Cross-over, thresholds, and interactions between science and technology: lessons for less-developed countries

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Abstract

Presently, science is an important precondition for the economic development of less-developed countries. This paper discusses the specific roles that science has at initial stages of development, pointing to its contributions for the countries’ absorptive capability. Furthermore, this paper specifies the role of science for initiating a positive interaction with technological development, since initial stages of development and during catching up processes. For less-developed countries, neither the linear model of technology nor an “inverted linear model” would take place: a more interactive approach is necessary for development. Using statistics of patents (USPTO) and scientific papers (ISI) for 120 countries (1974, 1982, 1990, and 1998), this paper analyses some evidences on thresholds levels of scientific production to originate an interactive relationship between science and technology. These data also document that the value of this threshold seems to double from one period to another. Although this paper presents tentative results, some policy implications are discussed: scientific institutional building must be seen as a component of modern industrial policies.

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1. Introduction

Science is not a “luxury” for less-developed countries, but an important precondition for contemporary economic development. This hypothesis follows Perez and Soete’s (1988) discussion of catching up process: they point the role of public science for lowering the costs of entry in new industries, a precondition for taking advantage of “windows of opportunity”. This approach conjectures that scientific resources are a prerequisite for development.

However, it seems that the literature presents an “inverted linear model” for less-developed countries: first economic development, then technology improvements and, only in the end, allocation of resources for science. This paper proposes that throughout the development process, a more interactive process (neither the traditional linear model, nor an “inverted linear model”) between science and technology may take place. For these interactions, scientific institutions, resources and capabilities are necessary.

The reasoning of this paper follows five steps (each corresponding to a section). The first step surveys the literature on the role of science for modern economic development, stressing its particular contribution for
the establishment of virtuous circles of interaction with technology. This survey suggests that science must be positioned to play this role with technology; otherwise this virtuous circle will not be triggered.

The second step discusses the specific role that science has at initial stages of development, pointing to its contributions for the countries’ absorptive capability. The third step specifies the role of science for the triggering of a positive interaction with technological development since initial stages of development and during catching up processes: this step suggests why it may be important to allocate resources for the improvement of scientific capability of poor countries since the beginning of development.

The fourth step deals with data collected for 120 countries, analysing some indications about thresholds levels for initiating an interactive relationship between science and technology. This step also discusses the data and evaluates how the arguments of previous sections could be supported and/or improved. The paper concludes with a summary of the main arguments and results, and with an initial discussion on the public policy implications of this analysis.

2. Institutions, science, technology, and development: a brief literature survey

The literature on national systems of innovation (NSI) is the main source of concepts and theoretical references for this paper (Nelson and Rosenberg, 1993; Freeman, 1995). NSI is an institutional arrangement, involving firms and their R&D departments, universities, research institutes, financial systems supporting innovation, education institutions, law, etc.

This literature is important for this paper for three reasons. First, it defines the different role of institutions from the scientific and technological dimensions. The NSI literature emphasises an institutional labour division between the production of science and the production of technology. Broadly speaking, universities and research institutes produce science, and firms produce technology. Of course, there are firms producing basic knowledge, publishing papers and advancing science (Hicks, 1995), and universities applying for patents, generating new products, etc. (Hicks et al., 2001). But the main technological labour division involves this basic labour division.

Second, these institutions interact with each other. Freeman (1992) advances the idea of a “narrow concept” of the NSI, which involves the mere existence of these institutions. However, these institutions per se are not enough to characterise a NSI in a “broad concept”: the interaction and the mutual feedbacks among their institutions are key. The example of the former USSR is mentioned here: there were institutions (research labs, universities, firms, R&D resources, etc.), but there were only weak interactions among them (Freeman, 1995).

Third, the NSI represents an institutional arrangement that articulates the economic wealth with the underlying technological competence. Nelson (1990) summarises this relationship presenting how the institutions of NSIs constitute the “engine of capitalist growth.” Fagerberg (1994) articulates the institutional building related to the NSI with the growth and development of nations.

The study of determinants of economic growth is both fascinating and complex. Abramovitz (1989) presents a broad view, suggesting a division between the “proximate sources of growth” (pp. 13–28) and the “deeper causes”, which involves “technological effort as investment” (pp. 28–41), and “national and historical determinants” (pp. 41–55). Abramovitz’s essays on growth summarise the multifarious and variegated sources of economic growth. The literature about economic growth, that boomed during the 1990s shows the role and relevance of sources like

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1 Nelson (1992), for instance, shows what is public and what is private in technology, warning about the risks of a privatisation of knowledge that should be public. This warning points to an inadequate labour division among various spheres of NSI.

2 Probably, the idea that technological and scientific institutions support capitalist development is as old as the Marxian elaboration. Marx pointed how the “specifically capitalist mode of production” is directly linked to the possibility of use of science in the production process. This reasoning underlies Marx’s formulation of the transition from the formal to the real subsumption of labour to capital (Marx, 1863–1864). Of course, at that time, the “systematic application of science to production” was in its beginnings. Dosi (1997) mentions that as time goes by the weight of science increases in subsequent technological paradigms. In this regard, the constitution and evolution of NSI could be seen as the institutionalisation of diverse and multitudinous channels of the “systematic application of science to production” pointed so early by Marx’s insights.
innovation, income distribution, education, health and nutrition, institutions, investment, trade, etc. This literature also shows how complex are the definitions about the direction(s) of causality and how difficult it is to evaluate the interactions between these diverse sources.

This paper focuses a very peculiar and specific dimension of this broad and complex picture: the relationship between the scientific and technological dimensions and economic growth. In this regard two approaches are useful: (1) the literature about the economics of technological change; (2) the debate about the endogenous growth.

Nelson and Rosenberg (1993, pp. 5–9) point the intertwining of science and technology as a key characteristic of NSI. They summarise the complex interactions between these two dimensions highlighting that science is both “a leader and follower” of technological progress (p. 6).

