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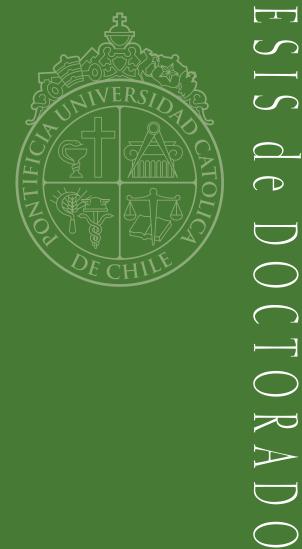
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Essays on Growth and Development in Small and Open Economies

Verónica Mies.

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por

Verónica Mies

Licenciado en Ciencias de la Administración, Universidad Adolfo Ibáñez, 1997
Magíster en Economía, Pontificia Universidad Católica de Chile, 1999

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Comité:
Raimundo Soto (profesor guía)
Rodrigo Fuentes
Felipe Zurita
Andrea Repetto

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La tesis de Verónica Mies fue aprobada:

Raimundo Soto (profesor guía)

Rodrigo Fuentes

Felipe Zurita

Andrea Repetto

Pontificia Universidad Católica de Chile

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Abstract

Essays on Growth and Development in Small and Open Economies

by

Verónica Mies

Doctor en Economía, Pontificia Universidad Católica de Chile

Raimundo Soto (Chair)

This thesis comprises two complementary approaches that study the determinants of growth rates and per capita income levels in the long run and analyze the possibility of growth divergence among countries. The first approach focuses on the determinants of technological change, particularly, on the role played by policies and the country's technological knowledge on the economies' adoption and innovation capacities. The model is capable of explaining a wide set of equilibria; for instance, economies that are trapped in a low growth equilibrium, countries growing at a high rate in the long run and economies that despite sharing the same long run growth rate exhibit differences in income levels. The paper discusses alternatives to escape growth traps which are related to improvements in the country's adoption capacity and to the target of technology goals that are plausible according to the stock of knowledge and the productivity of the economy. Under certain conditions, trying to adopt frontier technologies may difficult the process of growth. The second paper analyzes how the exploitation of natural resources determines the incentives to accumulate physical and

human capital and to develop labor or capital intensive sectors. In contrast with previous literature that stresses that the exploitation of natural resources is harmful for development, this study identifies new channels that show positive effects of this exploitation. There is only one specific case, in which the exploitation of a particular type of natural resources is detrimental for development.

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Raimundo Soto
Chair

Resumen

Essays on Growth and Development in Small and Open Economies

por

Verónica Mies

Doctor en Economía, Pontificia Universidad Católica de Chile

Raimundo Soto (profesor guía)

Mediante dos enfoques analíticos complementarios, esta tesis estudia los determinantes del crecimiento, de las sendas de desarrollo y de los niveles de ingreso per cápita de las economías en el largo plazo, explicando la posibilidad de polarización y divergencia entre países.El primer enfoque analiza los determinantes del cambio tecnológico, particularmente el rol que tienen las políticas y el conocimiento tecnológico sobre la capacidad de adopción y de innovación. El modelo explica un conjunto amplio de equilibrios con economías entrampadas en bajo crecimiento y otras creciendo a altas tasas y equilibrios convergentes en donde la diferencia es la duración de la transición. El trabajo sugiere alternativas para escapar de las trampas relacionadas con mejoras en la capacidad de absorción tecnológica y/o con establecer objetivos tecnológicos acordes con el conocimiento acumulado y la productividad de los sectores: tratar de adoptar tecnologías de frontera puede, bajo ciertas condiciones, dificultar el proceso de crecimiento. El segundo enfoque estudia como la explotación de recursos naturales determina los incentivos para desarrollar sectores capital o trabajo in-

tensivos (afectando el mix de producto), para acumular capital físico y humano y como afecta el nivel de ingreso de largo plazo. En contraste con la literatura que enfatiza el efecto negativo de los recursos naturales para el desarrollo, el trabajo identifica nuevos canales que muestran el efecto positivo de explotarlos, salvo en un caso particular analizado.

Raimundo Soto
Profesor Guía

To you, my best half, for your encouragement and daily joy in this adventure...

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Acknowledgments

I want to thank my committee for their invaluable help in improving my work and teaching

me the value of thinking rigorously.

CHAPTER 1

Adoption Technology Targets and Knowledge Dynamics: Consequences for Long-Run Prospects

1.1 Introduction

Medium-term per capita GDP growth rates and per capita income trajectories have shown striking differences among different groups of countries and periods. According to Maddison (2001), the per capita income ratio between the traditional developed world (Europe and Western offshoots[1]) and non-developed regions (Africa, Western Asia, Eastern Asia, and Latin America) were between 1.5 and 2.5 in 1820. In the following 130 years, this ratio increased for all non-developed groups and has shown decoupled patterns afterwards. African countries continued increasing their per capita income gaps with the developed world while Latin America slightly worsened its relative position. In contrast, Eastern Asian countries dramatically reduced this gap in the last 60 years. Can we say something about future growth?

The literature has taken two positions regarding this question. One approach states that every economy eventually starts a process of development that ends up with the economy sharing a common long-run growth rate with all other countries.[2] A second

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[1] Western offshoots correspond to the following countries: Australia, New Zealand, Canada, and the US (Maddison, 2001).

[2] Almost all papers that study technological transfers and focus on explaining per capita income differences share this view. Some exceptions discussed later are Howitt and Mayer-Foulkes (2005); Acemoglu and

group of models emphasizes the existence of growth traps that produce per capita income polarization and growth differences in the long run.[3] This paper presents an analytical model of innovation and technology adoption that encompasses both approaches and discusses conditions that make one or the other framework more likely. The argument builds on two assumptions. First, adoption and innovation activities require a domestic input to be produced. We assume that this input is domestic knowledge, which is accumulated in the R&D sector through costly R&D investment. Second, we assume that the productivity of the stock of knowledge in the adoption and innovation activities depends on the technology level that the economy is trying to obtain (in particular, the higher the technology target, the lower the productivity of a given stock of knowledge).[4] We argue that the type of development challenge that the economy faces depends crucially on how intense the adoption activity (and not innovation) uses knowledge for achieving a technology improvement.[5]

We identify two situations: If knowledge intensity in the adoption activity is low, then possessing a low stock of knowledge is not an obstacle for developing and all countries share the same growth rate in equilibrium. As the adoption activity does not intensively use knowledge to produce the technology improvement, a small stock of it reduces the profitability of R&D investment, but not to a prohibited threshold. If this intensity is high,

Zilibotti (2001); Basu and Weil (1998). Empirical studies coherent with this framework are Barro and Sala-i-Martin (1992), Mankiw et al. (1992), Evans (1996), and Rodrik et al. (2003), among others.

[3]These models generally point out some market failure or externality that leads to multiple equilibria. In particular, there are countries that grow at the rate of the developed countries and others that grow at a lower rate in the long run. Consequently, widening income ratios can characterize the long run. Theories that include technological transfers are scarce in this type of models. Pritchet (1997), Mayer-Foulkes (2002), and Feyrer (2007) give empirical support for this approach.

[4]The classical paper of Nelson and Phelps (1966) states that the adoption capacity depends on domestic conditions and, particularly, on the stock of human capital. In contrast to our paper, the adoption absorptive capacity never decreases.

[5]Empirical studies have pointed out many variables that affect economic growth, however, there seems to be a consensus on that long-run growth discrepancies are explained by differences in the technological progress process (e.g. Easterly and Levine, 2001; Klenow and Rodriguez-Clare, 1997).

in contrast, then the economy may fall in a growth trap if its knowledge stock and overall R&D efficiency are low. In such an environment, the lack of knowledge reduces severely the expected benefits of R&D which may lead the economy to fall in a vicious circle of low R&D investment, low technology improvement and knowledge accumulation which produces a lower capacity for adopting technologies and even lower incentives to invest in R&D.

Being in one or in the other case provides different implications for development. In the first case, all countries independently of their institutions, policies, endowments, share the same growth rate in the long run. For countries with bad economic conditions this rate is determined solely by external conditions, particularly by the growth rate of the countries that are moving systematically the technology frontier. Consequently, income gaps remain constant in the long run and the widening of income per capita ratios is only a transitory phenomenon. As in the neoclassical model, policies and economic conditions explain the differences in the level of per capita income. In the second case, a common long-run growth is not guaranteed. Particularly, if an economy is in a low growth-path, it has to produce a change (e.g. improve economic efficiency) to access better development paths as there is nothing self-propelling in this process. We show that if the economy is in a low growth path, making reforms that improve R&D efficiency may help to overcome the knowledge shortage in the early stages of development. We also show that in these cases, it is optimal to copy less advanced technologies during some periods. Moreover, once in a good path, the economy has to do continuous efforts to maintain this path.

The paper is organized as follows: besides this introduction, section 2 discusses intuitively the components and the mechanisms of the model and presents the main results

of the paper. The next two sections present the base model and discuss the conditions for achieving a high type- or low type growth equilibrium in the long run. In line with the literature, the base case assumes that firms always have as adoption target (an exogenous fraction of) the technology frontier. Section 5 extends the base model to analyze the determinants of an optimal adoption target. Section 6 presents some concluding remarks.

1.2   An overview of the model

The framework is a multi-sector and multi-country model of Schumpeterian growth in the spirit of the models of Aghion and Howitt (1992 and 1998) and Howitt (2000). Technological improvements results from costly and risky R&D, which are undertaken by R&D firms in different sectors in the economy. The size of the technological change depends on two factors: 1) the potential adoption and innovation improvement and 2) the capacity of the firm to attain this potential improvement.

In the case of innovation, the potential improvement is proportional to the technology level currently in use while in the case of adoption it is proportional to the technology gap. The technology gap is defined as the difference between the technology to be copied (technology goal) and the level of technology currently in use.[6]

The adoption and innovation capacities (i.e. the capacity to copy and to create technologies, respectively) are endogenously determined by i) R&D efficiency parameters that condition the productivity of R&D; ii) adoption and innovation barriers[7] that condition

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[6]Models that incorporate an adoption activity usually assume that the technology goal is the world technology frontier or a fraction of it, so that the goal follows an exogenous trajectory for the domestic economy. We study two cases. The base case follows the literature and assumes that the technology goal is the technology frontier. In the second exercise, we allow that the R&D firm chooses the adoption technology goal. Technology dynamics change significantly in this second case.

[7]Adoption and innovation barriers are assumed to be parameters and comprise all restrictions, policies,

the potential technology improvement; iii) the stock of knowledge and its productivity, which depends on the complexity of the technology that is being copied and created[8]; and iv) by the intensity in which this knowledge is used in these activities. The evolution and the determinants of the stock of knowledge in the economy is crucial for the results emphasized in this paper.

The aggregate equilibrium follows directly the disaggregate analysis. Productivity growth (and hence GDP growth) depends on the average technology gap, the average potential innovation improvement, and the average adoption and innovation capacities of the country. We distinguish two types of economies: leading and non-leading countries. Leading countries are in steady state and have acquired enough knowledge to adopt any technology and to produce systematic improvements in the technology frontier. Non-leading countries, in contrast, are still transitioning to the steady state and have relatively low both productivity and stock of knowledge. As we will show, these economies rely mostly on adoption activities to sustain positive growth rates.[9] The issue for the latter countries is how to provide a highly enough R&D reward to encourage R&D investment and whether this investment is capable to sustain a growth path based mainly on technology adoption.[10]

Within this framework, leading economies grow in steady state at their innovation rate. This equilibrium is unique. We define this long-run growth rate as the high-growth

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institutions or incentives to copy and to create new technologies.

[8]This assumption goes in line with the literature. In section 5, we relax this assumption obtaining interesting new results.

[9]Innovation is not crucial for non-leading countries to achieve high growth in the long run.

[10]Dynamics of the adoption absorptive capacity is as follows: the technology gap provides a reward to invest in R&D. This R&D investment produces a raise in the technology level and in the stock of absolute knowledge. The latter increase, though, does not ensure a raise in the adoption capacity as it depends on the stock of knowledge in relative and not in absolute terms. For the former not to decrease, it is necessary that the latter increases sufficiently to remain updated with the technology frontier. If this capacity declines, then R&D firms and the economy reduce its potential to benefit from adoption.

case. Unlike many models that analyze jointly leading and non-leading countries (e.g. north-south type models), these economies do not specialize in innovation. Moreover, we show that adoption is necessary to maintain the leading position.

In the case of non-leading countries, two situations arise: First, if knowledge intensity in the adoption activity is low, then all these countries achieve the high-growth equilibrium in the long run. In this case, R&D rewards are always high enough to sustain the minimum level of R&D investment and the adoption capacity of the country. The economy can start at any time its development race.[11] Consequently, only income differences remain in the long run, which are explained by differences in the economic structure (in our case, in the R&D environment): Two countries that share the same parameters converge to the same per capita income.[12] These results happen independently of the values of all remaining parameters.

The second case characterizes situations in which the knowledge intensity in the adoption activity is high. In this case, an economy may fall in a growth trap. The mechanism is the following: if knowledge intensity is high and the stock of knowledge is relatively low, then the adoption capacity can follow a decreasing path if R&D rewards are not high enough. This produces less knowledge accumulation and educes R&D rewards even more, hindering the accumulation of knowledge and reducing R&D investment further. The consequence is that the economy is not able to produce enough technology adoption (and

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[11]This start is understood as an opening to technological transfers. Lucas (2000) argues that this situation characterizes the developing process.

[12]Despite policies and economic environment in non-leading and leading countries being identical, technology in the former countries will not jump instantaneously to the leading countries' level. Reasons are: R&D is risky at the idiosyncratic level (in the line of Grossman and Helpman, 1991; Aghion and Howitt, 1992, 1998, and subsequent Schumpeterian growth models); and even though knowledge intensity is not a determinant factor for long-run growth, it does condition short- and medium term growth.

innovations) to catch-up with the leading economies remaining laggard or transiting to a polarized equilibrium.

Once in a path to a low growth equilibrium, improving institutions and economic policies may help to compensate the scarcity of the stock of knowledge. For high knowledge intensities, the adoption function exhibits increasing returns to scale in low levels of relative knowledge stock. In these cases, it is essential that the economy surpasses the increasing returns region if it is going to achieve the high-growth equilibrium in the long run.[13] Better policies and less adoption and innovation barriers may help to accomplish this goal. Notice that in this scenario, different policy parameters can explain growth rate differences in addition to income level disparities.

However, improving policies and institutions may be a difficult task, particularly for non-leading countries (see, among others, Acemoglu et al, 2006; Persson and Tabellini, 2000; Drazen, 2000). A complementary way to maintain the adoption capacity and to avoid a low growth equilibrium is to target a less advanced technology during some periods. The reason is that the bottleneck for developing is that the economy does not have enough knowledge to implement frontier technologies. As a result, it does not invest sufficiently in R&D and does not accumulate the necessary amount of knowledge to remain in line with the advances of the technology frontier in the long run. However, the economy's stock of knowledge may be large enough for targeting a less complex technology and for continuing profiting from adoption. The idea is that R&D firms in economies possessing a low stock of knowledge copy less advanced technologies than the technology frontier making the existing

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[13]Benhabib and Spiegel (2002) discuss the empirical implications of assuming technology functions with increasing returns in some regions and provide evidence in favor of such specification.

stock of knowledge more productive. Recall that the productivity of the existing stock of knowledge depends on the technology adoption/innovation target. Thus, when following a strategy of targeting less advanced technologies, R&D rewards increase and it is possible to sustain sufficient R&D investment. Note, however, that if an economy wishes to achieve the high growth rate in the long, it has to copy eventually (a fraction) of the technology frontier. We show that the optimal adoption target is a positive function of the development stage and the knowledge stock of the economy and a negative function of the knowledge intensity in the adoption activity. Moreover, the higher the knowledge intensity in the adoption activity, the longer the periods that the economy copies a technology that is lower than the technology frontier. Finally, only when knowledge intensities are very high and initial conditions very low, it may be necessary to do both, improve the economic environment and target lower technologies.

The two cases described (namely the low and high knowledge intensity in the adoption activity) complement other frameworks and mechanisms in the literature. The first case discussed relates to the literature that explains income disparities in the long run. These models assume that all countries share the same growth rate in the long run and to a large extend base their arguments on obstacles faced by non-leading economies to benefit from adoption. Contributions in this line are Parente and Prescott (1994, 1999), Basu and Weil (1998), Acemoglu and Zilibotti (2001), among others. For instance, Parente and Prescott (1994, 1999) argue that economic and legal restrictions are the main factors that prevent technological transfers. In our model, parameters associated to adoption and innovation barriers play the role of these restrictions and, together with a low knowledge intensity in

the adoption activity, explain an important fraction of per capita income disparities. In addition to this channel barriers play in our model a second role: they affect R&D rewards and thus the path of knowledge accumulation. This characteristic will be critical for the second case discussed.[14] Basu and Weil (1998) and Acemoglu and Zilibotti (2001) provide a complementary explanation. These authors sustain that difficulties for benefiting from technological transfers arise because technologies developed by leading economies are not appropriate for non-leading countries. In both models, leading economies' technologies are created for an input mix that is not available in the non-leading country. In Basu and Weil (1998), the non-leading economy is short of physical capital; in Acemoglu and Zilibotti (2001), the shortage is skilled labor. This type of models implies that development may be slow, but countries never fall in growth traps.[15]

The second case discussed is related to models that study growth traps. This literature is extensive;[16] however, models that include technological transfers are less abundant. For instance, Howitt (2000) presents a model in which the high-growth equilibrium is always reached provided that there is some investment in R&D. Implicitly, the model has a constant adoption capacity, so that long-run low growth is only reached when the economy fully closes its R&D sector. Aghion et al (2005) and Howitt and Mayer-Foulkes

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[14]This second effect produces that adoption barriers do not only explain differences in per capita income levels, as in the models of Parente and Prescott, but also differences in long-run growth.

[15]Slow technological diffusion can be obtained by including explicit costs to the adopting activity (e.g. Barro and Sala-i-Martin,1995; Aghion et al., 1997; Segerstrom, 1991) or by assuming that some time must elapse for an economy to be able to copy a more advanced technology (Segerstrom et al., 1990; Eeckhout and Jovanovic, 2002).

[16]These models generally introduce an economic friction or an externality that impedes the accumulation of a productive factor, such as physical or human capital. These factors enter directly the production function or are inputs of the technology production function. See, for instance, Becker, Murphy and Tamura (1990), Galor and Weil (1996), Becker and Barro (1989), Azariadis and Drazen (1990), Durlauf (1993), Benabou (1996), Galor and Zeira (1993), Galor, Moav and Vollrath (2008), Galor and Tsiddon (1997), Murphy, Shleifer and Vishny (1989), Galor (2005), McDermott (2002). Feyrer (2008) contrasts stylized facts with the implications of several of these models.

