Green Innovation and Economic Growth in a North-South Model

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Abstract

The standard Directed Technological Change model describes the choice by researchers between investing their effort in improving technologies for clean (low-emission) or dirty sectors. We expand the model to account for a business-stealing effect described in the endogenous growth literature. Subsequently, we use the model to describe the interaction between R&D sectors in two regions of the world: North and South. Because researchers in the South are able to create business-stealing innovations, they wish to work on the same technologies as researchers in the North. Consequently, a subsidy for clean technology R&D in the North leads to a shift of research in the South that reduces emissions in both regions. Moreover, with a fixed supply of researchers, the business-stealing effect leads to faster growth in the global technology frontier and in output in both regions. The effect encourages all researchers to work in one sector rather than to split the effort between the two substitutable sectors.

Keywords: directed technological change; green growth; endogenous growth; two-region model; unilateral policy; green R&D subsidies

JEL: O33, O41, O44, Q55, Q56

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1 Introduction

We develop a Directed Technological Change (DTC) model with two regions of the World: North and South. Each region has its own R&D sector with researchers who have to choose between developing technologies for the clean or the dirty sectors. Our central research question is under what conditions a redirection of research in the North towards the clean sector can induce a similar shift in the South.

By allowing for R&D to be performed in the Southern region, we depart from the usual setup of the North-South model, which has the North being a technological leader and the South imitating the innovations of the North. For the purpose of this paper, North is the label for a coalition of countries with ambitious environmental goals, while South labels the countries with solely economic objectives. Even though environmentalism traditionally has tended to go hand in hand with economic maturity and technological advancement, in recent decades one can observe a rapid growth of the R&D sector in large emerging, less-environmentally ambitious economies (see Dechezlepretre et al. 2011)

In order to better justify the interaction between the research sectors in the two regions, we make significant changes to the R&D specification in the standard DTC model by Acemoglu et al. (2012). The original DTC model assumed that 1) while researchers can choose between clean and dirty sectors, they are allocated randomly to the varieties within these sectors; 2) in each period a researcher generates a blueprint with some constant probability; and 3) after each period the researcher looses the property rights to the blueprint. We replace this setup with the specification based on the quality ladder models by Grossman and Helpman (1991) and Aghion and Howitt (1992). The model is solved in continuous time; i.e. the time periods are not separated. The researcher is allowed to allocate his or her research effort across varieties within a clean or dirty sector. We assume that the arrival of innovation follows the Poisson process. The arrival rate (i.e., the expected number of innovations per unit of research effort and per unit of time) is constant. Every innovation is materialized in the form of a new blueprint. The researcher holds the property rights to the blueprint forever. However, as we will demonstrate, he or she looses the market when a new innovation arrives. In other words, the model allows for business-stealing innovations: by investing effort, a researcher (or technology firm) has the chance to capture a market built by the competitor.

The presence of the business-stealing effect brings two important forces into the model when Northern researchers switch from the dirty to the clean sector. On the one hand, this switch implies more intensive innovation and business stealing in the clean sector and shorter expected periods in which a successful firm can enjoy its profits. It also implies less research and thus less competition in the dirty sector. On the other hand, more researchers working in the clean sector increase the value of the market that a potential innovator in the clean sector can capture.

The importance of the latter effect grows over time. A positive number of researchers in the clean sector allows the average value of the market in this sector to grow exponentially. This growth provides stronger and stronger incentives for the Southern researchers to switch to the clean sector. In contrast, the former effect (of an increased competition in the clean sector) leads only to a level decrease in the value of the blueprint in the clean sector. Consequently, it will be always dominated in the long-run. The total effect of an increase in the number of Northern researchers in the clean sector will always exert a force pulling Southern researchers to the same sector.

The pulling force will not be sufficient to ensure the switch of all researchers in the South if it is offset by an opposing force deriving from the the lock-in effect. When the initial stock of accumulated knowledge in the dirty sector is large, it encourages some of the researchers in the South to stay in the dirty sector, at least in the first period. These researchers will continue to produce growth in the dirty blueprint market, which in turn increases the incentive for other Southern researchers to stay in the dirty sector in the future.

The size of the lock-in effect in the long run depends on the size of the population of researchers in the South. If the research sector in the South is smaller than in the North, then in the long run the lock-in effect will be always dominated by the foreign pull effect described before. Otherwise, we can observe dirty sector lock-in in the South over the long run.

Subsequently we examine the macroeconomic effects of the two possible balanced growth paths: one in which all researchers are working in the clean sector and one in which researchers are split, with all Southern researchers working in the dirty sector and all Northern researchers working in the clean sector. Ironically, while at the micro level the concentration of all researchers in the same sector produces the strongest possible business stealing, at the macro level, such concentration produces the fastest possible economic growth. The entire global research effort is focused on building growth in the clean sector, which in the long run determines the final output growth in both regions. Along the alternative balanced growth path, the global research effort is split between two sectors producing substitutable goods. Since in the South the size of the clean sector shrinks to zero in the long run, the aggregate economy will not benefit from any innovations developed in the North.

Finally, we endogenize the behavior of the governments in the two regions. When the Southern government cares only about long-run growth, its optimal strategy will be always to set research subsidies that ensure the Southern researchers will be working in the same sector as the Northern researchers. If the Northern government values both long-run growth and the quality of an environment, the only possible subgame perfect equilibrium in this setup is the one with subsidies ensuring that both regions work only on the growth of the clean sector. Importantly, this result rests on the assumption that both governments ignore the economic costs of the policy during the transition period.

2 Related Literature

A theory of DTC was introduced by Acemoglu (1998) to explain the growth of the college wage premium in the United States. Acemoglu (2007, 2014) discussed the key assumptions behind the DTC model. The theory was first used in relation to environmental policy by Acemoglu et al. (2012), showing that dirty technology lock-in can in certain cases be overcome by temporary interventions of carbon pricing and clean innovation support (see also the survey by Fischer and Heutel 2013). Aghion et al. (2012) found empirical support for the theory using data on patents in the automobile industry. They found that the number of green patents depends on the after-tax fuel price, as predicted by the theory; moreover, they find that companies which innovated in green technologies in the past are more likely to generate green innovations. Similar findings for energy intensive industries were reported in Popp (2002) and Verdolini and Galeotti (2011).

Several recent studies apply the DTC theory in the two region (North-South) model with trade. Acemoglu et al. (2014) proposed the model in which innovations are generated in the North and could be imitated by researchers in the South. They demonstrate that a policy supporting green technologies in the North can induce imitation of green technologies in the South and thus reduce global emissions. However, if the two regions are allowed to trade with clean and dirty goods, carbon tax in the North will incentivise South to specialize in the dirty good leading to an increase in global emissions.

Hemous (2016) presented a model with two goods: polluting and non-polluting. The polluting good can be produced using dirty or clean inputs. Within this setup he provides a comprehensive analysis under what conditions the unilateral policies in the North could incentivise Southern researchers to work on clean technologies.