Evidence of this dual role can be drawn from the literature. First, Rosenberg (1982, pp. 141–159) discusses “how exogenous is science”, indicating how technology leads and precedes science. Rosenberg presents the role of technology as: (1) a source of questions and problems for the scientific endeavour; (2) an “enormous repository of empirical knowledge to be scrutinised and evaluated by the scientists” (p. 144); (3) technological progress contributes to the formulation of the “subsequent agenda for science” (p. 147); (4) a source of instruments, research equipments, etc. Rosenberg concludes that “powerful economic impulses are shaping, directing, and constraining the scientific enterprise” (p. 159).

Second, in the opposite direction of the flow, Klevorick et al. (1995) present empirical evidence about the role of universities and science as an important source of “technological opportunities” for industrial innovation. This study shows how different industrial sectors rank the relative importance of universities and science to their innovative capabilities. Klevorick et al. rank the relevance of scientific disciplines to different industrial sectors, justifying why firms monitor and follow developments in the universities. Particularly in high-tech industries, there are strong knowledge flows running from the scientific institutions to the industrial sectors.

Third, Pavitt (1991) investigates “what makes basic research economically useful”. Basic research is economically useful not only because it constitutes an “increasingly important direct input into technology”. According to Pavitt, “there are . . . other two other influences that are equally, if not more, important: research training and skills and unplanned applications” (p. 114).

Fourth, Rosenberg (1990) discusses “why do firms do basic research”, and suggests that basic research is an “entry ticket for a network of information”. This point is related to Cohen and Levinthal (1989) discussion about the two faces of R&D (innovation and learning), emphasising the importance of this investment as a way to develop “absorptive capability”.

Fifth, Narin et al. (1997) find empirical evidence for the “increasing linkage” between science (financed by the public sector) and the US industry. Finally, a recent OECD study describes the “intensification of industry-science relationships in the knowledge economy”, highlighting that “links to science are more important than in the past” (OECD, 2002, p. 16). Thus, these studies indicate the relevance of the two dimensions of the innovative activities, stress the division of labour between them, support the understanding of the strong and mutual feedbacks between science and technology in developed countries, and points the intensification of this relationship. Therefore, this literature suggests that for modern economic growth these interactions must be working.

Romer (1990) formulates a model where growth is caused by human capital allocated in the research sector of profit-seeking private firms. Knowledge flows are key in this model. However, there is no distinction between scientific production and technological sector: there are not research institutions in Romer’s model. Therefore, the role of interactions cannot be discussed. Pavitt (1998) interprets Romer’s model as one that suggests the causal links running from the scientific dimension (knowledge producing) to the technological dimension. Pavitt (1998) inverts the direction of causation.

Aghion and Howitt (1998) add two important points. First, the contribution of education to the growth of labour productivity does not take place, “unless education is being explicitly linked to the rate of innovations and the speed of catch up” (p. 339). Second, they discuss the “low-growth traps caused by the complementarity between R&D and education” (pp. 340-342).
In sum, the literature on economics of technology could be seen as evolving as follows: (1) starting with simple models as suggested by Schumpeter (1911), where innovation pushes economic development; (2) improving the understanding of the role of science for innovation in developed societies, criticising the linear model of technology and suggesting an interactive approach (Rosenberg, 1982, 1990); (3) indicating an institutional labour division between different components of NIS (Freeman, 1995; Nelson and Rosenberg, 1993); (4) investigating the specific roles of science, technology, and their interactions, for industrial and economic development (Pavitt, 1991; Rosenberg, 1990; Klevorick et al., 1995; Narin et al., 1997; Freeman and Soete, 1997). How may these lessons be applied to the case of less-developed countries?

3. Introducing the case of less-developed countries: science and absorptive capability

For discussing the case of less-developed countries, a category that includes the initial position of successful catching up countries few decades ago, it is necessary to understand their specificity. If these interactions underlie modern economic development, it is necessary to avoid an “inverted linear model” (implicit or explicit) for the less-developed countries. A complete “inverted linear model” would suggest the following schema: first economic development, then resources available for technological development, and finally the growth of scientific institutions. But, there is the rub: what does feed the economic development? In an increasingly sophisticated and science-based economic world, how could less-developed countries skip investments in science and technology? Without these investments, what would plug them in the international network of scientific and technological information?

This paper argues that for less-developed countries the interaction between science and technology is crucial too, if these countries have the aim of development. In this regard, stagnation and low development traps portrait the lack of this interaction. Therefore, if the arguments of this paper are correct, public policy implications will follow (and they are tentatively presented in Section 6).

The hypothesis of this paper suggests that the interactions between science and technology are important since the beginning of development process. These interactions, however, have different features vis-à-vis already developed countries. To introduce the discussion on the specific and peculiar nature of this interaction, this paper investigates, in first place, the specific role for science in less-developed countries: important qualifications of the role of science at the periphery are starting points for this paper’s arguments.

The literature on economics of technology has deeply criticised views that underplay the efforts necessary for technological imitation. Silverberg (1990, p. 179) shows how imitation and diffusion of technologies must be seen as a continuation of the innovative process. What are the implications of this finding for development? Initial stages of the development process depend heavily on imitation. As imitation is a continuation of the innovative process, it is necessary creativity to copy technologies developed abroad. Cimoli and Dosi (1995, pp. 258–259) point that the combination between acquisition of technology and learning, and the sequence that runs from copy to creativity are two sides of the same process.

This effort to imitate depends on internal capabilities: initial stages of development and catching up process depend on “absorptive capability”. Again, the literature on economics of technology shows important lessons: Cohen and Levinthal (1989) have pointed out the dual role of R&D for firms: innovation and learning. Rosenberg (1990) has described why firms invest in basic research: to monitor knowledge developed elsewhere. Mowery and Rosenberg (1988) have indicated the role of basic research as an “entry ticket” for a network of technological and scientific information. In sum: to imitate, to absorb knowledge from more advanced countries, internal capabilities are...
necessary. And a certain level of scientific capability is a key component of this absorptive capability.

