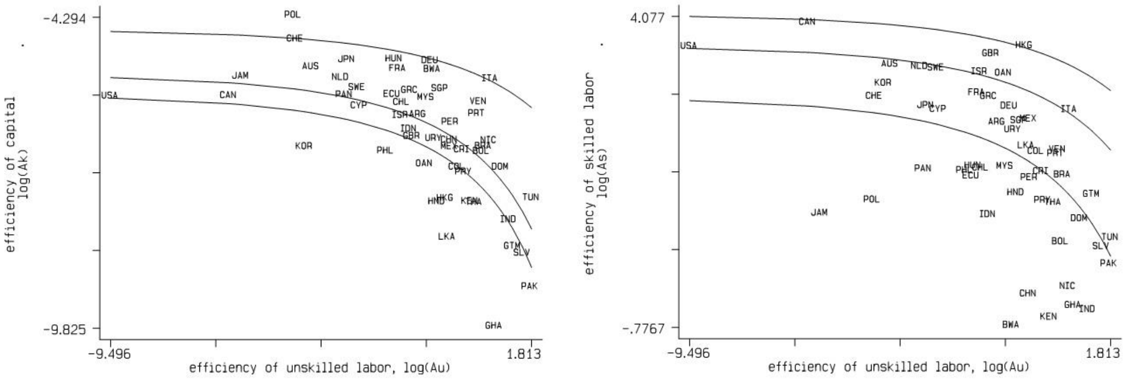


Figure 3.4 – Output loss if using the U.S./average frontier and the U.S. optimum point:

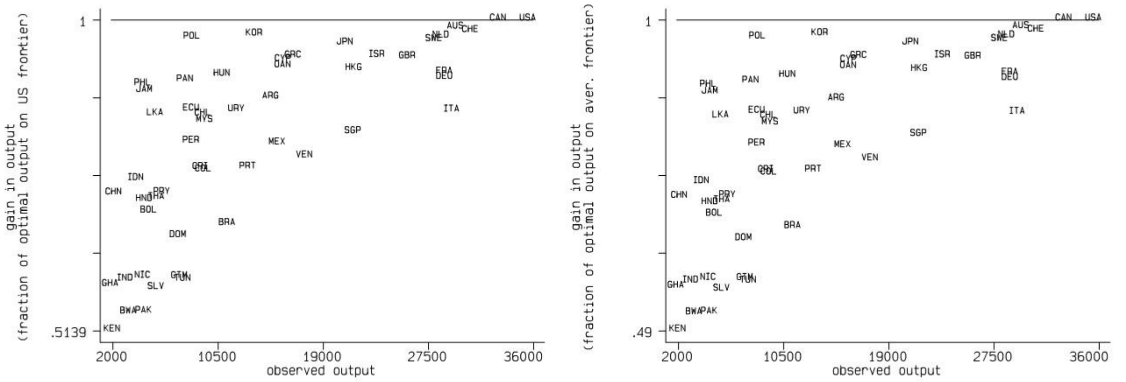
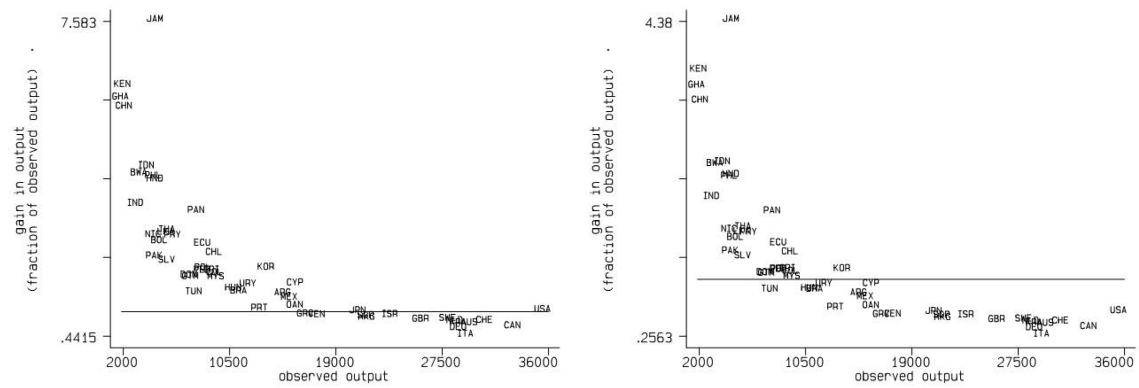


Figure 3.5 – Output gain if using the U.S./average frontier and proper optimum point:



happen, but the benefits that the whole world would get from it are incalculable (Caselli and Coleman, 2000).