(2005) extend this model to emphasize two channels that can lead to growth traps. The first paper focuses on credit constraints that impede that the less developed economy gets enough funding for financing R&D activities. The second paper, more in line with this paper, highlights the problems of skills acquisition, which are needed for R&D. The authors describe the current income distribution as a result of a positive one-time R&D productivity shock that is only enjoyed by workers that surpasses an exogenous skill threshold.[17] Our paper encompasses this case, but it is more general as it studies conditions under which raises (in our case) in knowledge intensities lead to low-growth or only to a decline in the development speed. Acemoglu, Aghion, and Zilibotti (2006) argue that technological advances depend on the economy's capacity to generate adequate institutional arrangements that maximize growth in every development stage. If economies do not change institutions in line with the development requirements, polarized equilibria may arise.

Finally, models that incorporate an adoption activity usually assume that the technology goal is the world technology frontier or a fraction of being exogenous for the domestic economy. By optimally determining the adoption technology target, we explicit the trade-off between choosing a high target that increases the size of the technological change due to a larger technology gap and a low target that increases the adoption capacity. Easing the restriction of copying (a fraction of) the technology frontier can change results significantly.

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[17]The model, however, does not explicit a mechanism that links R&D productivity with skills needs or how the skill threshold is determined. The paper is silent respect to how increases in R&D productivity can lead to growth traps or how technologies that use more skilled labor affect developing paths.

1.3   The Model

The model builds upon Howitt (2000). Consider one benchmark economy out of J countries of a world economy. The economy is small and open. Economies trade only the final consumption good and are open to capital flows. Households consume only the final good. There is no population growth.

The economy is composed of two types of sectors: a homogenous and competitive final goods sector and an intermediate sector producing different qualities of production inputs. The intermediate sector comprises a continuum of measure one of both, monopolies producing inputs and R&D firms trying to improve the technologies embedded in the inputs. Every firm is aware of the technologies available elsewhere. This awareness, however, does not imply that technologies can be implemented or mastered for free. Everyone using a technology has to have attained it through costly R&D. Technologies are general, and not rival. Technological progress is endogenous at the country and world levels.

We start presenting the household's problem. Then, we focus on the firms' problem in the final and in the intermediate production' sectors. As this framework is relatively standard, we describe it briefly and use it to introduce some notation. Next, we discuss in detail the R&D framework.

1.3.1   Households

There is a continuum of households that live infinitely. Households derive utility from the consumption of the final good only and supply inelastically their endowment of labor. The framework used ensures that there is no aggregate risk. We further assume

that markets are complete and that there is perfect access to foreign capitals. Under this setting, consumption and production decisions are independent. Optimal financial wealth allocation, in contrast, implies some arbitrage conditions that are used in the next sections. In particular, net return on physical capital, return on foreign bonds, and expected return on stocks are all equal in equilibrium. Thus, the complete development path of an economy can be characterized by studying the productive and R&D decisions and exploiting the mentioned arbitrage conditions. For completeness, we present the household's problem in appendix C.

1.3.2 Producers

Final goods sector. The final goods sector is competitive. The representative firm in this sector produces a perishable good. The final good $Y(t)$ is produced by a production function that uses labor flows L and inputs $x_i(t)$, (equation 1.1).[18] Input i embeds a productivity level of $A_i(t)$. The higher the productivity embedded in inputs $x_i(t)$, the higher the quantity of $Y(t)$ that one unit of $x_i(t)$ generates.

$$Y(t) = L^{1-\alpha} \int_0^1 A_i(t) x_i^\alpha(t) di \qquad (1.1)$$

Input i demand function is given by $\alpha A_i(t) x_i(t)^{\alpha-1}(t) L^{1-\alpha} \ \forall i$.[19] Willingness to pay for a unit of input $x_i(t)$ is increasing in the level of technology embedded in $x_i(t)$ as it increases the flow of final goods for a given quantity of $x_i(t)$. Similarly, willingness to pay increases with L as it raises the marginal productivity of $x_i(t)$.

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[18]x_i denotes the name and the quantity produced of input i.

[19]Optimal inputs demand correspond to the $\underset{x_i(t)}{\arg\max} \left[\int_0^1 L^{1-\alpha} A_i(t) x_i^\alpha(t) di - p_i(t) x_i(t) - \omega(t) L, \right]$ where $\omega(t)$ and $p_i(t)$ denote the wage rate paid for the flow of labor and the price of input $x_i(t)$, respectively.

Intermediate goods sector. Every input sector comprises a monopoly that is producing inputs (the incumbent) and an R&D firm that is not in the input's market, but that is investing in R&D to contest this producer. Inputs differ in the productivity that they provide. Productivity of input $x_i(t)$ is higher than the productivity of $x_z(t)$ if $A_i(t) > A_{zt}$.

The monopoly in sector i produces input i with the following technology: $x_i(t) = K_i(t)/A_i(t)$. Physical capital requirements to produce one unit of $x_i(t)$ depend on the technology level embedded in $x_i(t)$. The higher $A_i(t)$, the more physical capital is needed to embed this technology in $x_i(t)$

Firm i sells inputs i to the final goods firm at the monopoly price $p_i(t)$ and pays for the use of capital its competitive rental price $r(t)$. The firm chooses optimally the amount $x_i(t) = L \left(\alpha^2/r(t)\right)^{1/(1-\alpha)}$ which only depends on two aggregate variables: the rental price of capital and the total flow of labor.[20] In particular, this amount is independent of the level of technology embedded in the input, because revenues and costs of producing $x_i(t)$ are proportional to the level of technology. Therefore, every sector supplies an equal amount of inputs. Monopolists' profits, in contrast, depend on the technology embedded in input $x_i(t)$ and correspond to

$$A_i(t)\pi(t), \text{ where } \pi(t) \equiv \alpha \left(1 - \alpha\right) \left(\alpha^2/r(t)\right)^{\alpha/(1-\alpha)} L \qquad (1.2)$$

The flow $\pi(t)$ is equal across sectors as it depends only on aggregate variables. Therefore, differences in monopolists' profits are solely explained by differences in the productivity provided by the input.

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[20]Optimal amount of $x_i(t) = \underset{x_i(t)}{\arg\max}[p_i(t)x_i(t) - r(t)K_i(t)]$.

1.3.3   The R&D Market

Every sector comprises an R&D firm that is trying to displace the incumbent monopoly. Displacement occurs only if the R&D firm accomplish a better technology to embed in input $x_i(t)$. If the R&D firm contests the incumbent with the same input (i.e. embedding the same technology into it), we assume that both firms engage in a Bertrand competition that leaves each firm with zero benefits. Thus, the R&D firm only invests in R&D if it can improve the technology currently in use. We assume that every technology improvement is drastic, implying that if the R&D firm accomplishes a new technology, it becomes the only producer of the input and charges a monopoly price.[21] In this case, the R&D firm becomes the new monopoly and stops investing in R&D. Accordingly, the previous monopoly stops producing and starts engaging in R&D activities.[22] As it is shown next, it is not optimal for the incumbent to invest in R&D while it is the monopoly.

R&D's decision problem

R&D firms that are not producing engage in R&D activities to improve the current technology embedded in input i to get the monopoly profits (equation 1.2). This activity is risky. The probability of success depends on the R&D resources invested by the firm while the technology improvement depends on the adoption and innovation capacities of the firm. We first analyze the R&D investment decision. Next, we discuss the factors that affect the innovation and adoption capacities.

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[21]Innovation or adoption is drastic, if the previous incumbent cannot produce and make nonnegative profits when the current one is charging the monopoly price (see references in Aghion and Howitt, 1998)

[22]When the R&D firm is successful, it becomes the new monopoly and the previous monopoly starts contesting the new incumbent in the same sector. The restriction of contesting the same sector is not restrictive as under free choice R&D firms are indifferent about which sector to contest as ventures in all sectors render equal profits per unit of R&D invested.

R&D Investment. We assume that investment in R&D only affects the probability of success.[23] The R&D firm chooses the amount $I_i(t)$ to invest by considering the expected profits $W_i(t)$ that it will get if it is successful, the expenses in R&D, which are measured in terms of final output, and its effect on the probability of success $n_i(t)\beta$.

A successful firm is one that achieves a technology improvement to embed in input i and thus displaces the incumbent. Once in the market, the present value of the firm $W_i(t)$ is given by equation (1.3) which corresponds to the profits of the monopoly for as long as it remains producing and is not displaced by another contestant. According to equation (1.2), time t's profits are given by the term $\overline{A}_i(t)\pi(t)$, where $\overline{A}_i(t)$ is the level of technology that a successful R&D firm achieves. This technology level is constant for the whole period in which the firm remains as the monopoly. The firms discounts its flows at the cost of capital $rc(t)$ and the displacement rate $\phi(t)$. The displacement rate corresponds to the probability that the rival firm obtains an improved technology in the future. Once in the market, the value of the firm increases with higher profits $A_i(t)\pi(t)$.

$$W_i(t) = \int_t^\infty \overline{A}_i(t)\pi(t)e^{-\int_t^z (rc_s+\phi_s)ds}dz \tag{1.3}$$

The probability of success depends on the resources invested in R&D ($I_i(t)$) scaled by the technology goal $\overline{A}_i(t)$ that the R&D firms is trying to accomplish. Scaling R&D expenditures by the technology goal constitutes a way to account for the increasing complexity of mastering more advanced technologies. In addition, this probability depends on parameter β, a measure of the productivity of the R&D investment. Resources invested in

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[23]Assuming that R&D investment only affects the probability of success and not the technology improvement simplifies the discussion of the mechanisms and makes the model more tractable. The cost is that the framework does not allow to analyze how the technology improvement in a particular sector is affected by the resources invested. However, resources invested in every sector affect the average technology improvement of the economy (section 4 discusses implications for aggregate relations).

relative terms are defined as $n_i(t) \equiv I_i(t)/\overline{A}_i(t)$ and the probability of success is denoted as

$n_i(t)\beta$. The R&D firm can obtain $W_i(t)$ with probability $n_i(t)\beta$ by investing $I_i(t) = n_i(t)\beta$

$\overline{A}_i(t)$. This venture entails risk as R&D may fail. However, this risk is idiosyncratic; there is

no aggregate risk.[24] This implies that in equilibrium R&D firms will maximize the expected

net benefit from R&D as in equation (1.4). As the optimal scale of investment can be zero

or infinite, a positive but finite investment requires $\left(I_i(t)/\overline{A}_i(t)\beta \right) W_i(t) = I_i(t)$.[25]

$$\max_{I_i(t)} \ \left(I_i(t)/\overline{A}_i(t)\beta \right) \ W_i(t) - I_i(t) \tag{1.4}$$

$$FOC : \beta w_i(t) = 1 \tag{1.5}$$

The first order condition does not determine the amount of R&D investment at the

individual level. However, from the following equilibrium condition we can get the optimal

R&D investment. The equilibrium condition is obtained by deriving equation (1.3) with

respect to time.

$$\frac{\overline{A}_i(t)\pi(t)}{\overline{A}_i(t)w(t)} + \left(\frac{\dot{w}_i}{w_i} - \frac{\dot{\overline{A}_i(t)}}{\overline{A}_i(t)} \right) - \phi(t) = r_B(t) \tag{1.6}$$

The LHS of equation (1.6) corresponds to the expected instantaneous return of

the R&D firm (profits of the monopolist in time t plus the change in the value of the firm

minus the probability of being displaced) which is equal to the risk-free rate in equilibrium

(as there is no aggregate risk the cost of capital equals the risk-free rate $r_B(t)$). Deriving

equation (2.4) with respect to time, we get $\dot{w}_i(t) = 0$. The incumbent does not invest

in R&D to improve its own technology, so that $\dot{\overline{A}_i(t)}/\overline{A}_i(t) = 0$.[26] Combining the equi-

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[24]The continuum and independence of R&D firms ensure that all idiosyncratic risk can be diversified and that R&D firms can raise funds in the financial market at the risk-free rate.

[25]We assume that when facing two strategies that leaves the R&D firm with equal profits, it chooses the one that leads to the higher technology improvement.

[26]As the incumbent does not face any cost advantage for investing in R&D, it does not invest to improve

librium condition with the former result, we obtain the optimal R&D investment relative to $\overline{A}_i(t)$ and consequently the research level $I_i(t)$ presented in equations (1.7) and (1.8), respectively.[27]

$$n_i(t) = n(t) = (\pi(t)\beta - r_B(t)) / \beta \tag{1.7}$$

$$I_i(t) = \overline{A}_i(t)n(t) \tag{1.8}$$

Relative R&D investment $n(t)$ depends positively on the country's productivity parameter β and, as expected, negatively on the interest rate. The interest rate affects $n(t)$ in two ways. It affects the return required on the R&D investment and the cost of producing the input by changing the cost of using physical capital. Thus, if the interest rate increases, fewer resources are invested in R&D. R&D investment does not depend on any technological or sectoral variable and the probability of success is equal in all sectors.

The technology goal. We assume that R&D comprises adoption and innovation and that both activities are jointly undertaken.[28] Adoption corresponds to the copy of existing technologies while innovation to the creation of new ones. We further assume that adoption and innovation are separable as described in equation (1.9). This separation implies that adoption and innovation improvements are independent of each other. Successful R&D produces an improved technology denoted as $\overline{A}_i(t)$ (see equation 1.9). We call this technology, the technology goal.

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its current technology. For a given amount of R&D invested by the incumbent and the contestant, successful R&D would leave the incumbent with a technology $\overline{A}'_i$ and incremental profits $W(\overline{A}'_i) - W(\overline{A}_i)$ which are strictly less than the incremental profits $W(\overline{A}'_i)$ obtained by the contestant. As a result, the former would find no financing in equilibrium or, alternatively, it would prefer to invest in another R&D firm.

[27]Interior solutions and probability bounded in the range $[0, 1]$ require $r_B(t)/\pi(t) \leq \beta \leq (1 + r_B(t))/\pi(t)$.

[28]Treating them separately produces no relevant differences for the aggregate results.

$$\overline{A}_i(t) = A_i(t) + \lambda \ (kn(t)/kn^*(t))^\gamma \left(A_i(t) - A_i(t)\right) + A_i(t)s\mu \ (kn(t)/kn^*(t))^\varepsilon \qquad (1.9)$$

$$\gamma, \varepsilon \geq 0$$

$$\lambda, \mu \in [0, 1]$$

The second and third terms of the RHS of equation (1.9) conform the adoption and innovation components, respectively, and correspond to the improvement over the technology currently in use that the R&D firm can accomplish. Both activities depend on the sector's level of technology and on the country's characteristics. Next, we discuss each component separately.

Technology adoption. Adoption depends on the technology gap $(A_i(t) - A_i(t))$, where $A'_i(t)$ corresponds to any of the technologies that already exist in the world. The R&D firm knows the pool of existing technologies at any time and may try to target and copy any of them. In general, $A'_i(t)$ is assumed to be (a function of) the world technology frontier, $A_{\max}(t)$. The world technology frontier is defined as the highest technology in all sectors in all countries: $A_{\max}(t) = [\max(A_{ij}(t))|i \in [0, 1] \ , j = 1, ...,J]$. In this section, we follow the standard assumption and assume that all R&D firms always target the technology frontier so that $A'_i(t) = A_{\max}(t)$. In the next section, we relax this assumption and allow R&D firms to choose a different technology level.

Adoption also depends on barriers, policies, institutions, or incentives to copy foreign technologies.[29] Parameter λ comprises all these effects. This parameter reflects the kind of barriers emphasized by Parente and Prescott (1994) and fluctuates in the range

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[29]For example, access to internet and to communication systems, economic and legal regulations, adoption-related policies (e.g. opportunities to attend seminars and congresses) and all variables that affect the overall efficiency of the adoption activity.

$[0, 1]$. We will refer to λ as the adoption barriers' parameter. No barriers to adopt new technologies implies a value for λ equal to one and, conversely, maximum barriers imply a $\lambda = 0$. The value of this parameter can vary across countries.

The term $(kn(t)/kn^*(t))^\gamma \equiv \left(\frac{Kn(t)/A'_i(t)}{Kn^*(t)/A_{\max}(t)} \right)^\gamma$ accounts for the role of knowledge in the adoption activity. Adopting a new technology is not an automatic process in the sense that it requires local knowledge to be performed. The relevant measure of knowledge adjusts the absolute stock of knowledge $(Kn(t))$ in two dimensions.[30]

First, the productivity of the absolute stock knowledge depends on the difficulty of the targeted technology. We assume, that the more advanced is a technology, the more complex it is to implement and the more absolute knowledge it requires to be mastered: in other words, absolute knowledge has to be kept updated. We account for this effect by scaling the absolute stock of knowledge by the adoption technology goal. We call this measure of knowledge relative knowledge and denote it as $kn(t)$.

Second, likewise the policy parameter λ, the lack of relative knowledge acts as a constraint for achieving a higher technology improvement. We assume that this constraint becomes less binding as the domestic relative stock of knowledge approaches the corresponding stock of the economies that are systematically moving the technology frontier $(kn^*(t) \equiv Kn^*(t)/A_{\max}(t))$.[31] As a consequence, the effect of the overall knowledge component is bound at one $(0 \leq kn(t)/kn^*(t) \leq 1)$. Knowledge requirements may be determinant for adopting new technologies or non-essential. Parameter γ denotes the intensity in which the knowledge component is used in the adoption activity. This parameters is equal for all

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[30]The absolute stock of knowledge corresponds to the economy's stock built from domestic experiences in adopting and innovating.

[31]These economies will be the leading economies (starred variables). This assumption implies that the leading economy never is knowledge-constrained to adopt or to innovate.

countries. A value of $\gamma = 0$ implies that knowledge is not needed as an input for adopting and, consequently, does not affect the adoption possibilities. As the value for this intensity increases, knowledge as an input for adoption becomes more relevant.

Consequently, the complete term $\lambda \, (kn(t)/kn^*(t))^\gamma$ corresponds to the adoption capacity of the R&D firm and is jointly determined by adoption barriers, the relevant stock of knowledge, and the intensity of this knowledge in the adoption function. If there are no barriers to adopt new technologies ($\lambda = 1$) and adoption requires no specific knowledge ($\gamma = 0$, such that $[kn(t)/kn^*(t)]^\gamma = 1$), then the R&D firm is capable to fully copy any existing technology. An analogous situation happens if the economy has accumulated enough relative knowledge so that $kn(t) = kn^*(t)$ and $kn(t)/kn^*(t) = 1$. In both cases, the adoption capacity is at its maximum and the adoption possibilities are given by $(A'_i(t) - A_i(t))$. In these cases, the R&D firm can fully copy the technology frontier and successful adoption provides its highest technology improvement. Yet, if adoption barriers or knowledge are binding restrictions, then R&D firms will only be able to copy a fraction of it.