A related paper by Ravetti et al. (2016) describes the trade between North and South with North specializing in the production of manufacturing good and South, which is endowed with energy resources and hence specializes in the production of energy. The authors show that North can avoid environmental disasters in two ways. The first strategy is to develop technologies allowing for clean energy production. This would shift the comparative advantage of South from the production of energy into the production of manufacturing good. The second strategy is to purchase all energy resources of the South

We supplement these studies by concentrating our analysis on the case in which the two regions can only trade with the technological goods (machines). This assumption could correspond to the case in which clean and dirty good is electricity from renewable and non-renewable sources. Although the electricity cannot be traded with large quantities across large distances, the trade and competition on the markets for electricity generating technologies can play a significant role in the low-carbon transition.

3 The model

Final good and the demand for the the intermediate goods

The primary goal of the model is to understand what are the incentives for the researchers in the South region to switch from dirty to clean technologies if this switch has already taken place in the north region. Therefore in the following setup we will treat the south economy as 'domestic' economy and the North economy as a 'foreing economy'. The macroeconomic variables for the foreign economy will be marked with index f.

In line with the standard Directed Technological Change model, we assume that the final good is produced with two types of intermediate goods (dirty and clean), which are gross substitutes. Specifically, we assume the Constant

Elasticity of Substitution production function,

$$Y_t = \Phi_t \left(Y_{ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{dt}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}$$

where Y_{ct} and Y_{dt} denote clean and dirty intermediate goods, $\epsilon > 1$ is the elasticity of substitution between the two goods and Φ_t is the sector neutral productivity parameter. All variables in this section are expressed in per capita terms.

The final good producer takes the prices of its output as well as the prices of inputs as given. We take the price of the final good as the numeraire. The producer's optimization problem can then be stated as

$$\max_{Y_{ct}, Y_{dt}} \Phi_t \left(Y_{ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{dt}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}} - p_{ct} Y_{ct} - p_{dt} Y_{dt}$$

The first order conditions for the optimum defines the demand curves for the clean and dirty good:

$$\Phi_t^{\frac{\epsilon-1}{\epsilon}} Y_t^{\frac{1}{\epsilon}} Y_{jt}^{\frac{\epsilon-1}{\epsilon}} = p_{jt} Y_{jt} \tag{1}$$

We will use a hat to denote the value of prices or quantities in the clean sector relative to their value in the dirty sector., i.e. for any variable x, $\hat{x_t} = \frac{x_{ct}}{x_{dt}}$. Then the above translates into:

$$\hat{p}_{jt}^{-\epsilon} = \hat{Y}_{jt} \tag{2}$$

implying a simple log-linear relative demand curve.

Production of the intermediate goods.

The production of intermediate good $j \in \{c, d\}$ requires labor (L_{jt}), natural resources (R_{jt}) and a range of machines (with Z_{ijt} denoting a machine of the variety i devoted for sector j), each characterized by its own productivity parameter A_{ijt}:

$$Y_{jt} = R_{jt}^{\alpha_2} L_{jt}^{1-\alpha} X_{jt}^{\alpha_1}$$

with $\alpha = \alpha_1 + \alpha_2$ and $\ln X_{jt} = \int_0^1 \ln (A_{ijt} Z_{ijt}) \, di$, which is the composite of machines. The number of varieties of machines is normalized to unity (the predictions of the model do not change if we replace the unity with a positive parameter n). The machine of variety ij can be either supplied by domestic producers (delivering Z_{hijt}) or imported (at quantity Z_{mijt}). Domestic and Imported machines are perfect substitutes, i.e. $Z_{ijt} = Z_{hijt} + Z_{mijt}$. Let A_{ijt} denote the productivity of the best machine available on the market ij. The best technology could be either domestic or foreign. The production and characteristics of the machines are described in the subsequent subsection.

As in the case of final good producer, we assume that the intermediate goods producers takes all prices as given. If w_t denotes wages (which must be equal in both sectors as we assume free flow of labor) and p_{hijt} (p_{mijt}) is the price of machine ij by domestic (foreign) producer, then the optimization problem for the representative firm in the intermediate good sector reads:

$$\max_{\{Z,R,L,\}_{\tau=t}^{\infty}} p_{jt} R_{jt}^{\alpha_2} L_{jt}^{1-\alpha} X_{jt}^{\alpha_1}$$

$$-\int p_{hijt} Z_{hijt} di - \int p_{mijt} Z_{mijt} di - c_{jt} R_{jt} - w_t L_{jt}$$

subject to $\ln X_{jt} = \int \ln \left(A_{jit} Z_{jit}\right) di$ and $Z_{ijt} = Z_{hijt} + Z_{mijt}$

The first order conditions implies then the demand for labor, resources and each machine variety:

$$\alpha_2 p_{jt} Y_{jt} = R_{jt} c_{jt} \tag{3}$$

$$(1-\alpha) p_{jt} Y_{jt} = L_{jt} w_t \tag{4}$$

$$\alpha_1 p_{jt} Y_{jt} = Z_{ijt} p_{ijt} \tag{5}$$

where p_{ijt} is the price of a machine chosen by the firm at market ij. In addition, $Z_{ijt} = Z_{hijt}$, $Z_{mijt} = 0$ and $p_{ijt} = p_{hijt}$ if $\frac{p_{hijt}}{A_{hijt}^{1-\alpha_1}} \leq \frac{p_{mijt}}{A_{mijt}^{1-\alpha_1}}$, i.e. the intermediate producer always chooses the domestic machine if its quality adjusted price is lower than the one proposed by its foreign competitor. Otherwise, $Z_{jit} = Z_{mjit}$, $Z_{hjit} = 0$ and $p_{ijt} = p_{mijt}$.

Generation of blueprints

We assume that the technology firms own the blueprints which allow them to produce the machine of variety ij characterized by some quality level (A). In contrast to the original DTC model by Acemoglu et al. the firms do not loose the property rights of the blueprint after one period. Instead, the firm will loose the market when another firm comes up with an innovation in the same market. An innovation results in a new blueprint which allows the newcomer to produce a machine with a quality level which is higher than the previous best available technology by a factor $(1+\gamma)$. This allows the newcomer to capture the entire market for machine of variety ij.

An innovation is made by researchers hired by a technology firm. As in the original Grossman-Helpman model we assume that the arrival of innovations is random and follows the Poisson process: the number of innovations per unit of research effort and per unit of time is distributed according to the Poisson distribution with the arrival rate λ. This implies that the time between two successive innovations is also random and its expected value depends negatively on the parameter λ and on the total research effort devoted to variety ij.

The technological Paths

Let A_{jt} stand for the geometric average of technologies in sector j raised to the power $\frac{\alpha_1}{1-\alpha_1}$:

$$\ln(A_{jt}) = \frac{\alpha_1}{1-\alpha_1}\int \ln(A_{jit})\,di$$

differentiating this with respect to time

$$\frac{d\ln(A_{jt})}{dt} = \frac{\alpha_1}{1-\alpha_1}\int \frac{d\ln(A_{ijt})}{dt}di$$

As noted earlier, the intermediate producers purchase the best available technology, irrespective whether it was developed at home or abroad. However, we take into account that not every foreign innovation can be successfully adapted to the domestic market. In particular we assume that the probability of successful adaptation is given by ω.