In 2006, Caselli and Coleman have expanded their work, noting that in the last decades the skilled/unskilled efficiency ratio has increased, at least in some industrialized countries like the United States. We can visualize this transition by thinking about an assembly line with unskilled operators and a few skilled supervisors being replaced by a computer-controlled assembly line run by skilled workers in which the unskilled (if any is employed) have janitor duties. Skilled workers now control the whole operation, so they are responsible for the whole production and their efficiency goes up. Unskilled workers, on the other hand, are now janitors, with a lesser efficiency and a smaller salary. However, in poorer countries, where unskilled workers are relatively abundant, this switch does not happen: the country will continue using the relatively abundant factor and will not switch to automatic assembly lines. We can see it as an expression of the Hecksher-Ohlin Theorem with technological applications: every country will use and support with new technology the factor (skilled or unskilled work) in which it is relatively abundant (Caselli and Coleman, 2006).

The results obtained by Caselli and Coleman seem to be consistent with the actual data and they give us a new point of view in analyzing how a country reaches the technology frontier. They also manage to analyze separately the two phenomena that slow down economic growth in poor countries that do not adopt new technology: those countries are either unable to adopt because they lack experience, capital and funds, or because the new technology is simply not what the country needs given its characteristics. However, the main problem remains inaccessibility: as we have seen, every country would benefit from a larger set of innovations from which to choose.

Analyzing technological progress empirically is indeed a hard challenge to face, especially due to the lack of reliable data for poorer countries. The picture that my analysis of empirical researches gave us is very difficult to read and, with different interpretations, it can be seen in an optimistic and in a pessimistic way. To conclude the analysis, the one question remained unsolved is what is the future going to be: will poorer countries finally catch up? And is technological progress ever coming to an end?

3.5 – The Future of Technological Progress

Trying to make a prediction about how technological progress is going to be in the future is certainly not easy, considering the amount of variables the can possibly have an influence on it, but it's iteresting to try to make a guess. First of all, we have to distinguish between technological progress at the frontier and technological convergence.

Fist, let us analyze the frontier. As we know, technological progress has decreasing returns to scale: although previous knowloedge does have a positive effect on the ability to make innovations, it is also possible that, among all those possible innovations, all the "easy" ones have already been made: this negative effect is called "fishing out". In order to maintain technological progress stable at the current pace we need more researchers with better education and better equipment, hence the decreasing returns to scale: employing the same amount of resources as before won't be enough in the future. It is sufficient to consider what I explained before about 19th century inventors working at home in their spare time while now we have big and well equipped facilities with hundreds of people working. In the future, we have to assume that more and more people will work in the R&D sector, otherwise technological progress will simply stop. This assumption cannot be made lightly: in the last 60 years the amount of people working in R&D has grown 14-fold, is it possible that in the next 60 years we will have a similar growth? We can only guess, but the data can help in this case.

Research in the field of human population show that the recent population growth will come to an end in the near future: countries that are now experiencing a reduction in mortality will also be affected by the fertility reduction that is a reality in the western civilization. Moreover, the increase in the labor force in the last century in prominently due to women starting to work, but nowadays almost all of them work. This is why we cannot expect R&D employment growing as a result of an increase in the labor force, at least not in the amount that we need. It is true, however, that in the last half-century the portion of workers employed in the field has significantly improved, but can we expect this phenomenon to last forever? First of all, not everyone has the ability of doing a job of research, partly because of general attitude and predisposition, but also because the job itself is possibly inconclusive. In fact, for every researcher that makes a groundbreaking discovery, there are thousands of them whose hard work yields to nothing; a very strong motivation is also needed, and not everyone is willing to take this risk. Moreover, the retribution is not always secure, consistent and not necessarely superior than that of a production worker. In Italy, government researchers, especially in the medical field, often work for free: we are talking about many bright people working very hard and being paid very little and this doesn't prove to be very good advertising for the job, with many people prefering safer career paths or emigration (personal contribution). Not to mention the work wasted in developing a new invention while someone else is working on the same idea and succeeds before the other. Like I said, the nature of technology and innovation makes the idea non-rival in its use, so if someone successfully patents an invention before I do, all my work will go to waste.