Technology innovation. Similar variables determine the innovation improvement. Innovation builds on the technology in place $A_i(t)$ and we assume that it is proportional to this level. The highest possible innovation improvement in sector i is $A_i(t)s$, where s corresponds to a fixed jump. Such specification is standard in models of endogenous innovation (see models and references in Aghion and Howitt, 1998; Grossman and Helpman, 1991; Barro and Sala-i-Martin 2006; Acemoglu, 2009).[32] Analogously to parameter λ, parameter μ reflects economic conditions (barriers, incentives, policies) that affect the innovation

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[32]Changing the assumption of a proportional fixed jump does not alter significantly results for the aggregate relations as long as the new assumption does not depend (inversely) on the technology level of the sector.

activity.[33] We will refer to it as the innovation barriers parameter. Maximum innovation barriers imply a value for μ equal to zero implying that no innovation is possible. No barriers imply $\mu = 1$. The relevant stock of knowledge affects the innovation activity in a similar way as it affects adoption. Consequently, the lower this stock of knowledge the lower the flow of innovations that a successful R&D firm will accomplish. The intensity in which it is used in this activity, however, can be different and is captured by the parameter ε. The higher this intensity, the more important is the relevant stock of knowledge to produce innovations.

Technology improvement. With the previous elements we can characterize the technology improvement in sector i. As stated in equation (1.10), technology improves by $\lambda \left(kn(t)/kn^*(t)\right)^\gamma \left(A_i'(t) - A_i(t)\right) + A_i(t)s\mu \left(kn(t)/kn^*(t)\right)^\varepsilon$ if the R&D firms succeeds and remains unchanged otherwise.

$$\dot{A_i}(t) = \lambda \left(kn(t)/kn^*(t)\right)^\gamma \left(A_i'(t) - A_i(t)\right) + A_i(t)s\mu \left(kn(t)/kn^*(t)\right)^\varepsilon, \text{ prob } n(t)\beta$$

$$\dot{A_i}(t) = 0, \text{ prob } [1-n(t)\beta] \tag{1.10}$$

The probability of success is determined by optimal R&D investment according to equation (1.7). Now, we can analyze the technology growth of the aggregate economy.

1.4 Development paths and steady state

This section discusses the different development paths that an economy can follow. These paths are determined by the evolution of the average productivity (technology) which, in turn, depends on the law of motion of the relative stock of knowledge. Consequently,

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[33]This parameter captures, for example, infrastructure such as laboratories, public research centers, or promotions of innovation regions (e.g. Silicon Valley) .

we analyze the dynamics and steady state of both state variables and derive implications for long-run growth. Before continuing, we introduce some notation. Technology variables in lowercases are defined relative to the technology frontier, that is $a_x(t) = A_X(t)/A_{\max}(t)$. Variables without the sectoral index i correspond to sectoral averages. In all, notation is only used when strictly necessary to avoid confusion.

The knowledge stock. Following the seminal work of Romer (1986), we model the accumulation of absolute knowledge $Kn(t)$ in the economy as an externality resulting from R&D investment.[34] We assume that while performing R&D activities, the economy learns independently of the result of this research. Knowledge accumulation is obtained by aggregating all R&D investment of the economy as in equation (1.11).

$$Kn(t) \equiv \int_0^1 I_i(t)di = I(t) \tag{1.11}$$

Replacing optimal $I_i(t)$, equation (1.8) in equation (1.11), aggregating across sectors, and recalling that optimal $I(t)$ can be expressed as $n(t)\overline{A}(t)$, we get the equilibrium path for the absolute stock of knowledge (equation 1.12). Hereafter, $n(t)$ (R&D resources relative to $\overline{A}(t)$) refers to its optimized value according to equation (1.7). Accumulation of absolute knowledge depends on the incentives to perform R&D.

$$\dot{Kn}(t) = n(t)\overline{A}(t) \quad \text{where } \overline{A}(t) = \int_0^1 \overline{A}_i(t)di \tag{1.12}$$

Average productivity level. The probability of a successful innovation is given by the term $n(t)\beta$, which is equal for all R&D firm. As there is no aggregate risk, the economy's

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[34]Griliches (1992) and Branstetter (2001) give empirical support to the idea that R&D has significant spillovers.

average absolute technology $A(t)$ evolves as

$$\dot{A(t)} = n(t)\beta \int_0^1 \left(\overline{A}_i(t) - A_i(t)\right) di = n(t)\beta \left(\overline{A}(t) - A(t)\right) \tag{1.13}$$

Both, knowledge and average productivity dynamics depend on the stock of knowledge relative to the technology goal. Replacing the definition of $\overline{A}(t)$, equation (1.9) in equation (1.12) and dividing it by $A_{\max}(t)$, we obtain the law of motion of the stock of knowledge in relative terms presented in equation (1.14), where $g(t)$ corresponds to the growth rate of the technology frontier.

$$\dot{kn(t)} = n(t)\left[a(t) + \lambda \left(kn(t)/kn^*(t)\right)^\gamma (1-a(t)) + a(t)s\mu \left(kn(t)/kn^*(t)\right)^\varepsilon\right] - g(t)kn(t) \tag{1.14}$$

$$g(t) = \dot{A_{\max}}(t)/A_{\max}(t)$$

Knowledge accumulation in relative terms depends positively on the reward to perform R&D activities and negatively on the growth rate of the technology frontier. The last term in equation (1.14) indicates the relative obsolescence of the stock of knowledge due to advances in this frontier. This equation also shows that even if there is a large technology gap to close, when relative knowledge is sufficiently low, then R&D will be low and knowledge accumulation will be slow. In such scenarios, a growth trap, defined as being in or transiting to a low long-run growth equilibrium, is possible if knowledge accumulation cannot cope with its obsolescence.

To obtain the average productivity relative to the technology frontier, we replace the definition of $\overline{A}(t)$ in equation (1.13) to get

$$\dot{a(t)} = n(t)\beta \left[\lambda \left(kn(t)/kn^*(t)\right)^\gamma (1 - a(t)) + a(t)s\mu \left(kn(t)/kn^*(t)\right)^\varepsilon\right] - g(t)a(t) \tag{1.15}$$

When there is a large technology gap to close, then the economy obtains large

benefits from copying more advanced technologies. As the average technology is low, innovation explains a low fraction of the technological change. On the contrary, when average productivity is high, then the relative weight of adoption falls and innovation becomes more relevant. Thus, the model indicates that in the early stages of development, adoption will be the more significant source of growth. Consequently, the adoption capacity is crucial in these stages. This capacity depends on the degree of openness of the economy, captured by parameter λ, and on the relative stock of knowledge. As we assume that λ is fixed, the evolution of the knowledge stock becomes fundamental.

Next, we characterize the transition and steady state for a leading economy. Afterwards, we analyze different scenarios for non-leading countries.

1.4.1 Leading economies and the technology frontier

A leading economy is defined as one that systematically moves the technology frontier. Suppose that all economies were initially endowed with an equal stock of absolute knowledge and that technologies were equal worldwide, but that R&D parameters (adoption and innovation barriers) were different across countries.[35] Under this condition, a leading economy will emerge among those with best R&D parameters. We assume that this stand-in leading economy is in steady state and that its R&D parameters are $\lambda^* = u^* = 1$.[36] Another way to read it, is that the leading economy is the country with best practices and we measure the policy parameters of all other countries in relation to these best practices.

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[35]If all countries had equal policy parameters then all economies would follow the same development path.

[36]This assumption allows to follow the leading economy analytically. Changing this assumption allows to analyze how a leading economy can loose its position and how a non-leading economy can overcome a leading one. However, this richer environment does not alter the conclusions for convergence and polarization analyzed in this paper.

This stand-in leading economy shows the highest productivity average (not necessarily in every sector) and the largest stock of absolute knowledge ($Kn^*(t) = \max(Kn_j(t)) \mid j = 1...J$ and $A^*(t) = \max(A_j(t)) \mid j = 1...J$).[37]

The technology frontier expands by any innovation that produces a globally new technology. This expansion can occur in leading as well as in non-leading economies and depends on the innovative capacities of the countries. Under the assumption that $\lambda^* = u^* = 1$, the highest expansion is constant and occurs with probability one in the leading economy and is equal to s. If every country were only capable to adopt technologies, even in the most efficient way, but were not able to create a single new technology ($\mu^* = 0$), then the frontier would stagnate. Consequently, there would be no growth in the long run and all countries would converge to the same technology level and the same per capita GDP in the long run.

Steady state values for relative knowledge and relative average productivity are obtained by making $\dot{kn}(t)$ and $\dot{a}(t)$ equal to zero (equations 1.14 and 1.15) and by replacing the values $\lambda^* = u^* = 1$ and $g = s$ in these equations. These steady states values are given by equations (1.16) and (1.17), where $n_{ss}^* = \alpha(1-\alpha)\left[\alpha^2/(s\sigma + \rho + \delta)\right]^{\alpha/(1-\alpha)} - (s\sigma + \rho)/\beta^*$.[38] This equilibrium is unique and stable (see appendix A).[39] The stand-in leading economy grows at the growth rate of the innovation rate s. This rate also corresponds to the growth rate of the technology frontier. Long-run growth is driven by the world capacity of expanding

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[37]Variables for the stand-in leading economy are starred.

[38]The optimal R&D level relative to the technology goal trades-off average profits obtained by the monopolies $\left[\alpha(1-\alpha)\left[\alpha^2/(s\sigma + \rho + \delta)\right]^{\alpha/(1-\alpha)}\right]$ and the opportunity cost of the resources $(s\sigma + \rho)/\beta$.

[39]Supposing that the leading economy is in steady state simplifies the analytical solution and permits to analyze each country independently.

this frontier. Equation (1.16) describes the average relative technology in steady state:

$$a_{ss}^* = \frac{n^*\beta^*}{s + n^*\beta^*(1-s)} \leq 1 \tag{1.16}$$

The stand-in leading economy does not specialize in adoption or innovation ($a_{ss}^* < 1$) in steady state (i.e. this economy always performs a mix of both activities) and the economy never has all its sectors at the frontier.[40] Even the most advanced economy relies on adoption for maintaining a high productivity average in the long run. A higher innovation jump (s) decreases the steady state values of the average relative productivity: Although a fraction $n\beta$ of the R&D firms are successful and acquire the leading technology; however, the unsuccessful firms imply that the corresponding sectors are now further laggard. As a result, a_{ss}^* falls. An increase in the average productivity of R&D (β^*), increases R&D investment (n^*) and the probability of success in R&D activities. The higher probability of success translates into a larger technology improvement in the aggregate producing an increase in a_{ss}^*.

$$kn_{ss}^* = \frac{n^*}{s}\left[\frac{s + n^*\beta^*}{s + n^*\beta^*(1-s)}\right] \geq 0 \tag{1.17}$$

A higher innovation jump (s) decreases the steady state values of the average relative productivity and the relative stock of knowledge. The intuition is that a fraction $n\beta$ of the R&D firms are successful and acquire the leading technology; however, the unsuccessful firms imply that the corresponding sectors are now further laggard. As a result, average productivity relative to the technology frontier falls. Respecting the steady state relative stock of knowledge, a higher frontier growth rate increases the R&D reward and

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[40]North-south type models traditionally produce specialization, with the north specializing in innovation and the south in adoption (Segerstrom et al., 1990; Grossman and Helpman, 1991; Helpman, 1993; Barro and Sala-i-Martin, 1995; Acemoglu and Zilibotti, 2001; Basu and Weil, 2001).

the knowledge obsolescence rate. The latter effect, however, offsets the raise in the R&D reward producing that relative knowledge decreases in steady state. An increase in the average productivity of R&D (β^*), increases R&D investment (n^*) and the probability of success in R&D activities. The higher probability of success translates into a larger technology improvement in the aggregate producing an increase in a_{ss}^*. Two opposing effects affect R&D investment and thus knowledge accumulation. A higher productivity parameter β^* produces an increase in the rentability of R&D stimulating its investment, but it also produces a higher relative productivity (and consequently a reduction in the technology gap and R&D reward) discouraging thereby this investment. The latter effect dominates, so that an increase in β^* produces a raise in kn_{ss}^*.

1.4.2 Non-leading economies

A non-leading economy is not moving systematically the technology frontier. Particularly, we focus on economies with low relative average productivity and low stock of relative knowledge that are transiting to their steady state. We study their growth potential by analyzing the two-dimensional system in $a(t)$ and $kn(t)$. Laws of motion for the average relative productivity and relative knowledge are given by equations (1.14) and (1.15).[41] From these two equations we derive the loci for $\dot{a}(t) = 0$ and $\dot{kn}(t) = 0$ presented in equations (1.18) and (1.19), which provide the necessary relations to describe the dynamics

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[41]These equations show that a higher relative knowledge produces a higher relative productivity as it increases the adoption and innovation capacities in the economy. Moreover, higher relative productivity increases the knowledge stock as it raises the R&D reward and thus R&D investment (the source of knowledge accumulation). Consequently, relative productivity and relative knowledge stock are complementary processes.

and steady state of this type of economy.

$$a(t)|_{\dot{a}(t)=0} = \frac{n(t)\beta\lambda\left(kn(t)/kn_{ss}^*\right)^\gamma}{g + n(t)\beta\left[\lambda\left(kn(t)/kn_{ss}^*\right)^\gamma - s\mu\left(kn(t)/kn_{ss}^*\right)^\varepsilon\right]} \tag{1.18}$$

$$a(t)|_{\dot{kn^*}(t)=0} = \frac{gkn(t) - n(t)\lambda\left(kn(t)/kn_{ss}^*\right)^\gamma}{n(t)\left[1 - \lambda\left(kn(t)/kn_{ss}^*\right)^\gamma + s\mu\left(kn(t)/kn_{ss}^*\right)^\varepsilon\right]} \tag{1.19}$$

A non-leading economy can achieve two types of long-run growth equilibria: the high one ($a_{ss} > 0$), in which the economy grows at the rate of the technology frontier (which equals the growth rate of the leading economies, but not necessarily the same level) and the low one ($a_{ss} \to 0$), in which the economy grows at a rate given by their R&D conditions.[42] As the origin $(a, kn) = (0, 0)$ constitutes one possible steady state, the issue is to determine under which conditions this equilibrium is stable and whether there are other equilibria that leave the economy with higher long-run growth. Achieving one or the other equilibrium depends on the economy's ability to maintain the economy's R&D capacity.

These equations show that adoption activities are necessary to maintain a high growth rate and to catch-up in the long run (adoption capacities are expressed in the term $\lambda\left[kn(t)/kn_{ss}^*\right]^\gamma$). If the economy imposes full barriers to adoption ($\lambda = 0$), then it will transit to the low-growth equilibrium.[43] If the economy performs no innovation ($\mu = 0$), it may still achieve a high-growth rate ($a > 0$ in equation 1.18). The condition of performing some adoption has to be fulfilled independently of the innovation capacities of the country. The reason is that innovation, when successful, allows at most maintaining productivity in line with the technology frontier. However, as successes do not occur in every sector,

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[42]Recall that $a(t)$ and $kn(t)$ define the average productivity and the stock of knowledge relative to the technology frontier. If these variables are positive in steady state, then average productivity and the stock of knowledge grow at the rate of technology frontier. In contrast, if $a(t)$ tends to zero in the long run, then the average productivity is growing at a lower rate than the technology frontier, thus drifting away.

[43]If $\lambda = 0$, equation $\dot{a} = 0$ has two solutions: $a = 0$ and $n(t)\beta su\left(kn(t)/kn_{ss}^*\right)^\varepsilon = g$. However, as $g > n(t)\beta su\left(kn(t)/kn_{ss}^*\right)^\varepsilon$, the second solution can be discarded.

productivity relative to the technology frontier inevitably falls. Innovation is important, but technology adoption is the main vehicle for a non-leading economy to reach higher productivity. Minimum adoption to achieve high growth varies according to the knowledge intensity and the other parameters conditioning the R&D environment. In the next section, we analyze two distinct types of economic dynamics that an economy may be inserted in. We characterize them by the intensity in which knowledge is used in adoption.

Case 1: Low knowledge intensity

An economy follows a low knowledge intensity dynamics when the economy achieves a high-growth equilibrium, regardless of the values of the rest of the parameters (provided that $\lambda > 0$). In our model, this happens when $\gamma < 1$. The long-run growth rate does not depend on domestic conditions[44]; barriers to copy technologies or the R&D environment, in contrast, affect the medium-run growth and the long-run level of per capita income. As a result, these countries converge in growth rates, though not necessarily in levels. Figure (1.1) presents such case.[45]

Higher relative productivity (relative to $\dot{kn}(t) = 0$) implies larger R&D investment and higher relative knowledge growth in relation to the obsolescence rate. On the other

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[44]Excepting the case in which the non-leading economy becomes a leading one.

[45]For $\gamma < 1$ and ε not too large, both functions $\dot{a}(t) = 0$ and $\dot{kn}(t) = 0$ are positively sloped in their relevant domain.

$$\frac{\partial a(t)}{\partial kn(t)}\Big|_{\dot{a}_{(t)}=0} = \frac{n(t)\beta\lambda\left[\frac{g\gamma kn(t)^{\gamma-1}}{\left(kn(t)/kn_{ss}^*\right)^{2\gamma}} + n(t)\beta s\mu\left(kn(t)/kn_{ss}^*\right)^{\varepsilon-\gamma}(\varepsilon-\gamma)kn(t)^{\varepsilon-\gamma-1}\right]}{\left[\frac{g}{\left(kn(t)/kn_{ss}^*\right)^{\gamma}} + n(t)\beta\left(\lambda - s\mu\left(kn(t)/kn_{ss}^*\right)^{\varepsilon-\gamma}\right)\right]^2} \geq 0$$

$$\frac{\partial a(t)}{\partial kn_{(t)}}\Big|_{\dot{kn}(t)=0} = \frac{a(t)\left[1+(1-\varepsilon)s\mu\left(kn(t)/kn_{ss}^*\right)^{\varepsilon}\right]+\lambda\left(kn(t)/kn_{ss}^*\right)^{\gamma}(1-\gamma)(1-a_t)}{kn(t)\left[1-\lambda\left(kn(t)/kn_{ss}^*\right)^{\gamma} + s\mu\left(kn(t)/kn_{ss}^*\right)^{\varepsilon}\right]} \geq 0$$
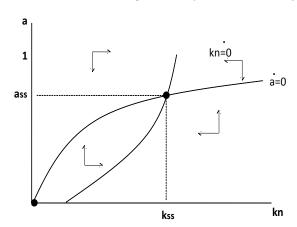
Figure 1.1: A non-leading economy: The case of $\gamma < 1$

hand, higher relative productivity (relative to $\dot{a}(t) = 0$) reduces the potential technological improvement producing a fall in its relative level. Steady state values for the relative average productivity and the relative stock of knowledge increase with lower adoption and innovation barriers (higher λ and μ) as they ease copying and innovating, thus raising the amount of technology that every unit of R&D generates.[46] The increase in average productivity, in turn, raises the resources invested in R&D producing more knowledge accumulation in equilibrium. In contrast, both state variables decrease with the growth rate of the technology frontier (g), as it enlarges the average technology gap since sectors in which R&D is not successful remain further lagged. As a higher frontier growth increases the knowledge obsolescence rate, it reduces the accumulation and the steady state stock of relative knowledge and reinforces the negative effect on relative productivity.