During the initial phases of development, scientific institutions are necessary mainly for the learning side of the innovative process. The necessity of scientific institutions to support learning processes and diffusion of technologies is greater now, because the later technological paradigms are more science-based than the earlier ones (Dosi, 1988, p. 1136), and current technology depends more heavily on science (OECD, 2002, p. 16). As a country develops, the mix between the learning and innovation faces of the R&D process changes.4

Bell and Pavitt (1995) have compared the successful development of latecomers in the 19th century (US textile industry) and present day conditions. Today there is a gap between productive and technological capability: it is not anymore automatic the transition between productive capability and technological capability, given the knowledge requirements for technological creation and change (p. 198). This gap points the increased knowledge requirements for contemporary catching up process.

Beyond their key role as supporting the absorptive capability, the scientific institutions have other important contributions for development. First, it acts as a “focusing device” in this process. Science at periphery is important to function as an “antenna” for the creation of links with international sources of technology. As a “focusing device”, scientific institutions could spot avenues of technological development that are feasible to backward countries, given national and international conditions. This means that scientific information is necessary even to advise in which industrial sectors entry is not feasible. This is very important for less-developed countries: “blind search” could be wasteful. Therefore, the scientific institutions provide “knowledge to focus search” (Nelson, 1982).

Second, the national scientific capability is a major support for industrial development, providing the knowledge necessary for the entry in key industries for the process of development. As Perez and Soete (1988) put forward, scientific knowledge provided by the public infrastructure reduces the entry costs in key sectors.

Third, there are other more intricate links between knowledge and growth, like a causal relationship chain between improvements in the scientific dimension and consequent improvements in health, which by its turn, leads to more economic growth.5 This might be an indirect link between science and growth: and one that would not be reached without internal investment in science health-related disciplines, given the broad global mismatch between health needs and research agenda (UNDP, 2001, p. 110).5,7

Fourth, another causal link might run between science and agricultural improvements. Technologies for agriculture have “ecological specificity”, given specific conditions such as irrigation, characteristics of the land, resistance of crops to insects, etc. Therefore, national investments in less-developed countries are necessary, because these technologies “cannot be transferred from one zone to another merely through tinkering” (UNDP, 2001, p. 96).

Fifth, given the current global divide in technology, major innovations come from countries that are high-income, temperate, countries that have completed

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4 Coe et al. (1995) discuss north–south R&D spillovers, using “commercial openness” as a proxy for a less-developed country access to the international R&D. This contrasts with their evaluation for developed countries (Coe and Helpman, 1995), where the internal R&D resources indicate to which level can a country use the international R&D. The lack of a measure of “absorbent capability” for less-developed countries is an important shortcoming in their analysis.

5 According to Sachs and Malaney (2002, p. 644), “suppressing malaria in poor, highly malarious regions, especially in sub-Saharan Africa, offers the potential to initiate a virtuous cycle in which improved health spurs economic growth, and rising income further benefits human health”.

6 This could be a rationale for an initiative from the World Health Organization: the tropical disease research (TDR). This initiative sponsors programs as the “Task Force on malaria research capability strengthening in Africa”. According to its homepage, “focusing on research areas of broad application in endemic countries, the Task Force provides support to strengthen African research groups in developing tools for effective malaria control, by promoting partnerships, collaboration, technology transfer, and training opportunities” (World Health Organization, 2002).

7 Other arguments for the need of local investments in science for health improvement in less-developed countries are put forward by Freeman and Miller (2001, p. 16): “without discriminating scientific capability, local populations are left to follow blindly protocols exported from afar, be it from national governments, international agencies, pharmaceutical or devices manufacturers, or others. Local scientific leadership engaging in shaping interventions will be prepared to help their communities understand the purposes and underlying theories of health interventions”.

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their demographic transition and have an epidemiological structure biased towards chronic diseases, etc. Assuming that imitation is the initial form of local innovation, it is unavoidable a huge effort to adapt technologies to a new environment (in terms of income, weather, demography, and epidemiology). This effort, in an age of increasingly science-based technologies, has an unavoidable scientific content. And national institutions (highly connected with international networks and communities) might provide this scientific content. Therefore, allocation of resources for scientific development is necessary since the beginning. The Human Development Report 2001 presents examples from countries like Thailand, Cuba, Brazil, and India in this regard (UNDP, 2001, p. 98).  

In sum, this section presents arguments for the role of science since the beginning of development processes. These arguments support the necessity of investments in scientific institutions before the catching up process. This section questions an “inverted linear model” for less-developed countries. The next section must address the opposite question: this paper does not support a “linear model” for less-developed countries. Rephrasing the question: how does the interaction between science and technology take place throughout development processes?

4. Scientific institutions and the interactions between science and technology throughout development processes

The discussion of the contrasting cases of Korea and Taiwan vis-à-vis Brazil, India, and Mexico may introduce the discussion about interactions during the development process. It is important to keep in mind that Korea and Taiwan were less developed than Brazil and Mexico, for instance, during the 1960s and the earlier 1970s (Dosi et al., 1994). Therefore, they began their processes as backward countries, overtook Brazil and Mexico, and did catch up with developed countries in the 1990s. Rapini (2000) presents three graphs (Schemes 1–3). These graphs illustrate the process, comparing, respectively, Taiwan, Korea, and Brazil. Further these graphs present data of scientific production (measured by papers indexed by the Institute for Scientific Information) and technological production (measured by patents granted by the USPTO).  

The contrast in these graphs is interesting: Korea and Taiwan show a pattern of concomitant growth between science and technology production, while Brazil shows a lower correlation between these two variables. Contrary to an “inverted linear model” assumption, the data on Korea and Taiwan show how the development of science and technology was mutually reinforced. Schemes 1 and 2 (for Taiwan and Korea, respectively) suggest that these countries did not wait until the end of the development process to increase investments in science. Country studies reveal how these countries committed resources for scientific institutions early in their catching up process (Amsden, 1989; Wade, 1990; Kim, 1993; Hou and Gu, 1993).