We assume that the number of researchers in the two regions is fixed. The population of domestic researchers is given by μ. The share of this population working on the technologies in the clean sector is given by s. The population of foreign researchers is normalized to unity and we let s_f to denote the share of foreign researchers working in the clean sector.

Recall that the number of innovations per unit of research effort and per unit of time is distributed according to the Poisson distribution with the Poisson arrival rate λ, This implies that in the clean sector on average there are $\lambda\mu s$ improvements per unit of time delivered by the domestic researchers and $\lambda\omega s_f$ domestically applicable improvements delivered by the foreign research sector. Due to the law of large numbers, there are $\mu\lambda s + \lambda\omega s_f$ varieties which are improved by a factor $1+\gamma$. This means that the growth of A_{jt} is given by:

$$\frac{d\ln(A_{jt})}{dt} = \frac{\alpha_1}{1-\alpha_1}\left(\mu\lambda s_{djt} + \lambda\omega s_{fjt}\right)\gamma$$

integrating this over time brings

$$A_{c\tau} = A_{jt} e^{\frac{\alpha_1}{1-\alpha_1}\gamma(\mu\lambda s + \lambda\omega s_f)(\tau - t)} \tag{6}$$

By analogy, the path of productivity in the dirty sector is given by

$$A_{d\tau} = A_{dt} e^{\frac{\alpha_1}{1-\alpha_1}\gamma(\mu\lambda(1-s) + \lambda\omega(1-s_f))(\tau - t)} \tag{7}$$

The competition between technology firms

Consider a domestic technology firm which has just made an innovation for a machine ij. Now the firm, which we label as the 'newcomer', has to compete with the incumbent firm in the market ij. We assume that this takes the form of the Bertrand competition. The incumbent cannot lower its price below the marginal cost, which we assume is constant and equal to ψ. The newcomer offers the price which is epsilon lower than $(1+\gamma)\psi$ and wins the competition. This implies that in equilibrium $p_{hijt} = (1+\gamma)\psi$. If the newcomer is the foreign firm which generated an adaptable innovation then exactly the same logic applies and $p_{mijt} = (1+\gamma)\psi$. Using 5, this implies that the demand for machines is given by

$$Z_{ijt} = \frac{\alpha_1 p_{jt} Y_{jt}}{(1+\gamma)\psi} \tag{8}$$

The instantaneous profit of a newcomer from domestic market is given by

$$\pi_t = (p_{hijt} - \psi) Z_{ijt} = \gamma\psi \frac{\alpha_1}{(1+\gamma)\psi}(p_{jt}Y_{jt}) = \frac{\gamma}{1+\gamma}\alpha_1 p_{jt} Y_{jt}$$

and the instantaneous profit of a newcomer from the foreign market is given by

$$\omega\pi_{ft} = \omega(p_{mijt} - \psi) Z_{ijt} = \omega\frac{\gamma}{1+\gamma}\alpha_1 p_{fjt} Y_{fjt}$$

Note that since the profit is the same for every variety i, the researchers will be indifferent between choosing to work on any of the varieties within intermediate sectors. The progress in each sub-sector will be therefore equally likely.

The symmetry between profits in sub-sectors ij is necessary for a tractable solution of the model. Importantly, in our model this symmetry emerges from the micro-foundations of the model. In contrast, the same symmetry in the original DTC model by Acemoglu et al (2012) was bought with a rather strong assumption on the random allocation of researchers. In that model, the researchers could choose whether they want to work on technologies in dirty or in clean sector, but once this choice was made, they could not choose which particular technology ij they wished to work on.

The value of a blueprint

As noted above, the innovation is associated with a loss of the monopoly power of the owner of the previous blueprint. This effect is known in the endogenous growth literature as the business-stealing effect. The presence of the effect was one of the central features in the Grossman and Helpman, and in the Aghion and Howitt models. It will play an important role in our model as it will encourage innovators in the South to operate in the same sector as the innovators in the North.

In this setting, the value of the blueprint depends on the length of the time period between an invention of the blueprint and a successive innovation in the same market. Note that since the innovators are indifferent between working on any variety within sector j, they distribute their effort equally across all varieties. Given that the number of innovations per unit of time and per unit of research effort is distributed with Poisson distribution, the distribution of time interval between two successive innovations in the clean sector is exponential with parameter $\lambda(\mu s + \omega s_f)$. This means that, if a firm innovated at time t, the probability that competitors did not come with any successful innovation in the same market by time τ is $e^{-\lambda(\mu s + \omega s_f)(\tau - t)}$. By the same logic the probability that a successful domestic firm is present in the foreign market at τ is given by $\omega e^{-\lambda(\mu\omega s + s_f)(\tau - t)}$. The value of the blueprint in sub-sector i in the clean sector, v_{ict} is then given by

$$v_{ict} = \int_{\tau=t}^{\infty} \pi_\tau e^{(-\rho-\lambda(\mu s_\tau + \omega s_{f\tau}))(\tau-t)} + \omega \int_{\tau=t}^{\infty} \pi_{f\tau} e^{(-\rho-\lambda(\mu\omega s_\tau + s_{f\tau}))(\tau-t)}$$

where ρ denotes the discount rate used by a firm.

Using the expression for profits derived earlier, we can restate the above as follows:

$$v_{ict} = \int_{\tau=t}^{\infty} \frac{\gamma}{1+\gamma} \alpha_1 p_{c\tau} Y_{c\tau} e^{(-\rho-\lambda(\mu s_\tau + \omega s_{f\tau}))(\tau-t)} +$$

$$\omega \int_{\tau=t}^{\infty} \frac{\gamma}{1+\gamma} \alpha_1 p_{fc\tau} Y_{fc\tau} e^{(-\rho-\lambda(\mu\omega s_\tau + s_{f\tau}))(\tau-t)} \tag{9}$$

Equilibrium revenues of dirty and clean sector

The revenues of the intermediate sector can be expressed as a function of the intermediate prices and total output using 1:

$$p_{jt} Y_{jt} = Y_t p_{jt}^{-(\epsilon-1)} \Phi_t^{\epsilon-1}$$

which implies that, for a given level of output, a drop in price of an intermediate good will increase the revenue for this intermediate as long as the two intermediates are substitutes ($\epsilon > 1$)

Next, using duality between cost and production functions, we can express the price of an intermediate good as:

$$p_{jt} = \Omega \Phi_t^{\alpha} A_{jt}^{-(1-\alpha_1)} c_{jt}^{\alpha_2} w_t^{1-\alpha} \tag{10}$$

where w_t is the wage of labor and Ω is a constant composed of the parameters of the model. The condition reflects the negative relation between average technology in sector j and the price of the intermediate good supplied by this sector.