Starting from every pair of points (a, kn), the economy achieves the high growth

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[46]Graphically, a higher λ produces a rightward movement of the function $\dot{kn}_t = 0$ and a higher slope of the function $\dot{a}_t = 0$ in figure (1.1). A higher μ produces an increase and a decrease of the slopes for $\dot{a}_t = 0$ and $\dot{kn}_t = 0$, respectively.

steady state.[47] This case is consistent with the view that all countries can start developing at any time and will share the same growth rate in the long run (Lucas, 2000). Low growth rates or widening per capita income gaps are only transitory. In this case, all economies can benefit from adopting technologies independently from their own developing stage. Achieving high growth in the long run occurs even in the presence of high adoption and innovation barriers. Development can start at any time without harming growth possibilities in the long-run. Achieving high per capita income, in contrast, requires an efficient R&D environment and minimum (if any) barriers to perform adoption and innovation.

Case 2: Medium and high knowledge intensity

This second case characterizes situations in which knowledge requirements are important to perform R&D. Therefore, the dynamics of knowledge accumulation relative to the technology frontier becomes relevant. That means that adoption and innovation capacities are not only determined by domestic conditions, but also by external forces; i.e., factors that affect the expansion of the technology frontier. In this case, economies can achieve both high and low long-run equilibria and domestic conditions can affect long-run growth. In the model, this happens when $\gamma \geq 1$. We define knowledge intensity as medium when the value of γ restricts the set of parameter values that leads to high growth and this set of parameters does not depend on initial conditions. This occurs when $\gamma = 1$. Knowledge intensity is high when initial conditions also matter for the type of equilibrium that an economy can achieve. In the model, this case arises when $\gamma > 1$. Next, we present both cases:

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[47]Appendix B proofs the instability of the equilibrium point $(a, kn) = (0, 0)$ when $\gamma < 1$.

Medium knowledge intensity. Contrary to the low knowledge intensity case ($\gamma < 1$), when knowledge is relatively important for copying technologies, there is a minimum R&D environment required for achieving high growth in the long run. When $\gamma = 1$ (and $\varepsilon = 1$), we can obtain the analytical solution for this threshold as presented in equation (1.20).[48,49] This threshold is expressed in terms of the maximum adoption barriers (minimum $\lambda \equiv \underline{\lambda}$) that are compatible with high growth.[50]

$$\lambda > \underline{\lambda} = \frac{gkn^*_{ss}}{n}\left[\frac{g}{n\beta + g}\right] = \left[\frac{n^*}{n}\frac{n^*\beta^* + s}{n\beta + s}\right]\left[\frac{s}{s + n^*\beta^*(1-s)}\right] \tag{1.20}$$

Maximum adoption barriers increases ($\underline{\lambda}$ decreases) with lower growth of the technology frontier g[51] and with higher R&D productivity β as both situations relax the restriction on knowledge accumulation compatible with high growth. Consequently, maximum adoption barriers compatible with high growth increase. A lower g makes it easier for countries to achieve the high growth equilibrium as it reduces the knowledge obsolescence rate decreasing thereby the amount of R&D investment required to maintain the stock of knowledge updated. A higher β increases the probability of success and thus the average productivity improvement resulting in a higher path of knowledge accumulation. On the contrary, a better R&D environment in the stand-in leading economy translates into a higher kn^*_{ss} making it more difficult for other countries to achieve the high growth equilibrium.

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[48]When $\varepsilon = 1$, the corresponding steady-state levels are:

$$a_{ss} = \frac{\lambda n(g+n\beta) - kn^*_{ss}g}{(g+n\beta)n(\lambda - s\mu)}; \quad kn_{ss} = \frac{\lambda n(g+n\beta) - kn^*_{ss}g^2}{\beta gn(\lambda - s\mu)}; \quad n_{ss} = \frac{\alpha(1-\alpha)\alpha^2}{(r_{Bt}+\delta)]^{\alpha/(1-\alpha)}\beta} - \alpha(1-\alpha)r_B.$$

[49]The condition stated in equation (1.20) does not depend on the innovation capacities of the economy. Innovation plays only a role when the economy has a positive productivity level. However, when $\gamma = 1$, the positive effect of larger innovation flows on knowledge accumulation does not compensate the negative effects of a smaller technology gap and a larger obsolescence flow. Graphically, in terms of panel b of figure 1.2, lower innovation barriers μ put both curves nearer, but never produces that both curves cross each other.

[50]Equation (1.20) is derived in appendix B and conditions that the origin is not a stable equilibrium.

[51]$\frac{\partial \underline{\lambda}}{\partial g} = \left[\frac{n^*}{n(n\beta+s)}\right]\left[\frac{s}{s+n^*\beta^*(1-s)}\right] + \underline{\lambda}\left[\frac{n\beta}{(n\beta+s)s} + \frac{n^*\beta^*}{s+n^*\beta^*(1-s)}\right] > 0.$
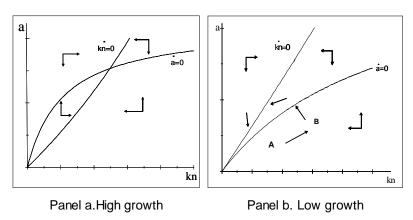
Figure 1.2: Long-run equilibria

Panel a.High growth   Panel b. Low growth

The reason is that in a better R&D environment, the stand-in leading economy produces larger technology improvements, invests more in R&D and accumulates more knowledge with the result of a higher average productivity and knowledge stock in steady state. If an economy wants to keep pace with the stand-in leading country, it has to produce larger technology improvements and accumulate a larger stock of knowledge. These two goals reduce the maximum level of adoption barriers that is acceptable. Finally, if the critical value is higher than one ($\underline{\lambda}> 1$), the economy achieves the low-growth equilibrium only (panel b in figure 1.2). This happens when the R&D productivity β is too low relative to β^*. In this case, the economy is not productive enough to successfully adopt better technologies (even when adoption barriers are extremely low, $\lambda = 1$).[52]

The dynamics of both type of equilibria is presented in figure 1.2. Barriers below the threshold achieve high growth in the long run (panel a, figure 1.2), while an economy with a bad R&D environment transits to a low growth equilibrium (panel b,figure 1.2).

Finally, even if knowledge and technologies could be transferred to an economy

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[52]Recall that the probability of success is given by $n(t)\beta = (\pi(t)\beta - r_B)$ in equilibrium.

that is in a low-growth path, this would not change the long-run growth rate. The economy would show a transitory raise in its growth rate, but would inevitable stay behind in the long run (see panel b in figure 1.2, where knowledge and technological transfers are presented as passing from point A to point B). The only way to raise the economy's long-run growth rate is to improve adoption and innovation capacities permanently.

High knowledge intensity. In this case, the particular steady state that the economy achieves does not only depend on the economy's R&D environment, but also on initial conditions. That means that a given R&D environment that led to high-growth in the previous case does not necessarily ensure achieving that path if adoption knowledge-intensity is high ($\gamma > 1$). Figure (1.3) presents an example of this case.

As knowledge is intensively used to produce technology improvements, a relatively small stock of knowledge (combined with a low relative productivity), may produce small technology improvements which, in turn, cause low investment in R&D and slow knowledge accumulation. This might lead to a vicious circle, where the economy ends up growing at a low rate (point A in figure 1.3). In contrast, if the economy trespasses a threshold of knowledge and productivity, it may remain in a high growth path in steady state (achieving point C in figure 1.3). Point B corresponds to an unstable equilibrium. In this case, it is not possible to obtain closed analytical solutions. We present in appendix B numerical exercises that show how changes in the values of the parameters affect the technology level achieved in steady state. This appendix also studies the implications of changing initial conditions.

When adoption is highly knowledge intensive, lower R&D barriers that enhance adoption and innovation improve the chances to achieve a high-growth path. However, there
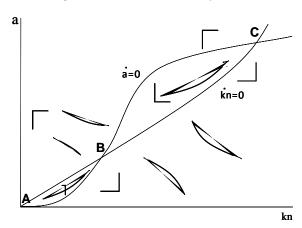
Figure 1.3: Various steady states

are cases in which even sharing the same policies and R&D environment with the stand-in leading economy may not guarantee reaching the high growth equilibrium.[53] The reason is that a low stock of relative knowledge inhibits the economy to adopt better technologies even in the absence of adoption barriers. Escaping the low growth equilibrium would require an unlikely increase in both state variables.

This scenario is coherent with the view that countries may remain in a growth trap in the long run (Howitt et al., 2005). Contrary to the previous cases, the longer an economy waits for starting its developing process, the more difficult it is to achieve the high growth equilibrium. The reason is that for a given stock of initial knowledge, the more time passes by, the more obsolescent becomes the absolute stock of knowledge. In this case, changes in the external environment may change the equilibrium path that an economy is following. Development requires continuous efforts to maintain low R&D barriers and efficient economic institutions: Better R&D conditions in the leading economies require a

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[53]In these cases, policies that raise effective R&D investment ($n(t)$) may help to transit to a better equilibrium. Note, however this strategy would imply to improve the R&D productivity above the leading economies' level.

matching upgrade in domestic conditions to sustain growth.

1.5   Optimal technology adoption target

In the previous sections, we assumed that the adoption technology target was the technology frontier.[54] We showed that an economy may transit to a low-growth equilibrium if it failed to maintain its stock of knowledge updated with this frontier. Targeting the technology frontier, nevertheless, may put a heavy burden on the adoption capacity of the country as it requires a high stock of knowledge. This can considerably hinder benefitting from and growing by adoption as the technology improvement can be severely reduced. However, even though absolute knowledge may be scant for acquiring the technology frontier, it may be sufficient for attaining less advanced ones. In fact, the lower the technology that the R&D firm is targeting, the more productive is the absolute stock of knowledge. This section analyzes the steady state and the dynamics properties of the economy when firms choose the adoption target that maximizes the technology improvement.

The problem faced by the R&D firm is presented in equations (1.21) to (1.23). The only variable that the R&D firm controls is the adoption technology target $(A_i'(t))$. As by assumption R&D firms in leading economies are not knowledge-constrained, they always choose the technology frontier as the adoption technology target.[55] Therefore, we focus on

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[54]A low adoption capacity, however, produces a final adoption flow that could be lower than this frontier.

[55]The leading economy maximizes

$$\max_{A_i'(t)} \quad A_i(t) + (A_i'(t) - A_i(t)) + A_i(t)s. \quad FOC : 1 > 0.$$

The first order condition is always positive so that it is always optimal to choose the highest target possible.

non-leading economies.

$$\max_{A_i'(t)} \lambda \left(\frac{Kn(t)/A_i'(t)}{Kn^*(t)/A_{\max}(t)} \right)^{\gamma} \left(A_i'(t) - A_i(t) \right) \qquad \text{st} \tag{1.21}$$

$$i: \qquad A_i(t) < A_i'(t) \leq A_{\max}(t) \tag{1.22}$$

$$ii: \qquad \frac{Kn(t)/A_i'(t)}{Kn^*(t)/A_{\max}(t)} \leq 1 \rightarrow A_i'(t) \geq \frac{Kn(t)}{Kn^*(t)} A_{\max}(t) \tag{1.23}$$

The intuition for this problem is the following: The adoption technology target has two opposite effects on $\overline{A}_i(t)$. On one hand, a high target raises the potential technology achievable due to a higher technology gap, which induces the R&D firm to choose a target that makes the technology gap the largest possible. On the other hand, a higher target requires a larger stock of knowledge to master the new technology. For that reason, the R&D firm would prefer to choose a low target. Additionally, the firm faces two constraints: The first constraint (equation, 1.22) states that the adoption target has to be higher than the current level of technology to provide a positive return (i.e. $A_i'(t) > A_i(t)$, but that this target can be at most the technology frontier $(A_i'(t) \leq A_{\max}(t)$, The second constraint (equation 1.23) reflects that knowledge constraint only binds when the effective stock of knowledge is lower that the corresponding stock of the leading economy. In other words, achieving a higher relative stock of knowledge (relative to $Kn^*(t)/A_{\max}(t)$) does not provide any further benefit for the economy. Consequently, the R&D firm never chooses adoption targets that increases its knowledge capacity over $Kn^*(t)/A_{\max}(t)$.

The first order condition for this problem yields the following expression:

$$\lambda \left(\frac{Kn(t)/A_i'(t)}{Kn^*(t)/A_{\max}(t)} \right)^{\gamma} \left[\frac{A_i'(t)(1 - \gamma) + \gamma A_i(t)}{A_i'(t)} \right] \geq 0 \tag{1.24}$$

Whenever equation (1.24) holds with inequality, the optimal target is the technology frontier $A_{\max}(t)$. However, if equation (1.24) holds with equality, then the R&D firm will choose to target a lower technology. The general solution is given by

$$A_i'(t) = \min\left[A_{\max}(t),\ \max\left(\gamma/(\gamma-1)A_i(t),\ Kn(t)/Kn^*(t)A_{\max}(t)\right)\right] \tag{1.25}$$

Equation (1.25) states that the R&D firm either chooses the technology frontier (when adoption is not knowledge intensive or when the economy approaches the leading country) or a lower target if adoption is a difficult task given the knowledge intensity of the activity, the sector's technology level, and the knowledge stock. For low knowledge intensities, precisely, for $\gamma \leq [A_{\max}(t)/(A_{\max}(t) - A_i(t))]$, the positive effect of a higher target on the technology gap dominates the adverse effect on the stock of knowledge and R&D firms target the technology frontier. Note that for all $\gamma \leq 1$, the optimal target is $A_{\max}(t)$. As the knowledge intensity increases, the effect on relative knowledge becomes more relevant. In this case, the target corresponds to the highest value among these two components: $A_i'(t) = \gamma/(\gamma - 1)A_i(t)$ and $A_i'(t) = Kn(t)/Kn^*(t)A_{\max}(t)$. The technology target is increasing in the sector's technology and decreasing in the knowledge intensity γ (first component). Consequently, we can find sectors targeting different levels of technologies in an economy: Laggard sectors may be targeting less advanced technologies while leading sectors may be targeting the technology frontier.

The optimal target, however, also depends on the ratio $Kn(t)/Kn^*(t)$, the stock of knowledge between non-leading and leading economies (second component). If this ratio is large, then R&D firms will target a technology that is close to the frontier, even if the sector's technology is low. The reason is that a relatively large knowledge stock makes

unnecessary to sacrifice a large technology gap. In particular, if a country has attained the stock of knowledge of the leading economy, then all its R&D firms will target the technology frontier independently of the knowledge intensity γ and the technology level of the sector.

Steady state. There is no closed analytic solution for the aggregate variables; so we describe the equilibria through simulations. Since in this setup, the aggregate production function can be expressed as a neoclassical production function with constant returns to scale in physical capital and labor, a few parameters can adequately describe the equilibrium.[56] Table 1 presents the parameters used in the simulations.

We assign a value of 0.35 to the capital share of output α[57], 0.02 to the discount rate ρ[58], and 0.03 to the depreciation rate δ.[59] These values are widely used in neoclassical growth models. We choose a value of one for the inverse of the intertemporal rate of substitution.[60] We assign to the innovation rate $s\mu$, which is also the long run growth rate, the value of 2.2%, the average per capita US growth rate for the years 1960-2006.[61] The calibration of the R&D productivity β, and thus of the probability of success, is more problematic and such empirical measure is scarce. As this probability also reflects the rate of creative destruction, we obtained this value from Caballero and Jaffe (1993), who estimate an average rate of 3.6%.[62] With these parameters, we obtain the values of all endogenous

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[56]The aggregate production function is described by the following Cobb-Douglas representation: $Y(t) = [A(t)L]^{(1-\alpha)} K(t)^{\alpha}$.

[57]See Gollin (2002).

[58]Gourinchas and Parker, 2002; Cagetti, 2003; and Laibson et al. (2007) estimate discount rates for the US in the range of 0.01 to 0.09. We choose 0.02 in order to obtain a plausible risk-free interest rate.

[59]Based on Musgrave (1992), who estimates depreciation rates with data for the US Manufacturing sector.

[60]This parameter typically is in the range of 1 to 3.5 (see Hall, 1998; Attanasio and Weber, 1993). As for the discount rate ρ, we choose $\sigma = 1$, in order to obtain a plausible risk-free interest rate. Changing this value, however, does not alter results.

[61]Calculation based on Maddison (2009). Averages for the years 1820-2006, 1900-2006 and 1960-2006 correspond to 1.84%, 2.08% and 2.21%, respectively. We choose the latter value as the US has shown a relatively constant GDP growth rate in this period.

[62]This rate corresponds to the average estimated creative-destruction rate for the period 1965-1981 for 21

variables. Implied steady states values are 4.5% for the risk-free interest rate, and 2.2 for the long-run growth rate of the high-growth equilibrium.
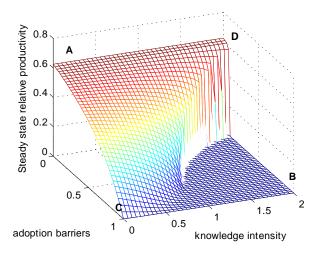
Table 1: Simulations' parameters

ρ	$= 2.3\%$	σ	$= 1.0$
α	$= 0.35$	$s\mu$	$= 2.2\%$
δ	$= 0.03$	$prob(success)$	$= 3.6\%$

Figure 1.4 presents the results. The vertical axis measures the average steady-state technology level (productivity) of a country relative to the frontier. The two horizontal axes measure adoption barriers and the intensity of knowledge in adoption. The barriers parameter varies between 0 and 1 (zero, corresponding to no barriers). We study knowledge intensities in the range of 0 and 2, which accounts for all relevant cases. This figure encompasses both steady-state technology levels and long-run growth rates. As the average steady-state technology is measured relative to the technology frontier, all values strictly positive ($a_{ss} > 0$) imply that the technology level is growing at the growth rate of the technology frontier (high-growth equilibrium). In all these cases, differences in steady state values imply level differences. Relative steady-state technologies equal to zero ($a_{ss} = 0$) imply that the economy is growing at a lower rate than the technology frontier in the long run. The average technology can still be growing in these economies (and technology levels are always positive), however measured relative to the technology frontier, technology levels are drifting away.

