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Abstract

We analyze public investment in basic research in a multi-country, multi-industry environment with international trade. In our economy, basic research generates ideas which private firms take up in applied research to develop new varieties. Such development requires industry-specific know-how. A country's current specialization in international trade thus determines which ideas can be commercialized domestically. We demonstrate that the equilibrium is consistent with key patterns observed from the data. We then compare basic research investments of national governments with optimal investments of a global social planner. We show that national investments are inefficient along three dimensions: (1) There is typically too little total investment in basic research. (2) Basic research is too heavily concentrated in industrialized countries. (3) And basic research is potentially insufficiently directed to support innovation in complex, high-tech industries.

Keywords

applied research, basic research, economic growth, international trade, knowledge spillover, optimal policy

JEL Classification

F10, F43, H40, O31, O38

'We will [guarantee that] we make money in Germany out of the products and ideas [from research]. It is nice to do research with taxpayers' money, but it is even nicer if we make money out of it [...].' (Annegret Kramp-Karrenbauer, 2018)[1]

1 Introduction

Public investment in basic research is an important policy instrument to foster innovation and economic growth. While the literature analyzing basic research policies mostly assumes a closed economy perspective, investments by national governments cannot be fully understood in isolation, as it will be detailed below. In this paper, we seek to fill the gap by jointly analyzing basic research investments of many countries that engage in international trade.

Basic research provides knowledge, networks, and understanding needed for innovation. It has, however, little commercial value in itself. The main motive for national investments in basic research is thus to support private innovation in the domestic economy. The costs and benefits associated with these investments critically depend on a country's integration in the world economy. On the one hand, innovative domestic firms benefit from supplying their products to the world market. On the other, innovation combines insights and ideas from basic research with industry-specific know-how. Such know-how is built-up via production, and a country's current specialization in international trade will thus feed back into its potential to innovate in different industries. Ceteris paribus, the more advanced and the more diverse the domestic economy, the higher its potential to innovate and, hence, the larger the domestic gains from investments in basic research. These effects are of first order importance for basic research policies. Our paper is the first to analyze them in a multi-country, multi-industry general equilibrium setting. This provides a coherent picture of public investment in basic research in a global economy. It also allows to analyze important policy questions that could not be addressed without such a comprehensive framework. In particular,

[1] Annegret Kramp-Karrenbauer, leader of the CDU Germany, stated at the electoral party convention on the 7^{th} of December 2018: *'Wir werden den Mut zur Forschung haben und vor allen Dingen werden wir die Klugheit haben, dass bei uns nicht nur geforscht wird, sondern dass von der Forschung die Wertschöpfungskette so gelegt wird, dass wir mit den Produkten, dass wir mit den Ideen auch in Deutschland Geld verdienen. Es ist ja schön, wenn auf unser Steuergeld hier geforscht wird, aber noch schöner ist es, wenn danach hier auch Geld verdient wird. Das ist doch der Sinn unserer Wirtschaft und der sozialen Marktwirtschaft.'*

we show that from a global perspective investments in basic research by national governments are inefficient along three dimensions: (1) There is typically too little global investment in basic research. (2) Basic research is too heavily concentrated in industrialized countries. (3) And basic research is potentially not sufficiently directed to support innovation in complex high-tech industries. Our framework also provides a new, global perspective on the Bayh Dole Act: We show that while such policies are never welfare optimal, they may mitigate global underinvestments in basic research.

Model and Key Results

Our model embeds a two-stage innovation process with public basic research and private applied research in a variant of the multi-country, multi-industry general equilibrium model of international trade developed in Schetter (2018). Basic research generates ideas that are industry-specific and can be taken up by the private sector to develop new varieties in that industry. There is a global patent for each variety, and the owner of that patent is free to choose his location for production. Transportation costs are zero, as are tariffs on imports or exports. Countries differ in their productive knowledge while industries differ in their complexity. Firms can freely choose the quality of their variety which—for a given complexity level of their industry—gives them endogenous control over the production requirements. Quality differentiation is, however, subject to functional minimum requirements that are the more demanding to be satisfied the more complex an industry.

To analyze the model we proceed in two steps. We first study the equilibrium for a given set of varieties in each industry. In the second step, we examine basic research investments and applied research by the private sector which develops the varieties. In the ensuing equilibrium in the first step, countries with higher productive knowledge are more diversified. In particular, in countries with the highest productive knowledge, production takes place over the whole range of industries, from complex to simple ones, while countries with low productive knowledge are unable to attract firms in particularly complex industries such as aircraft or high-tech engineering or pharmaceutical, in line with what we observe from the data (Hausmann and Hidalgo, 2011; Bustos et al., 2012; Schetter, 2018). We show in the second step that this pattern of international specialization has profound consequences for countries' investments in basic research.

To study these investments, we start from key characteristics of basic research and stylized facts as documented in Section 2. We assume that public basic research impacts the economy indirectly via the generation of ideas that private firms can take up in applied research to develop new varieties in an industry. Ideas diffuse locally and then globally, reflecting the importance of both local effects of basic research and global spillovers through the dissemination of ideas.[2] To commercialize an idea, industry-specific, tacit know-how is needed. It is acquired via domestic production, i.e. a country's manufacturing base (broadly defined) is a pivotal element of its innovation system (Nelson, 1959; Arrow, 1962; Pisano and Shih, 2012; McKinsey Global Institute, 2012; Akcigit et al., 2016). We document stylized facts to corroborate this conjecture in Section 2. We allow governments to target their basic research investments to support innovation in specific industries, e.g. by prioritizing certain scientific fields. Such targeting, however, is necessarily imperfect.

National governments decide how many scientists they need to employ in basic research to maximize the well-being of their citizens, which boils down to weighing the costs associated with these investments against the domestic social value of patents for new varieties. We establish an equilibrium, henceforth called 'decentralized equilibrium', involving government decisions in basic research, applied research by private firms, an endogenous distribution of developed varieties across countries and industries, and production patterns and wage patterns across countries.

In this equilibrium governments of countries with high productive knowledge face both higher costs and benefits: Scientists earn higher wages in these countries, as they are more productive if they were employed as production workers. In addition, the domestic economy is more diversified which allows to commercialize ideas in a large set of industries.[3] We show that the latter dominates when basic research is at least as skill intensive as production, implying that countries with higher productive knowledge will employ more scientists in basic research.[4] In addition, thanks to their broad manufacturing base, these countries benefit more from knowledge spillovers from the

[2]A large literature documents various forms of international knowledge spillovers and spatial dependence in the diffusion of knowledge (Jaffe, 1989; Jaffe et al., 1993; Keller, 2002, 2004; Keller and Yeaple, 2013; Bahar et al., 2014).

[3]A more diversified economy is beneficial for two reasons: First, from the set of industries with domestic production, the government will target its basic research investments to the ones with highest value of new varieties. Ceteris paribus, the larger the set of industries where ideas can be commercialized domestically, the higher the gains from targeting basic research. Second, a more diverse economy increases the probability that ideas that do not fall in the targeted industries can nonetheless be commercialized domestically.

[4]This assumption is in line with the cumulative nature of basic research (Scotchmer, 1991, 2004; Nelson, 2004). More generally, it is a weak version of the idea that a stock of knowledge and technical expertise is needed to be able to effectively perform basic research.

rest of the world, and thus are highly innovative. Their high level of innovation allows these countries to capture a disproportionate share of global profits. These equilibrium results are consistent with salient features in the data (see Sections 2 and 5). To the best of our knowledge, our paper is the first to jointly rationalize these basic observations in general equilibrium.

We then compare investments by national governments to the optimal solution of a global social planner, to find that coordinated basic research policies would yield welfare improvements along three dimensions.[5] First, we document that the social planner would distribute investments in basic research more equally across countries. The basic intuition is that developing countries invest little in basic research because their domestic economy is not effective in science-driven innovation, implying that they suffer more from knowledge spillovers to the rest of the world compared to industrialized countries.

Second, we show that in spite of the inefficiently high concentration of basic research investments in countries with a high productive knowledge, global investments may not be targeted sufficiently towards high-tech industries. This counterintuitive result is rooted in the importance of tacit know-how for innovation and the 'nestedness' of countries' exports, i.e. in the fact that countries with a high productive knowledge successfully export varieties in both simple and complex industries while developing countries specialize in the simpler ones. Interestingly, inefficient targeting is particularly likely to occur if new industries—or products, for that matter—are relatively complex, high-tech industries.

Third, we show that aggregate investments are typically too low in the decentralized equilibrium. Hence, the decentralized solution in which each country decides on basic research investments produces too little knowledge for the world. In summary, a social planner will increase aggregate investments in basic research and—as a consequence of the first and second inefficiencies—correct the distribution of basic research investments across countries and industries. In turn, these redistributions of basic research imply that the social planner is able to stimulate more and more valuable innovations than in the decentralized equilibrium with a given amount of basic research investments.

[5] In this paper, we are comparing equilibrium investments by national governments to the preferred solution of a *global* social planner. The term (global) social planner will always refer to the latter while we speak of the former as the 'decentralized equilibrium'.

Our set-up also has interesting implications for the Bayh Dole Act[6] that incentivizes university researchers to get more engaged in the commercialization of their work. Such incentives arguably come at the cost of lowering their productivity in terms of pure science. Yet, they may be welfare-improving as they allow countries to capture a larger share of the gains from their own basic research. In turn, this induces countries to invest more in basic research and thereby contributes to closing the gap to globally efficient levels of investment in basic research.

Relation to the Literature

Our paper builds on a large literature that provides a thorough understanding of basic research and its effects on the overall economy. Let us briefly summarize this literature to show how it guides our modeling choices for the innovation process in Section 2.

Our model can be seen as an extension of an expanding variety model following Romer (1987, 1990) to a multi-country, multi-industry setting with basic and applied research, international trade, and knowledge diffusion. Accordingly, our work is related to the following strands of literature.

It is closest related to the literature that analyzes basic research investments with theoretical models. This literature mostly considers closed economies (Aghion and Howitt, 1996; Mansfield, 1995; Morales, 2004; Cozzi and Galli, 2009, 2014; Gersbach et al., 2018; Akcigit et al., 2013). Notable exceptions are Gersbach et al. (2013) who consider basic research investments of a small open economy, and Gersbach and Schneider (2015) who consider strategic basic research investments in a two-country model with access to foreign markets. Our set-up is very different and substantially richer insofar that we consider the general equilibrium with trade among many countries and an endogenous choice of location for production by private firms. Moreover, we allow that ideas produced by basic research efforts in one country diffuse locally and then globally and thus can be taken up by applied researchers in other countries which is absent in Gersbach and Schneider (2015). Hence, our model provides a framework for a comprehensive account of the effects of basic research investments by national governments. The multi-country set-up produces predictions about the distribution of basic research investments across countries and they can be related to cross-country data on these investments. With this connection, our work complements recent papers that assess various innovation policies in closed-economy models using micro data (Akcigit et al.,

[6]See https://www.energy.gov/gc/bayh-dole-act-usc retrieved on the 12^{th} of March, 2018.

2013; Garicano et al., 2016; Atkeson and Burstein, 2018).[7]

We also contribute to the literature analyzing innovation in the global economy that goes back at least to Grossman and Helpman (1991).[8] Recent contributions involve Atkeson and Burstein (2010), who consider a two-country Melitz-type model with product and process innovation. They find approximately the same effects of a change in trade costs on aggregate productivity as in models with product innovation only. Arkolakis et al. (2018) develop a variant of a Melitz model where firms can disentangle the location of market entry (innovation) from the location(s) of production. They use a calibrated version of their model to study the implications of a decline in the cost of multinational production. Our model shares the feature that highly innovative countries benefit from extracting a disproportionate share of global profits. In our model, however, this potential depends on governments' investments in basic research, which is the main focus of our work.

The diffusion of ideas from basic research and the ability to commercialize these ideas domestically are at the heart of the underlying government decision in our model. Our work is thus also, but less closely, related to recent work on the diffusion of ideas (Lucas and Moll, 2014; Buera and Oberfield, 2016). Compared to these papers, we use a simpler idea diffusion model but we focus on the distribution of national basic research policies that generate the ideas.

Organisation of the Paper

The remainder of this paper is organized as follows. In Section 2 we summarize key characteristics of basic research and present stylized facts that will guide our modeling choices. In Section 3, we introduce our model, first the macroeconomic environment and then the innovation process. Sections 4 and 5 present the equilibria for exogenously given and for endogenous investments in basic research, respectively. Section 6 analyzes the optimum of a global social planner. Section 7 compares the decentralized equilibrium and the social planner's solution. Section 8 provides extensions and discussions on complementary policy tools. Section 9 concludes.

[7]We analyze efficient levels of basic research. In that sense, our work is also related to a somewhat older empirical literature that measures the gains from (public) basic research (Mansfield, 1980; Griliches, 1986; Toole, 2012). Hall et al. (2010) provide a survey of the literature on measuring the returns to R&D in general.

[8]At a more general level, our work relates to the literature analyzing the growth effects of international trade, e.g. Peretto (2003), Acemoglu (2003), Galor and Mountford (2008), and Nunn and Trefler (2010).

2 Motivating Facts on Basic Research

In this section, we will summarize key characteristics of basic research and present stylized facts that will guide our modeling choices in the next section.

The OECD (2002) defines basic research as *'experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view.'* This definition immediately points to important characteristics of basic research.

First, new knowledge is the key outcome of basic research. This knowledge is a global public good. This observation and the associated lack of appropriability of the gains from basic research by private firms were at the center of the early literature identifying a need for public funding of basic research (Nelson, 1959; Arrow, 1962). Indeed, the major part of basic research is publicly funded and provided (Akcigit et al., 2013; Gersbach et al., 2018). While there are some joint efforts, e.g. at the EU level, the vast majority of basic research funding is provided by national (or even subnational) governments.[9] This may seem surprising given that new knowledge from basic research features key characteristics of a *global* public good. However, a series of influential papers (Jaffe, 1989; Jaffe et al., 1993; Anselin et al., 1997; Audretsch and Lehmann, 2004) documents that basic research also has significant local effects on innovation. In particular, basic research provides domestic firms with problem solvers, trained scientists, access to scientific networks and, in general, better access to new knowledge. This fosters the innovativeness and growth of local firms and their competitiveness on the world market.[10] Indeed, Figure 1 shows that on balance countries that had a high basic research intensity in the past patent more, and they earn a disproportionate share of global profits as measured by the ratio $\frac{GNI-GDP}{GDP}$.[11] These local effects are a key

[9]The Horizon 2020 program, for example, the largest EU funding program for research and innovation so far, amounts to EUR 77bn over the period 2014-2020. This compares to total EU-28 expenditures for R&D in the government and higher education sectors of over EUR 100bn in 2015 alone.