Those are all reasons why it is unlikely for the portion of workers employed in R&D to grow much and even assumig that it will, there is always the 100% barrier: what do we do when everyone is employed in R&D? However, there is another thing to consider: where technological progress is located. Innovation is now world wide: companies have to look out for more innovative competitors from every market and there is not a single technology leader but as a matter of fact, there are still only a few countries in which those innovations actually happen. Only a few countries produce new technology, and this happens because those are the only ones to have enough money to spend in R&D: as we have seen before, there are only a few countries with efficient R&D sectors. Many of those countries are new-comers: young economies that have risen from poverty and embraced economical succes in the last decades and are now ready to put their ideas to work, like they have largely done (Weil, 2013).

Whether this is going to happen for poorer countries or not, we are unable to say: the available data can only describe the experience of relatively high-income economies, while the picture for developing countries is incomplete. However, based on the scarce data that we are able to use, the situation for them does not always inspire optimism. Empirical and theoretical researches have shown how the growing openness of the world wide economic system has been having conflicting effects: some countries have experienced a constant growth and have been moving towards convergence, while others have seen their gap widening. This process has intensified during the last decades and the consequence of this lack of economic convergence may worsen the problems of capital accumulation (which is essential for technological development) that developing countries have been having, since the dynamics foreign investments seem to have a crucial role in divergence (Di Vaio and Enflo, 2011). Moreover, these problems possibly depend on the same causes, which may be congenital (geography is an example), but can also be the result of a general deficiency of effective institutions and policies towards market openness, communication and the attraction of beneficial foreign investment.

We can say that the path towards convergence and the abatement of technological barriers is a very long and hard one, if even possible. Some of those barriers concern characteristics that are very hard to exclude from the picture and a change in the attitude of the whole country might be needed as well, and this is a very hard task to accomplish. As far as skill- and capital-bias, openness to the market, communication, investments and other economic factors are concerned, stonger and more effective policies are needed, accompanied by the co-operation of the advanced countries. The empirical evidence has shown the importance of this last condition with the experience of South-East Asia and South America: partnerships with advanced countries are essential and the ability of not turning these partnerships into exploiting and offering profits in activities that benefit the country itself is the key to economic progress. Eliminating corruption and lobbying, as we have seen, may be the first important step to take. However, there is no reason to believe that there is no hope at all for developing countries. If they will be able to introduce the right policies in order to attract technology spillovers and investment, hopefully they will increase their income per capita to a level that will allow them to catch up with the advanced economies and eventually invest extensively in the R&D sector, and having new people and new ideas enhancing technological progress can only be a good thing for the whole world in economic terms.

Conclusion

The dynamics of economic growth have always had a great influence on my academic career: in my opinion, the efforts of every economic entity is (or should be) always towards growth. Producing more and better products, trying to make the most out of the money you have, invest it in order to obtain more. In times like these, economic growth becomes the subject that follows the search for stability, because with all the efforts that are being made to reach stability, the real question that no one has dared to answer is: then what? Once we reach stability, how do we make economy start to grow again? This is why analyzing the determinants and the dynamics of development becomes a key aspect of an economic researcher's work: finding new boosts for the world's economy is fundamental.

Technology has always been one of those boosts: as I have shown, no one ever doubted the enormous potential of technological progress in providing new methods of productions, new commodities, new knowledge, new income and essentially better life conditions. Technological progress may be the thing that pulls us out from the recession spiral, but here as well, we need to understand how it works exactly. Like in every economic research field, the determinants are too many and too hard to find. The researches that I analyzed, in spite of being the remarkable results of the hard work of brilliant economists, always suffer from the lack, the unavailability and the unreliability of data and there always seems to be something missing, some factor that has not been taken into account.