By summing the demand for labor in 3 for the two sectors, we can show that the labor compensation is a constant fraction of GDP: $w_t L_t$=$(1-\alpha) Y_t$. Since we consider all variables in per capita terms, labor can be normalized to unity. Combining this with equation 10 we can then express the revenue in sector j as a function of total GDP, price of resource and the technology used in sector j:

$$p_{jt} Y_{jt} = \left[\alpha_2^{\alpha_2} \left(\frac{\alpha_1}{(1+\gamma)\psi} \right)^{\alpha_1} \right]^{\epsilon-1} A_{jt}^{-\varphi_1} c_{jt}^{-(\epsilon-1)\alpha_2} Y_t^{(1+\varphi)} \Phi_t^{-\varphi} \tag{11}$$

where $\varphi_1 = (1-\alpha_1)(1-\epsilon)$ and $\varphi = (1-\alpha)(1-\epsilon)$. This expression can be now used in equation 9 to show how the values of the blueprints in the two sectors depend on the path of technology, GDP and resource prices. However, before we do so, we make one simplification to the model: we approximate $Y_\tau \approx Y_t e^{g(\tau-t)}$ and $Y_{x\tau} \approx Y_{xt} e^{g_x(\tau-t)}$, i.e. we approximate the growth of the total economy to be constant within the time horizon considered by the blueprint developer.

In order to better understand when this approximation is exact and when it fails, let us derive the true growth rate of GDP in equilibrium. Total output can be derived by summing left and right hand side of 11 over the two sectors and noting that $p_{ct}Y_{ct} + p_{dt}Y_{dt} = Y_t$. This results in

$$Y_t = \left[\alpha_2^{\alpha_2}\left(\frac{\alpha_1}{(1+\gamma)\psi}\right)^{\alpha_1}\right]^{\frac{1}{1-\alpha}} \Phi_t \left(A_{ct}^{-\varphi_1} c_{ct}^{-(\epsilon-1)\alpha_2} + A_{dt}^{-\varphi_1} c_{dt}^{-(\epsilon-1)\alpha_2}\right)^{-\frac{1}{\varphi}} \quad (12)$$

The growth rate of output can then be obtained by taking logs and differentiating with respect to time:

$$g_t = \frac{1-\alpha_1}{1-\alpha}\left(\sigma_{ct} g_c + \sigma_{dt} g_d\right) \quad (13)$$

where $\sigma_{jt} \equiv \frac{p_{jt}Y_{jt}}{Y_t} = \frac{\left(A_{jt}^{1-\alpha_1} c_{jt}^{-\alpha_2}\right)^{\epsilon-1}}{\left(A_{dt}^{1-\alpha_1} c_{dt}^{-\alpha_2}\right)^{\epsilon-1} + \left(A_{ct}^{1-\alpha_1} c_{ct}^{-\alpha_2}\right)^{\epsilon-1}}$ is the share of sector j in the total output, and $g_c \equiv \frac{d\ln A_{ct}}{dt}$ and $g_d \equiv \frac{d\ln A_{dt}}{dt}$ are the growth rates of the unit productivities in the clean and dirty sectors respectively. Now suppose that at the initial point of time, the dirty sector is the dominant sector in the economy (σ_d is large). Furthermore, suppose that all researchers have moved from the dirty sector to the clean sector, that is the growth in the large sector halts and the growth in the small sector commences. Temporarily (until the clean sector grows large) this implies the slowdown of the aggregate output.

The approximation that the output growth rate in the expression for the value of the blueprint is constant, will work well if this slowdown is short-lived. In this case firms, when doing optimization, assume that the growth of the economy will be equal to the the long-run growth rate, which indeed is constant because σ_c approaches unity in the long run.

The alternative interpretation of the constant growth rates would be that the research firms are short-sighted (perhaps due to large discount rate or large business stealing effect which reduces the time horizon for the profits) and they take the shares of output as constant because they believe that by the time the shares of clean and dirty sector will be significantly changed, the innovation, which they consider right now will be already out of the market. For the constant shares the expression above indeed predicts a constant growth rate.

What happens when the approximation fails significantly? The switch of research from large dirty sector to a small clean sector would imply an economic slowdown followed by economic recovery. That is the growth rate is smaller in the first years and faster in the latter years. This implies larger weights on the future years than the ones implied by our model and more incentives to switch to the sector which grows faster, which, in our central case, will be a clean sector.

4 Symmetric Regions

We will first analyze the simplest case when the two regions are symmetric in the sense that they have the same labor force, the same prices of resources, c's, the same sector-neutral productivity, Φ. We also assume that $\omega = 1$, and that the initial values of A's are the same in both regions. Since all technologies are available for any firm in any region, the two regions will be characterized by the same levels of A_c and A_d and, therefore, with the same output and sector shares. Finally, and most importantly, we assume that the number of researchers in both regions is equal, that is $\mu = 1$. In section 4 we will consider a more complex case when the regions are asymmetric and when the above assumptions are relaxed.

In the symmetric case, equation 9 reduces to

$$v_{ict} = 2\int_{\tau=t}^{\infty} \frac{\gamma}{1+\gamma}\alpha_1 p_{c\tau} Y_{c\tau} e^{(-\rho-\lambda(s_\tau+s_{f\tau}))(\tau-t)}$$

We can then combine this with 11, 6 and 7 and the approximation $Y_\tau \approx Y_t e^{g(\tau-t)}$ to find the value of the blueprint in the clean sector:

$$v_{ict} = \int_{\tau=t}^{\infty} e^{(\alpha_1(\epsilon-1)\gamma\lambda(s+s_f)+(1+\varphi)g-\rho-\lambda(s+s_f))(\tau-t)} A_{ct}^{-\varphi_1} c_c^{-\alpha_2(\epsilon-1)}$$

We assume that $(\alpha_1(\epsilon-1)\gamma-1)\lambda(s+s_f)+(1+\varphi)g-\rho<0$ and

$(\alpha_1(\epsilon-1)\gamma-1)\lambda(1-s+1-s_f)+(1+\varphi)g-\rho<0$ (e.g. ρ sufficiently large) to ensure that this integral and the analogous integral for the dirty sector are defined. In this case the above simplifies to

$$v_{ict} = \frac{\left(A_{c0}^{-\varphi_1} e^{-\alpha_1(\epsilon-1)\gamma\lambda(s+s_f)t}\right) c_c^{-\alpha_2(\epsilon-1)} Y_0 e^{g(s,s_f)t}}{[\alpha_1(\epsilon-1)\gamma\lambda(s+s_f)]-(1+\varphi)g(s,s_f)+\rho+\{\lambda(s+s_f)\}} \tag{14}$$

We can also find the expression for the value of a blueprint in the dirty sector by following the analogous derivations:

$$v_{idt} = \frac{\left(A_{d0}^{-\varphi_1} e^{-\alpha_1(\epsilon-1)\gamma\lambda(1-s+1-s_f)(\tau-t)}\right) c_d^{-\alpha_2(\epsilon-1)} Y_t e^{g(s,s_f)(\tau-t)}}{\left[\alpha_1(\epsilon-1)\gamma\lambda(1-s+1-s_f)\right] - (1+\varphi)\, g(s,s_f) + \rho + \{\lambda(1-s+1-s_f)\}} \tag{15}$$

Choices of Researchers

Since we assume a free entry of technology firms, the zero profit condition will imply that the compensation (or wage) for researchers will be equal to the expected return to research. The return to research in sector j is given by $\lambda v_{ijt} + \xi_j$, where ξ_j denotes the research subsidy for technologies in sector j. The subsidy is financed from the lamp-sum tax on the consumers income in order to avoid any distortionary effect of taxes.