Discussing the Korean and the Taiwanese cases, five stylised facts about the relationship between scientific infrastructure and catching up process can be listed: (1) a high correlation between the growth of scientific and technological output; (2) high opportunity taking indicators, hinting an interaction between scientific output and industrial technology; (3) high concentration in few interrelated scientific disciplines; (4) increase in the concentration in scientific disciplines during the catching up; (5) decrease in concentration in patent classes during the catching up phase. These stylised facts point not only to the quantitative aspect of the interaction (the concomitant growth of papers and patents), but also the qualitative aspect (the concentration of scientific production in disciplines...}

8 Freeman (1996) suggests a reorientation of the direction of technological progress, in regard to environmental targets. In his discussion, there is a critique about the weakness of market to select technologies environmental-friendly, and Freeman suggests a sophisticated planning network, involving government, firms and universities. These projects may be ‘mission-oriented’, aiming in that case the environment. This new approach of mission-oriented research projects could be very useful for less-developed countries; there are problems (as presented above: social, agricultural, health, infrastructure) that are country-specific and should be confronted with well-aimed strategies.

9 This section summarises arguments presented in a previous paper (Albuquerque, 2001).


SOURCE: ISI and USPTO (Rapini, 2000)
with deep impact upon industrial technology, like several engineering fields, computing, applied physics, materials science, chemistry, etc.) (Albuquerque, 2001).

These findings suggest that there could be a combination between dispersion and concentration across scientific disciplines. On the one hand, dispersion: a country should have capabilities to follow and monitor developments in a broad range of fields, connected to the “focusing device” side of the scientific capabilities. On the other hand, concentration: a country might need to concentrate limited resources in disciplines deeply related to industrial needs, connected to the “provision of public knowledge” side of the scientific capabilities. Probably, Korea and Taiwan have built both, while Brazil only has built the “focusing device” aspect.

Furthermore, according to Rapini (2000), there is a statistical causality running both ways (Granger-causality). This is an initial evidence of interactions between science and technology during development process. She finds that, on the one hand, in Korea and Taiwan the scientific production Granger-causes technological production and that the technological production also Granger-causes scientific production. On the other hand, for Brazil, Rapini finds that only scientific production Granger-causes technological production.

This section presents data for two catching up countries, gathering evidence on the concomitant growth of science and technology in their developmental process. Therefore, the mutual feedback and the interaction between science and technology seem to be components of catching up process. The next question is: how is this interaction triggered?

5. Data description: scientific papers, patents, and GNP per capita

To answer this question, this section presents and evaluates data from 120 countries, involving countries in different stages of development. Do these data suggest any empirical regularity in the relationship between science and technology?
The option for collecting a broader sample of countries has three reasons: first, it includes countries from different stages of development, therefore including less-developed countries; second, it provides an overall picture of broad relationships discussed in the earlier sections of this paper; and third, it allows a comparison between developed and less-developed countries, including the transitional position of catching up countries as Korea and Taiwan, that have begun their process in the group of more backward countries and have ended achieving a position near the more developed countries.

For this purpose, data about GNP per capita (US$, PPP, according to the World Bank, for 1998), patents (for 1998, 1990, 1982, and 1974, according to the USPTO, 2001), and scientific papers (for 1998, 1990, 1982, and 1974, according to the Institute for Scientific Information, 2001) were collected for 120 countries.\[11\]

Papers are not a perfect measure of scientific production, and patents are not a perfect measure of technological innovation. The literature has both used these data and warned about their problems, limitations and shortcomings.

Scientific papers, the data collected by the ISI, have various shortcomings, from language bias to the quality of research performed: there could be important research for local needs that does not translate in international papers, but only in national publications not captured by the ISI database. There is a huge literature on the problems of this indicator (Patel and Pavitt, 1995; Velho, 1987). Paper citations improve the quality of this indicator, but it would not be so useful for this paper, further biasing the data against papers produced in countries with low developed scientific institutions.\[12\]

Patents, the USPTO data, also have important shortcomings, from commercial linkages with the US to the quality of the patent: again, local innovation necessarily is limited to imitation in the initial phases of development, and imitation or minor adaptations do not qualify for a patent in the USPTO). There is a huge literature on the problems of this indicator (Griliches, 1990; Patel and Pavitt, 1995).

Therefore, this paper acknowledges these important limitations, and this literature must be kept in mind to qualify the results discussed in the next sub-sections. Despite these problems, these two datasets appear to provide useful and under-utilised information for research.

This broad sample is important: on the one hand, studies about technological indicators are mainly concentrated in data about developed and OECD countries (for example, Fagerberg, 1994; Stern et al., 2000); on the other hand, more broad samples as those provided by the Penn World Table do not use indicators of science and technology (Barro and Sala-i-Martin, 1995). And the range and usefulness of these indicators should be highlighted: there are 115 countries out of 120 that have published at least one scientific paper in 1998; and 89 countries out of 120 applied at least one patent at the USPTO in 1998. Only one country (Trinidad Tobago) out of 120 has zero patents and zero papers in 1998.

The countries are: Albania, Algeria, Argentina, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bolivia, Bosnia and Herzegovina, Brazil, Bulgaria, Cameroon, Canada, Chile, China, Colombia, Congo (Democratic Republic), Congo (Republic), Croatia, Cuba, Czech Republic, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Estonia, Ethiopia, Finland, France, Germany, Ghana, Greece, Guinea, Haiti, Honduras, Hong Kong (China), Hungary, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Korea (Republic), Korea (Democratic Republic), Kuwait, Kyrgyzstan, Latvia, Lebanon, Libya, Lithuania, Macedonia, Madagascar, Malaysia, Malawi, Mali, Mauritania, Mauritius, Mexico, Mongolia, Morocco, Myanmar, Namibia, Nepal, The Netherlands, New Zealand, Niger, Nigeria, Norway, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Senegal, Sierra Leone, Singapore, Slovakia, Slovenia, South Africa, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Taiwan, Tanzania, Thailand, Trinidad and Tobago, Tunisia, Turkey, UK, USA, Uganda, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Venezuela, Vietnam, Yemen, Yugoslavia, Zambia, and Zimbabwe.