As discussed in previous sections, the steady-state relative technology level in-

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sectors in the US. The annual rate of creative destruction varies in the range of 2 to 7 percent over different periods.

Figure 1.4: Steady state average technology: Different knowledge intensities and adoption barriers for optimal adoption targets
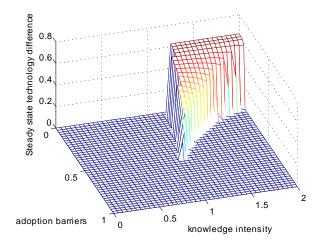

creases with lower adoption barriers and lower knowledge intensities. For a given R&D investment, point A is the highest relative steady-state technology level that can be observable. It reflects an R&D environment without barriers and an adoption production function that does not require knowledge (recall that the knowledge intensity parameter characterizes the adoption function and is given and equal for all countries). Point B, in contrast, reflects the opposite situation. At this point adoption barriers and adoption knowledge intensity are at their highest level. In such scenario, the economy shows the lowest growth and the lowest average technology.[63] In fact, point B characterizes an equilibrium of low growth. Point C denotes economies that have highest adoption barriers, but face an adoption activity that requires no knowledge. From this point, lowering adoption barriers produces increases in the steady state technology level (moving along the $\overline{CA}$ axis). For low knowledge intensities, a high long-run equilibrium is achieved provided that some

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[63]The figure shows only relative relations. Consequently, it is not possible to discriminate between growth rates and technology levels for countries that transit to a zero average relative technology.

adoption is made. The higher the knowledge intensity (moving from point C to points B or D), the lower the adoption barriers that are coherent with high growth.

Targeting lower technologies allows the economy to achieve higher income levels and higher growth rates. The reason is that this strategy demands a lower knowledge stock increasing thereby the expected technology improvement and the incentives to invest in R&D. Figure 1.5 shows the steady-state gains in relative average technology, when R&D firms choose the adoption target. All positive differences correspond to situations in which the economy achieves high growth by targeting a less-advanced technology, but would have reached low growth, had it targeted the technology frontier. These gains are decreasing in the adoption barriers. There are no gains for low adoption knowledge intensities ($\gamma \leq 1$) since in these cases it is optimal to target the technology frontier. Relaxing the restriction of copying frontier technologies generates that resources are used in a more efficient way; this would indicate that too ambitious R&D policies may be misleading.
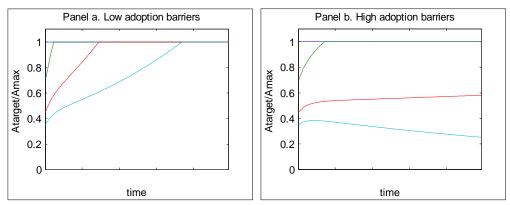
Figure 1.5: Steady state average technology gains from allowing R&D firms to choose the adoption target instead of targeting the technology frontier

Turning now to the dynamics of the target choice, figure (1.6) shows the evolution

of the ratio of the technology target (described in condition 1.25) relative to the technology frontier. When the target is the technology frontier, the ratio takes the value of one. Curves closer to the vertical axis correspond to less knowledge-intensive adoption activities. The horizontal axis measures time intervals.[64]

Figure 1.6: Evolution of the optimal technology target (A_{target}) relative to the technology frontier ($A_{\max}$)

When the level of relative technology is low, R&D firms choose a low technology target. This target raises as the relative technology of the sector increases. Knowledge accumulation and technology improvement lead the R&D sector eventually to target the technology frontier. The more knowledge intensive is adoption, the longer R&D firms are targeting less advanced technologies and the lower is the adoption target for a given technology in use in sector i. If adoption barriers are relatively low, eventually R&D firms will target the technology frontier independently of the adoption knowledge intensity and of initial conditions (panel a of figure 1.6). If, however, knowledge intensity and adoption barriers are high, then the economy may not be able to copy the frontier technology even

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[64]The simulations were made for initial conditions that proxy the gap between the 20 poorest countries and the US as described in appendix C.

in the long run (panel b of figure 1.6).[65] In this case, R&D firms will permanently copy less-advanced technologies. Growth will be positive and higher than in the case in which the target is always the technology frontier, but growth will be lower than that of the leading economies.

The knowledge intensity of the adoption activity determines the type of growth equilibria that the economy can reach. However, lowering barriers and improving the incentives to perform R&D are crucial to transit to a high growth equilibrium when low growth is a possibility. Economies may be targeting a lower adoption technology goal during the transition, but in the presence of high barriers, expected technology improvements can drastically fall, discouraging thereby R&D investment and reducing knowledge accumulation. In these cases, targeting lower technologies and improving the R&D environment may be the only way to elude the low growth equilibrium.

1.6   Concluding remarks

We develop a theoretical framework of endogenous adoption and innovation that is coherent with a wide set of income and growth trajectories. In particular, we discuss conditions that make economies more likely to be in a path of high growth (in which all economies share a common long-run growth rate) or in an environment in which growth traps are a possibility. The features of the model encompass, thereby, these two strands in the literature. The economic environment, the incentives to perform R&D, the adoption knowledge intensity, and the dynamics of the knowledge stock relative to the technology that R&D firms are aiming to implement define the type of path that the economy is following.

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[65]Steady-state levels that tend to zero in figure 1.4.

The stock of knowledge needed to absorb foreign technologies depends on the technology that the economy is targeting. Within this framework, two situations arise: If knowledge intensity in the adoption activity is low, then a low stock of relative knowledge does not affect decisively the adoption capacity of the economy. In this case, all countries achieve a high-growth equilibrium in the long run. However, differences in income levels and in the transition speed emerge if economies have different economic structures. If knowledge intensity in the adoption activity is high, then the economy may fall in a growth trap if its stage of development and relative knowledge are low. In this case, the adoption capacity can follow a decreasing path becoming an impediment for growth. Reducing adoption and innovation barriers may help to escape the low-growth equilibrium, as a better R&D environment can compensate the scarcity of knowledge in the early stages of development. However, the model shows that a complementary way to elude the low-growth equilibrium is to target technologies that are not at the frontier, as less advanced technologies require less knowledge and less R&D resources for being implemented. The model suggests that countries will adopt laggard technologies when they possess a low stock of knowledge and will target more advanced technologies as they develop. The speed of development may still be slow, but the economy eventually will target frontier technologies and achieve high growth.

Finally, numerical solutions precise the relation between R&D policies and knowledge intensity in the adoption activity that leads to one or the other type of equilibrium and explicit the effect of choosing the adoption technology target on long-run growth.

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Appendices

A. The dynamic system

A1. The leading economy

The following equations correspond to the dynamic system of a leading economy with a unique equilibrium described by equations (1.16) and (1.17). As $n(t)$ is constant, we omit the time subscript for this variable.

$$\begin{bmatrix} \dot{a}(t) \\ \dot{kn}(t) \end{bmatrix} = \begin{bmatrix} -n\beta + n\beta s - g & 0 \\ -n + ns & g \end{bmatrix} \begin{bmatrix} a(t) \\ kn(t) \end{bmatrix} + \begin{bmatrix} n\beta \\ -n \end{bmatrix}$$

This system has two negative eigenvalues, $n\beta(s-1) - g$ and $-g$, implying a stable equilibrium.

A2. The non-leading economy

This subsection analyzes the conditions for the equilibrium point $(a, kn) = (0, 0)$ to be locally stable. We omit time subscripts The dynamic system is given by equation (1.18) and (1.19). Its linearization is given by:

$$\begin{bmatrix} \dot{a}(t) \\ \dot{kn}(t) \end{bmatrix} = \begin{bmatrix} a_1 & a_2 \\ a_3 & a_4 \end{bmatrix} \begin{bmatrix} a(t) - a_{ss} \\ kn(t) - kn_{ss} \end{bmatrix},$$

where a_1, a_2, a_3, a_4 correspond to the following expressions, where all variables are evaluated at their steady state values.

$$a_1 = n\beta \left[s\mu \left(\tfrac{kn}{kn^*} \right)^{\varepsilon} - \lambda \left(\tfrac{kn}{kn^*} \right)^{\gamma} \right] - g$$

$$a_2 = \tfrac{n\beta}{kn^*} \left[\lambda\gamma \left(\tfrac{kn}{kn^*} \right)^{\gamma-1} (1-a) + as\mu\varepsilon \left(\tfrac{kn}{kn^*} \right)^{\varepsilon-1} \right]$$

$$a_3 = n \left[1 - \lambda \left(\frac{kn}{kn^*} \right)^\gamma + s\mu \left(\frac{kn}{kn^*} \right)^\varepsilon \right]$$

$$a_4 = \frac{n}{kn^*} \left[\lambda\gamma \left(\frac{kn}{kn^*} \right)^{\gamma-1} (1-a) + as\mu\varepsilon \left(\frac{kn}{kn^*} \right)^{\varepsilon-1} \right] - g$$

There are three cases.

Case 1: $\gamma < 1$**.** In this case, the dynamic system has a positive and a negative root, being saddle-path stable. However, the stable arm can be discarded as it is defined for negative values of the state variables. In this case, the origin is not a stable equilibrium.

Case 2: $\gamma = 1$**.**

$$\begin{bmatrix} \dot{a}(t) \\ \dot{kn}(t) \end{bmatrix} = \begin{bmatrix} -g & \frac{n\beta\lambda}{kn^*} \\ n & \frac{n\lambda}{kn^*} - g \end{bmatrix} \begin{bmatrix} a(t) \\ kn(t) \end{bmatrix}$$

The eigenvalues are:

$$r_1, r_2 = \frac{1}{2}\frac{n\lambda}{kn^*} - g \pm \sqrt{\left(\frac{n\lambda}{kn^*} - 2g \right)^2 + \frac{4}{kn^*} \left(-kn^*g^2 + \lambda gn + \beta\lambda n^2 \right)}$$
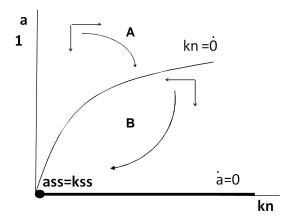
If $\lambda - 2g\frac{kn^*}{n} \equiv v_1 > 0$, there is at least one positive eigenvalue. In this case, the origin is not a stable equilibrium. However, if v_1 is negative, then the equilibrium point $(a, kn) = (0,0)$ is stable provided that $\lambda < \frac{gkn^*_{ss}}{n} \left[\frac{g}{n\beta+g} \right]$. This condition corresponds to equation (1.20) in the main section of the paper. Condition (1.20) also satisfies that $v_1 < 0$.

Case 3: $\gamma > 1$**.** In this case, the eigenvalues at $(a, kn) = (0,0)$ are negative and both equal to $-g$. Thus, the origin is a locally stable equilibrium. In this case, however, there are other equilibria. Initial conditions determine the equilibrium to which the economy transits.

A3. Full adoption barriers: The case of $\lambda = 0$

Figure 1.7 presents the phase diagram for the case of $\lambda = 0$. Function $\dot{a}(t) = 0$ coincides with the horizontal axis. Pair of points (a, kn) above the equation $\dot{kn}(t) = 0$ produce paths with increasing knowledge. A higher relative technology implies larger R&D investment and higher knowledge growth relative to the obsolescence rate (see equation 1.14). On the other hand, points (a, kn) above the equation $\dot{a}(t) = 0$ produce decreasing relative technology paths. A higher relative technology reduces the potential technological improvement producing a fall in its relative level (see equation 1.14). An analogous argument follows for pair of points (a, kn) below both curves.

Figure 1.7: $\lambda = 0$

A minimum amount of adoption is necessary to achieve and maintain a high-growth rate in the long run. Successful innovation maintains at most the sector's productivity in line with the technology frontier. However, as successes do not occur in every sector, average relative technology inevitably falls. As innovation improvements are not enough to maintain the relative position of the economy, relative technology falls from every starting

pair of points (a, kn). The stock of knowledge can increase for some periods if average productivity provides a sufficient innovation base to stimulate R&D (region A). However, this stock eventually starts to fall.

B. Simulation exercises

The following exercises complement the results in the main sections of the paper, whenever analytical solutions are not possible. The simulations are based on the parameters presented table 1, section 5. Sources and definitions are described in section 5.

Simulations' parameters

ρ	$= 0.02$	σ	$= 1$
α	$= 0.35$	$s\mu$	$= 0.020$
δ	$= 0.03$	$prob(success)$	$= 0.036$

Knowledge intensity and adoption efficiency relation

The following figures present steady state relative technology levels for different pairs of knowledge intensities (γ) and adoption barriers (λ). In the figure, a no-barriers case corresponds to a value of zero. Figure 1.8 presents the high-growth case. In this situation, the economy always achieves a positive relative technology steady state. As discussed in the paper, different knowledge intensities and adoption barriers have only level effects.

Next, we present the case in which the economy can reach a low-growth rate in the long run. As these cases can depend on initial conditions, we analyze two different starting points for non-leading economies. Highly poor initial conditions were proxied by the relation of the 20 poorest countries (in terms of per capita GDP) related to the per capita US GDP in 2008. This measure accounts for a difference in per capita income of ca. 63 times. The better initial condition considers the World average per capita GDP in relation to the per

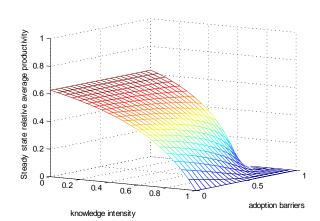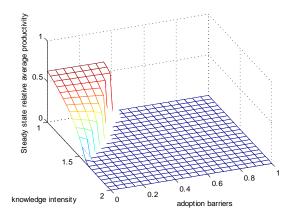Figure 1.8: Low knowledge intensities and adoption barriers

capita US GDP. The income difference falls to 4.5 times if income-weighted average are used

and to 3.7 if simple average are taken (source: The CIA World Factbook, 2008, PPP per

capita GDP). Figure 1.9 presents the results for the basic case considering the less favorable
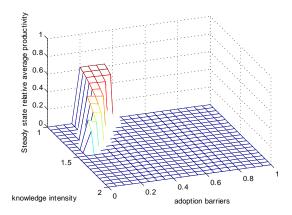
average.

Figure 1.9: High knowledge intensities and adoption barriers

Effects of initial conditions

Figure 1.10 presents the gains in steady state average productivity of having the initial conditions of the world average group relative to the initial conditions of the poorest group (both groups as defined in the previous paragraph). All positive differences correspond to situations in which the economy achieves high growth by having average initial conditions, but would have reached low growth, had it the conditions of the poorest countries.

Figure 1.10: High knowledge intensities: Effect of initial conditions (differences in steady-state productivity values)

C. Households

There is a continuum of households of measure two that live infinitely. Households derive utility from the consumption of the final good only and supply inelastically their endowment of labor equal to one half. There is no aggregate risk, markets are complete, and there is perfect access to foreign capitals.

Households have the option to save in an external asset that yields r_{Bt}, in physical capital with return $r(t)$, and in stocks of R&D firms. All assets are denominated in con-

sumption units, the numeraire of the economy. Even though households face a stochastic problem, an optimal path involves no aggregate risk. We present the problem in terms of this optimal path. As all agents are identical in terms of preferences and consumption choices, the path of aggregate consumption $C(t)$ can be obtained from the maximization of the problem stated in equation (1.26). As usual, σ denotes the coefficient of relative risk aversion, ρ the discount rate, and δ the depreciation rate. $B(t)$ and $K(t)$ define the aggregate stocks of foreign bonds and physical capital, respectively. $S(t)$ corresponds to the aggregate stock portfolio that renders $\overline{r_{St}}$ and $\omega(t)$ to the salary. Households own all firms in the economy. $R(t)$ corresponds to the consolidated residual benefits of these firms.

$$Max \; U\left(C(t)\right) = Max \int_t^\infty \frac{C(t)^{1-\sigma}}{1-\sigma} e^{-\rho t} dt \;\; \text{subject to} \tag{1.26}$$

$$\dot{K}(t) + \dot{B}(t) + \dot{S}(t) = \left(r(t) - \delta\right) K(t) +$$

$$B(t) + \overline{r_s}(t) S(t) + R(t) + \omega(t) L - C(t) \tag{1.27}$$

The Euler equation states that:

$$\frac{\dot{C}(t)}{C(t)} = \frac{1}{\sigma}\left(r_B - \rho\right) \tag{1.28}$$

Equilibrium conditions for holdings of bonds, physical capital, and the stock portfolio imply that:

$$\left(r(t) - \delta\right) = \overline{r_s}(t) = r_B$$

CHAPTER 2

Development Paths and Dynamic Comparative Advantages: When Leamer Met Solow

2.1 Introduction

The observed economic performance of countries over the last century has been very dissimilar. Differences in growth rates and level of per capita income are still open issues. Economists have made great efforts to find the "right conditionals" behind the convergence prediction of the neoclassical growth model. Arguments regarding the nature of economic policies and the quality of institutions are at the heart of empirical explanations. The theoretical model underlying these studies is usually a variant of the standard one-sector neoclassical growth model.[1] While this simple framework is useful for explaining many of the empirical findings, the one-sector model hides relevant development paths that can be explored using multi-sector models. In particular, an important condition for convergence is that countries share the same technology for the aggregate production function. If countries produce a different mix of products, they will exhibit different aggregate production functions.

The kind of issues that we have in mind are, for example, why Finland and Argentina now have different per capita income levels and production structures despite having

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[1]Galor (1996) argues that empirical findings in cross-country regression could be also explained by club convergence and variants of endogenous growth models.

started with almost the same capital per worker at the beginning of the last century; or why Japan and Sweden have similar levels of per capita income, while the former has twice as much capital per worker as the latter.[2] In this context, our interest is to analyze why countries starting with a similar capital-labor ratio show different dynamics of physical or human capital accumulation, face incentives to develop distinct productive structures, and converge to both different capital-output ratios and per capita consumption in the long run.