A researcher compares the wages in the two sectors and allocates its entire research effort in the clean sector if and only if $v_{ict} + \frac{\xi_c}{\lambda} > v_{idt} + \frac{\xi_d}{\lambda}$.

Note that in this specification for any parameter values any government has always possibility to incentivise the movement of all researchers to any sector, simply by choosing the appropriate levels of research subsidy in the two sectors.

Suppose now that the government of the foreign country (i.e. the North region) increases the subsidy for the clean research in order to shift researchers to this sector and away from the dirty sector. We are interested what will be the consequence of this shift for the allocation of researchers in the South region. We distinguish between four types of effects.

First observe that an increase of s_f in 14 and 15 will increase the business-stealing effect in the clean sector and decrease the size of this effect in the dirty sector. In other words, more researchers working in the clean sector implies that the likelihood of a successful innovation of a competitor in this sector increases and thus the innovator can enjoy its profit for a shorter period. Also, fewer competitors in the dirty sector implies lower risk of losing the market in this sector. We marked this effect with curly brackets in 14 and 15 above.

Second, note that when firm has the monopoly in the market of variety i in the clean sector, the unit productivity of other varieties will grow at the rate $\gamma\lambda(s + s_f)$. This means, that although a small fraction of researchers in clean sector will be aiming at 'stealing' the market i, the remaining fraction will be working on improvement of other varieties. Since in our model the varieties within each sector are not gross substitutes, this improvement will increase the revenue for variety i. In expressions 14 and 15 this effect is marked with a square brackets.

Third, s_f will influence the value of blueprints in both sectors through its effect on aggregate growth rate. If at the initial stage clean sector is relatively small, a deprivation of the large dirty sector of its growth engine implies a slow-down for an entire economy. If the technology firm is short-sighted this effect will depress the values both, in dirty and in the clean sector. However note that it will not affect the *relative* value of blueprints in the clean and dirty sector in the long-run.

Finally, the most important effect for the long-run is framed in the exponential term, $e^{-\alpha_1(\epsilon-1)\gamma\lambda(s+s_f)(\tau-t)}$. This effect is also related to the business-stealing: the more researchers are working in the clean sector, the larger is the value of the businesses operating in this sector. This implies more benefit from capturing one of such businesses in the event of successful innovation.

Note that contrary to the first two effects which change the level of values of the blueprints, the last effect changes the growth rate of the blueprint value. As a result this is the most powerful effect shaping the relative value of the blueprint in the long-run. It always dominates the other three effects as t approaches infinity.

As a result the switch of foreign researchers to the clean sector will have a positive effect on the value of clean blueprints in the long run. However, this does not guarantee that the foreign switch will suffice to incentivise the switch of domestic researchers. We clarify what are the condition for the Southern switch in the proposition:

Proposition 1. Allocation of Southern researchers when there is no South government:

Suppose that the two regions are symmetric. If at time $t = 0$ all researchers in the South work in the dirty sector and if all researchers in the North work on the clean technologies, then in the long run the Southern researchers will stay in the dirty sector if and only if

$$A_{c0}^{-\varphi_1} c_c^{-\alpha_2(\epsilon-1)} \leq A_{d0}^{-\varphi_1} c_d^{-\alpha_2(\epsilon-1)}$$

Otherwise, in the long-run all researchers will work in the clean sector.

Proof The 'if' part:

When all Southern researchers are working in the dirty sector ($s = 0$), then the condition above implies that

$$\frac{\left(A_{c0}^{-\varphi_1}e^{-\alpha_1(\epsilon-1)\gamma\lambda t}\right)c_c^{-\alpha_2(\epsilon-1)}}{\left[\alpha_1\left(\epsilon-1\right)\gamma\lambda\right]-\left(1+\varphi\right)g\left(0,1\right)+\rho+\left\{\lambda\right\}}\leq$$

$$\frac{\left(A_{d0}^{-\varphi_1}e^{-\alpha_1(\epsilon-1)\gamma\lambda t}\right)c_d^{-\alpha_2(\epsilon-1)}}{\left[\alpha_1\left(\epsilon-1\right)\gamma\lambda 1\right]-\left(1+\varphi\right)g\left(0,1\right)+\rho+\left\{\lambda\right\}}$$

that is, the value of the clean blueprint is lower than the value of the dirty blueprint so noone has an incentive to move from the dirty sector to the clean sector. Since the research effort is equally split between the two sectors ($s_f = 1-s = 1$), the two sectors grow at exactly the same rate and the condition holds in all subsequent periods.

The 'only if' part:

If the condition is violated then clean blueprints are more valuable than the dirty blueprint and at least some researchers flow from dirty to clean sector. However in this case the growth of productivity in the dirty sector (by 7 equal to $\frac{\alpha_1}{1-\alpha_1}\gamma\lambda\left(1-s\right)$) is slower than the growth in the clean sector (by6 equal to $\frac{\alpha_1}{1-\alpha_1}\gamma\lambda\left(1+s\right)$). In the long run this implies that the value of the dirty blueprints relative to the value of the clean blueprint is falling and reaches zero asymptotically. Consequently, in the long-run all researchers work in the clean sector.

QED.

Let us define the Balanced Growth Path as the situation in which the number of researchers in the two sectors is constant over time.The proposition above shows that if North commits to put all its research in the clean sector, in the long-run there are only two possible Balanced Growth Paths: one with all Southern researchers choosing the clean sector (s=1) and one with all Southern researchers choosing the dirty sector ($s=0$).

The proposition implies that if the accumulation of knowledge stock in the dirty sector is sufficiently advanced (A_d is large) and if Southern government is absent, then the world economy will follow a balanced growth path with the two sectors growing at the same pace. The reason why the switch in the North is not propagated in the South is that the positive effect of foreign switch is offset by the lock-in effect in the South. In the symmetric model with equal number of researchers in the South and in the North these two effects will be exactly equal to each other. For the change of the balanced growth path we would need the former force to be at least marginally larger than the latter force. This case will be discussed in the case of asymmetric regions in the subsequence section.

Another important assumption behind proposition 1 is the absence of governmental subsidies in the South. In section 5 we will demonstrate that if the Southern government cares about the long-run growth of its economy, it will have both, an opportunity and an incentive to introduce a system of subsidies which encourages Southern researchers to follow the Northern switch and to move the economy to the balanced growth path with all world researchers working in the same sector.

5 Asymmetric regions

In this section we drop the assumption of the symmetry between region, i.e. we allow the workforce, the population of researchers, sector neutral productivity growth and prices of resources to differ between regions. In addition we allow $\omega \leq 1$, that is we take into account that not every innovation which is developed in one region can be successfully adapted to the economy of the other region. We will view the allocation of researchers from the perspective of the south (thus all variables indexed with f refers to the value for North) and we will consider the case when all Northern researchers work in the clean sector.