However, those researches helped us understanding the phenomenon better and showed the way that have to follow for further research: we know now that in order to innovate there has to be a strong R&D sector, and the countries that cannot afford it are more or less able to rely on spillovers. On this matter, we realized how international trade, communication and foreign investment (especially private) are the determinants of technological diffusion and how larger and faster have these effects become through the years. However, researches can and will be more precise in the future, the work on this matter must not stop in order to reach a brighter picture and hopefully understand and put the mechanisms of technological and economic growth to work effectively for the well-being of the whole world.

Bibliography:

ACEMOGLU Daron: "Advanced Economic Growth: Lecture 10, Appropriate Technology and Barriers to Technology Adoption"; *Massachussetts Institute of Technology* (economics.mit.edu). 2007.

BAUMOL William J.: "Productivity Growth, Convergence and Welfare: What the Long-Run Data Show"; *American Economic Review* vol. 76, no. 5, pp. 1072-1085. 1986.

BERRILL Kenneth: "Economic Development with Special Reference to East Asia"; *St. Martin Press*, New York. 1964.

BESSEN James: "Technology Adoption Costs and Productivity Growth: The Transition to Information Technology"; *Research On Innovation* (researchoninnovation.org). 2010.

BOLT J. & VAN ZANDEN J.L.: The Maddison Project Database "The First Update of the Maddison Project; Re-Estimating Growth Before 1820"; *Maddison Project Working Paper* 4. 2013.

BUSINESS DICTIONARY (http://www.businessdictionary.com/)

CASELLI Francesco, **COLEMAN Wilbur John II**: "The World Technology Frontier"; *NBER Working Paper Series* 7904, *National Bureau of Economic Research* (nber.org). 2000.

CASELLI Francesco, **COLEMAN Wilbur John II**: "The World Technology Frontier"; *The American Economic Review*, vol. 96, n. 3, pp. 499-522. 2006.

CASTELLACCI Fulvio: "Convergence and Divergence among Technology Clubs"; *DRUID Working Paper* No. 06-21, *Danish Research Unit for Industrial Dynamics* (www.druid.dk). 2006.

CASTELLACCI Fulvio: "Closing the Technology Gap?"; *Review of Development Economics*, vol. 15, no. 1, pp. 180-197, *Blackwell Publishing Ltd*. 2011.

COE David T., **HELPMAN Elhanan**: "International R&D Spillovers"; *European Economic Review* 39 (1995), pp. 859-887, *Elsevier*. 1995.

COMIN Diego, **HOBIJN Bart**: "Cross-Country Technology Adoption: Making the Theories Face the Facts"; *Federal Reserve Bank of New York Staff Report* no. 169. 2003.

The CONFERENCE BOARD: *Total Economy Database* (http://www.conference-board.org/data/economydatabase/). 2013.

DI VAIO Gianfranco, **ENFLO Kerstin**: "Did Globalization Lead to Segmentation? Indentifying Cross-Country Growth Regimes in the Long Run"; *European Economic Review* 55 (2011), pp. 832-844. 2011.

DOMAR Evsey: "Capita Expansion, Rate of Growth and Employment"; *Econometrica*, vol. 14. 1946.

GOLDSCHEIDER Robert: "The Classic 25% Rule and the Art of Intellectual Property Licensing"; *The International Technology Network*. 2011.

GOODWIN Jonnie: "Embrace the UK's Digital Revolution or Be Swept Aside"; *The Telegraph* (telegraph.co.uk). 2013.

GRILLI Enzo: "Crescita E Sviluppo Delle Nazioni - Teorie, Strategie e Risultati"; *UTET*. 2005.

GROWIEC Jakub: "On the Measurement of Technological Progress across Countries"; *National Bank of Poland Working Paper* no. 72, *National Bank of Poland Education and Publishing Department*, Warsaw. 2010.

HARROD Roy: "An Essay in Dynamic Theory"; *Economic Journal*, vol. 49. 1939.