The conventional answers to many of these questions are quality of policies and institutions. We offer an explanation based on the exploitation of a natural resource type of factor. We argue that the inclusion of such a factor strongly determines the pattern of production and trade, and thus the path of development and the level of per capita consumption of a small open economy. The study of the relation between growth and natural resources is not new (e.g. Krugman, 1987; Lane and Tornell, 1996; Sachs and Warner, 2001; Torvik, 2001, among many others). However almost all these models base their argument on Dutch disease and dynamic disadvantages generated by learning by doing mechanisms that affect perversely the country that exploits its natural resource. These views have been important for rationalizing why natural-resource rich countries grow less than non-abundant countries. Without denying the importance of those findings, we offer a new explanation based on the classical view of trade and growth. Our key interest is to give a fair chance to the existence of natural resources in answering these questions, without endowing any sector of the economy with externalities, economies of scale, learning by doing or market imperfections. This approach provides a complementary explanation to the view

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[2]At the beginning of the XIX century Japan and Finland enjoyed higher level of income than Argentina. The situation was the opposite at the beginning of the XX century. In the context of our model, changes in the world relative prices of goods can account for this reversion.

that abundant natural resources are a curse because they are a source of corruption or due to they crowd-out resources from sectors with dynamic economies of scale.

We are interested in two aspects of development in relation with the exploitation of a natural resource: industrialization patterns and output composition; and the level of per capita income/consumption. Álvarez and Fuentes (2006) find that mineral resources abundant countries are less likely to have positive net exports of the industrial good compared to economies endowed with agricultural land or forestry resources. The second concern is whether industrialization is always consumption enhancing as is the common concern in growth promoting policies and natural resources discovery decreases long-run consumption. In all, our analysis is strictly positive and not normative.

This paper builds on the classical frameworks of Solow (1956), Cass (1965), and Koopmans (1965), and the more recent paper of Atkeson and Kehoe (2000). The framework is thus a dynamic model of comparative advantages for a small open economy with three tradable goods and one nontradable good. Being a small economy, it takes the prices of the tradable goods in the world market as given. One of the tradable sectors uses natural resources, capital, and labor as production factors, while the other two (namely, labor-intensive manufacturing and capital-good producer sectors) use only capital and labor. The nontradable sector uses only labor. The production functions differ in input intensities across sectors, but not across countries. The traditional approach to analyze convergence, which assumes equal production functions for all economies, is no longer valid when we add more factors and goods. In that respect, our paper is related to the work of Leamer (1987). With three factors and n-goods, the traditional model of international trade is able

to generate several cones of diversification characterized by factor price equalization within each cone. The model thus generates a rich set of development paths, characterized by different patterns of production as the economy accumulates physical capital and transits from one diversification cone to the next.

In Leamer (1987), capital accumulation is exogenous and the dynamics are not modeled. Atkeson and Kehoe (2000) use a dynamic Heckscher-Ohlin model (with two goods and two factors) to examine why countries under free trade do not converge to the same level of per capita output. In this setting, an economy that develops later (and starts with a low labor-capital ratio) specializes in the labor-intensive manufacturing good and ends up with a permanently lower level of income relative to the economies that started their development process earlier. Thus, while Leamer (1987) provides a picture with a rich set of development paths when countries accumulate capital in a setting with three factors and n-goods, Atkeson and Kehoe (2000) concentrate on the dynamics and the implications for the convergence process, but in a two-by-two framework with two specialization patterns.

The analysis of multi-sector neoclassical growth models and the study of natural resources have been widely addressed in the literature, but from a different perspective that the one developed here. The pioneer work by Uzawa (1961) shows the conditions for the existence of stable long-run equilibria in a two-sector growth model. The literature of endogenous growth has analyzed the growth process in a context of many sectors, too; for instance, Jones and Manuelli (1990) with convex technologies; or Romer (1990), Aghion and Howitt (1998) and others with endogenous innovations The growth effect of opening to trade has been analyzed in the context of models with learning by doing as in Young (1991),

learning by doing and natural resources as in Matsuyama (1992), and human capital and demographic transitions as in Galor and Mountford (2008).

The detrimental effect of natural resources on growth under free trade (Dutch disease type of effect) has been analyzed in Krugman (1987) and Sachs and Warner (2001) among others. In these models, the presence of a natural resource hurts growth, because it crowds out resources from sectors with positive spillovers and potential learning by doing. Torvik (2001) presents a more eclectic view on the potential effects of natural resources in a free trade situation. In a context, in which there are spillovers between tradables and nontradables, the value of the parameters determine whether natural resources are a blessing or a curse. Another common view is to treat natural resources as a source of rent-seeking activities, which are harmful to growth (Lane and Tornell, 1996).

We assert that when natural resources are included as another production factor, they strongly determine the comparative advantages and thus the development path of a small open economy. Natural resources are usually a blessing, but under certain conditions, they could become a curse. Expressly, we do not endow any sector of the economy with any specific advantage or disadvantage by assumption; in this sense, all sectors are symmetric. Even in such a model we can find situations in which the exploitation of the natural resource diminishes long-run per capita consumption. Furthermore, the presence of natural resources can generate incentives to develop the industrial good (defined as the capital-intensive one) as well as the labor-intensive good. However, in this setting none of the two sectors, and particularly the industrial one, is associated necessarily with a higher consumption per capita. Using a standard dynamic model of comparative advantages, we show that the

driving forces of these results are simply trade, specialization, factor abundance, and factor intensity.

Our paper is also related to the literature that studies long-run equilibria in dynamic Heckscher-Ohlin models. Chen (1992), Baxter (1992), Ventura (1987), Cuñat and Maffezzoli (2003), and Bajona and Kehoe (2006) mainly study how trade can generate a variety of long-run equilibria, building frameworks that replicate some aspects of the empirical growth literature. We claim that introducing a natural resource sector allows us to explain many of the stylized facts.[3] As in many of the previous works quoted, we are also able to generate different long-term equilibria.

We derive the steady state and the development path of the economy with and without natural resources. We show that the type of natural resources (more precisely, the intensity of capital per worker used in this sector relative to the other sectors and the income generated by the natural resource factor) is the key variable that determines the pattern of specialization and the steady-state level of per capita consumption. We also offer an explanation of why some countries become more industrialized than others and why some economies face fewer incentives to accumulate capital than others.

Next, we extend our base model to introduce human capital as another production factor and we allow for international capital flows. This extension is necessary and relevant because it captures the fact that in many developing countries the exploitation of natural resources is financed by foreign direct investment. It also provides a check on the robustness of the previous results.

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[3]See, for example, Álvarez and Fuentes (2006), who present stylized facts on how natural resources affect the production structure and trade patterns in both the transition and the steady state.

The main results of the model can be summarized in four points. First, once we allow for the possibility of producing in more than one sector and free international trade, the model naturally leads to the existence of several steady-state equilibria. This outcome follows from the fact that economies converge to different cones of diversification that leave them, in the long run, with different levels of capital per capita. This result is obtained in a similar fashion as in Atkeson and Kehoe (2000) under the standard case without natural resources. In that paper, however, the pattern of specialization is explained solely by the timing of the development process. Consequently, two countries having the same initial capital-output ratio that open their economy at the same time show identical transitions and steady states. In our paper, in contrast, two economies that started with the same capital-output ratios can exhibit different development paths as lacking or possessing natural resources (and the type of them) conditions the transition and the steady-state.

Second, the differences in income and capital per capita observed between countries with and without natural resources (and within the group that has different types of natural resources) are explained by two key variables: the capital/labor ratio used in the natural resource sector relative to the other sectors in the economy; and the income provided by the natural resource factor. The aggregate capital-labor ratio is not longer a sufficient indicator of the development path. We show that if an economy discovers natural resources and this sector is more capital intensive than the capital goods sector, the economy will unambiguously enjoy a higher level of both per capita income and consumption. This stems from the incentives for further capital accumulation. In this case, natural resources are a blessing. Nevertheless, if this sector is more labor-intensive than the labor-intensive

manufacturing sector, the final effect is ambiguous: the economy is richer thanks to this endowment, but its level of consumption may be lower in steady state if it loses capital on its path to the new steady state. The final result will depend on whether the additional income provided by the natural resource compensates the income lost due to the less capital stock that the economy has in steady state. In this setting, under certain (restrictive) conditions, natural resources are a curse. This result follows the assumption that all factors are fully employed and could be motivated as a coordination failure across agents. In such a case, it may be efficient not to exploit the natural resource.

Third, economies with a large stock of natural resources can end up having a less industrialized productive sector, but enjoying a higher level of consumption than an industrial economy without them. In the limit, if the additional income provided by the natural resource is too high, the economy may not produce any other good except for the nontradable and the one associated with the natural resource sector. On the other hand, depending on the type of natural resource and the income it provides, the economy could also wind up producing capital-intensive goods and no labor-intensive manufactured goods. In contrast to most standard models, economies with no natural resources that specialize in the industrial good do not rank necessarily (in terms of consumption per capita) above economies with natural resources that specialize in the manufactured labor-intensive good: an economy that earns high incomes with their natural resources may enjoy higher level of consumption per capita.

Finally, our results hold when we include foreign direct investment and human capital accumulation. The key assumption is that the natural resource sector is the least

human capital intensive among the tradables. The presence of the natural resource discourages human capital accumulation, but increases consumption. In terms of growth rates, and controlling for the initial stock of human capital, an economy without natural resources grows faster in the transition than an economy endowed with these resources as the latter is closer to its steady state. In the presence of human capital, foreign direct investment does not produce an instantaneous jump of the stock of physical capital to its steady state value. The reason is that the relative scarcity of human capital in the early stages of development avoids the instantaneous adjustment. During all the transition, however, the domestic return on physical capital remains pegged to its international value. The openness to capital flows in terms of foreign direct investment does not alter the production mix in steady state. However, it affects consumption per capita in both, the long-run, because a fraction of the physical capital belongs to foreign investors; and the transition, because returns on human capital and labor change as a result of the capital mobility.

The rest of the paper is organized as follows. Section 2 presents the analytical model, and section 3 analyzes the equilibria with and without natural resources. Section 4 presents the relationship between natural resources and paths of development, highlighting the relevance of the sector's capital intensity and income. We also briefly discuss some welfare aspects and industrialization patterns. Section 5 extends the base model to include foreign direct investment and human capital. Section 6 concludes.

2.2   The Model

We model a small open economy that faces tradable goods prices as given. There are three tradables sectors and one nontradable. In the spirit of Heckscher-Ohlin, we assume the same preferences, the same technology to produce each good in all countries, and no cross-country factor mobility. Comparative advantages will thus be driven by relative factor endowments. The three tradables sectors are classified as labor intensive, capital intensive, and natural resource intensive. The latter may or may not be available for the economy. That is to say, natural resources endowments are distributed independently of any development variable. Households consume the labor-intensive manufactured good, the natural resource commodity, and the nontradable good. The capital good is not consumed, but is used to accumulate capital.

2.2.1   Consumers

The economy is populated by a continuum of identical and infinitely lived households. Each household is endowed with L units of labor, which are inelastically supplied. When available, the property of the stock of natural resources is uniformly distributed among these households. Households choose the time path of consumption so as to maximize the present discounted value of the infinite utility stream stated in equation (2.1). Consumption corresponds to a consumption basket, C, composed of the manufactured good (M), the natural resource commodity (F), and the nontradable good (N); ρ stands for the subjective discount rate. Lowercases refer to variables in per worker terms. Time and households' indexes are omitted to simplify the notation.

$$U = \int_0^\infty \ln c \; e^{-\rho t} dt \tag{2.1}$$

Aggregate consumption is collected through a Cobb-Douglas function defined as

$$c = m^{1/3} f^{1/3} n^{1/3} \tag{2.2}$$

Supplies are defined as m^s, f^s, and n^s. The intratemporal problem is given by the following Lagrangian function, expressed in terms of the manufactured good (the numeraire):

$$\mathcal{L} = m^{1/3} f^{1/3} n^{1/3} - \theta \left[m + p_f f + p_n n + p_x x - y \right] \tag{2.3}$$

where y corresponds to the income earned and p_i to the price of good $i = f, x, n$ relative to good m. With the first-order conditions, we solve for the aggregate consumption basket given by equation (2.5):

$$m = p_n n = p_f f \tag{2.4}$$

$$c = m \left(p_n p_f \right)^{-1/3} \tag{2.5}$$

The economy demands the capital good, x, to accumulate capital, k, that depreciates at the rate δ. The capital-labor ratio of this economy evolves as

$$\dot{k} = x - \delta k \tag{2.6}$$

The economy has no access to capital flows, so its current account is always balanced, defining the following budget constraint (in units of labor) at any moment of time:

$$m + p_x x + p_f f + p_n n = w + rk + \phi t \tag{2.7}$$

where w, r, and ϕ correspond to the return on labor (L), capital (K), and the natural resource (T). Households solves the dynamic problem of maximizing equation (2.1) subject to equations (2.6) and (2.7). The Hamiltonian for the problem is

$$H = \ln c \; e^{-\rho t} + \lambda \left(\frac{w + rk + \phi t - 3c \left[p_n p_f \right]^{1/3}}{p_x} - \delta k \right) \tag{2.8}$$

The optimal paths for capital and consumption are given by

$$\frac{\dot{c}}{c} = \left(\frac{r}{p_x} - \delta - \rho \right) - \frac{1}{3} \left(\frac{\dot{p}_n}{p_n} + \frac{\dot{p}_f}{p_f} \right) + \frac{\dot{p}_x}{p_x} \tag{2.9}$$

$$\dot{k} = \frac{w + (r - \delta p_x) \, k + \phi t - 3c(p_n p_f)^{1/3}}{p_x} \tag{2.10}$$

As usual, $\dot{z}$ corresponds to the time derivative of variable z.

2.2.2 The Firms

Production of $j = M^s$, N^s, F^s, X^s is characterized by Leontief technology. Although the Leontief assumption may appear restrictive, the lack of substitution is not relevant in steady state and does not affect the main results of the paper (the choice of Leontief technologies simplifies enormously the algebra and allows for a straightforward discussion of the model's mechanisms and results). We denote with a_{ij} the requirement of factor $i=$

K, L, T to the production of one unit of good j. Constant returns to scale and perfect competition ensure that the following zero-profit conditions hold for each sector:

$$1 = a_{Lm}w + a_{Km}r \tag{2.11}$$

$$p_x = a_{Lx}w + a_{Kx}r \tag{2.12}$$

$$p_f = a_{Lf}w + a_{Kf}r + a_{Tf}\phi \tag{2.13}$$

$$p_n = a_{Ln}w \tag{2.14}$$

Leontief technology plus the nontradables sector ensure full employment of every factor in equilibrium. The factor-market-clearing conditions are

$$1 = a_{Lm}m^s + a_{Lf}f^s + a_{Lx}x^s + a_{Ln}n^s \tag{2.15}$$

$$k = a_{Km}m^s + a_{Kf}f^s + a_{Kx}x^s \tag{2.16}$$

$$t = a_{Tf}f^s \tag{2.17}$$

In addition, the market for nontradables must clear at all times:

$$n = n^s \tag{2.18}$$

2.3   Competitive equilibrium

In this section, we solve the dynamic model to find the steady-state equilibrium and the stable path for capital and aggregate consumption. As a benchmark, we first present the case for an economy without natural resources. We then analyze how the equilibrium

shifts when the country discovers natural resources, focusing on its link to the capital-labor intensity of the natural resource sector.

2.3.1   Equilibrium without natural resources

Consider the case of a small open economy without natural resources. Its development path is characterized by the dynamics of consumption and capital given by equations (2.9) and (2.10). In addition to this economy, the model includes a large economy that sets international prices and that is already in steady state.[4] Here we use the steady-state assumption to simplify the first-order conditions by assuming that the international prices of goods are constant. This assumption is not restrictive, since a change in relative prices in the world market will cause a shift in the diversification cones derived in the model, as well as in the long-run equilibrium for the small economy. For instance, if we allow for technological changes at different rates in different sectors, relative prices will adjust and the diversification cone will shift accordingly. The small open economy will reach the region of $\dot{c} = 0$ only when $r = r^*$, that is, when the domestic interest rate equals the international rate.[5] Within this region, firms are indifferent in their choice of producing any mix of tradables. We call this situation the full diversification case.

To characterize this steady state, we study the conditions for producing the two tradable goods (m and x) and the nontradable good. Since the economy does not have natural resources, the presence of two factors and two tradable goods implies that the factor rewards are given by the international prices of tradable goods, as stated in equations

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[4]Atkeson and Kehoe (2000) call these economies the early bloomer (for the large economy) and the late bloomer (for the small economy).

[5]An asterisk on a variable denotes international values.

(2.11) and (2.12). The price of the nontradable good is determined only by supply-side conditions (see equation 2.14). To produce both tradable goods, the capital-labor ratio net of labor used by the nontradables sector must lie between the capital-labor ratio used in the manufacturing sector and the capital goods sector. That is,

$$k_x \geq \frac{k}{1 - a_{Ln}n} \geq k_m \tag{2.19}$$

From here we can obtain the possible values of n:

$$\frac{k_x - k}{k_x a_{Ln}} \geq n \geq \frac{k_m - k}{k_m a_{Ln}} \tag{2.20}$$

From equations (2.4) and (2.5) we obtain a relationship between n and c, the consumption basket. Combining these equations with equation (2.20) yields the possible values for consumption under full diversification as a function of the capital-labor ratio of the economy. Since the economy is producing in the diversification cone, $p_n = a_{Ln}w^*$, where w^* represents the international wage rate. Thus the bounds for consumption are
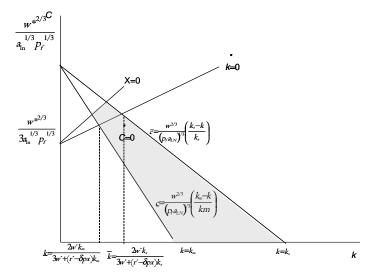
$$\frac{w^{*2/3}}{(p_f a_{Ln})^{1/3}} \left(\frac{k_x - k}{k_x} \right) \geq c \geq \frac{w^{*2/3}}{(p_f a_{Ln})^{1/3}} \left(\frac{k_m - k}{k_m} \right) \tag{2.21}$$

Equation (2.21) provides the combination of c and k that allows for full diversification. Another condition that must be imposed is that of nonnegative investment. This condition is given by

$$c \leq \frac{w^* + r^*k}{3 \left(a_{Ln}w^*p_f \right)^{1/3}} \tag{2.22}$$

The diversification cone given by equation (2.21) is truncated according to equation (2.22), as shown in figure (2.1).