In the asymmetric case the unit productivities for the two sectors, A_c and A_d will differ between the two regions. In particular, while the domestic unit productivities follows the processes described in 6 and 7, the unit productivities abroad will follow

$$A_{fc\tau} = A_{fct} e^{\frac{\alpha_1}{1-\alpha_1}\gamma\lambda(\mu\omega s+1)(\tau-t)} \tag{16}$$

$$A_{fd\tau} = A_{fdt} e^{\frac{\alpha_1}{1-\alpha_1}\gamma\lambda\mu\omega(1-s)(\tau-t)} \tag{17}$$

The value of a blueprint in a clean sector can then be derived by combining 9, 11, and the paths of unit productivities (6, 7 and the two equations above) :

$$v_{ict} = \frac{c_c^{-\alpha_2(\epsilon-1)} A_{ct}^{-\varphi_1} Y_t^{(1+\varphi)}}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\mu s+\omega s_f)-(1+\varphi)g-r} +$$

$$\frac{(1+\xi_c)\omega c_{fc}^{-\alpha_2(\epsilon-1)} A_{fct}^{-\varphi_1} Y_{ft}^{(1+\varphi)} \left(\frac{N_f}{N}\right)^{(1+\varphi)}}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\omega\mu s+s_f)+(1+\varphi)g_f+r} \tag{18}$$

The value of the dirty sector is given by

$$v_{idt} = \frac{c_d^{-\alpha_2(\epsilon-1)} A_{dt}^{-\varphi_1} Y_t^{(1+\varphi)}}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\mu(1-s)+\omega(1-s_f))-(1+\varphi)g-r} +$$

$$\frac{(1+\xi_d)\,\omega c_{fd}^{-\alpha_2(\epsilon-1)} A_{fdt}^{-\varphi_1} Y_{ft}^{(1+\varphi)} \left(\frac{N_f}{N}\right)^{(1+\varphi)}}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\omega\mu(1-s)+(1-s_f))+(1+\varphi)g_f+r} \tag{19}$$

As in the previous section, we define the balanced growth path in this economy as the situation in which s is constant over time. We will distinguish between two types of the balanced growth path: when $\frac{v_{id}}{v_{ic}} \to 0$ (and so $s = 1$), $\frac{v_{id}}{v_{ic}} \to \infty$ with $s = 0$. In the appendix A1, we demonstrate that there is no balanced growth path with $s = s^* \in (0, 1)$. We can now state the key results predicted by the model

Proposition 2 the Balanced Growth Path with all Southern researchers in the dirty sector is only possible when number of researchers in South is larger than the number of researchers in North i.e. $\mu \geq 1$

Proof

We will first consider the long-run growth of the value of the clean blueprint and then compare it to the growth of the value of the dirty blueprint

The value of the clean blurprint is determined by expression 14. The first term in this expression grows at the growth rate of $A_{ct}^{-\varphi_1} Y_t^{(1+\varphi)}$ given by $\alpha_1(\epsilon-1)\gamma\lambda(\mu s+\omega)+(1+\varphi)g$. The second term grows at the growth rate of $A_{fct}^{-\varphi_1} Y_{ft}^{(1+\varphi)}$ given by $\alpha_1(\epsilon-1)\gamma\lambda(\omega\mu s+1)+(1+\varphi)g_f$.

In the long-run, the growth of total output is determined by the growth of the fastest growing sector: if sector i grows faster than the other sector, σ_i, the share of sector i in total output approaches unity[1] and thus the growth of output is determined by the growth of the economy in the long run. In the case of the foreign economy, if $\mu < 1$ the clean sector is always the fastest sector and thus $g_f = \frac{\alpha_1}{1-\alpha}\gamma\lambda$. In the case of the domestic economy, we have to distinguish between the two cases. If $\mu < \omega$, then $g_c > g_d$ and $g = \frac{\alpha_1}{1-\alpha} g_c = \gamma\lambda\omega$. If $\mu < \omega$, then $g_c < g_d$ and $g = \frac{\alpha_1}{1-\alpha} g_d = \gamma\lambda\mu$.

[1] recall that throughout the paper we assume that the two goods are sufficiently substitutable to ensure that dirty resource declines when all research is channelized to the clean sector, i.e. $(1+\varphi) < 0$

Next, note that when $\mu < 1$ and when $s = 0$, in the long run the first term in 18 grows slower than the second term and thus the long-run growth rate of the value of the blueprint in the clean sector is equal to $\alpha_1 (\epsilon - 1) \gamma\lambda + (1 + \varphi) \frac{\alpha_1}{1-\alpha}\gamma\lambda$. Meanwhile, the growth rate of the value of the blueprint in the dirty sector will be equal to

$$\max \left\{ \left(\alpha_1 (\epsilon - 1) \gamma\lambda\mu + (1 + \varphi) \frac{\alpha_1}{1-\alpha}\gamma\lambda \max \{\mu, \omega\} \right), \left(\alpha_1 (\epsilon - 1) \gamma\lambda\omega\mu + (1 + \varphi) \frac{\alpha_1}{1-\alpha}\gamma\lambda \right) \right\}$$

which is always smaller than the growth in the clean sector stated above. This implies that at some point in time the value of the clean blueprint overtakes the value of the dirty blueprint and all researchers move to the clean sector. This would violate the condition that s stays constant over time.

QED

This condition brings important implications for the effectiveness of the policy support for the dirty sector in South. When the population of researchers in South is smaller than the population of researchers in North, there is no positive (and finite) research subsidies ξ_d and ξ_c which could keep researchers in South in the dirty sector in the long-run.

Second, note that the Balanced Growth Path with all Southern researchers working in the clean sector is possible for any parameter μ. To understand this, note that when $s = 1$ then the growth of the first term in 19 ($(1 + \varphi) g$) as well as the growth of the second term ($(1 + \varphi) g_f$) is negative[2] . Meanwhile the growth of both terms in 18 must be positive [3]

This implies that if A_c is sufficiently high to ensure that all researchers work in the clean sector the economy will follow the balanced growth path with $s = 1$.

As a result the government in South is always able to incentivize switch of its researchers. Indeed, all what is needed is a temporary subsidy ξ_c which ensures that researchers work in the clean sector to allow A_c to grow sufficiently large. In the long-run, the subsidy can be withdrawn since now the lock-in effect works in favor of the clean sector.