\[11\] The countries are: Albania, Algeria, Argentina, Armenia, Australia, Austria, Azerbaijan, Belarus, Belgium, Bolivia, Bosnia and Herzegovina, Brazil, Bulgaria, Cameroon, Canada, Chile, China, Colombia, Congo (Democratic Republic), Congo (Republic), Croatia, Cuba, Czech Republic, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Estonia, Ethiopia, Finland, France, Germany, Ghana, Greece, Guinea, Haiti, Honduras, Hong Kong (China), Hungary, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Korea (Republic), Korea (Democratic Republic), Kuwait, Kyrgyzstan, Latvia, Lebanon, Libya, Lithuania, Macedonia, Madagascar, Malaysia, Malawi, Mali, Mauritania, Mauritius, Mexico, Mongolia, Morocco, Myanmar, Namibia, Nepal, The Netherlands, New Zealand, Niger, Nigeria, Norway, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Senegal, Sierra Leone, Singapore, Slovakia, Slovenia, South Africa, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Taiwan, Tanzania, Thailand, Trinidad and Tobago, Tunisia, Turkey, UK, USA, Uganda, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Venezuela, Vietnam, Yemen, Yugoslavia, Zambia, and Zimbabwe.

\[12\] It is justifiable to study less-developed countries with data from scientific papers because the existence of a scientific infrastructure hints: (1) the level of development of the educational resources of the country; (2) the quality of their universities; (3) their connections with the international flows of scientific knowledge; and (4) the commitment of these universities with research activities. This assumption implies that the number of published papers may be taken as an indicator of the general situation of the educational conditions of the country and of their usefulness to the economic development.
5.1. A simple model about stages of development, science production, and interactions between science and technology

To perform the statistical analysis (in the next sub-sections), this sub-section puts forward a very simple model. This model describes the relationship and the interactions among science, technology and economic growth. It simplifies the complex and multifarious connections, interactions, and causal chains that constitute the province of economic growth. However, this model contributes to organise the data in a very simple way, differentiating countries between those that already produce science and technology, according to the proxies, and those that do not have both productions.

The theoretical background and the intuitions of this very simple model are discussed in Sections 2–4. From them, three stylised facts could be drawn.

(1) Developed countries have strong scientific and technological capabilities, and there are interactions and mutual feedbacks between the two dimensions (Section 2).

(2) The role of science during the catching up process is crucial and it is two-folded: source of absorptive capability and provider of public knowledge for the productive sector (Sections 3 and 4).

(3) Less-developed countries are caught in a “low-growth trap” given, inter alia, the low levels of scientific production (Section 3).

To suggest this very simple model, six steps are necessary. The support to each of these steps is presented in the literature and the data surveyed in Sections 2–4.

(1) The first step is the recognition of two different dimensions of innovation-related activities—the scientific infrastructure and the technological production.

(2) The second step is the identification of a division of labour between them.

(3) The third step is the identification of interactions between the scientific and technological dimensions, as well as the dynamics of these interactions.

(4) The fourth step is the suggestion that these interactions change during the development process, reaching at last a level of strong and mutual reinforcing relationships found in developed economies.

(5) The fifth step is the conjecture that this evolutionary path depends on the scientific infrastructure (at least, the improvement and the growth of the scientific infrastructure is a necessary, but not sufficient condition for initiating technological development), and that there are thresholds of scientific production that must be overcome to reach new stages (and new levels of interaction between science and technology).

(6) Finally, these interactions in the science and technology field might be integrated in the causal chains of economic growth.

The data gathered for this paper provide one feature for this simple model: among the 115 countries that produced at least one paper in 1998, 85 countries were granted with at least one patent. The 30 countries with scientific production, but no patents are the countries that compose a special class: countries in a “low-growth trap”, where their scientific production is so low that does not yet feed technological production (these countries are included in “regime I”, according to Fig. 1).

These steps and comments lead to the very simple model displayed in Fig. 1. This figure shows three different “regimes”, ranging from the least developed countries (regime I) to the developed countries (regime III).13

The very simple model uses four sets of variables: scientific production; technological production; economic growth; and “others” (representing a broad range of factors and variables left out of this simplified model—labour, availability of natural resources, health conditions, demographic factors, income distribution, etc.).

The very simple model suggest that as the “regimes” change, the number and the channels of interactions between scientific infrastructure, technological production and economic growth concomitantly also change. As the country evolves, more connections are “turned on” and more interactions operate (the arrows in Fig. 1). The “regime III” is the case where all

13 The term “regime” is not a good one, but it is useful to delimit the different forms of operation of the relationship and interactions among the four variables used in the model in its present (and very initial) level of elaboration.
connections and interactions are working (they have been “turned on” during previous phases).
As long as the development takes place, the role of “others” in the causation of economic growth decreases. In other words, as a country upgrades its economic position, its economic growth is more and more “caused” by its scientific and technological resources. The mutual feedbacks between them contribute to explain why the modern economic growth is fuelled by strong scientific and technological capabilities (Fagerberg, 1994; Dosi et al., 1994). This very simple model is suggested to enable the data analysis of Section 5, focusing the interactions between science and technology.
5.2. Correlation between scientific and technological production, and GNP per capita

Fig. 2 shows a three-dimensional plot, where the log_{10} of the GNP per capita is plotted against the log_{10} of the number of articles per million of inhabitants (A^*) and the log_{10} of the number of patents per million of inhabitants (P^*). The data are for the year 1998. Only countries with data available and scores different from zero are represented.

Fig. 2a shows clearly the correlation between the three variables. The higher is the scientific and technological production, the higher is the GNP. Fig. 2b and c show the projections of the points, respectively, in the GNP × articles plane and in the articles × patents plane. In Fig. 2c there is a concentration of points in the upper part of the plot, representing the developed countries. The same aspect could be observed in Fig. 2a.