Figure 2.1: Phase Diagram without Natural Resources: The Steady State under Complete Diversification

Having described the conditions for $\dot{c} = 0$, we now analyze the conditions for capital accumulation. If the rest of the world has reached its steady state, then $r^* = p_x(\delta + \rho)$ and $\dot{k} = 0$ implies the following positive relation between k and c.

$$\dot{k} = 0 \Rightarrow c = \frac{1}{3}\left(\frac{w^* + \left(r^* - \delta p_x\right)k}{[a_{Ln}w^*p_f]^{1/3}}\right) \tag{2.23}$$

Note that c is an increasing function of k and the condition of nonnegative investment is never binding in steady state, since $x \geq 0$ lies above $\dot{k} = 0$ (see figure 2.1). By combining equations (2.23) and (2.21), we obtain the range for k consistent with a steady-state equilibrium and full diversification:

$$\bar{k} \equiv \frac{2k_x w^*}{3w^* + (r - \delta p_x)k_x} \geq k \geq \frac{2k_m w^*}{3w^* + (r - \delta p_x)k_m} \equiv \underline{k} \tag{2.24}$$

For $k < \underline{k}$, $\dot{k} = 0$ is still an upward-sloping function. Outside the diversification cone, however, the price of the nontradable good is not given by external conditions, since both the wage rate and the price of the nontradables increase as the economy accumulates capital. Thus, the $\dot{k} = 0$ curve is concave. While in this region, the economy always produces the nontradable good, and the fact that the economy only produces one tradable good (the labor-intensive manufactured good) makes all prices dependent on domestic conditions. From equation (2.9) we obtain that in this region, consumption is rising, so the unique possible path toward a steady state is given by the saddle path in which the capital stock is increasing too. The economy accumulates capital until converging to the edge where $k < \underline{k}$. At this point the economy has no incentive to accumulate further, since $r = r^*$ and prices are again determined only by external conditions and $\dot{k}$ and $\dot{c}$ are simultaneously equal to zero. For all capital values, $\dot{k} = 0$ is continuous in k.

This steady-state equilibrium is characterized by relatively low capital and income per worker and the production of the labor-intensive manufactured good and the nontradable good. This is the prediction from Atkeson and Kehoe (2000). A poor country will inevitably end up with a lower income per worker. We show that this prediction no longer needs to hold when natural resources are included. The steady-state capital-labor ratio is said to be relatively low since the equilibrium with natural resources can lead the economy to a lower k in steady state. An analogous result follows when $k > \overline{k}$. In that case, the economy will produce the nontradable and the capital good.

2.3.2 Equilibrium with natural resources

Next we analyze the case of an economy endowed with natural resources. Figure (2.2) shows the capital-labor ratio for goods m and x, labeled k_m and k_x. Straight lines from the origin represent the capital-labor intensities in each sector. Dashed lines represent the bounds of diversification cones once labor devoted to nontradables is subtracted from the total endowment of labor. For example, if we assume that the capital-labor ratio net of labor used in the nontradables sector of the aggregate economy is located at point E and that the economy has an endowment of natural resources, then the natural resource sector will absorb capital and labor available to the other two sectors. If the natural resource sector is more capital-intensive than x, then the endowment available for the other two tradables sectors could move from E to a point like C (provided that the new equilibrium for the nontradables leaves the economy at such a point). The economy will be out of the full diversification cone, so returning to equilibrium will require accumulating capital up to the point where it reaches the edge of the diversification cone (point E^C)—that is, where the capital-labor ratio net of factors used in the nontradables and natural resource sectors equals k_m. At that point, the economy will not produce the capital good, and the accumulation of capital will stop.

On the other hand, if the natural resource sector is more labor intensive than m, the endowment available for the other two tradables sectors could move from E to a point like A. The economy will again be out of the full diversification cone, but now it will converge to the edge where it produces x and does not produce m (point E^A). The capital-labor ratio net of capital and labor used in the natural resource and the nontradables sectors will

Figure 2.2: Diversification Cones Net of Natural Resources and Nontradables

E: Initial endowment, excluding labor used in the non-tradable sector

equal k_x in steady state.

As in the previous section, we formally derive the conditions for an economy that produces all four goods (that is, the full diversification case). In this situation, the return on the three factors is determined only by the world prices of the three tradable goods (equations 2.11 to 2.13). Moreover, supply-side conditions determine the real exchange rate (in terms of the manufactured good) according to equation (2.14). Later, we study the steady-state equilibrium, which is consistent with full diversification. As mentioned above, the final equilibrium depends on the capital intensity of the natural resource sector relative to that of the other tradables sectors.

For a country to be producing in the full diversification cone (region B in figure 2.2), the capital-labor ratio, net of the capital and labor used in the natural resources sector and net of labor used by the nontradables sectors (defined as k_n), has to be between the capital-labor ratio used by manufacturing and that used in the capital goods sector.

$$k_x \geq \widetilde{k_n} \geq k_m \tag{2.25}$$

Equation (2.26) defines possible values for n consistent with complete diversification, where $t_f = a_{Tf}/a_{Lf}$ (the land per worker used in the natural resource sector):

$$\frac{k_x - k + (t/t_f)\,(k_f - k_x)}{k_x a_{Ln}} \geq n \geq \frac{k_m - k + (t/t_f)\,(k_f - k_m)}{k_m a_{Ln}} \tag{2.26}$$

From the former conditions, and given that n cannot be negative and the price of nontradables is solely determined by external conditions, combining (2.26) with (2.4) and (2.5) yields the following conditions for the level of consumption per worker consistent with the production of all four goods:

$$\overline{c} \equiv \frac{w^{*2/3}\left\{1 - (k/k_x) + (t/t_f)\,[(k_f/k_x) - 1]\right\}}{(p_f a_{Ln})^{1/3}} \geq c \geq \frac{w^{*2/3}\left\{1 - (k/k_m) + (t/t_f)\,[(k_f/k_m) - 1]\right\}}{(p_f a_{Ln})^{1/3}} \equiv \underline{c}$$

$$\tag{2.27}$$

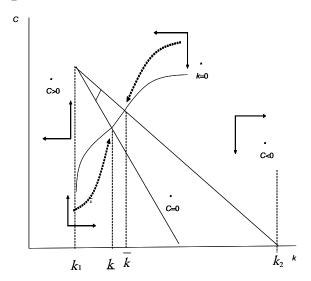We add two necessary conditions for equation (2.27) to be satisfied:

$$\begin{aligned} k &\geq k_f \tfrac{t}{t_f} \equiv k_1 \\ k &\leq k_x + \tfrac{t}{t_f}\,(k_f - k_x) \equiv k_2 \end{aligned} \tag{2.28}$$

The diversification cone no longer starts at $k = 0$ as in the case without natural resources, since the full employment of natural resources requires at least a k given by the first condition in equation (2.3.2). The second condition is needed for the nontradables to

remain positive. As in the previous case, the limits for k depend on the demand for non-tradables or—equivalently—on the level of consumption per worker. Figure (2.3) displays the combinations of c and k at which the economy is fully diversified.

Figure 2.3: Phase diagram with Natural Resources. The transition and the steady state

The presence of natural resources affects the range for consumption and capital per worker within which the economy produces all goods. These bounds depend on the capital intensity of the natural resource sector relative to the other sectors. When an economy produces all four goods, factor prices are given by external conditions, which mean that $\dot{w} = \dot{r} = \dot{\phi} = 0$, so $\dot{c} = 0$:

$$\frac{\dot{c}}{c} = \left(\frac{r}{p_x} - \frac{r^*}{p_x} \right) = 0 \tag{2.29}$$

The condition for the production of the capital good to be positive provides another bound for k and c. This can be written as follows:

$$x = \frac{w^* + r^* k + \phi^* t - 3c \left(a_{Ln} w^* p_f\right)^{1/3}}{p_x} \geq 0 \Rightarrow c \leq \frac{w^* + r^* k + \phi^* t}{3 \left(a_{Ln} w^* p_f\right)^{1/3}} \qquad (2.30)$$

The expression for the law of motion of capital is

$$\dot{k} = \frac{w^* + \left(r^* - \delta p_x\right) k + \phi^* t - 3c(p_n p_f)^{1/3}}{p_x} \qquad (2.31)$$

Given that in steady state $r^* = p_x(\delta + \rho)$ and $\dot{k} = 0$, we obtain the following positive relation between k and c:

$$c = \frac{1}{3} \left(\frac{w^* + p_x \rho k + \phi^* t}{[a_{Ln} w^* p_f]^{1/3}} \right) \qquad (2.32)$$

As shown in figure (2.3), $\dot{k} = 0$ is linear within the region for $\dot{c} = 0$. All possible state equilibria lie over the straight line, $\dot{k} = 0$, between $\underline{k}$ and $\overline{k}$. These values are obtained by equating equation (2.32) with the limits given by equation (2.27):

$$\overline{k} \equiv \frac{k_x \left\langle w^* \{2 + (3t/t_f) [(k_f - k_x)/k_x]\} - \phi^* t \right\rangle}{3w^* + (r^* - \delta p_x) k_x} \geq k \geq \frac{k_m \left\langle w^* \{2 + (3t/t_f) [(k_f - k_m)/k_m]\} - \phi^* t \right\rangle}{3w^* + (r^* - \delta p_x) k_m} \equiv \underline{k}$$

$$(2.33)$$

Figure (2.3) also presents the optimal saddle path for this economy. If the production of the natural resource good leaves the rest of the economy with a relatively low (high) capital-labor ratio, it will converge to a steady state in which it produces all goods except the capital good (labor-intensive manufactured good). Thus, the group of countries with natural resource endowments may present different steady-state values for the capital-labor ratio, output composition, and per worker income, independently of having started with the same capital-labor ratio.

2.4   Natural Resources and the Development Path

In this section, we compare the equilibria with and without natural resources. We compare the steady state equilibrium for both cases and we analyze the development path followed by a country that discovers a natural resource.

2.4.1   Steady-state equilibrium

Our focus here is on comparing the new equilibrium with that of countries without natural resources. Natural resources will affect the function for $\dot{k} = 0$. The latter can be seen by comparing equations (2.23) and (2.32), where the difference is ϕt, the income provided by the natural resource. For an economy with natural resources, the function $\dot{k} = 0$ will thus lie somewhere above the function for an economy without them. This shows that at each level of k, the economy is able to enjoy a higher level of consumption (see figure 2.4). The range for $\dot{c} = 0$ is also affected by the presence of natural resources, depending on the capital intensity of the different sectors. The set of all possible equilibria will be given by equation (2.24) for the case without natural resources and by equation (2.33) for the case with natural resources. Comparing the limits from those inequalities, the minimum (maximum) capital per worker in steady state will be higher when the natural resource is exploited if equation (2.34) is positive (negative):

$$\left(\frac{k_f}{k_i} - 1\right) - \frac{t_f \, \phi^*}{3w} \gtrless 0, \qquad i = m, x \qquad (2.34)$$

Figures (2.4) to (2.6) compare examples of the possible steady-state equilibria for an economy with natural resources and one without. The capital-labor ratio equilibria

depend on the capital-labor ratio used in the natural resource sector relative to the capital-labor ratio used in m or x, and on the ratio of the natural resources to labor payment $(t_f \phi^*/w)$. The larger the income obtained by the owners of the natural resources vis-à-vis the amount received by the workers, the smaller the capital ratio in steady state, all things equal. If compensation from natural resources is very high, the economy will not need to accumulate capital to enjoy a higher level of consumption: in that sense, the availability of natural resources is a blessing. However, welfare is best analyzed by comparing consumption sets. When we compare the minimum and maximum possible values for consumption in steady state for the case with and without natural resources (Δc_{ss}), while restricting the economy to fully employing its resources, the steady-state level of consumption will rise if equation (2.35) is positive. However, since the total effect on welfare includes the changes in consumption during the transitional dynamics, consumption and capital per worker could rise in the transition, but then drop to a lower level in the steady state. The final result will thus depend on the present value of utility generated by this stream of consumption. Again the results will depend on the capital-labor ratio used in each industry relative to the natural resource sector and the income received by the owners of the natural resources.

$$\Delta c_{ss} = \phi^* + \frac{1}{t_f} \left(r^* - \delta p_x \right) \left(k_f - k_i \right) \gtrless 0, \qquad i = m, x \tag{2.35}$$

As posted, Δc_{ss} may be negative. This result is driven by the assumption of full employment of all factors. This result can also be rationalized in a decentralized setting with coordination problems. However, if not exploiting is a possible choice, then having natural resources can never be welfare reducing. Given the small open economy assumption and
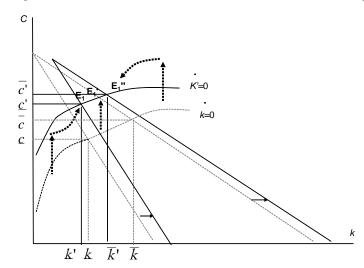
Figure 2.4: Complete diversification with Natural Resources: Case 1 ($k_f < k_x < k_m$)

that in steady state all factor rewards are constant, the choice is to exploit the total stock of natural resources or none at all, so there is no incentive to exploit just some proportion of the stock.

2.4.2   The Transition Following a Natural Resource Discovery

Next, we analyze what happens when an economy without natural resources discovers a natural resource. We distinguish three cases.

Case 1: $k_f > k_x > k_m$

Assume that an economy with no natural resource is in steady state. This is shown in figure (2.4) for points within $\underline{c}$ and $\bar{c}$ on the function $\dot{k} = 0$.

Suppose now that this economy discovers a natural resource. If the natural resource sector is the most capital intensive of the economy, then it will absorb a large capital/labor ratio compared to the average of the economy, leaving the rest of the productive sectors

with a relatively lower capital/labor ratio. Thus comparative advantages will be more likely developed in labor-intensive manufactured goods and the new diversification cone will move rightward according to equation (2.27). The new bounds are $\underline{c}'$ and $\overline{c}'$. The $\dot{k} = 0$ function jumps to $\dot{k}' = 0$. The new range for capital per worker compatible with full diversification can be lower or higher than the range without natural resources, depending on the sign of equation (2.34). The lower capital/labor ratio available for the non-natural resources tradable sectors generate incentives to accumulate more capital. However, the exploitation of the natural resource produces also an income effect that expands the nontradable sector. As this sector only absorbs labor, a large income effect may cause that the non-natural resources tradable sector faces an excess of supply of capital per worker, discouraging capital accumulation even up to the point where the steady state capital stock is lower (the case shown in figure 2.4). Nevertheless, the level of income and consumption per worker unambiguously increases by the amount stated in equation (2.35). This result happens regardless of whether the economy specializes in the manufactured or the capital good or whether the economy started with a low or high capital-labor ratio.

If, prior to the discovery, the economy had a capital-labor ratio below $\underline{k}'$, then it will move toward equilibrium point E_1, as shown by the saddle path in figure (2.4). If the economy was situated between $\underline{k}'$ and $\overline{k}$, then consumption will jump and the economy will reach an equilibrium located between E_1 and E_1', at impact. On the other hand, if the economy was not at steady state and had $k > \overline{k}$, then it will jump above $\dot{k}' = 0$. It will reduce the capital-labor ratio in steady state, but it will enjoy a higher consumption level. As mentioned, the intuition for this result is that a high return on the natural resource (ϕ)
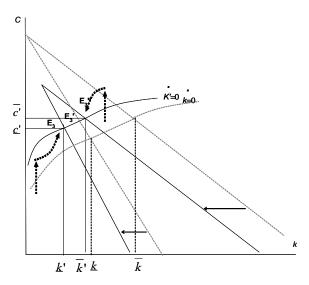
generates a wealth effect that expands the nontradables sector, which requests labor but not capital. If this effect is large, the economy reduces the capital-labor ratio in steady state.

In summary, as a result of the discovery, the economy will have an equal, higher, or lower steady-state capital-labor ratio, but it will unambiguously enjoy higher income and consumption per worker. If income from the natural resource sector is too high, $\dot{k} = 0$ will move up causing a shrinkage of the other tradable sectors. This is a case of Dutch disease. The cause, however, is not an appreciation of the real exchange rate, but a wealth effect that increases the size of the nontradable sector at the expense of the tradable sectors.

Case 2: $k_x > k_m > k_f$

This case is illustrated in figure (2.5).

Figure 2.5: Complete Diversification with Natural Resources: Case 2 ($k_x < k_m < k_f$)

If the natural resource sector is the most labor-intensive of the economy, then it will absorb a lower capital/labor ratio relative to the average of the economy, leaving the

rest of the productive sectors with a relatively higher capital/labor ratio. Thus comparative advantages will become more concentrated in the capital-intensive good and the new diversification cone will move leftward. Again, the income effect due to the income provided by the natural resources will produce that the function $\dot{k} = 0$ moves upwards. The possible paths of development are represented by the dotted arrows.

The fewer incentives to accumulate capital cause that the economy ends up with a fewer or equal capital-labor ratio relative to the equilibrium without natural resources. If the new equilibrium capital-labor ratio is lower, then the economy will erode part of its former income base. However, as the economy enjoys a new source of income, the final effect on total income is ambiguous. Thus consumption can be higher or lower in the new steady state. The latter case is the one shown in figure (2.5). This situation happens if the return on the natural resource, ϕ, is too low to compensate the revenues provided by the lower amount of capital in steady state, that is, $\phi^* t_f < (r^* - \delta p_x)(k_f - k_x)$. Households, however, will enjoy a higher level of consumption in the early stages of the transition, a level that is decreasing towards the new steady state. Thus, the final effect has to account for changes in the transition and the steady state. Welfare is improved if the lost in terms of cumulated return on lost capital is compensated by the total return gained through the exploitation of the natural resource. Technically, the potential reduction in welfare is driven by the full-employment assumption of all productive sectors. Economically, it can be rationalized as a coordination failure across households.

Output composition could be very different from the case without natural resources. For example, if the economy was originally situated between $\underline{k}'$ and $\overline{k}'$ producing

only the labor-intensive manufacturing good, it will achieve the new steady state instantly producing all goods. If the cone moves sufficiently leftward, then the economy could stop producing the labor-intensive good and specializing partially in the labor-intensive manufacturing good. This could be the case of an economy that discovers a resource that is highly labor intensive: in the new equilibrium, the economy will not produce the labor-intensive good.

Summarizing: if the economy was located in the range $[\underline{k}', \overline{k}']$, (that is, transitioning to the steady state), consumption will jump up to a point like E_3' on the curve $\dot{k}' = 0$, and k will remain constant since the economy will automatically be in steady state. In this case, the economy was not initially producing the capital good, but in the new steady state it produces both the labor-manufactured and the capital good (although the economy had an initial capital-labor ratio equal or less than $\underline{k}'$).

Finally, if the capital-labor ratio was in the $\left[\overline{k}', \overline{k}\right]$ range before the discovery, consumption will jump up, and the labor-intensive manufactured sector will become non-competitive. The transition and the steady state will both be characterized by a productive structure composed of the capital good, the natural resource commodity, and the nontradable good.

Case 3: $k_x > k_f > k_m$

This case is illustrated in figure (2.6) and combines previous cases.