KELLER Wolfgang, "The Geography and Channels of Diffusion at the World's Technology Frontier"; *Hamburg Welt-Wirtschafts-Archiv (HWWA) Discussion Paper* 123, *Hamburg Institute of International Economics*. 2001.

KRUGMAN Paul: "A Model Of Innovation, Technology Transfer and the World Distribution of Income"; *The Journal of Political Economy*, vol. 87, no. 2, pp. 253-266. 1979.

LECHMAN Ewa: "Cross National Technology Convergence. An Empirical Study for the Period 2000-2010"; *MPRA Paper* No. 37442, *Munich Personal Research Papers in Economics Archive* (mpra.ub.uni-muenchen.de). 2012.

MAUGH Thomas H. II: "General Electric chemist invented process for making diamonds in lab"; *Los Angeles Times* (articles.latimes.com). 2008.

MEYER Thomas, **EHMER Philipp**: "Capital Markets Reward R&D"; *Deutsche Bank Research* (dbresearch.com). 2011.

MOKYR Joel: "Knowledge, Technology and Economic Growth During the Industrial Revolution"; *Northwestern University* (faculty.wcas.northwestern.edu). 1999.

MUYO-SAN MAT: "Can the Ubuntu Edge Kickstart a Mobile Tech Revolution?"; *Mobility* (mobility.com.ng). 2013.

PARENTE Stephen L., **PRESCOTT Edward C.**: "Barriers to Technology Adoption and Development"; *The Journal of Political Economy*, vol. 102, issue 2, pp. 298-321. 1994.

PERI Giovanni: "World Economy Technology Spillovers"; *University of California, Davis* & *National Bureau of Economic Research* (economics.ucdavis.edu). 2012.

PREBISCH Raúl: "Industrialization and Development" in "Development Problems in Latin America"; *Economic Commission for Latin America*, Austin, *University of Texas Press*. 1970.

QUAH Danny: "Empirics for Growth and Distribution: Stratification, Polarization and Convergence Clubs"; *Centre for Economic Performance Discussion Paper* no. 324. 1997.

ROBBINS Lionel: "The Theory of EconomicDevelopment in the History of Economic Thought"; *Macmillan*. 1968.

ROMER Paul M.: "Increasing Returns and Long Run Growth"; *Journal of Political Economy*, vol. 94. 1986.

SMITH Adam: "An Inquiry into the Nature and Causes of the Wealth of Nations"; *W. Strahan and T. Cadell*. 1776.

SOLOW Robert: "A Contribution to the Theory of Economic Growth"; *Quarterly Journal of Economics*, vol. 70. 1956.

SOLOW Robert: "We'd better watch out"; *New York Times Book Review*, July 12, 1987, page 36. 1987.

StudyMode: "Industrial Revolution: How Did the Industrial Revolution Transform Society?"; *StudyMode* (studymode.com). 2006.

SUGAR CANE (sugarcane.org). 2013.

TEECE David J.: "Technology Transfer by Multinational Firms: the Resource Cost of Transferring Technological Know-how"; *United Nations Conference on Trade and Development* (unctc.unctad.org); source: *Economic Journal* LXXXVII (June 1977), pp. 242-261. 1977.

TECHNOPEDIA (technopedia.com). 2013.

ULKU Huljya: "R&D, Innovation, and Economic Growth: An Empirical Analysis"; *International Monetary Fund Working Paper* WP/04/185. 2004.

UNITED STATES PATENT AND TRADEMARK OFFICE (USPTO); (uspto.gov). 2013.

The WORLD BANK: *The World Bank Database* (data.worldbank.org). 2013.

WEIL David N.: "Economic Growth - Third Edition (International Edition)"; *Pearson*. 2013.

XUEMEI BAI: "China's Solar-Powered City"; *Renewable Energy World* (renewableenergyworld.com). 2007.

YOSKOWITZ Andre: "Global Mobile Phone Shipments Reach 1.6 Billion Units in 2012"; *Strategy Analytics* (strategyanalytics.com). 2013.

ZEIRA Joseph: Unpublished material; *LUISS*. 2013