At this stage of the discussion, it is not the main interest to look for a function that might fit those points. In a three-dimensional plot it should be very hard to find it. However, at the present, it is clear the correlation between the variables. Table 1 organises the data (patents per million inhabitants, scientific papers per million inhabitants and a ratio...
Table 1

Averages and standard deviation of articles per million inhabitants (A∗); patents per million inhabitants (P∗); and the ratio between articles per million inhabitants and patents per million inhabitants (A∗/P∗), according to their income level (GNP per capita) in 1998

<table>
<thead>
<tr>
<th>Group of countries (GNP per capita: US$)</th>
<th>A∗ (average)</th>
<th>S.D.</th>
<th>P∗ (average)</th>
<th>S.D.</th>
<th>A∗/P∗ (average)</th>
<th>Number of countries in group</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;19,000</td>
<td>957.99</td>
<td>377.69</td>
<td>154.42</td>
<td>121.54</td>
<td>6.07</td>
<td>19</td>
</tr>
<tr>
<td>10,000</td>
<td>476.59</td>
<td>432.32</td>
<td>64.68</td>
<td>107.37</td>
<td>7.41</td>
<td>13</td>
</tr>
<tr>
<td>19,000</td>
<td>115.68</td>
<td>133.58</td>
<td>1.45(a)</td>
<td>1.76</td>
<td>79.78</td>
<td>25</td>
</tr>
<tr>
<td>5,000</td>
<td>40.87</td>
<td>50.10</td>
<td>0.43(b)</td>
<td>0.58</td>
<td>95.04</td>
<td>17</td>
</tr>
<tr>
<td>3,000</td>
<td>14.79</td>
<td>25.06</td>
<td>0.10(c)</td>
<td>0.18</td>
<td>147.90</td>
<td>40</td>
</tr>
<tr>
<td>&lt;3,000</td>
<td>14.81</td>
<td>28.89</td>
<td>0.04(d)</td>
<td>0.10</td>
<td>370.25</td>
<td>6</td>
</tr>
<tr>
<td>GNP not available</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adapted from World Bank (2000), USPTO (2001), ISI (2001) (authors’ elaboration): (a) three countries (with P∗ = 0); (b) two countries (with P∗ = 0); (c) twenty-one countries (with P∗ = 0); (d) five countries (with P∗ = 0).

between these two data) according to countries income levels.

Table 1 shows the correlation displayed by Fig. 2, as the scientific and technological production are directly related to the income level. The scientific and technological production are higher for the richer countries (for GNP per capita greater than US$ 19,000, A∗ = 957.99, P∗ = 154.42) than for poorer countries (for GNP per capita less than US$ 3000, A∗ = 14.79, P∗ = 0.10).

Table 1 presents an initial hint about the existence of thresholds of scientific production. The third column presents the ratio between A∗ and P∗ (the ratio A∗/P∗ is calculated dividing the average A∗ and average P∗ for each group of countries). This ratio may be understood as an indicator of efficiency in the transformation of scientific production into technological outputs. The more efficient a group of countries is, the smaller is the ratio (the countries in that group, in average, produce more patents for a given stock of scientific papers).

In addition, one remark is necessary. Countries with zero patents or zero scientific papers have been excluded from Fig. 2 (115 countries out of 120 have published at least one scientific paper in 1998; and 89 countries out of 120 applied at least one patent at the USPTO in 1998). There are 30 countries with scientific publications but without USPTO patent, which constitute the “regime I” as displayed in Fig. 1. These 30 countries have not reached even the first threshold, the threshold necessary to trigger the beginnings of a technological production (as captured by the proxy of USPTO patents).

The next step in this analysis is to divide the sample countries between the three regimes suggested in the previous sub-section. So far, it is only possible to indicate general relationship between income, science and technology, and to identify the countries included in the “regime I” (30 countries with papers but no patents). To divide between “regimes II and III” it is necessary to investigate thresholds of scientific production.

5.3. Preliminary evidences about thresholds of scientific production

Fig. 2c suggests the existence of two behaviours in the relation between A∗ and P∗. The remainder of this section discusses and presents preliminary statistical evidences about the existence of thresholds between different stages of development, and about the changes in those thresholds as time goes by.

5.3.1. The threshold in 1998 data

The cross-over and the threshold level can be better observed in Fig. 3. This figure displays the data for the year 1998 in a two-dimensional plot in log-log scale. In this plot, it is possible to define two regions. Roughly speaking, they are separated by the point (A∗ ≈ 100 and P∗ ≈ 1). The technologically immature countries are at left/lower of this point and the mature countries at right/upper.
Those points can be fitted by two power functions $P^* \propto (A^*)^\beta$, what has been done by dividing the set of points in two subsets, which are shown with different symbols (filled squares and open circles) in Fig. 4.

The fit of the first subset gives an exponent $\beta = 0.76$, with correlation coefficient $R = 0.65$. On the other hand, the second subset gives $\beta = 2.39$ with $R = 0.79$ (see Tables 3 and 4). The cross-over between the two lines occurs at $A^* \approx 150$. This is the threshold that identifies the transition from regimes II to III, according to Fig. 1 (Section 5.1).

The data plotted in Figs. 3 and 4 give important clues for the behaviour of the interactions within the process of development: these data suggest a non-linear dynamics. In contrast with different approaches that suppose linear relations between science (or scientific production), technology (or technological production) and economic growth, with one variable determining other in a unidirectional chain of causation.

In the last two decades, the notions that economic systems evolve as complex systems have gained space in the physical and economic communities.14

The basic features of economic systems, like the large number of agents, dispersed interaction, no global controller, adoption, etc. justify this so called “complex approach”. However, in many of those discussions, economic systems are basically restricted to financial systems (Voit, 2001; Mantegna and Stanley, 2000). Besides, it is well accepted today that the network of scientific interactions can be modelled by free-scale networks (Barabasi and Albert, 1999). This fact might be a signal that the scientific and technological systems in a country (or a region) should also work as a complex system.

Non-linear dynamics are one of the basic features of complex systems. The different regimes shown in those figures are, in this paper’s proposal, related to different levels of complexity in the scientific and technological systems. Coming from regimes II to III, the correlation between $A^*$ and $P^*$ increases, but it does not increase linearly. The increase in com-

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14 See, for example, the pioneering book of Arrow et al. (1988).
plexity means the incorporation of more and more people, institutions, companies, etc. the increase of that network of interaction. It, as observed in complex systems, could be related to the creation of long-range correlations, in the same way as observed in other complex systems.