[10]Since the early studies by Mansfield (1980) and Link (1981), a series of empirical studies has shown that basic research has a significantly positive effect on productivity and growth in manufacturing industries (Griliches, 1986; Adams, 1990; Guellec and Van Pottelsberghe de la Potterie, 2004; Luintel and Khan, 2011; Czarnitzki and Thorwarth, 2012; McKinsey Global Institute, 2012). Local effects from basic research are also consistent with the spatial dependence in the diffusion of knowledge, cf. Footnote 2.

[11]We use average past investments because basic research impacts the economy with time lags and because entitlement to foreign profits is built up gradually through past innovation. Ireland has been excluded from Figure 1 (b) as it is an outlier due to its tax policy. Note that the regression line would

motive for national governments to invest in basic research.

Second, the definition of basic research also implies that basic research is embryonic in the sense that it has little or no commercial value in itself. New knowledge and ideas from basic research need to be commercialized through private applied research, which, in turn, results in new or improved products or production processes.[12] The use of ideas from basic research, however, requires industry-specific tacit know-how (Nelson, 1959; Arrow, 1962; Akcigit et al., 2013, 2016). Such know-how is mostly acquired through production and there is a rationale for a close proximity of innovation and production activities (Pisano and Shih, 2012; McKinsey Global Institute, 2012). A country's current specialization in production will therefore be an important determinant of the domestic economy's capability to make use of ideas from basic research. This is also reflected in the countries' patenting: As Figures 2(a) and (b) show, countries have a higher propensity to actively patent in industries with domestic production. In addition, on balance, countries tend to patent more in industries where they export more. This is true both when considering log exports and patents, normalized by industries' size and countries' population, respectively (Figure 2(c)), and when considering log RCA in exporting and patenting (Figure 2(d)).

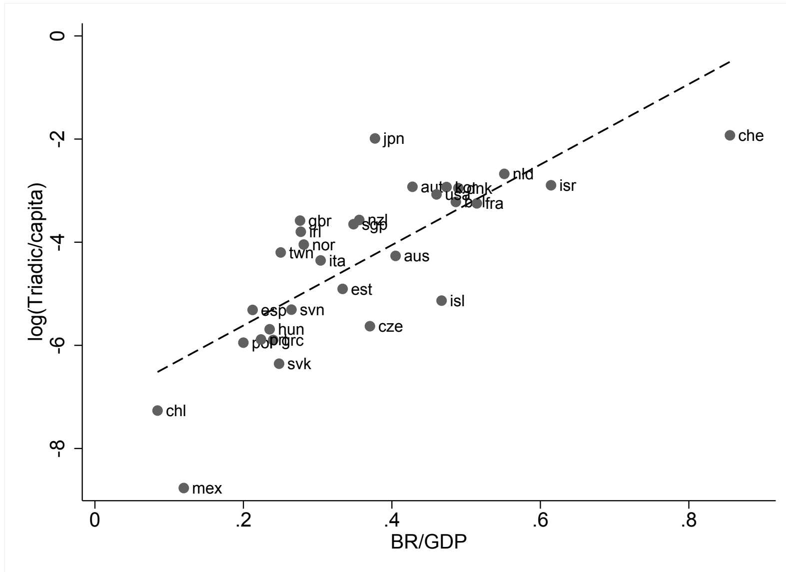
Third, with this relationship between domestic production and innovation in mind, governments may seek to target their basic research investments in order to best support innovation in the domestic economy. Indeed, the idea to optimally target basic research investments to industries or fields of science features prominently in policy debates (European Commission, 2012; Research Prioritisation Project Steering Group, Ireland, 2012). While the generation of new knowledge is inherently highly uncertain, there is some room for prioritizing basic research investments (Cohen et al., 2002). In our theoretical set-up, we will allow governments to target ideas from basic research to certain industries, but this targeting will be imperfect.

be more steeply upward sloping if it included Ireland.

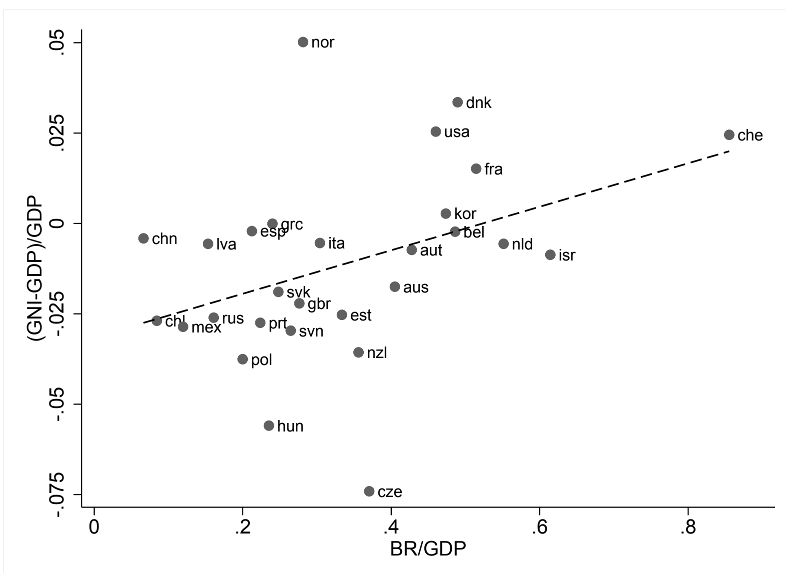
[12]A hierarchy of R&D activities is also the predominant view in the literature on basic research (Aghion and Howitt, 1996; Cozzi and Galli, 2014; Gersbach and Schneider, 2015; Akcigit et al., 2013).

Figure 1: Basic Research and Innovation

(a) Patenting



(b) Gains



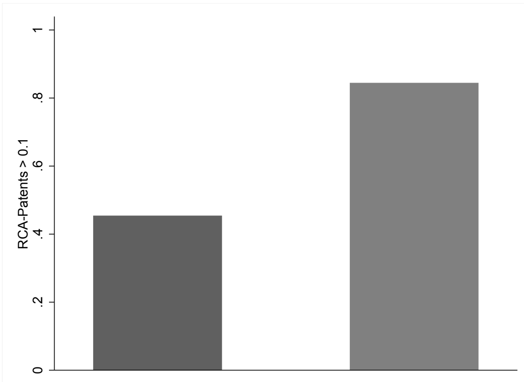
Notes: Data on basic research investments relative to GDP are taken from the OECD dataset 'Main Science and Technology Indicators' (downloaded in December 2017) and refer to the 20-year average from 1995 to 2015. The variables on the ordinate are for the year 2015.

Figure (a): Own illustration. Data are taken from the OECD dataset 'Main Science and Technology Indicators' (downloaded in December 2017). Triadic patents count the number of priority filings of triadic patent families by a country's inventors. We relate this number to the population size and take logs.

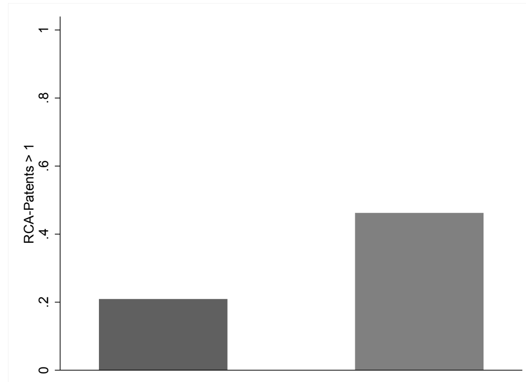
Figure (b): Own illustration. Data are taken from the OECD dataset 'National Accounts' (downloaded in December 2017).

Figure 2: Innovation and Production

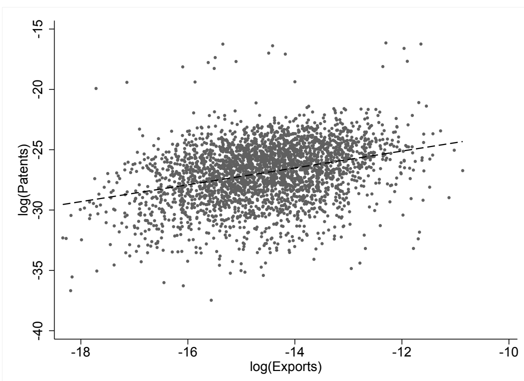
(a) Patenting with and without exporting (RCA 0.1)



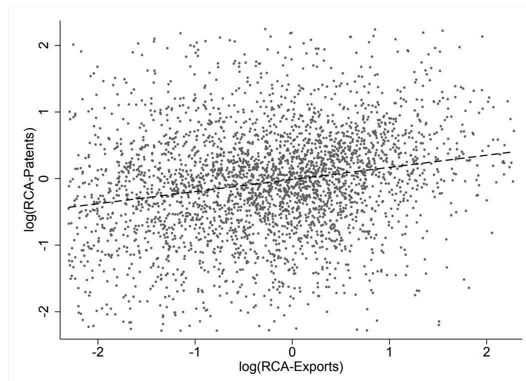
(b) Patenting with and without exporting (RCA 1)



(c) Exports and patents by industry



(d) RCA in exporting and patenting



Notes: Patents and exports are per country and per industry (ISIC Rev 3) in 2013. Exports are taken from CEPII BACI and converted from the HS6 classification system to the ISIC Rev 3 classification using the Worldbank's concordance tables. Patents are taken from the OECD 'Patents by Technology' dataset and converted from the IPC 4 patent classification system to the ISIC Rev 3 classification using the ALP concordance tables (Lybbert and Zolas (2014)).
Figure (a): Own illustration. The dark (bright) bar shows the fraction of country-industry pairs with RCA in patenting greater than 0.1 when RCA in exporting is smaller (greater) than 0.1 in 2013.
Figure (b): Own illustration. The dark (bright) bar shows the fraction of country-industry pairs with RCA in patenting greater than 1 when RCA in exporting is smaller (greater) than 1 in 2013.
Figures (c) and (d): Own illustration. A dot refers to a country-industry pair. Outliers with an RCA in exporting or patenting of smaller than 0.1 or greater than 10 are excluded. In Figure (c) export and patent data are normed by a country's population and an industry's total global exports.

3 Model

Starting from the key characteristics of basic research, we will now develop a theory of a country's investment in basic research in the global economy. To that end, we embed a two-stage innovation process with public basic research and private applied research into a variant of the multi-country, multi-industry model of international trade developed in Schetter (2018). In this model, industrialized countries successfully export varieties in both simple and complex industries, while developing countries systematically specialize in simple industries, in line with what we observe from the data. It is therefore particularly well suited for our purposes.

We begin by describing the macroeconomic environment before introducing innovation.

3.1 Macroeconomic Environment

We consider a world with a continuum of countries of measure 1.[13] Countries differ in some parameter r. For sake of concreteness, we think of r as representing a country's *productive knowledge*, but we can allow different interpretations of the origins of r or of r itself.[14] Across countries, r is assumed to be distributed on $\mathcal{R} := [\underline{r}, \bar{r}] \subset (0, 1)$ according to some density function $f_r(r)$ with associated distribution function $F_r(r)$. For convenience, we will assume that $f_r(r)$ is atomless, allowing us to uniquely identify countries with their productive knowledge r, and that $f_r(r)$ has continuous support.[15] The set of countries is identified with $\mathcal{R}$.

Country r is populated by $L^r > 0$ households. We assume that L^r is integrable on $[\underline{r}, \bar{r}]$. Each household is endowed with one unit of labor that he supplies inelastically. Labor is perfectly immobile across countries, but perfectly mobile across a finite set $\mathcal{I}$ of industries, indexed by $i \in \mathcal{I} := \left\{\underline{i}, ..., \bar{i}\right\}$ with $0 < \underline{i} < \bar{i}$. The index i identifies the industry and simultaneously characterizes the complexity of varieties in the industry, as detailed below.[16] $\underline{i}$ and $\bar{i}$ denote the lowest and highest complexity levels of industries in the world, respectively. Within each industry, there is a continuum of horizontally differentiated varieties, $j \in [0, N_i]$, where N_i is the (endogenous) measure of varieties in industry i. We can identify a given variety—henceforth called a product—by a pair (i, j). All products are final consumption goods. They can be offered in different

[13] With a continuum of countries, individual basic research investment decisions do not impact other countries' decisions. This arguably provides the most realistic set-up for analyzing real-world basic research investments. We provide further discussions in Section 8.

[14] The variable r is a reduced-form parameter that can capture anything that contributes to a country's productive potential. It may include a country's infrastructure and institutions that foster complex, high-tech industries, for example, or simply the skill level of labor.

[15] At the expense of additional notational complexity, the analysis can be performed for distributions with mass points or without continuous support.

[16] Analogously to the productive knowledge of countries, we will assume that industries differ in their complexity such that there is a one-to-one mapping from an industry to its complexity. This is again for convenience only and not essential in any way.

qualities, as detailed below, and are freely traded across the world. We use $\mathcal{Q}_{i,j}$ to denote the set of qualities of product (i, j) offered.

3.1.1 Households and Consumption

Households derive utility from the quality and the quantity consumed of each of the available products, $(i, j) \in \mathcal{I} \times [0, N_i]$ according to the following nested CES-utility

$$U\left(\{c_{i,j,q}\}_{(i,j,q)\in\mathcal{I}\times[0,N_i]\times\mathcal{Q}_{i,j}}\right) = C, \tag{1}$$

where[17]

$$C := \left[\sum_{i\in\mathcal{I}}\left[\psi_i^{\frac{1}{\sigma_I-1}}\left(\int_0^{N_i}\left(\int_{q\in\mathcal{Q}_{i,j}} qc_{i,j,q}\,dq\right)^{\frac{\sigma_v-1}{\sigma_v}}dj\right)^{\frac{\sigma_v}{\sigma_v-1}}\right]^{\frac{\sigma_I-1}{\sigma_I}}\right]^{\frac{\sigma_I}{\sigma_I-1}}. \tag{2}$$

In the consumption basket defined in (2), $c_{i,j,q}$ is the consumed amount of product (i, j) at quality level q. The parameter ψ_i is an industry-specific demand shifter. With the above specification, higher qualities of a unit of product (i, j) are valued higher by the household, and different qualities of the product (i, j) are perfect substitutes.[18] The parameter σ_v describes the elasticity of substitution between varieties within a given industry, and the parameter σ_I describes the elasticity of substitution between different industries. We will assume that products are more substitutable within industries than across industries, and that both elasticities are greater than 1, i.e. $\sigma_v > \sigma_I > 1$.