[2] Recall that throughout the paper we assume that the two goods are sufficiently substitutable to ensure that dirty resource declines when all research is channelized to the clean sector, i.e. $(1 + \varphi) < 0$

[3]This is because by 13 g cannot be larger than $\frac{\alpha_1}{1-\alpha}\gamma\lambda (\mu + \omega)$ and g_f cannot be larger than $\frac{\alpha_1}{1-\alpha}\gamma\lambda (1 + \omega\mu)$. Thus $\alpha_1 (\epsilon - 1) \gamma\lambda (\mu + \omega) + (1 + \varphi) g > \alpha_1 (\epsilon - 1) \gamma\lambda (\mu + \omega) + (1 + \varphi) \frac{\alpha_1}{1-\alpha}\gamma\lambda (\mu + \omega) = \frac{\alpha_1}{1-\alpha}\gamma\lambda (\mu + \omega) > 0$ and, analogously, $\alpha_1 (\epsilon - 1) \gamma\lambda (\omega\mu + 1) + (1 + \varphi) g_f > 0$

6 The consequences of the switch and the choices of the South Government

In the analysis until now we have assumed the absence of governmental subsidies in the South. In this section we will demonstrate that if the Southern government cares about the long-run growth of its economy, it will have both, an opportunity and an incentive to introduce a system of subsidies which encourages Southern researchers to follow the Northern switch and to move the economy to the balanced growth path with all world researchers working in the same sector. To do so, we first have to examine the consequences of the two balanced growth paths for economic growth and the use of dirty resource.

Consequences for economic growth in South

In this subsection we will explore what is the long-run growth rate of the Southern economy when all researchers in both regions work in the clean sector ($s = s_f = 1$) and when the research effort is split: researchers in North work in the clean sector and researchers in South work in the dirty sector ($s = 0$, $s_f = 1$). In the former case the growth of productivity in the clean and dirty sector can be derived using 6 and 7 as$g_c = \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\left(\mu+\omega\right)$ and $g_d = 0$, respectively. Inserting it into the expression for GDP growth in 13, we obtain

$$g_t = \frac{\alpha_1}{1-\alpha}\left(\sigma_{ct}\gamma\lambda\left(\mu+\omega\right)\right)$$

Notice that in the long-run the clean sector will dominate in the economy (i.e. $\sigma_{ct} \equiv \frac{p_{ct}Y_{ct}}{Y_t} = \frac{\left(A_{ct}^{1-\alpha_1}c_{ct}^{-\alpha_2}\right)^{\epsilon-1}}{\left(A_{dt}^{1-\alpha_1}c_{dt}^{-\alpha_2}\right)^{\epsilon-1}+\left(A_{ct}^{1-\alpha_1}c_{ct}^{-\alpha_2}\right)^{\epsilon-1}} \to 1$). Therefore the expression above implies that the long-run growth of the Southern economy is given by $g = \frac{\alpha_1}{1-\alpha}\gamma\lambda\left(\mu+\omega\right)$

In the case of split ($s = 0$, $s_f = 1$), the two sectors will grow at exactly the same rate, $g_c = \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\omega$ and $g_d = \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\mu$. When this is inserted in the expression for growth, we obtain

$$g = \frac{\alpha_1}{1-\alpha}\gamma\lambda\left(\sigma_{ct}\omega+\sigma_{dt}\mu\right)$$

Since in along this balanced growth path, the productivity in the dirty sector grows faster than the clean sector[4], in the long run the dirty sector will dominate

[4] Recall from proposition 2 that for the balanced growth path with $s = 0$, it must be that $\mu > 1 > \omega$ and hence $g_c = \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\omega < \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\mu = g_d$

the economy implying that the long run growth of the Southern economy is given by $g = \frac{\alpha_1}{1-\alpha}\gamma\lambda\mu$. This is strictly smaller than in the case of all research effort concentrated in the clean sector.

Consequences for the use of dirty resource

The next step is to examine the effects of the two possible balanced growth paths on the use of dirty resource. By combining 3 with 11 and 12, we can find that the equilibrium level of the use of the dirty resource is given by

$$R_{dt} = constant * \left[\frac{\left(A_{dt}^{-\varphi_1} c_{dt}^{\alpha_2(1-\epsilon)}\right)}{\left(A_{dt}^{-\varphi_1} c_{dt}^{\alpha_2(1-\epsilon)}\right) + \left(A_{ct}^{-\varphi_1} c_{ct}^{\alpha_2(1-\epsilon)}\right)} \right]^{\frac{\varphi+1}{\varphi}} \left(A_{dt} c_{dt}^{-1}\right)^{\frac{1-\alpha_1}{1-\alpha}}$$

When all researchers in the world work in the clean sector, the growth of A_d is equal to zero. On the other hand A_c follows a constant growth. The expression inside the square brackets goes to zero asymptotically when the dirty and clean goods are substitutes ($\epsilon > 1$ and so $\varphi < 0$). This will translate into a decline of R_d towards zero as long as $-\varphi > 1$. In other words the technological progress in the clean sector will lead to a decline of use of dirty resource only if the elasticity of substitution between clean and dirty goods is high enough to ensure that $-\varphi = (\epsilon - 1)(1 - \alpha) > 1$. This condition mirrors the condition on elasticity of substitution in the Acemoglu et al. paper.

In contrast in the Balanced Growth Path with all Southern researchers working in the dirty sector, the productivity in the dirty sector grows faster than the productivity in the clean sector. In this situation, the term within the square brackets approaches unity. Consequently, in the long-run the use of dirty resource grows exponentially at the rate $\frac{1-\alpha_1}{1-\alpha} g_d = \frac{\alpha_1}{1-\alpha}\gamma\lambda\mu > 0$. This result does not depend on the elasticity of substitution between the two goods.

Subgame Perfect Nash Equilibrium

In order to endogenize the behavior of the North and South governments we consider the following game: first the North region, as technology leader, chooses the the subsidy rate for clean and dirty research. This choice is observed by the government in South which now has to make its own decision. To simplify this game as much as possible, we assume that the sole objective of the North government is to maximize the long-run growth of welfare, which is increasing in the growth of output and decreasing in the growth of the use of dirty resource. We assume that the sole objective of the South government is to maximize the long-run growth of output.

Notice that in our specification either government can always choose a pair ξ_c and ξ_d which flips the sign of $(v_{ict} + \xi_c) - (v_{idt} + \xi_d)$ in any direction. This means that the governments always have a possibility to induce the switch of research to either sector.

The Southern government will always set a subsidy which ensures that Southern researchers work in the same sector as the North researchers. By the argument in the previous subsection, this will bring the long-run growth rate equal to $\frac{\alpha_1}{1-\alpha}\gamma\lambda\,(\mu+\omega)$. Otherwise, i.e. if the government let its researchers to choose a different sector, the long-run growth of the economy will be $\frac{\alpha_1}{1-\alpha}\gamma\lambda \max{(\mu,\omega)}$.

Recalling that the two regions are symmetric, this strategy of the Southern government implies that, no matter which sector North will subsidize, the long-run growth in North will always be equal to $g = \frac{\alpha_1}{1-\alpha}\gamma\lambda\,(\mu+\omega)$.

As a result if the government in North was rational, in this model it shall always choose the subsidy to the clean sector. This ensures that all research resources are focused on the development of this sector.

The proposition summarizes this result

Proposition 3 If South and North play a Stalkerberg game where the payoffs for South is the long-run economic growth and the payoff for North depends positively on long-run economic growth and quality of an environment, then the unique subgame perfect Nash equilibrium is defined as follows:

- South will always choose the structure of the research subsidies which ensures that South researchers work in the same sector as North researchers
- North will choose a subsidy which ensures that all North researchers work for the clean sector.