Limits, $\underline{c}$ and $\overline{c}$ move to the right and left, respectively shrinking thereby the area for $\dot{c} = 0$ and making less likely that the economy produces all tradables. The minimum value for $k = \underline{k}$ can increase or decrease according to equation (2.34). The maximum level
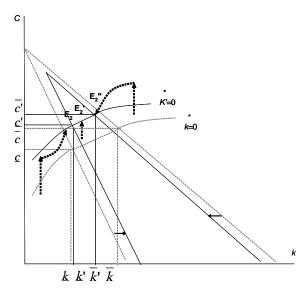
Figure 2.6: Complete Diversification with Natural Resources: Case 3 ($k_x < k_f < k_m$)

for $k = \overline{k}$ will fall. Consumption will rise if the economy converges from the left to a capital-labor ratio of $k = \underline{k}$, but steady-state consumption could decrease if the economy ends up producing at $k = \overline{k'}$ and the return on natural resources is not sufficiently high[6].The intuition for the latter situation were described in the previous case.

If the economy was situated at the left of the new k minimum, it will move toward the equilibrium E_2, which is characterized by producing the labor-intensive manufactured good and none of the capital good. If k was located between the new bounds, consumption will jump to a point like E'_2, and the economy will instantaneously reach its new steady state. When $k > \overline{k'}$, consumption per worker will jump above $\dot{k'} = 0$ at impact, and the economy will then converge to an equilibrium characterized by no production of the labor-intensive manufactured good. Initially this economy was producing all goods, but in the

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[6]This case is not shown in the figure, but it is easily characterized. This case would also require that the economy had started with a capital-output ratio that had left it in (or right to) the diversification cone when opening to trade.

end it is producing everything except one good. It will lose capital during the transition, ending with a lower capital-labor ratio. Nevertheless, that does not mean that the economy will reduce its consumption. It may still rise if ϕ^* is high enough.

2.5   Allowing for FDI and Human Capital Accumulation

Foreign direct investment (FDI) is one of the most common sources of funding for the extraction of natural resources in developing economies. The inclusion of FDI should increase the speed of convergence to the steady state and keep the return on physical capital pegged at all times to the international rate. Given the increasing amounts of FDI toward natural-resource-rich countries, it is important to analyze if the previous results still hold in the presence of international capital mobility.

This section extends the previous analysis in two dimensions. We allow for some international capital mobility in the form of FDI and we introduce human capital as another factor of production.

In contrast to physical capital, human capital is not internationally mobile. Human capital and physical capital are perfect substitutes in the portfolio of consumer savings. This implies that returns will differ throughout the transition, but will converge in steady state. We introduce human capital for two reasons. On one hand, we want to avoid the economy's instantaneous arrival to the steady state's equilibrium. On the other hand, we want to endow our analysis with an extra flavor of reality, particularly in the sense that the lack of both, human and physical capital, is what characterizes less developed countries.

In this section, we analyze the case in which the natural resources sector is the least

human capital-intensive sector. Furthermore, for simplicity we assume that human capital

is not used at all in the production of the natural resource-intensive good. We choose this

assumption for being the most likely case in practice. In this direction, Leamer et al (1999)

provides evidence on how the low demand for human capital by the natural resource sectors

has affected income distribution in Latin America (a natural resource abundant region)

compared to Asia (a natural resource scarce region).[7]

Consumer   Consumers now demand the generic capital good, x, to accumulate both

physical and human capital (k and h, respectively). Neither physical nor human capitals

are reversible inputs. The law of motion of physical capital is still given by equation (2.6).

Equation (2.36) shows the path of human capital. For simplicity, we assume that both types

of capital depreciate at the same rate δ.

$$\dot{h} = x_h - \delta h \tag{2.36}$$

$$\dot{k} = x_k - \delta k$$

$$x = x_k + x_h$$

$$x_h \geq 0 . \tag{2.37}$$

As the economy has access to FDI, the budget constraint stated in equation (2.7),

is replaced by

$$-p_x\dot{b} = -r^*b + w + r^*k + r_{_h}h + \phi t - p_xx_k - p_xx_h - 3c(p_np_f)^{1/3}, \tag{2.38}$$

where r_h represents the return on human capital, and $\dot{b}$, the flow of foreign direct

investment to the economy (in terms of the capital good). Having access to FDI implies

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[7]The analysis can be easily generalized to all possible cases. As the mechanism has been already explained
in the main sections of the paper, we will not discuss it here.

that instantaneous capital flows will equate the domestic and external return on physical capital. We assume that the economy lacks both physical and human capital, so that $\dot{b} = x_k$ and that financial openness occurs at time zero. Thus, the budget constraint is reduced to

$$p_x x_h = w + r^* k_0 e^{-\delta t} + r_h h + \phi t - 3c(p_n p_f)^{1/3}, \tag{2.39}$$

where k_0 represents the stock of physical capital at time zero.[8] Households solve the dynamic problem of maximizing their utility subject to equations (2.36) and (2.39). Optimal paths for consumption and human capital accumulation are given by

$$\frac{\dot{c}}{c} = \left(\frac{r_h}{p_x} - \delta - \rho\right) - \frac{1}{3}\frac{\dot{p}_n}{p_n}. \tag{2.40}$$

In this case the interest rate relevant for the consumer is the one associated to human capital.

$$\dot{h} = \frac{w + r^* k_0 e^{-\delta t} + (r_h - \delta p_x) h + \phi t - 3c(p_n p_f)^{1/3}}{p_x}. \tag{2.41}$$

Firms. This block is almost identical as the one explained in the central section. However, zero-profit conditions (equations 2.11 to 2.14) have to be expanded to take into account the added production factor as follows.

$$1 = a_{Lm}w + a_{Km}r + a_{Hm}r_h \tag{2.42}$$

$$p_x = a_{Lx}w + a_{Kx}r + a_{Hx}r_h \tag{2.43}$$

$$p_f = a_{Lf}w + a_{Kf}r + a_{Tf}\phi \tag{2.44}$$

$$p_n = a_{Ln}w + a_{Hn}r_h \tag{2.45}$$

---

[8]If the domestic stock of capital could be sold, the economy would sell it to finance the scarce human capital.

The market-clearing conditions expressed in (2.15) to (2.18) are expanded with the following condition for human capital.

$$h = a_{Hm}m^s + a_{Hx}x^s + a_{Hn}n^s \tag{2.46}$$

2.5.1 Full diversification case

We characterize the steady state for an economy with natural resources that is fully diversified. Analogous to the previous section, the condition for producing all tradable goods is that the human capital/labor ratio, net of human capital and labor used in both the nontradable and the natural resource sectors, lies between the human capital/labor ratio used in the manufacturing sector (h_m) and the one used in the capital goods sector (h_x). In order to make the specification more general, we let the nontradable sector use human capital as a production factor. Conditions are the following:

$$h_x \geq \frac{h - a_{Hn}n}{1 - a_{Ln}n - a_{Lf}f^s} \geq h_m. \tag{2.47}$$

Assuming that the nontradable is more human-capital-intensive than the labor-manufacturing good (i.e., $h_n > h_m$), the possible values for n have to satisfy the following conditions:

$$\frac{h_x - h - h_x t/t_f}{(h_x - h_n) a_{Ln}} \geq n \leq \frac{h - h_m + h_m t/t_f}{(h_n - h_m) a_{Ln}}. \tag{2.48}$$

Equation (2.48) is equivalent to equation (2.26) in the base model. The main difference is that the nontradable sector uses also human capital. Consequently, n has two upper bounds. At a low level of h, the right hand side of (2.48) is binding. As the economy accumulates h, the left hand side bound becomes relevant. The intuition is simple. For full

diversification to be possible, the nontradable sector cannot be too large as it has to leave enough human capital to produce both tradables.

The steady state in the full diversification cone could be represented, similarly as in the previous section, in the total consumption and human capital space. In steady state, $p_n = a_{Ln}w^* + a_{Hn}r_h^*$. Moreover, $r^* = p_x(\delta + \rho) = r_h^*$, as for the world economy both types of investment are perfect substitutes, $w = w^*$, $\phi = \phi^*$, and restriction (2.37) is not binding. As in the base model we can combine (2.48) with (2.4) and (2.5) to derive the limits for consumption in the cone of full diversification. Equations (2.49a-2.49b) characterize the space that allows for full diversification. In this region $\dot{c} = 0$.

$$\overline{c_1}' \equiv \frac{(w^* + h_n r_h^*)^{2/3}}{(a_{Ln}p_f)^{1/3}} \left(\frac{h - h_m + h_m t/t_f}{h_n - h_m} \right) \geq c \quad \text{if } h < h_n(1 - t/t_f) \quad (2.49\text{a})$$

$$\overline{c_2}' \equiv \frac{(w^* + h_n r_h^*)^{2/3}}{(a_{Ln}p_f)^{1/3}} \left(\frac{h_x - h - h_x t/t_f}{h_x - h_n} \right) \geq c \quad \text{if } h > h_n(1 - t/t_f). \quad (2.49\text{b})$$

As in the case of the nontradables, there are two upper limits for consumption. These functions are represented in the consumption-human capital space as shown in figures (2.7) and (2.8). Figure (2.7) illustrates the cone of diversification of a country lacking natural resources. In this case, t/t_f is equal to zero and the vertex of the cone corresponds to $h = h_n$. The cone with natural resources has the same shape. However, as the natural resource sector does not use human capital, the cone for those economies lies leftwards. The same result would be obtained by assuming that the natural resource sector uses human capital at the lowest intensity.

The function $\dot{h} = 0$ implies a positive relation between human capital and consumption as stated in equation (2.50). For the existence of a steady state in the full diversification cone, we need that $\dot{h} = 0$ crosses the diversification zone. This condition is

Figure 2.7: Complete Diversification with Human Capital and without Natural Resources
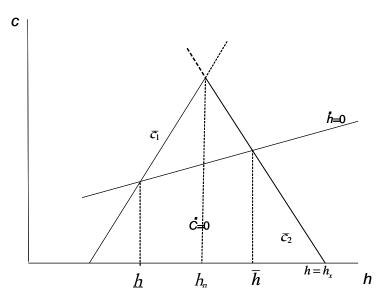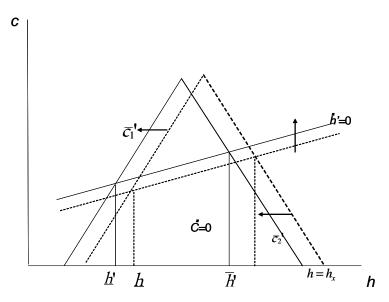

Figure 2.8: Complete Diversification with Human Capital and Natural Resources

fulfilled if the initial stock of capital, k_0, is not very large. However, as a steady state is only reached asymptotically, initial capital is fully depreciated thereat.[9]

$$\dot{h} = 0 \Rightarrow c = \frac{w + (r_h - \delta p_x)\, h + rk_0 e^{-\delta t} + \phi t}{3\,(p_n p_f)^{1/3}}. \tag{2.50}$$

In steady state

$$\dot{h} = 0 \Rightarrow c = \frac{w^* + (r^* - \delta p_x)\, h + \phi^* t}{3\,(p_f a_{Ln})^{1/3}\,(w^* + h_n r^*)^{1/3}}. \tag{2.51}$$

By combining equation (2.51) with equations (2.49a) and (2.49b), we obtain the lower and upper limit for human capital consistent with a fully diversified equilibrium (equations 2.52a and 2.52b). Once more, by making the natural resource endowment, t, equal to zero, we obtain the limits for an economy that is devoid of natural resources. These bounds are labeled as $(\underline{h}, \overline{h})$ in figures (2.7) and (2.8).

$$h \ \leq \ \frac{3\left(r_h^* h_n + w^*\right)(h_x - t/t_f) - (h_x - h_n)\,(w^* + \phi^* t)}{3\left(r_h^* h_n + w^*\right) + (r_h^* - \delta p_x)(h_x - h_n)} \equiv \overline{h'} \tag{2.52a}$$

$$h \ \geq \ \frac{3\left(r_h^* h_n + w^*\right)(h_m - t/t_f) + (h_n - h_m)\,(w^* + \phi^* t)}{3\left(r_h^* h_n + w^*\right) - (r_h^* - \delta p_x)(h_n - h_m)} \equiv \underline{h'}. \tag{2.52b}$$

As stated previously, the discovery of natural resources moves both consumption bounds $\overline{c_1}$ and $\overline{c_2}$ leftwards, as less labor is available for the rest of the sectors. Due to the exploitation of the natural resource, function $\dot{h} = 0$ moves upward by the amount of the natural resource's income.

Comparing the full diversification equilibria with and without natural resources, we get that the human capital's upper limit is unambiguously lower in the former case.

[9]Another condition (also valid in the transition) is that human capital net of the stock used by the nontradable sector has to be nonnegative. This condition is never restrictive.

However, the lower limit could be higher or lower than in the latter case. This ambiguity has it source in two opposing effects. On one hand, the extra income provided by the natural resource (ϕt) encourages human capital accumulation through a wealth effect that stimulates the production of the nontradable good. On the other hand, the share of labor used in the natural resource sector ($t/t_f = L_f/L$) increases relatively the human-capital/labor ratio in the rest of the economy, thereby reducing the incentive for further human capital accumulation. As in the base model presented in the previous section, the discovery of the natural resource can lead to higher or lower consumption in steady state. If the return to the natural resource is not large enough to compensate the loss of income produced by the discouragement of human capital accumulation, welfare can be lower. In this case, it will be suboptimal to exploit them. In contrast, if the natural resource's income is high enough, consumption will increase.

On one hand, this extension shows that the exploitation of a natural resource sector may discourage human capital accumulation. Thus, countries rich in natural resources will tend to show lower levels of human capital, all other things being equal. Moreover, two developing economies with the same human-capital/labor ratio, that are transiting to the steady state, will exhibit different growth rates if one is exploiting natural resources while the other is not. In fact, the one with natural resources will be closer to its steady state and therefore will grow at a lower rate. This result is consistent with the evidence shown in cross-country regressions for growth that control for natural resources and human capital (Sachs and Warner, 2001). Results regarding industrialization derived in the previous section still hold when adding physical capital mobility and human capital.

The key factor for the results presented here, is that the natural resource sector does not use human capital or uses it at the lowest intensity in the economy. A difference with the model presented in the previous section is that the nontradable sector uses human capital. This assumption does not drive the results at all. In fact, it weakens the mentioned effects, as the use of human capital by this sector encourages human capital accumulation.

On the other hand, the openness to FDI does not change the output composition in steady state, but it changes the consumption path and the steady-state level of consumption. When a physical capital scarce economy opens its capital account, capital flows in, reducing its domestic return (pegging it to the international level) and raising the return on human capital and unskilled labor This fact increases consumption instantaneously and provides further incentives to accumulate human capital. As the economy accumulates human capital, the demand for physical capital increases, encouraging additional physical capital inflows.

When the capital account were closed, consumers had to split their savings into human and physical capital. Now, physical capital needs are funded by foreign investors; thus, domestic investment requirements only apply to human capital. As all savings can be diverted to human capital accumulation, convergence speed increases. However, output composition in steady state remains unaltered. The inclusion of human capital prevents the economy from jumping immediately to the steady state. The reason is that the relatively scarce human capital constrains the production possibilities and the demand for physical capital.

There is a difference between steady states in a capital account opened economy

with respect to a closed one. In steady state, GDP is equal in both cases. However, GNP is lower in the case of the open economy, as some fraction of physical capital stock belongs to foreign investors.

2.6 Concluding Remarks

Building on the basic neoclassical growth model, we show that the discovery of natural resources can determine the development path, the income per capita, and the pattern of production of a small open economy. Within a model characterized by three tradable goods, one nontradable good, and three factors, we make predictions for several types of economies assuming different capital intensities for the various production sectors. The capital goods sector is more capital intensive than the labor-intensive manufacturing sector, while the nontradable sector uses only labor as input. We obtain interesting results as we vary the capital intensity in the natural resource commodity sector and the income obtained from the ownership of natural resources.

An economy without natural resources that starts with a relatively low capital/labor ratio will move to a steady state with lower income per worker and no production of the capital good (Atkeson and Kehoe, 2000). As long as the economy stays small, there is no way of escaping this result. If this economy discovers natural resources and the new sector is more capital intensive than the rest of the economy, households will enjoy a higher consumption level and will have more capital per worker. Comparative advantages will be more likely developed in the labor-intensive manufactured good. If the economy was producing both tradable goods before the discovery, the capital goods sector could become

noncompetitive in steady state. Nevertheless, welfare measured as consumption and income per worker will be unambiguously higher. In this case, producing only the labor-intensive manufactured good instead of the capital good is not a curse.

Alternatively, if the natural resource sector is more labor intensive than the labor-intensive manufactured good, comparative advantages favor relatively more the capital good. In this case, the economy could end up producing any mix of product. For instance, the developing economy could stop producing the labor-intensive manufactured good and produce and export the capital good. In this case, consumption per worker could be higher or lower, depending on the relative gains in the natural resource sector and the loss of income caused by the reduction in capital per worker. However, if full employment is no longer a restriction, welfare is not reduced as long as the natural resource is not exploited. As in the previous case, there is no direct link between industrialization (understood as producing the capital good) and welfare.

Conclusions are robust to the inclusion of foreign direct investment and domestic human capital accumulation. The key assumption underlying these findings is that the natural resource sector has the lowest human capital intensity in the economy. In this setting, a developing economy with large endowments of natural resources provides fewer incentives to accumulate human capital. As a result, and with respect to an economy rich in these resources, it ends up with a relatively lower stock of human capital, but with a higher level of consumption. Moreover, in terms of growth rates, and controlling for the initial stock of human capital, this economy grows faster in the transition as it is closer to its steady state. FDI does not change the final steady state in terms of production composition

and the human capital accumulated, but decreases the level of consumption (part of the production belongs to foreigners). However, households can enjoy a higher consumption level during some periods in the transition to the steady state.

One aspect worth exploring in a further work is the parallel between these findings and the Dutch disease prediction. The discovery of a natural resource may lead the economy to stop producing one of the tradable goods. However, the mechanism is different from the real exchange rate argument emphasized in the Dutch disease literature. In our model, depending on the structure of the natural resource sector, the real exchange rate may depreciate or appreciate on impact (at the moment of the discovery) and move in the opposite direction during the transitional dynamics.

Another valuable application of this framework would be to analyze the impact of China's entry into the global economy. The diversification cones and the steady state depend crucially on the relative prices of goods (and factors). Knowing how these prices will change provides insight into how production structures will evolve for the different types of economies (with or without natural resources and with different types of natural resources).

In summary, including natural resources in the analysis enriches the possible outcomes for the path of specialization and the production composition in steady state within the neoclassical framework. Moreover, the presence of natural resources increases the possible patterns of convergence, since the economy can reach alternative steady-states characterized by different capital-labor ratios and levels of consumption per worker.

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