Perfect substitutability between different qualities of the same product implies that all qualities of a product will be sold at the same quality-adjusted price. This quality-adjusted price is denoted by $\rho_{i,j} := \frac{p_{i,j,q}}{q}$, where $p_{i,j,q}$ denotes the globally prevailing price of product (i, j) of quality q.

Our economy admits a global representative household. While domestic production and consumption will matter for basic research policies of national governments, it suffices to consider this representative household to characterize the demand side of our economy. Let $c_{i,j} := \int_{\mathcal{Q}_{i,j}} qc_{i,j,q}dq$ denote total quality-adjusted consumption of product (i, j). The representative household maximizes (1) with respect to his budget constraint

$$\sum_{i\in\mathcal{I}}\int_0^{N_i}\rho_{i,j}c_{i,j}\,dj \leq \int_{\underline{r}}^{\overline{r}}\left[w^r\left(L^r - L^r_{BR}\right) + \Pi^r\right]f_r(r)dr\ , \tag{3}$$

[17]The equilibrium approach also works for a finite or discrete countable set of quality levels. In this case the inner integral is replaced by the corresponding sum.

[18]Note that perfect substitutability is conditioned on a variety within a given industry.

where w^r denotes the wage of the representative household in country r, L^r_{BR} denotes labor employed in basic research in country r, and Π^r aggregate profit income of the population in country r as will be detailed below. It is well-known (Dixit and Stiglitz, 1977), that such an optimization problem yields the following demand for product (i, j)

$$c_{i,j} = \psi_i \left(\frac{P_i}{\rho_{i,j}}\right)^{\sigma_v} \left(\frac{P}{P_i}\right)^{\sigma_I} C \ , \tag{4}$$

where $P_i = \left(\int_0^{N_i} \rho_{i,j}{}^{1-\sigma_v}\, dj\right)^{\frac{1}{1-\sigma_v}}$ and $P = \left(\sum_{i\in\mathcal{I}} \psi_i P_i{}^{1-\sigma_I}\right)^{\frac{1}{1-\sigma_I}}$ are the globally prevailing industry-specific and aggregate price indices.

3.1.2 Production Technologies

Industries differ in their complexity i, which is the same for all varieties within a given industry. To model complexity of production, we follow Schetter (2018). Specifically, if a firm in industry i fabricates products of a quality q in country r and hires an amount of labor $l_i(r)$, its expected output denoted by $\mathbb{E}[x_i]$ is given by

$$\mathbb{E}[x_i] = [r]^{iq^\lambda} l_i(r), \quad q \geq 1 \ , \tag{5}$$

where λ ($\lambda > 0$) is a parameter and the lower bound of q is a minimum-quality functional requirement that is assumed to be 1 for all industries.[19] The rationale for the technology embodied in (5) is as follows. Production of a product with complexity i and quality q requires that a measure of tasks iq^λ is simultaneously performed successfully. We can think of i as representing the number of tasks involved in production, where quality q scales the intensity or overall difficulty of each task. The parameter λ measures the elasticity of this intensity with respect to quality. In the special case of $\lambda = 1$, this intensity is linear in quality. The higher the productive knowledge of a worker, r, the better he is at performing tasks. Specifically, $[r]^{iq^\lambda}$ is the probability of success of a worker with productive knowledge r producing a product of complexity i and quality q. Overall, the production technology implies that productive knowledge r is valuable in production, and more so for higher quality and more complex products.

There are constant returns to scale with respect to labor. Hence, we can apply the law of large numbers with regard to the amount of units that are produced successfully

[19] Such requirements are product-intrinsic and arise from the necessary characteristics that a given product needs to satisfy in order to serve its intended purpose. Stricter requirements may also be introduced by law. Cf. Schetter (2018) for a detailed account of these requirements.

by a density of labor input equal to $l_i(r)$ and thus we dispense with the expectation operator in (5) and in the remainder of the paper.[20]

3.1.3 Market Structure and Firm Optimization

There is a monopolist for each variety j of each industry i who owns a global patent to manufacture his variety. A patent covers all qualities of the respective variety. All firms within a given industry face the same optimization problem, independent of the specific variety $j \in [0, N_i]$. For convenience, we will henceforth use the index i to identify both an industry and a *representative* firm within this given industry that produces a product. Hence the complexity level, the representative firm, and the representative product are indexed with i. The pair (i, j) is only used when there is a need to differentiate explicitly between varieties.

The representative firm i chooses a set of countries, where it is willing to open up production sites. This set is denoted by $\mathcal{R}_i$. Moreover, in each production site where it is operating, the firm selects a product quality level, $q_i(r)$, and chooses a globally prevailing quality adjusted price ρ_i. Finally, the firm chooses a distribution of output among the production sites, $x_i(r)$, to meet the demand for its variety which it takes as given. To produce the output in each production site, the firm demands the necessary amount of labor, $l_i(r)$. The optimization problem of firm i is thus as follows:

$$\max_{\mathcal{R}_i,\rho_i,\{q_i(r)\}_{r\in\mathcal{R}_i},\{x_i(r)\}_{r\in\mathcal{R}_i},\{l_i(r)\}_{r\in\mathcal{R}_i}} \int_{r\in\mathcal{R}_i} \left[\rho_i q_i(r) x_i(r) - l_i(r) w^r\right] f_r(r) dr \ , \tag{6}$$

$$\begin{aligned} s.t. \quad & x_i(r) = [r]^{i q_i(r)^\lambda} l_i(r) \ , \\ & \int_{r\in\mathcal{R}_i} q_i(r) x_i(r) f_r(r) dr = c_{i,j} = \psi_i \left(\frac{P_i}{\rho_i}\right)^{\sigma_v} \left(\frac{P}{P_i}\right)^{\sigma_I} C \ , \\ & q_i(r) \geq 1 \ , \forall r \in \mathcal{R}_i \ , \\ & \mathcal{R}_i \subseteq \mathcal{R} \ . \end{aligned}$$

It is useful to introduce the notion of *effective output* of representative firm i,

$$\chi_i := \int_{r\in\mathcal{R}_i} q_i(r) x_i(r) f_r(r) dr \ .$$

With this notion, representative firm i's decision problem boils down to the following two sub-decisions:

[20] Throughout this paper, we follow the convention and apply an appropriate law of large numbers to a continuum of random variables.

(i) The choice of locations for production and associated qualities to minimize the cost per unit of effective output;

(ii) The choice of a quality-adjusted price, given the minimal costs per unit of effective output. Effective output and also the labor input are then determined by the size of the demand.

Note that a firm will open up production sites in two or more countries only if they share the minimal costs per unit of effective output, in which case the firm is indifferent as to the allocation of the production of its total effective output, χ_i, to these countries.

For each production site, firms will endogenously choose the quality which best complements the local skill level. In particular, they choose the quality that maximizes their productivity in quality-adjusted terms, $q\,[r]^{iq^\lambda}$. Taking derivatives and considering the minimum-quality constraint yields the optimal quality for the product of firm i in country r

$$q_i(r) = \max\left\{1, \left[-\frac{1}{\lambda i \ln(r)}\right]^{\frac{1}{\lambda}}\right\}, \qquad \forall (i,r) \in \mathcal{I} \times \mathcal{R}_i \ . \tag{7}$$

Whenever a firm is not constrained by the minimum-quality requirement, we have $q_i(r) = \left[-\frac{1}{\lambda i \ln(r)}\right]^{\frac{1}{\lambda}}$ and we will say that it is operating at *preferred quality*. Preferred quality is increasing in r, i.e. countries with higher productive knowledge will produce higher quality, in line with empirical evidence.[21]

It is useful to introduce notation for the boundary complexity and skill levels that just allow production at preferred quality. These boundaries are determined by the optimality of the minimum-quality

$$\tilde{i}(r) := -\frac{1}{\lambda \ln(r)} \quad \text{and} \quad \tilde{r}(i) := e^{-\frac{1}{\lambda i}} \ .$$

The value $\tilde{i}(r)$ denotes the highest complexity level that can be produced in country r without being constrained by the minimum-quality requirement ($q \geq 1$). In turn, $\tilde{r}(i)$ denotes the minimal skill level needed to have an unconstrained quality choice when producing complexity level i. Note that both $\tilde{i}(r)$ and $\tilde{r}(i)$ are strictly increasing. With this notation at hand, we make three assumptions with regard to the distribution of productive knowledge over countries: First, the most complex industry in the economy operates at a complexity level $\bar{i}$. Note that all countries with $r \geq \tilde{r}(\bar{i})$ are able to

[21] See e.g. Schott (2004); Khandelwal (2010); Feenstra and Romalis (2014); Schetter (2018).

produce even in the most complex industry without being constrained by the minimum-quality requirement. We assume that there is always a set of countries of strictly positive measure for which this will be the case, i.e. $\overline{r} > \tilde{r}(\overline{i})$. Second, we assume that for each country there is an industry in which it can produce at preferred quality, i.e. $\underline{r} \geq \tilde{r}(\underline{i})$. Finally, we assume that not all countries can produce all products at preferred quality, i.e. there is always a set of countries of strictly positive measure for which this is not the case, $\tilde{i}(r) < \overline{i}$ for some $r > \underline{r}$.

With the optimal choice of quality, the productivity of the representative firm i in producing *effective* output in country r is given by

$$z(i,r) := q_i(r)[r]^{iq_i(r)^\lambda} = \begin{cases} [-e\lambda i \ln(r)]^{-\frac{1}{\lambda}} & \text{if} \quad r \geq \tilde{r}(i) \ , \\ [r]^i & \text{otherwise} \ . \end{cases} \tag{8}$$

It will turn out (see Section 4.1) that in equilibrium, the minimum-quality constraint is never binding, i.e. productivity in terms of effective output is always given by the upper term in (8).

The representative firm will open up production sites in the subset of countries that share the minimum cost per unit of effective output

$$\mathcal{R}_i = \left\{ r \in \mathcal{R} : \frac{w^r}{z(i,r)} = MC_i \right\} \ ,$$
$$MC_i = \min_{r \in \mathcal{R}} \left\{ \frac{w^r}{z(i,r)} \right\} \ .$$

It will then set its price to charge the well-known constant mark-up over its marginal costs

$$\rho_i = \frac{\sigma_v}{\sigma_v - 1} MC_i \ .$$

3.2 Innovation

We introduce innovation into the framework. Thereby, the measure of varieties for each industry is endogenized. Our modeling choices for the innovation process are guided by the key characteristics of basic research, as detailed above. In particular, we consider a two-stage hierarchical innovation process: Governments invest into basic research in order to generate ideas for new varieties. Ideas diffuse with spatial dependence, at first they only diffuse domestically, later they spill over to other countries, reflecting the local effects and international spillovers of public basic research. Ideas typically consist of new materials, methods, or discoveries. They have no commercial value by themselves, but can be taken up in applied research and commercialized. Applied research benefits from industry-specific production know-how, capturing the critical role of domestic manufacturing for innovation. Commercialization results in a blueprint for a new product.

We now elaborate on the two hierarchical stages of the innovation process, first basic research then applied research.

3.2.1 Basic Research

In each country, the government decides how many workers to employ in the basic research sector, whom we call 'scientists' or, equivalently, 'researchers'. These scientists undertake basic research and generate ideas that are industry-specific and later on turned into new varieties in the respective industry through applied research. Scientists' productivity is determined by their innate ability, denoted by a ($a \geq 0$), and a country-specific productivity shifter $\eta_1(r)$ satisfying $\eta_1(\underline{r}) > 0$ and $\eta_1'(\cdot) \geq 0$. Without loss of generality we define $\eta_1(\bar{r}) := 1$. In particular, if the government in country r hires L_{BR}^r scientists with ability a, then they produce an amount of η^r ideas

$$\eta^r = \eta_1(r) a L_{BR}^r \ . \tag{9}$$

Hence, there are no congestion effects with respect to total employment in science, but as outlined below, ability for undertaking basic research is scarce.[22] In what follows, we will assume that basic research is at least as skill intensive as production which requires

$$\epsilon_{\eta_1} \geq -\frac{1}{\lambda \ln(r)} \ , \tag{10}$$

where ϵ_{η_1} denotes the elasticity of $\eta_1(r)$ with respect to r.[23]

Households are perfectly mobile between becoming a scientist or working in production. They differ in their innate ability of being scientists but there are no additional

[22] We thus focus on limits on idea generation in basic research that are imposed by abilities and not by the size of the pool of potentially fruitful research endeavors.

[23] Observe from Equation (8) that $[-\ln(r)]^{-\frac{1}{\lambda}}$ governs cross-country differences in production efficiency for the case of an interior solution for quality. In particular, with an interior solution for quality, the elasticity of productivity in terms of effective output with respect to r is equal to $-\frac{1}{\lambda \ln(r)}$. $\epsilon_{\eta_1} \geq -\frac{1}{\lambda \ln(r)}$ is our model-counterpart of the view often found in the literature that a certain stock of technological knowledge is required to be able to effectively perform basic research. It will imply that basic research investments are non-decreasing in a country's skill level, in line with what we observe from the data.

utility components attached to being employed as scientists.[24] Abilities are distributed according to some strictly increasing and continuous distribution function $F_a(a)$ on $[\underline{a}, \infty)$ with $F_a(\underline{a}) = 0$ and $F_a'(a) > 0$, $\forall\, a \geq \underline{a}$, where $\underline{a}$ is the lowest innate ability level.[25] We assume that this distribution is the same for all countries.[26]

The government invests in basic research, financed via lump-sum taxes. It will hire the most talented scientists and pay them the equilibrium wage rate in production, i.e. a unique wage w^r will prevail in country r.[27] By investing BR^r in basic research, the government in country r will therefore generate an amount of η^r ideas

$$\eta^r = \eta_1(r) L^r \eta_2\left(\frac{BR^r}{L^r w^r}\right) \ , \tag{11}$$

where

$$\eta_2\left(\frac{BR^r}{L^r w^r}\right) := \int_0^{\frac{BR^r}{L^r w^r}} F_a^{-1}(1-x)\ dx \ . \tag{12}$$

$\eta_2(\cdot)$ satisfies $\eta_2(0) = 0$ and $\eta_2'\left(\frac{BR^r}{L^r w^r}\right) > 0$, $\eta_2''\left(\frac{BR^r}{L^r w^r}\right) < 0$, as detailed in Appendix A.1. In what follows it will be convenient to use ξ^r to denote the share of the population in country r that is working as basic researchers, i.e. $\xi^r := \frac{BR^r}{L^r w^r}$.