Proof

In the text

7 Conclusions

Building on the framework of Acemoglu et al. (2012) and Grossman and Helpman (1991) we have presented a North-South model in which both regions can innovate in clean or in dirty technologies and which allows the regions to trade with the technological goods (machines, which embodies the innovations). A successful innovation in the South allows the innovator to capture the domestic market and, if the innovation is applicable externally (which happens with exogenous probability), the market in the North region. A successful innovator will then receive a stream of profits until his market will not be 'stolen' by a subsequent innovation - again coming either from South or from North

We find that a policy which gives an incentivise for Northern innovators to switch from dirty to clean technologies has two effects which are related to business stealing: On the one hand the switch implies more intensive business stealing in the clean sector and shorter expected period in which a successful firm can enjoy its profits. It also implies less research and so less competition in the dirty sector. On the other hand, more researchers working in the clean sector increase the value of the market which a potential innovator in the clean sector can capture. In the long run the latter effect dominates.

More generally, in the absence of any policy, the possibility of business stealing innovation implies that the two groups of researchers will tend to concentrate effort in the same sector in the long run. An exogenous shift of a group of researchers to a clean sector could be sufficient to attract the remaining part of the research population.

Importantly, concentration of the effort in one sector has an important consequences for economic growth. If the two groups of researchers work on two substitutable technologies, the final output grows slower than if the effort of an entire population is concentrated. A Southern government which cares about long-run economic growth might then be willing to remove any obstacles for the transition of Southern researchers to the sector, which has been selected by the Northern researchers.

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Appendix A1 - Proof that there in no balanced growth path with $s = s^* \in (0,1)$ in the asymmetric case

First note that for $s^* \in (0,1)$, the researchers must be indifferent between the work in the two sectors, i.e. $v_{id} = v_{ic}$ at any moment in time

Second note that this implies that the growth of the blueprint value in the two sectors must be exactly equal. The growth of the clean sector blueprint would be given by

$$\frac{1}{v_{ic}}\frac{c_c^{-\alpha_2(\epsilon-1)}A_{ct}^{-\varphi_1}Y_t^{(1+\varphi)}}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\mu s+\omega s_f)-(1+\varphi)g-r}(\alpha_1(\epsilon-1)\gamma\lambda(\mu s+\omega)+(1+\varphi)g)$$

$$+\frac{1}{v_{ic}}\frac{\omega c_{fc}^{-\alpha_2(\epsilon-1)}A_{fct}^{-\varphi_1}Y_{ft}^{(1+\varphi)}\left(\frac{N_f}{N}\right)^{(1+\varphi)}}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\omega\mu s+s_f)+(1+\varphi)g_f+r}(\alpha_1(\epsilon-1)\gamma\lambda(\omega\mu s+1)+(1+\varphi)g_f) \tag{20}$$

and the growth of the dirty sector blueprint would be given by

$$\frac{1}{v_{id}}\frac{c_d^{-\alpha_2(\epsilon-1)}A_{dt}^{-\varphi_1}Y_t^{(1+\varphi)}}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\mu(1-s)+\omega(1-s_f))-(1+\varphi)g-r}(\alpha_1(\epsilon-1)\gamma\lambda\mu(1-s)+(1+\varphi)g)$$

$$+\frac{1}{v_{id}}\frac{\omega c_{fd}^{-\alpha_2(\epsilon-1)}A_{fdt}^{-\varphi_1}Y_{ft}^{(1+\varphi)}\left(\frac{N_f}{N}\right)^{(1+\varphi)}}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\omega\mu(1-s)+(1-s_f))+(1+\varphi)g_f+r}(\alpha_1(\epsilon-1)\gamma\lambda\omega\mu(1-s)+(1+\varphi)g_f) \tag{21}$$

Now, let Ω be an element from the set $\left\{A_{ct}^{-\varphi_1}Y_t^{(1+\varphi)}, A_{fct}^{-\varphi_1}Y_{ft}^{(1+\varphi)}, A_{dt}^{-\varphi_1}Y_t^{(1+\varphi)}, A_{fdt}^{-\varphi_1}Y_{ft}^{(1+\varphi)}\right\}$, which has the fastest growth rate. By equating 20 and 21, using that $v_{id} = v_{ic}$ and dividing both sides by Ω, we get

$$\frac{c_c^{-\alpha_2(\epsilon-1)}(\alpha_1(\epsilon-1)\gamma\lambda(\mu s+\omega)+(1+\varphi)g)}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\mu s+\omega s_f)-(1+\varphi)g-r}\left[\frac{A_{ct}^{-\varphi_1}Y_t^{(1+\varphi)}}{\Omega}\right]$$

$$+\frac{\omega c_{fc}^{-\alpha_2(\epsilon-1)}\left(\frac{N_f}{N}\right)^{(1+\varphi)}(\alpha_1(\epsilon-1)\gamma\lambda(\omega\mu s+1)+(1+\varphi)g_f)}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\omega\mu s+s_f)+(1+\varphi)g_f+r}\left[\frac{A_{fct}^{-\varphi_1}Y_{ft}^{(1+\varphi)}}{\Omega}\right]$$

$$-\frac{c_d^{-\alpha_2(\epsilon-1)}(\alpha_1(\epsilon-1)\gamma\lambda\mu(1-s)+(1+\varphi)g)}{(1-\alpha_1(\epsilon-1)\gamma)\lambda(\mu(1-s)+\omega(1-s_f))-(1+\varphi)g-r}\left[\frac{A_{dt}^{-\varphi_1}Y_t^{(1+\varphi)}}{\Omega}\right]$$

$$-\frac{\omega c_{fd}^{-\alpha_2(\epsilon-1)}\left(\frac{N_f}{N}\right)^{(1+\varphi)}\left(\alpha_1\left(\epsilon-1\right)\gamma\lambda\omega\mu\left(1-s\right)+\left(1+\varphi\right)g_f\right)}{\left(1-\alpha_1\left(\epsilon-1\right)\gamma\right)\lambda\left(\omega\mu\left(1-s\right)+\left(1-s_f\right)\right)+\left(1+\varphi\right)g_f+r}\left[\frac{A_{fdt}^{-\varphi_1}Y_{ft}^{(1+\varphi)}}{\Omega}\right]=0$$

This condition would need to define the equilibrium value of Ω. Note that at least one of the elements in the square bracket is constant. The terms with the constant square brackets will define the s^* for $t \to \infty$. However, since we cannot select s which would equate all growth rates of the elements in the set $\left\{A_{ct}^{-\varphi_1}Y_t^{(1+\varphi)}, A_{fct}^{-\varphi_1}Y_{ft}^{(1+\varphi)}, A_{dt}^{-\varphi_1}Y_t^{(1+\varphi)}, A_{fdt}^{-\varphi_1}Y_{ft}^{(1+\varphi)}\right\}$, there will be at least one term which will be zero when $t \to \infty$ and which will be positive when t is finite. This implies that s will be different between t finite and t infinite. This violates the condition of the balanced growth path.

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