5.3.2. The three regimes: general overview
With the thresholds identified, it is now possible to resume the analysis from Section 5.2, focusing on how the performance of the sample varies according to the three regimes. Table 2 reorganises the data, distributing the 115 countries according to their "regimes" in 1998.

Table 2 highlights features of these different "regimes", but also presents elements that call for caution in the analysis. According to Table 2, as countries evolve from regimes I to III, the averages of all indicators increase (scientific production, technological production, and income). It is interesting to note that the ratio $A^*/P^*$ decreases as the scientific production increases: as the scientific production

<table>
<thead>
<tr>
<th>Regime</th>
<th>$A^*$</th>
<th>S.D.</th>
<th>$P^*$</th>
<th>S.D.</th>
<th>$A^<em>/P^</em>$</th>
<th>S.D.</th>
<th>PPP GNP per capita</th>
<th>S.D.</th>
<th>Number of countries in group</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>11.89</td>
<td>17.29</td>
<td>0</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>1,635.65</td>
<td>1,443.40</td>
<td>30</td>
</tr>
<tr>
<td>II</td>
<td>37.53</td>
<td>35.30</td>
<td>0.65</td>
<td>0.94</td>
<td>143.65</td>
<td>190.61</td>
<td>4,431.35</td>
<td>2,626.01</td>
<td>47</td>
</tr>
<tr>
<td>III</td>
<td>665.58</td>
<td>418.92</td>
<td>94.91</td>
<td>118.95</td>
<td>71.24</td>
<td>121.80</td>
<td>16,698.17</td>
<td>7,008.35</td>
<td>38</td>
</tr>
</tbody>
</table>

Adapted from World Bank (2000), USPTO (2001), ISI (2001) (authors' elaborations)
grows, the capacity of the technological sector to use this knowledge increases, becoming more efficient in the transformation of scientific information into technological products. Taking as reference the discussion of Section 5.1, probably this means that at the “regime III” (Fig. 1), there are more connections “turned on” and more interactions working. Probably, mutual feedbacks and virtuous cycles are working. On the other hand, Tables 1 and 2 show that as the income level falls, the efficiency of the transformation of scientific production into technological output also falls (the ratio $A^*/P^*$ increases, according to Table 2 fourth column). In other words, probably there are fewer connections, less and weaker interactions, unidirectional causal links, making room for low-growth traps: the cases of “regimes I and II” (Fig. 1) take place.

Table 2 also highlights some limitations of this analysis. Table 2 shows that, for “regimes II and III”, the averages for $P^*$ and $A^*/P^*$ are smaller than the standard deviation, showing a large variance within these two set of countries. Table 2 also reveals that, for “regime I”, the average for $A^*$ is smaller than the standard deviation. Although there are these limitations, for the objectives of this paper, these data hint an answer for the question that concluded Section 4: the interactions between science and technology seem to be triggered after a certain threshold of scientific production has been attained. Or in a more cautious statement: the attainment of a threshold of scientific production seems to be a precondition for improved technological production.


The threshold is not observed only in the year 1998. The same behaviour can be observed at different times, as shown in the sequence of Fig 4a–c. In this sequence the number of patents per million of inhabitants is plotted against the number of articles per million of inhabitants for three different years: 1974, 1982, and 1998.

Table 3 shows this, presenting the correlation between $A^*$ and $P^*$ for the three “regimes” for the different years analysed in this paper.

<table>
<thead>
<tr>
<th>Year</th>
<th>Regime I</th>
<th>Regime II</th>
<th>Regime III</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>0.17</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>1982</td>
<td>0.41</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>0.64</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>0.62</td>
<td>0.79</td>
<td></td>
</tr>
</tbody>
</table>


In Fig. 5, again the plot is divided in two regions, and fitted with two power functions. As observed in Fig. 4, the points below the threshold are much more dispense, what leads to a lower correlation coefficient. Again only countries with scores higher than zero are included. It is interesting to highlight that the number of countries increases from Fig. 5a to c (and to Fig. 4, which refers to 1998 data). In 1974 there were 62 countries that had at least one patent and one paper. This number increases to 65 in 1982, 67 in 1990, and 85 in 1998. For 1998 there is a larger number of countries, given the end of the former USSR, the division of Czechoslovakia and Yugoslavia. More important is that the exponent for both regions increases consistently, from 1974 to 1998, as observed in Table 4. This behaviour implies that the thresholds change in time, as shown in Table 5. One interesting aspect of this table is that the value of this threshold seems to double from one period to another.

This moving threshold could be interpreted as a signal of the increasing role of science in newer technological paradigms, supporting empirically Dosi’s suggestion (1988, p. 1136) and OECD report (2002, Chapter 1). Additionally, as a corollary, this indicates the inter-temporal increase in the weight of the scientific infrastructure as a precondition for the beginning of a catching up process.

15 Probably, further analysis, using tools like cluster analysis, could indicate an improved division between these countries. Comparing Tables 1 and 2, probably there is a set of high-income countries that may constitute an independent sub-group. Observing Figs. 3 and 4, it seems that a sub-group might include the more advanced countries of “regime II” with the more backward countries of “regime III.”

16 The number of countries increases because more countries reach the minimum level of technological and scientific production that represents the regime II. The sample involves 98 countries in 1974 and 120 in 1998.
Fig. 5. The log–log plot of articles per million of inhabitants vs. patents per million of inhabitants for the year 1974 (a); 1982 (b); and 1990 (c).
Table 4
Exponents for the power functions which have been used to fit the two subsets of the plots articles per million of inhabitants vs. patents per million of inhabitants (Figs. 4 and 5)

<table>
<thead>
<tr>
<th>Year</th>
<th>$\beta_{left}$</th>
<th>$\beta_{right}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>0.13</td>
<td>1.27</td>
</tr>
<tr>
<td>1982</td>
<td>0.56</td>
<td>1.63</td>
</tr>
<tr>
<td>1990</td>
<td>0.70</td>
<td>1.80</td>
</tr>
<tr>
<td>1998</td>
<td>0.46</td>
<td>2.39</td>
</tr>
</tbody>
</table>

$\beta_{left}$ represents the exponent of the left part of the plot (filled squares) and $\beta_{right}$ the exponent for the right portion (open circles). Adapted from World Bank (2000), USPTO (2001), ISI (2001) (authors’ elaboration).