Each idea belongs to one industry. There is a one-to-one mapping between an idea and a potential new variety in its industry.[28] Basic research is generally considered as being

[24]Such benefits can easily be incorporated and would lower the wages that need to be paid to scientists.

[25]We consider distributions of innate ability that are unbounded from above as they deliver the empirically attractive feature that most or all countries devote some, potentially very small, funds to scientific research (UNESCO, 2015). Introducing an upper bound for innate abilities $\overline{a}$ would not affect the essence of our analysis. It might imply that some countries find it optimal not to invest in basic research at all.

[26]However, note that countries differ in terms of their basic research productivity, related to differences in r, as detailed above.

[27]The household's innate ability may be private knowledge. In this case, the government can hire the most talented scientists at the prevailing equilibrium wage rate by conditioning wages on research outcomes. In particular, the government in country r can hire the L_{BR}^r most talented scientists by offering

$$w_{BR}^r \begin{cases} = w^r & \text{if } \eta^{r,h} \geq F_a^{-1}\left(1 - \frac{L_{BR}^r}{L^r}\right)\eta_1(r) \ , \\ < w^r & \text{otherwise,} \end{cases}$$

where $\eta^{r,h}$ denotes household h's research outcome in country r. This will induce the most productive households to become scientists. Alternatively, households with highest ability will self-select into becoming researchers if they care about prestige and prestige is based on research outcomes (see also Footnote 24).

[28]In reality, of course, insights from basic research may be valuable in many different contexts and important cross-industry spillovers exist. In fact, heterogeneous applications of insights from basic research and the associated lack of appropriability have been identified as a key reason for underinvestment in basic research by private firms (Nelson, 1959; Arrow, 1962). Note that we do not

undirected. There may, however, be some room for targeting basic research investments to certain industries, for example.[29] We will allow such targeting in our framework. In particular, the government can decide to target its basic research investments to a subset of industries $\mathcal{I}_{BR}^r \subseteq \mathcal{I}$, if desired. Targeting will be successful with probability $\kappa \in [0,1]$. With probability $(1-\kappa)$, the targeting is not successful, and the basic research effort results in an idea that has equal chance to belong to any particular industry. Thus, the probability that such an idea belongs to industry i is $\frac{1-\kappa}{I}$, where I denotes the total number of industries.

We will use η_i^r to denote the amount of ideas in industry i that originates in country r

$$\eta_i^r\left(\xi^r, \mathcal{I}_{BR}^r\right) = \left[\frac{\kappa}{I_{BR}^r}\mathbb{1}_{[i\in\mathcal{I}_{BR}^r]} + \frac{1-\kappa}{I}\mathbb{1}_{[i\in\mathcal{I}]}\right]\eta_1(r)L^r\eta_2(\xi^r) \ , \tag{13}$$

where I_{BR}^r is the number of elements in $\mathcal{I}_{BR}^r$. Furthermore, $\mathbb{1}_{[\cdot]}$ denotes the indicator function, i.e. $\mathbb{1}_{[i\in\mathcal{I}]} = 1$ for all industries and $\mathbb{1}_{[i\in\mathcal{I}_{BR}^r]} = 1$ for industries in subset $\mathcal{I}_{BR}^r$ only.

3.2.2 Applied Research

There is spatial dependence in the diffusion of ideas. In particular, we assume that there is a time span T ($T > 0$) during which an idea diffuses only locally within its country of origin. We can think of time T as being the time of publication of the underlying research for an idea, i.e. the time of public dissemination of the results. Prior to that, domestic households learn about ideas through local interactions, e.g. via personal encounters with the scientists involved, in line with positive local effects of basic research as described in Section 2.[30] These interactions follow some arbitrary stochastic process, the exact nature of which will not matter for our subsequent analyses, and we shall simply assume that the probability that at least one domestic household learns an idea prior to global dissemination is given by $\theta_D \in [0,1]$.[31,32] θ_D is a parameter

impose any restrictions on how fundamental insights from basic research translate into ideas, and in particular that our set-up allows an interpretation where a given insight from basic research translates into many ideas in several (or all, for that matter) industries.

[29]Such targeting features prominently in policy debates. Cf. the discussion in Section 2.

[30]Cf. Arrow (1969) for an early account of the idea that the diffusion of tacit know-how requires personal contact.

[31]This probability is independent of the number of scientists and the population size, reflecting the fact that the share of scientists in a population is generally small. To account for potential congestion effects, the probability could be made dependent on the ratio of households to scientists. This would not qualitatively affect our results, as this effect would simply reinforce the concavity of $\eta_2(\xi^r)$.

[32]An equally valid interpretation is one where commercialization benefits from personal engagement of basic researchers and where θ_D is the probability that this engagement will happen.

capturing the strength of local effects of basic research in our model.

Once ideas enter the public domain, they become accessible to households in all other countries, following some arbitrary stochastic process, which we detail later.[33] We will assume without loss of generality that the local gains from ideas are negligible once they enter the public domain, and that there is no waste of ideas.[34] In summary, we operate under the following assumption:

Assumption 1 (Local Effects of Basic Research)
In any given country, a share θ_D of ideas from basic research are learnt by domestic households first.

There are positive spillovers from domestic production to commercialization, as documented in Section 2. To capture these, we assume that industry-specific tacit production know-how is a necessary condition for the successful commercialization of ideas. Such know-how is built up through production.

Assumption 2 (Applied Research and Manufacturing)
In every country $r \in \mathcal{R}$ ideas can only be commercialized in industries with domestic production.

As we will see in Section 4 below, in the equilibrium of interest each country is competitive in all industries up to the country-specific threshold complexity level $\tilde{i}(r)$, and no firm $i > \tilde{i}(r)$ is willing to produce in country r. Hence, only ideas in industries $i \leq \tilde{i}(r)$ can be commercialized in country r.[35,36]

Whenever a household learns about an idea, he can decide to commercialize the new product by investing v in order to set up a research lab. Commercialization of an

[33]The empirical literature points to a rich pattern of spatial dependence of the diffusion of knowledge (Keller, 2002; Keller and Yeaple, 2013; Bahar et al., 2014). Note that the precise form of the diffusion process of ideas from the public domain will not matter for governments' basic research investment decisions, neither in the decentralized equilibrium nor in the social planner solution. The diffusion of ideas will, however, impact the global distribution of innovation and associated gains. We will get back to this in Section 5 where we discuss the properties of equilibrium investments in our economy.

[34]Note that introducing local gains from domestic ideas once they enter the public domain is isomorph to an increase in θ_D, and that a waste of ideas is isomorph to a proportionate change in $\eta_1(r)$.

[35]The equilibrium will exhibit indifference in terms of location of production. We will assume that all countries have positive production in all industries for which they are competitive.

[36]Domestic production know-how is a necessary condition for commercialization. As an alternative, we could assume that domestic production fosters the productivity of commercialization. This would not impair our main insights.

idea results in a global patent for the product.[37] This patent is subsequently sold to the highest bidding firm. We assume many (at least two) bidding production firms and thus standard Bertrand competition reasoning implies that the price of the patent equals the ex-post profits of the representative production firm in industry i, which is denoted by π_i. Note that the product market profits π_i in industry i do not depend on the location of the inventor, as the subsequent production decisions are separated from the applied research process. Hence, all profits from production are transferred to patent holders. In what follows, we assume that υ is negligible, such that it is always profitable to commercialize an idea. In particular, we study the limit as υ goes to zero. This simplifies the analysis and allows to focus on basic research investments alone.[38] Then, a household in country r will always commercialize an idea as long as it is feasible, and his decision to do so can be summarized by the following indicator function

$$\mathbb{1}_{[i \leq \tilde{i}(r)]} \ .$$

In turn, this implies that the share of country r's ideas in industry i that are commercialized domestically is given by[39]

$$\theta^r_{D,i} = \mathbb{1}_{[i \leq \tilde{i}(r)]} \theta_D \ . \tag{14}$$

The diffusion and commercialization of ideas imply that ideas are not forgotten, i.e. in equilibrium we have

$$N_i = \int_{\underline{r}}^{\overline{r}} \eta^r_i(\xi^r, \mathcal{I}^r_{BR}) f_r(r) dr \ , \quad \forall\, i \in \mathcal{I} \ . \tag{15}$$

[37]We implicitly assume that there is no duplication of applied research efforts. This can be rationalized in two ways: First by a patent race in which one agent learns an idea first and sets up a research lab earlier than potential competitors. Then the first-mover can always deter entry by other R&D firms in a patent race, by choosing high enough applied research intensities, which renders the success of second-movers sufficiently unlikely. Another rationale are small fixed entry costs into a patent race. Then, a second R&D firm does not enter the patent race once the first one has entered, since it anticipates that subsequent R&D efforts would match the profit π_i, and the entry costs could not be recovered. However, duplication of research efforts could also be integrated into the model by explicitly accounting for these additional costs.

[38]Of course, costs of applied research can be deducted in all of the formulas. Moreover, if applied research costs are a substantial fraction of the industry profits, and thus the profits from patenting are dissipated, incentives of governments to invest in basic research will decline.

[39]Commercialization is random. Throughout the paper, we consider expected values and ignore the expectation operator. This follows from appropriately defining the set of countries and of varieties within an industry and from applying a law of large numbers to a particular constellation. Note, that households are risk-neutral with respect to their aggregate income and, hence, we could easily allow for uncertainty at the household or country level since such risks are fully diversified.

We note that Equation (15) expresses the conservation of ideas, and (14) and the upcoming Equation (23) in Section 5 describe the distribution of applied research.

3.3 Sequence of Events

The sequence of events may be summarized as follows:

1. In all countries governments decide on how much basic research to provide.
2. Ideas diffuse throughout the economy and are turned into patented blueprints for new products by applied research.
3. Patents for new products are sold to production firms.
4. Production firms choose locations for production and supply the world market.

4 Equilibrium for Given Basic Research Investments

In this section, we analyze the equilibrium in our economy, taking government policies, ξ^r and $\mathcal{I}^r_{BR}$, as given. We start with its definition.

Definition 1 (Equilibrium)
An equilibrium for given basic research policies, ξ^r, $\mathcal{I}^r_{BR}$ $\forall r \in \mathcal{R}$, is

(i) an applied research firm for every idea j in each industry, $\{\eta_i^r\}_{(i,r)\in\mathcal{I}\times\mathcal{R}}$,

(ii) a set of countries $\mathcal{R}_i \subseteq \mathcal{R}$ for the representative firm of each industry i, where the firm is operating a production site,

(iii) for each production site of each representative firm i, a quality level $\{q_i(r)\}_{(i,r)\in\mathcal{I}\times\mathcal{R}_i}$, an effective output level $\{\chi_i(r)\}_{(i,r)\in\mathcal{I}\times\mathcal{R}_i}$, and a mass of labor employed, $\{l_i(r)\}_{(i,r)\in\mathcal{I}\times\mathcal{R}_i}$,

(iv) a set of quality-adjusted consumption levels for the representative household for each representative product i, $\{c_i\}_{i\in\mathcal{I}}$,

(v) a quality-adjusted price for each representative product i, $\{\rho_i\}_{i\in\mathcal{I}}$,

(vi) a set of wage rates, $\{w^r\}_{r\in\mathcal{R}}$,

such that

(A) all ideas $\{\eta_i^r\}_{(i,r)\in\mathcal{I}\times\mathcal{R}}$ *are commercialized according to* (14) *and* (15)*,*

(B) $\mathcal{R}_i$*,* $\{q_i(r)\}_{r\in\mathcal{R}_i}$*,* $\{\chi_i(r)\}_{r\in\mathcal{R}_i}$*,* $\{l_i(r)\}_{r\in\mathcal{R}_i}$*, and* ρ_i *solve the representative firm* i*'s profit maximization problem,* $\forall i\in\mathcal{I}$*,*

(C) $\{c_i\}_{i\in\mathcal{I}}$ *maximizes utility of the representative household, subject to his budget constraint, equation* (3)*,*

(D) goods markets clear for all products,

(E) labor markets clear in all countries.

4.1 Equilibrium in the Labor Market

We begin by analyzing the equilibrium in the labor market. Basic research policies will have two effects on the labor market. There is a direct effect via tying up labor in basic research, L_{BR}^r, which is no longer available for production. The supply of labor for production, L_p^r, is given by

$$L_p^r = L^r - L_{BR}^r \ .$$

There is an indirect effect via the generation of varieties across industries through basic research, which in turn affects the demand for labor in each industry. The amount of varieties in industry i, N_i, is given by (15). We will endogenize these effects later on. For now, we take L_p^r and N_i as given. Labor markets then are in equilibrium if firms take up all labor available for production in each country.

For all industries $i\in\mathcal{I}$ and for any two countries $r,r'\in\mathcal{R}$ with $r,r'\geq\tilde{r}(i)$, the relative productivities in terms of *effective* output are the same

$$\frac{z(i,r)}{z(i,r')} = \left[\frac{\ln(r')}{\ln(r)}\right]^{\frac{1}{\lambda}} \quad , \quad \forall (i,r,r')\in\mathcal{I}\times[\tilde{r}(i),\bar{r}]^2 \ .$$

In a world with no minimum-quality requirements, the unique equilibrium wage would then be

$$w^r = \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \quad , \tag{16}$$

where we choose $w^{\bar{r}}=1$ to be the numéraire. As shown in Schetter (2018, Proposition 2), the unique equilibrium wage scheme is still given by (16), even with minimum-quality requirements, if there are *sufficient skills* in the economy. This logic also applies here, and we next derive the sufficient skills condition in our economy where also basic research takes place.

Intuitively, the minimum-quality requirement, if binding, introduces inefficiency for production. Hence, with wages given by (16), the representative firm i is willing to operate in all countries $r \in \mathcal{R} : r \geq \tilde{r}(i)$. In turn, this implies that two conditions have to be satisfied in order for (16) to constitute the equilibrium wage scheme. First, the representative firm in every industry i must be able to satisfy its total demand for labor in countries with skill level $r \geq \tilde{r}(i)$. Second, the overall labor market must clear.

To formalize these conditions, note first that $\tilde{r}(i)$ is increasing in i, i.e. firms in less complex industries are willing to produce in all countries where firms in more complex industries are willing to produce, plus some additional countries with lower productive knowledge. Second, it is useful to introduce the notion of effective labor at the country and the firm level. Specifically, we define

$$\tilde{L}^r := L^r \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} . \tag{17}$$

$\tilde{L}^r$ is called *effective labor* of country r and measures labor in country r in terms of its productivity relative to labor in the country with the highest productive knowledge, $\bar{r}$.[40] If a firm i can produce at *preferred quality*, $q_i(r) = \left[-\frac{1}{\lambda i \ln(r)}\right]^{\frac{1}{\lambda}}$, its demand for *effective labor* is independent of the skill level $r \geq \tilde{r}(i)$ it uses in production. This demand for effective labor of firm i is given by

$$\tilde{l}_i := \int_{\mathcal{R}_i} l_i(r) \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} f_r(r) dr = \left[-e\lambda i \ln(\bar{r})\right]^{\frac{1}{\lambda}} \chi_i \ , \tag{18}$$

and hence linearly depends on the firm's effective output, χ_i. With these notations, we can define sufficient skills as follows:

Definition 2 (Sufficient Skills Condition—SSC)

$$\int_{\tilde{r}(\hat{i})}^{\overline{r}} [L^r - L^r_{BR}] \left[\frac{\ln(\overline{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} dF_r(r) \geq \sum_{i \in \mathcal{I}: i \geq \hat{i}} N_i \tilde{l}_i \ , \quad \forall \hat{i} \in \mathcal{I} \ . \tag{SSC}$$

The sufficient skills condition SSC guarantees that the supply of skills is always greater or equal to the demand for skills, such that the minimum-quality constraint will never

[40] With no minimum-quality requirements, $\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}}$ is the marginal rate of technical substitution of labor in country $\bar{r}$ for labor in country r.

be binding for any firm in any industry. In that sense we say that there are *sufficient skills* in the economy. Whenever this is the case, the wage scheme of equation (16) must hold,[41] and if SSC holds with equality for $\hat{i} = \underline{i}$, where by assumption $\underline{i} \leq \tilde{i}(\underline{r})$, then the overall effective labor market clears and labor markets are in equilibrium.

Condition SSC depends on the endogenous demand for effective labor, $\tilde{l}_i$, and basic research policies, which enter both sides of SSC. In each country, labor available for production is reduced by the number of scientists. In addition, basic research policies impact the cross-industry distribution of the number of varieties N_i and, hence, the total demand for effective labor for production. In the end, condition SSC translates into an assumption on parameter values, in particular the successfulness of basic research targeting (expressed by κ) and the distributions of productive knowledge, labor, complexities, and demand shifters.

From an economic perspective, SSC simply guarantees that the countries with the highest productive knowledge are not only active in the few most complex industries, but that country r will be competitive for all industries $i \leq \tilde{i}(r)$, i.e. we are in a situation where more developed economies are more diversified, in line with what we observe from the data. This is our equilibrium of interest and we will henceforth limit attention to situations where SSC is satisfied. It follows that wages are pinned down by international competition on goods markets and are independent of the exact basic research policies, which is economically attractive, given that in practice only a small share of the population is engaged in basic research, and this fraction is well below 1% of the labor force.

Note that we can always find parameter values such that SSC is indeed satisfied in both, the decentralized equilibrium of basic research investments and the global social planner solution considered below. We discuss these issues in Online Appendix C.

4.2 Equilibrium Values

With the equilibrium wage at hand, the derivations of Section 3, along with some straightforward algebra, allow to characterize the equilibrium for given basic research policies.

Proposition 1

Suppose that basic research policies $\xi^r, \mathcal{I}^r_{BR}$ are given and that Condition SSC holds.

[41] Any other constellation would violate labor market clearing.

Then there exists a unique equilibrium with

(i) $N_i^\star = \int_{\underline{r}}^{\overline{r}} \eta_i^r \left(\xi^r, \mathcal{I}_{BR}^r\right) f_r(r)dr \quad \forall\, i \in \mathcal{I},$

(ii) $w^{r\star} = \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \quad \forall\, r \in \mathcal{R},$

(iii) $\mathcal{R}_i{}^\star \subseteq \{r \in \mathcal{R} : r \geq \tilde{r}(i)\} \quad \forall\, i \in \mathcal{I},$

(iv) $q_i{}^\star(r) = \left[-\frac{1}{\lambda i \ln(r)}\right]^{\frac{1}{\lambda}} \quad \forall\, (i, r) \in \mathcal{I} \times \mathcal{R}_i^\star,$

(v) $\rho_i{}^\star = \frac{\sigma_v}{\sigma_v - 1}\left[-e\lambda i \ln(\bar{r})\right]^{\frac{1}{\lambda}} \quad \forall\, i \in \mathcal{I},$
$P_i^\star = \frac{\sigma_v}{\sigma_v - 1}\left[-e\lambda i \ln(\bar{r})\right]^{\frac{1}{\lambda}} N_i{}^{\star\frac{1}{1-\sigma_v}} \quad \forall\, i \in \mathcal{I},$
$P^\star = \frac{\sigma_v}{\sigma_v - 1}\left[-e\lambda \ln(\bar{r})\right]^{\frac{1}{\lambda}} \left[\sum_{i\in\mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} N_i{}^{\star\frac{1-\sigma_I}{1-\sigma_v}}\right]^{\frac{1}{1-\sigma_I}},$

(vi) $\tilde{l}_i{}^\star = \frac{\psi_i N_i{}^{\star\frac{\sigma_v - \sigma_I}{1-\sigma_v}} i^{\frac{1-\sigma_I}{\lambda}}}{\sum_{\hat{i}\in\mathcal{I}} \psi_{\hat{i}} N_{\hat{i}}{}^{\star\frac{1-\sigma_I}{1-\sigma_v}} \hat{i}^{\frac{1-\sigma_I}{\lambda}}} \tilde{L}_p{}^\star \quad \forall\, i \in \mathcal{I},$

(vii) $\chi_i{}^\star = \left[-e\lambda i \ln(\bar{r})\right]^{-\frac{1}{\lambda}} \tilde{l}_i{}^\star \quad \forall\, i \in \mathcal{I},$

(viii) $\pi_i{}^\star = \frac{\tilde{l}_i{}^\star}{\sigma_v - 1} \quad \forall\, i \in \mathcal{I},$

(ix) $C^\star = \left[-e\lambda \ln(\bar{r})\right]^{-\frac{1}{\lambda}} \left[\sum_{i\in\mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} N_i{}^{\star\frac{1-\sigma_I}{1-\sigma_v}}\right]^{\frac{1}{\sigma_I - 1}} \tilde{L}_p{}^\star$ *and* $P^\star C^\star = \frac{\sigma_v}{\sigma_v - 1} \tilde{L}_p{}^\star.$

where $\tilde{L}_p{}^\star := \int_{\underline{r}}^{\bar{r}} \left[L^r - L_{BR}^r\right] \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} f_r(r)dr$ *is aggregate supply of effective labor for production. The values of the representative firm of each industry* i *hold for all firms* $j \in [0, N_i{}^\star]$ *in that industry.*

Note that all varieties in the economy are the result of basic and applied research efforts which we will discuss next. In the remainder of the paper, we will use the equilibrium of Proposition 1, and simplify the notation by disposing of superscript * in all expressions.

5 Decentralized Investment in Basic Research

In the previous sections, we have outlined our model and derived the equilibrium for given basic research policies. In this model environment, we will first analyze basic research investments in the decentralized equilibrium with investments undertaken by national governments. Then, we will confront this decentralized equilibrium with the solution of a global social planner. Throughout, we will assume that, once basic research investments have been chosen, we can apply Proposition 1.[42]

Governments in all countries decide how much basic research to provide, ξ^r, and on which industries to target, $\mathcal{I}_{BR}^r$, in order to maximize the domestic gains from the associated innovations net of the costs of doing research. They anticipate the optimization behavior of all other governments. With a continuum of countries, however, they will take this behavior and all equilibrium values as given.

Among the set of industries where ideas can be commercialized domestically, governments will always target the industries where blueprints for new varieties are most valuable, i.e. those industries that yield the highest profits for the representative firm. In turn, this immediately implies that among industries that receive non-zero targeting of basic research, profits have to be non-decreasing in complexity in equilibrium.

Let i_{BR}^r denote the industry with highest profits among all industries $i \leq \tilde{i}(r)$, i.e. among all industries where ideas can be commercialized in country r. The government in country r will target this industry.[43] It chooses its level of basic research investments to maximize the total domestic income from selling blueprints for new varieties, net of basic research investment,

$$\max_{\xi^r} \left\{ \eta_1(r) L^r \eta_2\left(\xi^r\right) \theta_D \left[\kappa \pi_{i_{BR}^r} + \frac{1-\kappa}{I} \sum_{i \in \mathcal{I}(r)} \pi_i \right] - \xi^r w^r L^r \right\} , \tag{19}$$

where $\mathcal{I}(r) := \{i \in \mathcal{I} : i \leq \tilde{i}(r)\}$ denotes the set of industries with domestic production.

The associated first order condition is

$$\eta_1(r) \eta_2'\left(\xi^r\right) \theta_D \left[\kappa \pi_{i_{BR}^r} + \frac{1-\kappa}{I} \sum_{i \in \mathcal{I}(r)} \pi_i \right] - w^r = 0 , \tag{20}$$

where governments consider $\{\pi_i\}_{i \in \mathcal{I}}$ as given since an individual country cannot affect these profits. In economic terms, Equation (20) simply requires that the marginal profit of an additional scientist equals her marginal costs.

[42] The equilibrium of Proposition 1 exists and is unique, once basic research investments have been determined, if the implied distributions of labor supply across countries and labor demand across industries satisfy Condition SSC. As we discuss in Section 4.1, this will ultimately depend on the exogenous distributions of productive knowledge, labor, complexities, and demand shifters. We document in Online Appendix C, that we can always find exogenous parameter values such that SSC is necessarily satisfied in both, the decentralized equilibrium of basic research investments and the global social planner solution considered below (see Proposition 8 in Online Appendix C).

[43] In principle, $\mathcal{I}_{BR}^r$ may contain multiple industries. In such case, the government will be indifferent between targeting any of the industries in $\mathcal{I}_{BR}^r$, and we will assume that it targets any one of these, i.e. to simplify notation, we will consider the case of $\mathcal{I}_{BR}^r$ being a singleton, i.e. i_{BR}^r.

In Section 3.2.1 we have established that for any distribution of innate abilities, $F_a(\cdot)$, with continuous support on $[\underline{a}, \infty)$ $\eta_2(\cdot)$ is strictly increasing and concave. Moreover, as we show in Appendix A.1, it satisfies $\tilde{a}(\xi^r) := \eta_2'(\xi^r) = F_a^{-1}(1-\xi^r)$. The optimal level of basic research investment in country r is therefore the unique solution to the above first order condition,

$$\xi_E^r = 1 - F_a\left(\frac{w^r}{\eta_1(r)\theta_D\left[\kappa\pi_{i_{BR}^r} + \frac{1-\kappa}{I}\sum_{i\in\mathcal{I}(r)}\pi_i\right]}\right), \tag{21}$$

where here and below we use a subscript $_E$ to denote an optimal solution of a national government. We summarize our insights in the following proposition.

Proposition 2

In the decentralized equilibrium, the government in country r targets its basic research investments to industry $i_{BR}^r := \arg\max_{i\in\mathcal{I}(r)} \pi_i$ and its basic research intensity is given by (21).

Proposition 2 implies that countries with high productive knowledge conduct more both basic and applied research. To see this, note that (21) can be rewritten as

$$\tilde{a}(\xi^r) = \frac{w^r}{\eta_1(r)\theta_D\left[\kappa\pi_{i_{BR}^r} + \frac{1-\kappa}{I}\sum_{i\in\mathcal{I}(r)}\pi_i\right]}, \tag{22}$$

where $\tilde{a}(\xi^r) = F_a^{-1}(1-\xi^r)$ is the innate ability of the marginal scientist. Scientists in countries with higher productive knowledge r earn higher wages. On the other hand, they are more productive as researchers, $\eta_1'(\cdot) > 0$, and their economy is weakly more diversified,[44] which increases the chance that the scientist discovers an idea that can be commercialized domestically. This also weakly increases the targeting potential for the government. Whether or not the basic research intensity will be increasing in r then depends on the magnitudes of the different effects. We consider the case of basic research being at least as skill intensive as production. Thus, $\frac{w^r}{\eta_1(r)}$ is weakly monotonously decreasing in r and $\theta_D\left[\kappa\pi_{i_{BR}^r} + \frac{1-\kappa}{I}\sum_{i\in\mathcal{I}(r)}\pi_i\right]$ non-continuously increasing. It follows that ξ_E^r is weakly monotonously increasing in r.