Table 5
Cross-over points between the two functions used to fit the two subsets of the plots of articles per million of inhabitants ($A^*$) vs. patents per million of inhabitants ($P^*$) (Figs. 4 and 5)

<table>
<thead>
<tr>
<th>Year</th>
<th>Threshold ($A^*$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>7</td>
</tr>
<tr>
<td>1982</td>
<td>28</td>
</tr>
<tr>
<td>1990</td>
<td>60</td>
</tr>
<tr>
<td>1998</td>
<td>150</td>
</tr>
</tbody>
</table>


6. Conclusion: evidences about the threshold and public policy implications

This paper presents initial results of a research that needs further development. The results deserve both attention and caution. Attention because they highlight an important contribution of an under-investigated subject (scientific infrastructure in countries outside the OECD area), which demands discussion of public policy implications. Caution because the data have limitations and the set of determinants of economic growth is too complex to be captured by any simple model.

This paper suggests three tentative conclusions: (1) the interplay between science and technology may be taken in account for the study of development process, as the levels of scientific and technological production are correlated to income levels; (2) there seems to be a threshold level in the scientific production (for 1998, in the neighbourhood of 150 scientific papers per million inhabitants), beyond which the efficiency in the use of scientific output by the technological sector increases; (3) there is an inter-temporal dynamics of this threshold, as it changes in time (comparing data for 1974, 1982, 1990, and 1998), and its value seems to double from one period to another.

Although this paper deals with tentative results, policy implications could be preliminarily discussed. First, it is important to avoid, while discussing the development process, both the well-known and well-criticised “linear model of technology” and an implicit “inverted linear model”. During development process, the interactive model that articulates science and technology and economic growth should be operating too. As a matter of fact, the underdevelopment could be seen (or reinterpreted) as a condition, inter alia, that lacks this interaction. This paper explored the role of scientific institutions to catalyse this interaction, aware that the growth of scientific production does not lead automatically to technological production. But, it seems that without reaching the neighbourhood of these thresholds, there are no or weak interactions, and the low-growth trap could prevail (and this is the point that this paper would like to stress).

Assuming that technological production is not automatically attained when scientific threshold is reached, other public policies tools are called for: there is an indispensable role for industrial policies. They are crucial for bringing about and improving interactions between science and technology. Furthermore, industrial policy may be an important component and guide of scientific policies: an intelligent industrial policy can indicate which disciplines are more important for each level of industrial development. For example, concomitant growth of scientific and technological production may depend on a fine-tuning of priorities within and between both dimensions. On the other hand, modern industrial policies for less-developed countries cannot skip the scientific institutional building.

Using the NSI literature and concepts, it is possible to rephrase this paper’s objectives: the formation of a NSI is a general precondition for development (Fagerberg, 1994), and the scientific institutional building, a part of this general policy target, should be part of this effort since the beginning. The concept of NSI provides a more integrated framework for the discussing the contributions of scientific institutions, in particular for their integration with industrial policies.
If this paper provides evidence for the threshold, one preliminary policy implication follows: investments in institutional building are necessary to escape the low-growth trap. Scientific institutions should be created, improved, and supported in less-developed countries. Furthermore, the growth of scientific capabilities implies deep commitment to social improvement, especially at the educational level. Probably this is one important factor blocking present day development of poor countries.

For countries in “regime I”, in particular of the poorest countries, probably without resources to be allocated to scientific activities and to begin the building of their research institutions, there might be a case for international aid and support. As argued in Section 3, there is a list of priorities in terms of scientific disciplines, with health, agriculture, and engineering disciplines certainly topping the list. Besides, intense collaborative work should aim the inclusion of students and researchers of these countries in international networks. The Human Development Report 2001 (UNDP, 2001, p. 92) writes about a “high level of brain drain” from African countries. The lack or weakness of local scientific resources, inter alia, contribute to the waste of human resources.

For countries in “regime II”, a combination of three elements could be suggested. First, quantitatively, it is necessary the allocation of more resources to the scientific institutions, allowing them to reach the neighbourhood of the thresholds (this could be an useful target for policy makers, and a way to scrutinise the performance of the local science). Second, qualitatively, it would be useful to push the improvement of key disciplines more related to national priorities and industrial needs, leading to a greater but more concentrated scientific production throughout the catching up process. And third, for “regime II”, an articulation between industrial and scientific policies may run both ways: scientific institutions would help the formulation of industrial policy as “focusing devices”, and industrial policy would help to transform scientific knowledge (generated abroad and locally) into new firms, new products, etc. The interaction between these two pillars of a modern developmental policy may help the establishment of the interactions discussed in this paper.

For this paper, the main objective of policy is the entry in “regime III”. Therefore, it is far beyond the scope of this paper to present policy suggestions for countries already there. Notwithstanding, there is one comment about “regime III” that could be made here. Within “regime III” there is a subset of countries that have overcome the threshold level, but have a technological production in the level of the most advanced countries of “regime II”. Bulgaria ($A^* = 188.45$, $P^* = 0.36$) and Poland ($A^* = 219.73$, $P^* = 0.49$) illustrated this subset. Their level of scientific production is a good starting point for developmental policies, probably demanding some reform in the scientific side to improve its articulation with specific industrial policy goals.

Finally, further research is necessary, specifically: (1) a deeper investigation of connections and causal links that run from the scientific and technological dimension to the economic growth (and vice versa); (2) a closer focus on the relationship between science disciplines and sub-disciplines and related industrial sectors and sub-sectors; (3) an improvement of the simple model presented in this paper, taking initial steps to formalise it.

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References


17 The reader would refer to works of Branscomb et al. (1999), OECD (2002), Slaughter and Rhoades (2002), and the special number of research policy on “innovations in European and US innovation policy” (Shapira et al., 2001), for the specificities of the agenda of these already high-income and high-tech countries.