The fact that ξ_E^r is increasing in r also feeds back into applied research intensities in different countries. These, however, not only depend on a country's own basic research, but also on spillovers of ideas from the rest of the world. Hence, for the

[44] For any pair of countries $r^h > r^l$, $\mathcal{I}(r^h)$ is a superset of $\mathcal{I}(r^l)$.

equilibrium distribution of applied research activities, the diffusion of ideas—once they have entered the public domain—will matter. Again, it is often argued that innovation is at least as skill intensive as production.[45] In the context of our model, this suggests that applied researchers encounter ideas in the public domain with a probability that is proportionate to their endowment with effective labor, so we may assume that an idea from the public domain is commercialized in country $r \in \mathcal{R}$ with probability

$$\theta^r_{G,i} = \mathbb{1}_{[i \leq \tilde{i}(r)]} \cdot \frac{\tilde{L}^r}{\int_{\tilde{r}(i)}^{\bar{r}} \tilde{L}^r \, dF_r(r)} \ , \tag{23}$$

where $\int_{\tilde{r}(i)}^{\bar{r}} \tilde{L}^r \, dF_r(r)$ is the total effective labor in countries having a sufficiently high productive knowledge to commercialize ideas in industry i. Then applied research intensities and resulting product innovations are increasing in r. This is the case for two reasons: First, countries with a higher r invest more in basic research, and they are more productive in doing so, i.e. they generate more ideas. Second, they can commercialize a greater fraction of ideas due to their stronger manufacturing base. This applies to both, domestically generated ideas and ideas that spill over from other countries.

Corollary 1

A country's investments in basic (and applied) research are increasing in its productive knowledge.

While a rigorous test of our model is not possible, due to a lack of good data, it is worth noting that these patterns of equilibrium research investments are consistent with salient features in the data. In particular, as documented in Figure 3, on balance, countries closer to the frontier devote larger shares of their GDP to both basic and applied research.[46]

These equilibrium outcomes also have important distributional consequences: As industrialized countries innovate more, they are able to appropriate a disproportionately large share of global profits. In particular, in Appendix B.1, we show that the ratio

$$\frac{GNI^r - GDP^r}{GDP^r}$$

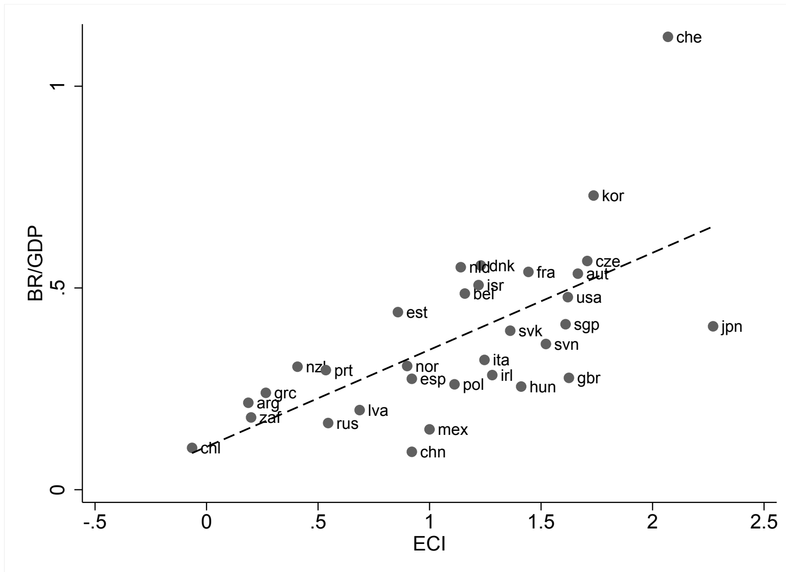
is increasing in r.

[45] Insofar that innovation is considered more skill intensive than production, the following spatial diffusion assumption can be regarded as fair-minded.

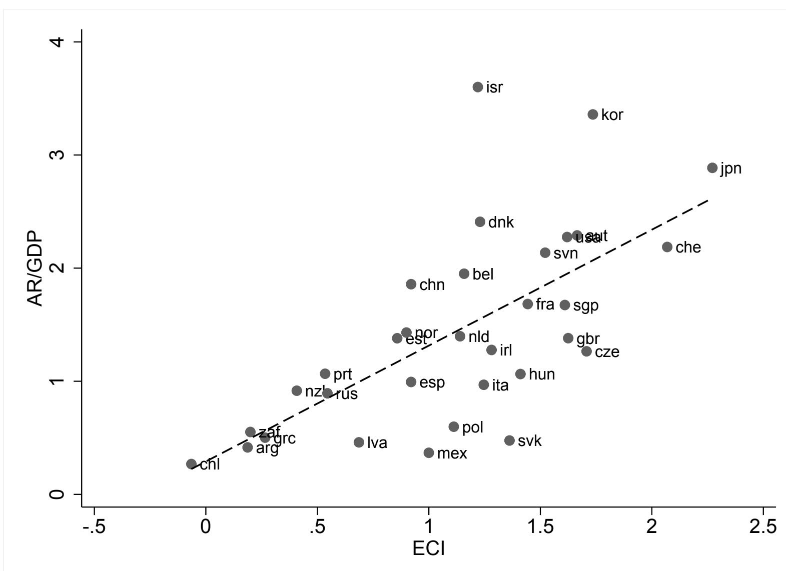
[46] The pattern is robust to measuring countries' productive knowledge by their GDP per capita or their diversification, measured by the number of industries with strong exporting.

Figure 3: Productive Knowledge and Basic Research

(a) Basic Research



(b) Applied Research



Notes: Own illustration. ECI is the economic complexity index developed by Hausmann and Hidalgo (2011) and taken from their open database (downloaded in July 2016). Data on basic research and applied research is taken from the OECD dataset 'Main Science and Technology Indicators' (downloaded in December 2017). Applied research is calculated by subtracting basic research from gross domestic expenditures on R&D. All data is averaged over a 5-year span with the last observation in 2015.

Corollary 2

Countries with high productive knowledge appropriate a disproportionately large share of global profits.

The proof of Corollary 2 is given in Appendix B.1. We note that Corollary 2 is consistent with Figure 1(b) in our motivating Section 2.

6 Social Planner Solution

In this section, we analyze the optimal basic research investment of a global social planner (henceforth simply social planner). For the economic environment we are considering, it is well known that conditional on investment in basic research equilibrium outcomes will be efficient.[47] This, however, is generally no longer the case with endogenous innovation fueled by basic research. In that case various external effects emerge that may introduce inefficiencies. In particular, foreigners benefit from cross-border spillovers of ideas and a widening of the variety-base for consumption. Negative externalities arise from rent-seeking of governments (through increasing N) and the loss of profit potential associated with a diminution of the labor force available for production.

In contrast to the national governments, the social planner takes these externalities into account. His decision problem boils down to choosing the level of basic research investment and targeting it for each country in the economy, such that he maximizes the utility of the global representative household in the implied equilibrium according to Proposition 1. He will not care about the distribution of burdens of basic research investment and associated benefits across the world. The optimization problem of the social planner is

$$\max_{\left\{\xi^r, i^r_{BR}\right\}_{r\in\mathcal{R}}} \quad C = \left[-e\lambda\ln(\bar{r})\right]^{-\frac{1}{\lambda}} \left[\sum_{i\in\mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} N_i^{\frac{1-\sigma_I}{1-\sigma_v}}\right]^{\frac{1}{\sigma_I - 1}} \left[\tilde{L} - \tilde{L}_{BR}\right] , \tag{24}$$

$$\text{s.t.} \quad N_i = \int_{\underline{r}}^{\bar{r}} \eta_i^r \left(\xi^r, i^r_{BR}\right) f_r(r) dr \quad \forall\, i \in \mathcal{I} , \tag{25}$$

$$\tilde{L}_{BR} = \int_{\underline{r}}^{\bar{r}} L^r \xi^r \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} f_r(r) dr . \tag{26}$$

[47] Cf. e.g. Epifani and Gancia (2011). Note that in itself, this is not a limitation of our theoretical framework, given that our main focus of interest lies in comparing socially efficient (coordinated) basic research investment to decentralized investments.

It will be instructive to tackle this optimization problem in three steps. In particular, note that targeting impacts social welfare only via its effect on the distribution of varieties across industries, $\left\{n_i := \frac{N_i}{N}\right\}_{i\in\mathcal{I}}$. It will neither impact the total number of varieties, N, nor the cost of providing these varieties in terms of effective labor, $\tilde{L}_{BR}$. For any total investment in basic research, as reflected in N, and allocation of this investment across countries, the social planner will thus always seek to distribute varieties across industries to maximize total utility from consumption of these varieties. Second, conditional on N, allocation of basic research investments across countries will only impact the total cost of providing N, $\tilde{L}_{BR}$. A necessary condition for welfare maximization is therefore to minimize the cost of providing N which will determine allocation of basic research investment across countries. We will use $\tilde{L}_{BR,S}(N)$, to denote this minimal cost as a function of N, with a subscript $_S$ denoting the social planner solution from now on. The social planner problem then boils down to choosing the optimal level of N, given optimal targeting thereof, and taking into account its bearings on total cost of providing basic research, $\tilde{L}_{BR,S}(N)$.

We next study each of these subproblems in turn.

6.1 Optimal Targeting

Industries differ in their *attractiveness*, reflected in the term $\psi_i i^{\frac{1-\sigma_I}{\lambda}}$. Ceteris paribus, they are more attractive if the industry-specific consumption bundle has a higher demand shifter (ψ_i higher) or if the industry is less complex (i lower), which, in turn, implies that productivity is higher. The social planner targets his basic research investments to exploit this cross-industry heterogeneity. As we detail in Appendix A.2.1, the associated decision problem boils down to the following

$$\begin{aligned} \max_{\{n_i\}_{i\in\mathcal{I}}} \quad & \left[\sum_{i\in\mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} n_i^{\frac{1-\sigma_I}{1-\sigma_v}}\right]^{\frac{1}{\sigma_I - 1}} , \\ \text{s.t.} \quad & n_i \geq \frac{1-\kappa}{I} , \quad \forall\, i \in \mathcal{I} , \\ & \sum_{i\in\mathcal{I}} n_i = 1 , \end{aligned} \tag{27}$$

where $n_i = \frac{N_i}{N}$ is the share of varieties in industry i. The lower bound on n_i arises from the constraint that targeting must be non-negative. It is zero with perfect targeting ($\kappa = 1$) only, and strictly positive else.

The term in brackets in the above objective is strictly increasing and concave in each of its arguments. It immediately follows that the social planner would ideally equate the marginal returns to n_i,

$$\frac{1-\sigma_I}{1-\sigma_v}\psi_i i^{\frac{1-\sigma_I}{\lambda}} n_i^{\frac{\sigma_v-\sigma_I}{1-\sigma_v}}, \tag{28}$$

across industries. Note that this would imply that the share of varieties in industry i is positively related to its attractiveness. Equating the marginal returns to varieties across industries may, however, not always be feasible due to limited scope of targeting. In such a case, the social planner can do no better than hierarchically targeting industries in descending order of attractiveness to equate marginal returns to varieties among industries that receive positive targeting, up to the point where he has fully exploited his targeting opportunities. We formally characterize the resulting distribution of varieties across industries in Appendix A.2.2. For our subsequent analysis, it will be sufficient to note that irrespective of total investment in basic research and its distribution across countries, targeting will result in the same optimal value of the above objective in (27), which will henceforth be denoted by ω_S.

We summarize these insights in the following lemma:

Lemma 1
Let industries be ranked by attractiveness $\psi_i i^{\frac{1-\sigma_I}{\lambda}}$, in descending order. The social planner will target the most attractive industries up to some threshold industry. Targeting is increasing in an industry's attractiveness and is such that the social returns to an additional variety are equal across all industries that receive strictly positive targeting. The optimal value of the above objective will henceforth be denoted by ω_S,

$$\omega_S := \left[\sum_{i\in\mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} n_{i,S}^{\frac{1-\sigma_I}{1-\sigma_v}}\right]^{\frac{1}{\sigma_I-1}} .$$

In the above expression, $n_{i,S}$ denotes the share of all varieties that fall into industry i in the social planner solution.

6.2 Optimal Basic Research Allocation

We now turn to the optimal allocation of basic research investments to countries. As argued above, for any desired level of investment in basic research as reflected in N, the social planner will allocate basic research investment such that he minimizes the cost in terms of effective labor. This allocation thus solves the following decision problem

$$\min_{\{\xi^r\}_{r\in\mathcal{R}}} \quad \tilde{L}_{BR} = \int_{\underline{r}}^{\bar{r}} L^r \xi^r \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} f_r(r)dr \ ,$$
$$\text{s.t.} \quad \int_{\underline{r}}^{\bar{r}} \eta^r(\xi^r) f_r(r)dr = N$$
$$0 \le \xi^r \le 1 \quad \forall r \in \mathcal{R} \ .$$

Note that with the assumptions made, $\xi^r = 0$ will never be optimal. To simplify the exposition, we will focus on the economically most meaningful scenario where the same holds true for $\xi^r = 1$.[48] The necessary and sufficient first order condition then requires that relative marginal costs of hiring additional scientists equate their relative marginal products across countries

$$\left[\frac{\ln(r')}{\ln(r)}\right]^{\frac{1}{\lambda}} = \frac{\eta_1(r)\eta_2{}'(\xi^r)}{\eta_1(r')\eta_2'(\xi^{r'})} \ , \quad \forall r, r' \in \mathcal{R} \ , \tag{29}$$

and we can infer, using $\eta_1(\bar{r}) = 1$, that the optimal basic research intensity given N, $\xi^r_S(N)$, satisfies

$$\xi^r_S(N) = 1 - F_a\left(\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1 - \xi^{\bar{r}}_S(N))\right) \ , \tag{30}$$

and where $\xi^{\bar{r}}_S(N)$ is the unique solution to[49]

$$N = \int_{\underline{r}}^{\bar{r}} \eta_1(r) L^r \eta_2\left(1 - F_a\left(\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1 - \xi^{\bar{r}}_S(N))\right)\right) f_r(r)dr \ . \tag{31}$$

The associated cost of providing basic research are

$$\begin{aligned}\tilde{L}_{BR,S}(N) &= \int_{\underline{r}}^{\bar{r}} L^r \xi^r_S(N) \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} f_r(r)dr \\ &= \int_{\underline{r}}^{\bar{r}} L^r \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \left[1 - F_a\left(\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1 - \xi^{\bar{r}}_S(N))\right)\right] f_r(r)dr \ ,\end{aligned} \tag{32}$$

where the second equality follows from using (30) above and where $\xi^{\bar{r}}_S(N)$ is implicitly defined in (31). Note that $\xi^r_S(N)$ is continuous on $\mathcal{R}$, and that $\xi^{\bar{r}}_S(N)$ is strictly increasing in N and, therefore, so is $\tilde{L}_{BR,S}(N)$.

[48] At the expense of additional notational complexity we could account for corner solutions in the subsequent discussions. Economic insights are, however, limited and we therefore refrain from doing this. Cf. also Footnote 61.

[49] Note that the right hand side of (31) is strictly increasing in $\xi^{\bar{r}}_S(N)$. Intuitively, the more basic research in the highest-skilled country, the more basic research there will be in all other countries according to the first order condition above and, hence, the higher N will be.

6.3 Optimal Number of Varieties

From the above, the social planner's decision on the optimal number of varieties boils down to the following

$$\max_{N} \quad C = [-e\lambda \ln(\bar{r})]^{-\frac{1}{\lambda}} \omega_S N^{\frac{1}{\sigma_v - 1}} \left[\tilde{L} - \tilde{L}_{BR,S}(N)\right] . \tag{33}$$

The associated first order condition is

$$\frac{1}{\sigma_v - 1} = \frac{\partial \tilde{L}_{BR,S}(N)}{\partial N} \frac{N}{\tilde{L} - \tilde{L}_{BR,S}(N)} . \tag{34}$$

This condition is very intuitive: The CES aggregator is just aggregate productivity in welfare terms, $[-e\lambda \ln(\bar{r})]^{-\frac{1}{\lambda}} \omega_S N^{\frac{1}{\sigma_v - 1}}$, scaled by the effective labor available for production. In optimum, the social planner thus chooses N so as to equate the elasticities of these two with respect to the number of varieties. As we show in Proposition 3, the optimal number of varieties is then the unique solution to

$$\begin{aligned} \frac{1}{\sigma_v - 1} \frac{\tilde{L} - \tilde{L}_{BR,S}(N_S)}{N_S} &= \frac{1}{F_a^{-1}(1 - \xi_S^{\bar{r}}(N_S))} \\ &= \frac{1}{\tilde{a}_S^{\bar{r}}} , \end{aligned} \tag{35}$$

where $\tilde{a}_S^{\bar{r}}$ is the ability in basic research of the marginal scientist in country $\bar{r}$, and $\frac{1}{\tilde{a}_S^{\bar{r}}}$ therefore corresponds to the marginal increase in effective labor for basic research needed in order to marginally increase N.

We summarize our key insights in the following proposition:

Proposition 3

(i) The social planner's optimal number of varieties is the unique solution to (35).

(ii) The social planner's basic research allocation function is implicitly defined in (30) *and* (31). *It is continuous on* $\mathcal{R}$.

(iii) The social planner's optimal targeting strategy is as characterized in Lemma 1.

Most elements of Proposition 3 follow from our discussions above. We prove the missing parts in Appendix B.2.

Note that neither the optimal number of varieties nor the allocation of required basic research investment to countries depends on targeting of basic research. Intuitively, targeting impacts both, benefits arising from an increase in the number of varieties, and the costs in the form of tying up effective labor in basic research in the same way, i.e. it does not affect the trade-off between the two. Hence, the targeting problem can be entirely separated from the decision where and how much to invest in basic research.

We characterize globally efficient basic research investment in the following corollary:

Corollary 3

(i) The globally optimal allocation of basic research investment to countries depends only on the distribution of innate abilities, $F_a(\cdot)$, and the ratio of basic research to production productivities, $\eta_1(r)(\ln(r))^{\frac{1}{\lambda}}$. It will be socially desirable to invest a larger share of GDP in basic research in higher-skilled countries whenever $\epsilon_{\eta_1} > -\frac{1}{\lambda \ln(r)}$.

(ii) The optimal basic research intensity $\xi_S^{\bar{r}}$ is not affected by a proportional increase of the population in all countries, of skills in production, of the innate abilities of all households, or of the basic research productivities.[50] Ceteris paribus, it is higher the lower the substitution between varieties (σ_v lower) and the larger the elasticity ϵ_{η_1}.

The proof of Corollary 3 is provided in Appendix B.3.

7 Comparing the Decentralized Equilibrium to the Social Planner Solution

In the previous sections, we have characterized in detail both the decentralized equilibrium of national investments in basic research and the optimal solution of a global social planner. One attractive feature of our theoretical approach is that it allows to compare the two and to identify policy measures for improving global outcomes of the decentralized equilibrium. We will consider these issues next.

Our economic environment is one with many countries and industries. Naturally, we may then be concerned about global efficiency along three dimensions: Aggregate investments, allocation thereof to countries, and targeting thereof to industries. We will consider each of them in turn. We begin by analyzing targeting of basic research.

[50] Of course, the optimal basic research intensity depends on the distribution $F_a(a)$ and on the cross-country heterogeneity of the basic research productivitiy $\eta_1(r)$.

7.1 Targeting

Industries differ in terms of their ex-ante attractiveness, as determined by their complexity i and their demand shifter ψ_i. This attractiveness, along with the distribution of skills, will drive optimal targeting of basic research investments in our economy. In particular, industries with a greater attractiveness will ceteris paribus be associated with higher profits for the representative firm and hence attract more basic research investments. Such targeting, in turn, will tend to attenuate the ex-ante differences in attractiveness.

Among the set of industries with domestic production, national governments will always target the ones with highest profit. From Proposition 1, we know that for any pair of industries i, i', relative profits are

$$\frac{\pi_i}{\pi_{i'}} = \frac{\psi_i i^{\frac{1-\sigma_I}{\lambda}} N_i^{\frac{\sigma_v-\sigma_I}{1-\sigma_v}}}{\psi_{i'} i'^{\frac{1-\sigma_I}{\lambda}} N_{i'}^{\frac{\sigma_v-\sigma_I}{1-\sigma_v}}} .$$

Observe from (28) that this ratio is equal to the ratio of marginal social benefits from increasing the number of varieties in each of the industries. This is intuitive, as with CES preferences, ratios of profits of varieties reflect ratios of expenditures on these varieties between industries. In turn, this immediately implies that there can never be too much targeting of basic research towards complex industries. Governments with domestic production in all industries will, ceteris paribus, face the same trade-off as the social planner. And governments in lower-skilled countries never target complex industries, given that ideas cannot be commercialized domestically. The opposite is, however, not always true. Precisely because governments in less skilled countries will always target simpler industries, this may result in inefficiently many ideas being targeted towards these industries in the decentralized equilibrium. We summarize these insights in the following proposition:

Proposition 4
Targeting in the decentralized equilibrium is either globally efficient or else inefficiently concentrated in industries with low complexity.

The proof of Proposition 4 is given in Appendix B.4.

Ceteris paribus, inefficient targeting is the more likely, the higher the (relative) gains from innovation in complex industries. In our static set-up, these gains depend only on industries' attractiveness as governed by the exogenous parameters ψ_i and i. More generally, however, the gains from innovation in different industries will also depend on the number of industry-specific varieties inherited from the past.[51] If complex, high-tech industries are relatively new, i.e. if new industries—or products, for that matter—are relatively complex, for example, then complex industries may have inherited fewer varieties from the past and gains from innovation will be particularly large in these industries.[52] In turn, this increases the share of global basic research investments that the social planner targets to complex industries and, therefore, makes it more likely that targeting is not efficient in the decentralized equilibrium.

7.2 Allocation to Countries

We next consider the cross-country distribution of basic research investments. In particular, we ask how the social planner would allocate total investment in basic research across countries in order to achieve the decentralized equilibrium number of varieties. Note that while targeting outcomes will matter for the distribution of basic research investments in the decentralized equilibrium, it will not affect the optimal allocation to countries of the social planner as we have shown above.

Observe from (29) that the social planner allocates basic research investments so as to equate the marginal basic research productivity of effective labor across countries. In turn, this implies that the relative productivity of the marginal basic researcher in any pair of countries $r' > r$ satisfies

$$\frac{\tilde{a}_S^r}{\tilde{a}_S^{r'}} = \left[\frac{\ln(r')}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{\eta_1(r')}{\eta_1(r)} = \frac{w^r}{w^{r'}} \frac{\eta_1(r')}{\eta_1(r)} \ .$$

The second equality follows from using the equilibrium wage rate. Intuitively, the social planner will require the marginal scientist to have higher ability in country r compared to country r' if he is more expensive (w^r higher) or less productive ($\eta_1(r)$ lower).

[51] We discuss a dynamic extension of our model in Section 8.2.

[52] The assumption that new industries are relatively complex is similar in spirit to Acemoglu and Restrepo (2018), for example, who consider arrival of new tasks and assume that these are more complex than pre-existing ones. Relatively large gains from innovation in new, high-tech industries are also consistent with e.g. the fact that, as of 31 March 2018, the five most valuable companies in the world were all tech companies, namely Apple, Alphabet, Microsoft, Amazon, and Tencent (see https://www.pwc.com/gx/en/audit-services/assets/pdf/global-top-100-companies-2018-report.pdf, retrieved on 12 November 2018).

As opposed to this, (20) implies

$$\frac{\tilde{a}_E^r}{\tilde{a}_E^{r'}} = \frac{w^r}{w^{r'}} \frac{\eta_1(r')}{\eta_1(r)} \frac{\kappa \pi_{i_{BR}^{r'}} + \frac{1-\kappa}{I} \sum_{i \in \mathcal{I}(r')} \pi_i}{\kappa \pi_{i_{BR}^{r}} + \frac{1-\kappa}{I} \sum_{i \in \mathcal{I}(r)} \pi_i} \geq \frac{w^r}{w^{r'}} \frac{\eta_1(r')}{\eta_1(r)} = \frac{\tilde{a}_S^r}{\tilde{a}_S^{r'}} \ . \tag{36}$$

The inequality follows from the fact that the expected profits from commercialization of domestic ideas are non-decreasing in r. It is strict whenever a larger set of industries can be commercialized in country r', i.e. whenever $\mathcal{I}(r) \subsetneq \mathcal{I}(r')$, and holds with equality otherwise. The above inequality implies that in the decentralized equilibrium basic research investment are inefficiently concentrated in the high-skilled countries.

Proposition 5

To generate the same number of varieties as in the decentralized equilibrium, the social planner will allocate basic research investments such that $\xi_S^r > \xi_E^r$ for all $r < \tilde{r}_1$ and $\xi_S^r < \xi_E^r$ for all $r \geq \tilde{r}_2$ where $\underline{r} < \tilde{r}_1 \leq \tilde{r}_2 < \overline{r}$ and $\xi_S^r = \xi_E^r$ for all $\tilde{r}_1 \leq r < \tilde{r}_2$ in case of $\tilde{r}_1 < \tilde{r}_2$.

The proof of Proposition 5 is given in Appendix B.5.

7.3 Basic Research Investment

We finally turn to the analysis of total investment in basic research.

Suppose first that the social planner is constrained to adopt the decentralized equilibrium allocation scheme of basic research investments to countries. In particular, while he can freely choose aggregate investments, $\tilde{L}_{BR}$, he is constrained to allocate these to countries, such that for every pair of countries r, r' it holds

$$\frac{\xi^r}{\xi^{r'}} = \frac{\xi_E^r}{\xi_E^{r'}} \ .$$

As we show in Appendix B.6, in such case, the technological spillovers imply the following result:

Proposition 6

Suppose the social planner is constrained to adopt the decentralized equilibrium allocation scheme of basic research investments to countries. Then, he will choose strictly higher aggregate investments in basic research compared to the decentralized equilibrium.

Note that the aggregate basic research investment decision of the social planner is unique for any given basic research allocation (see Appendix B.6). The allocation of basic research investments to countries is, however, socially inefficient, as shown in the previous section. In turn, this implies that when allocating these investments efficiently, the social planner can achieve a larger number of varieties with the same input, which, all else equal, increases the marginal social cost of investments in basic research (see (33)). At the same time, the allocation of basic research investments to countries impacts the marginal social benefit from investments in basic research. As we show in Appendix B.7, with a Pareto distribution of abilities these effects just offset each other, such that the optimal aggregate investments in basic research of the social planner are the same, irrespective of their allocation to countries. In turn, this immediately implies that in such case, aggregate investments in the decentralized equilibrium will be lower than in the social planner solution.[53]

Proposition 7
With a Pareto distribution of abilities, there is too little aggregate investment in basic research in the decentralized equilibrium.

Proposition 7 suggests that there are efficiency gains from coordinate increases of basic research investments. Note that this is true irrespective of the ability distribution if knowledge spillovers are sufficiently large.[54]

While there is too little investment in basic research at the aggregate level, the inefficient allocation vis-à-vis the social planner solution implies that it may still happen that some countries, the highest-skilled ones, invest too much in the decentralized equilibrium. From Proposition 5 we know that this would always be the case if aggregate investments in the decentralized equilibrium were globally efficient. This, however, is not the case, and whether or not investments are too high in the highest-skilled countries will depend on parameter values, the strength of the local effect of basic research and the global distribution of skills, in particular.

Corollary 4
For some parameter values, the highest-skilled countries invest less in basic research than in the social planner solution and for some parameter values they invest more.

[53]Empirical distributions of economic variables often follow power laws (Newman, 2005; Gabaix, 2016). This is also roughly the case for the (upper tail of the) income distribution and, more to the point, for the (upper tail of the) distribution of citations of scientific papers (Newman, 2005).

[54]This follows immediately from considering the limiting case where $\theta_D \to 0$. Interestingly, Keller (2002, 2004) points to a 'globalization of technology', i.e. strong technology spillovers.

The proof of Corollary 4 is given in Appendix B.8.

8 Complementary Policy Tools and Extensions

In this section we discuss complementary policy tools and extensions of the model. A main motive for public investment in basic research is to stimulate innovation in the domestic economy. Governments may therefore seek to strengthen local effects of basic research and the domestic commercialization of ideas. We discuss a prominent example of such policies: the Bayh-Dole Act.[55] We then discuss extensions of our theoretical set-up which may provide useful frameworks for further policy analyses.

8.1 The Bayh-Dole Act

So far, we have treated the strength of the local effects of basic research (θ_D) as exogenously given. However this need not be the case in reality. For example, governments can more or less incentivize basic researchers to engage in the commercialization of their work. In fact, the desire to increase the domestic commercial gains from publicly funded basic research features very prominently in policy debates.[56]

One prominent policy intervention to stimulate such commercialization is the Bayh-Dole Act of 1980, allowing US universities to acquire patent rights over innovations from federally funded research. Arguably, this opportunity increases incentives for scientists to contribute their tacit knowledge to applied research.[57] On the downside, it may undermine the Mertonian norms of science and divert scientists from truly basic to more applied research (Nelson, 2004).

University patenting and, closely related to it, upstream patenting is the subject of a large economic literature (Scotchmer, 1991; Heller and Eisenberg, 1998; Hopenhayn

[55] One could also think of subsidizing applied researchers in order to incentivize them to commercialize a larger share of ideas.

[56] Canada, for example, intends to transform its National Research Council into a business driven, industry-relevant research and technology organization (National Research Council Canada, 2012). David and Metcalfe (2007, p. 22) even argue that *'... it is hard to find a policy document from government, business or university sources that does not call for greater, wider or deeper 'interactions' between private business firms and the universities'.*

[57] Thursby and Thursby (2002) suggest several reasons why additional incentives are needed. In particular, they argue that researchers may dislike being involved in commercialization because of delay-of-publication clauses in licensing agreements, or because they are unwilling to spend their time on applied research. Cf. also the discussion in Howitt (2013).

et al., 2006; Cozzi and Galli, 2014, 2017; Akcigit et al., 2013). This literature typically focuses on closed economies. Our work allows a new, global perspective on this issue. In particular, in the context of our model, we may think of university patenting as increasing θ_D at the cost of potentially lowering $\eta_1(r)$. From the perspective of a global social planner this is, of course, a wasteful policy intervention, as the social planner is not concerned with θ_D. It may, however, be a feasible second-best solution if coordination of basic research investments is impossible. In particular, rational governments will only implement such policies if the domestic net effect is positive. In turn, such higher gains induce governments to invest more in basic research, thus closing the gap to the socially optimal level of investment. Depending on which effect dominates, the greater investment or the loss in basic research efficiency, an equilibrium with Bayh-Dole may be globally strictly more desirable.[58]

8.2 Extensions

Two extensions—dynamics and strategic investments in basic research—will bring the model closer to frameworks that may be connected to the empirical work on how varieties expand in the global market place (see e.g. Broda et al. (2017)).

Dynamics

We have considered a static environment. As long as governments only care about the benefits of their basic research investment decisions for the current generation of households, a static framework is appropriate. Our current static model can, however, also be directly embedded into a dynamic set-up with non-overlapping generations of households and corresponding governments. If governments only care about the generation they represent, all our analyses apply directly to this dynamic variant, with the sole change, that the number of varieties in the economy, N, is strictly positive with zero aggregate investments in basic research, and that this number increases over time fueled by the efforts of each generation. Importantly, with $N_i > 0$ at the beginning of the period and if complex, high-tech industries are relatively new, inefficient targeting

[58]Cf. Proposition 7. In a very different context, Akcigit et al. (2013) also present public basic research in combination with intellectual property rights as a feasible second-best solution. In their model, however, first-best would be to subsidize basic research by private firms which, they argue, may not be feasible due to asymmetric information, and intellectual property rights mitigate the 'ivory tower property' of public basic research.

of global basic research investments may be reinforced.[59]

Yet, our main insights apply even when including forward-looking behavior of governments in such a dynamic set-up. In such a case, governments weigh the current costs of investments against discounted future benefits. Along a balanced growth path, discounted future profits are a constant multiple of per-period profits, i.e. the main trade-offs involved are qualitatively the same as in the static model we consider.

Strategic investment

We have considered a continuum of countries. The main implication of this assumption is that an individual government's basic research decision does not trigger a feedback via change of investment decisions by other countries, and countries only care about the aggregate amount of basic research investments by other countries. Again, this is arguably one of the most relevant scenarios for understanding real-world policies. Yet, the main mechanisms remain intact even when considering a finite number of countries and allowing for strategic interaction. In either case, such interaction does not concern the global social planner. Moreover, strategic interaction would typically not affect optimal targeting of basic research to industries by national governments, and, as long as the associated effects are not strongly biased in favor of developing countries, these investments would still be inefficiently concentrated in the industrialized countries. In the model we are considering, countries' investments in basic research are strategic substitutes and, depending on the distribution of innate abilities, aggregate investment would tend to be higher with strategic interaction. Yet, it would typically fall short of the globally efficient level, in particular if knowledge spillovers to the rest of the world are strong enough.

9 Conclusion

We have analyzed basic research policies in a general equilibrium framework with many countries, many industries, and international trade. We have shown that decentralized investments in basic research are inefficient along three dimensions: They may not be sufficiently directed to support innovation in complex high-tech industries, they are inefficiently concentrated in industrialized countries, and the aggregate level is typically too low for reasonable parameter assumptions. The latter finding further implies that

[59] See Section 7.1.

regulations, such as the Bayh-Dole Act, that seek to stimulate technology transfers from universities to the domestic economy may yield welfare improvements.

Our work is a step towards a better understanding of innovation policies in a globalized world. Many related research questions deserve careful scrutiny in future work. Scientists and inventors are, for example, mobile internationally (Hunter et al., 2009; Stephan, 2012; Miguelez and Fink, 2013). If the most able scientists migrate to places with greatest investments in basic research, this will contribute to mitigating aggregate inefficiencies, yet possibly at the cost of reinforcing cross-country differences in innovation abilities and incomes. Carefully analyzing migration in this context and disentangling different effects is a promising avenue for future research. More generally, it would be interesting to scrutinize the distributional effects of innovation in a globalized world.

Appendix

A Detailed Derivations

A.1 Production Function for Ideas

In this appendix, we provide details on the production function for ideas (11) and (12).

The government employs the workers with highest ability as scientists, i.e. all workers with ability $a \geq \tilde{a}^r$ for some cutoff $\tilde{a}^r$

$$\eta^r = \eta_1(r) L^r \int_{\tilde{a}^r}^{\infty} a f_a(a) da \ .$$

The costs of employing the scientists are

$$BR^r = w^r L^r \int_{\tilde{a}^r}^{\infty} f_a(a) da \ ,$$

and therefore $\tilde{a}^r = F_a^{-1}\left(1 - \frac{BR^r}{L^r w^r}\right)$. Using this expression yields

$$\eta^r = \eta_1(r) L^r \eta_2\left(\frac{BR^r}{L^r w^r}\right) = \eta_1(r) L^r \int_{F_a^{-1}\left(1-\frac{BR^r}{L^r w^r}\right)}^{\infty} a f_a(a) da \ ,$$

and finally using integration by substitution results in the expression shown in the main text

$$\eta_2\left(\frac{BR^r}{L^r w^r}\right) = \int_0^{\frac{BR^r}{w^r L^r}} F_a^{-1}\left(1 - x\right) dx \ .$$

Note that $\eta_2(0) = 0$. Moreover, using Leibniz's Rule we obtain

$$\eta_2'\left(\frac{BR^r}{L^r w^r}\right) = F_a^{-1}\left(1 - \frac{BR^r}{L^r w^r}\right) > 0$$

and

$$\eta_2''\left(\frac{BR^r}{L^r w^r}\right) = -\frac{1}{f_a\left(1 - \frac{BR^r}{L^r w^r}\right)} < 0 \ ,$$

i.e. $\eta_2(\cdot)$ is indeed strictly increasing and concave.

A.2 Details on the Optimal Targeting Problem of the Social Planner

In this appendix, we provide details on the optimal targeting problem of the social planner. We begin by showing that this problem can indeed be reduced to the problem analyzed in Section 6.1. Throughout, it will be convenient to use $\eta^r(\xi^r) := \eta_1(r)L^r\eta_2(\xi^r)$ to denote the amount of ideas generated in country r.

A.2.1 Optimal Targeting Problem

Using

$$\eta_i^r\left(\xi^r, i_{BR}^r\right) = \begin{cases} \eta^r\left(\xi^r\right) \frac{1-\kappa+\kappa I}{I} & \text{if } i = i_{BR}^r \\ \eta^r\left(\xi^r\right) \frac{1-\kappa}{I} & \text{otherwise,} \end{cases}$$

we obtain the number of varieties that fall in industry i

$$\begin{aligned} N_i &= \int_{\underline{r}}^{\overline{r}} \eta^r\left(\xi^r\right) \left[\frac{1-\kappa}{I} + \mathbb{1}\left[i = i_{BR}^r\right]\kappa\right] f_r(r)dr \\ &= \left[\frac{1-\kappa}{I} + \kappa s_i\right] \int_{\underline{r}}^{\overline{r}} \eta^r\left(\xi^r\right) f_r(r)dr \ , \end{aligned}$$

where

$$s_i := \frac{\int_{\underline{r}}^{\overline{r}} \eta^r\left(\xi^r\right) \mathbb{1}\left[i = i_{BR}^r\right] f_r(r)dr}{\int_{\underline{r}}^{\overline{r}} \eta^r\left(\xi^r\right) f_r(r)dr}$$

denotes the share of ideas targeted towards industry i. We can thus rewrite the set of constraints (25) as

$$\begin{aligned} n_i &= \frac{1-\kappa}{I} + \kappa s_i \ , \quad \forall\, i \in \mathcal{I} \ , \\ N &= \int_{\underline{r}}^{\overline{r}} \eta^r\left(\xi^r\right) f_r(r)dr \ . \end{aligned}$$

We note that $\sum_{i\in\mathcal{I}} n_i = 1$ since $n_i := \frac{N_i}{N}$ $\forall i \in \mathcal{I}$. Further, using the definition of n_i, we can rewrite the objective as

$$C = \left[-e\lambda \ln(\bar{r})\right]^{-\frac{1}{\lambda}} N^{\frac{1}{\sigma_v-1}} \left[\tilde{L} - \tilde{L}_{BR}\right] \left[\sum_{i\in\mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} n_i^{\frac{1-\sigma_I}{1-\sigma_v}}\right]^{\frac{1}{\sigma_I-1}} \ ,$$

implying first that targeting can be reduced to the choice of $\{s_i\}_{i\in\mathcal{I}}$, and second that it will enter the social planner problem only via its impact on the term

$$\left[\sum_{i\in\mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} n_i^{\frac{1-\sigma_I}{1-\sigma_v}}\right]^{\frac{1}{\sigma_I-1}} \ . \tag{A.1}$$

The objective is always positive, and the social planner will thus target basic research to maximize (A.1), irrespective of N and $\tilde{L}_{BR}$, i.e. targeting can be separated from the choices of $\{\xi^r\}_{r\in\mathcal{R}}$, as argued in the main body of the text. Taking into account that targeting must be non-negative, the problem reduces to the optimal targeting problem studied in Section 6.1.

A.2.2 Details on the Optimal Distribution of Varieties Across Industries

Note that maximizing the objective in (27) is equivalent to maximizing $\sum_{i \in \mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} n_i^{\frac{1-\sigma_I}{1-\sigma_v}}$. We will thus use the latter. The marginal return to n_i is then

$$\frac{1-\sigma_I}{1-\sigma_v} \psi_i i^{\frac{1-\sigma_I}{\lambda}} n_i^{\frac{\sigma_v - \sigma_I}{1-\sigma_v}} .$$

First note that this marginal return depends only on n_i, and in particular does not depend on the distribution of varieties across all other industries. Note further that in the absence of targeting, the marginal return to n_i is strictly increasing in the industry's attractiveness. Finally, note that n_i is the same across all industries that do not receive any targeting, and that targeting one industry $\hat{i}$ will increase $n_{\hat{i}}$ at the expense of decreasing n_i in all other industries, where this decrease is the same for all industries.

Now, let industries be ranked in descending order of attractiveness, $\{i_1, i_2, ..., i_I\}$, such that $\forall m, n \in \{1, 2, ..., I\}, m < n$, it holds $\psi_{i_m} i_m^{\frac{1-\sigma_I}{\lambda}} \geq \psi_{i_n} i_n^{\frac{1-\sigma_I}{\lambda}}$. The social planner will target the industries that yield the highest returns. Starting from a situation without targeting, he will thus start targeting the most attractive industry first. This will increase n_{i_1} and decrease n_i in all other industries. Targeting more and more basic research to i_1, he will eventually reach a point where

$$\psi_{i_1} i_1^{\frac{1-\sigma_I}{\lambda}} n_{i_1}^{\frac{\sigma_v - \sigma_I}{1-\sigma_v}} = \psi_{i_2} i_2^{\frac{1-\sigma_I}{\lambda}} n_{i_2}^{\frac{\sigma_v - \sigma_I}{1-\sigma_v}} ,$$

at which point he will start to jointly target these industries. Targeting more and more basic research to industries i_1 and i_2, he will eventually reach a point where

$$\psi_{i_1} i_1^{\frac{1-\sigma_I}{\lambda}} n_{i_1}^{\frac{\sigma_v - \sigma_I}{1-\sigma_v}} = \psi_{i_2} i_2^{\frac{1-\sigma_I}{\lambda}} n_{i_2}^{\frac{\sigma_v - \sigma_I}{1-\sigma_v}} = \psi_{i_3} i_3^{\frac{1-\sigma_I}{\lambda}} n_{i_3}^{\frac{\sigma_v - \sigma_I}{1-\sigma_v}} ,$$

at which point he will start to jointly target these industries. He will continue in the same manner until he has targeted all of his basic research investments. This will result in a situation where all industries up to some rank t receive positive targeting. For each of these industries, marginal return to n_i will be equal to the marginal return to increasing n_{i_1}. All other industries will receive zero targeting. This will give rise to the following distribution of n_i across industries

$$n_{i_m} = \begin{cases} \left[\frac{\psi_{i_m} i_m^{\frac{1-\sigma_I}{\lambda}}}{\psi_{i_1} i_1^{\frac{1-\sigma_I}{\lambda}}} \right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}} n_{i_1}(t) & \text{if } m \leq t \\ \frac{1-\kappa}{I} & \text{otherwise,} \end{cases}$$

where m denotes the ranking of the industry according to its attractiveness. Using these industry shares in the constraint that

$$\sum_{i \in \mathcal{I}} n_i = 1$$

and solving for $n_{i_1}(t)$ yields

$$n_{i_1}(t) = \frac{1 - \sum_{m>t} \frac{1-\kappa}{I}}{\sum_{m \leq t} \left(\frac{\psi_{i_m} i_m^{\frac{1-\sigma_I}{\lambda}}}{\psi_{i_1} i_1^{\frac{1-\sigma_I}{\lambda}}} \right)^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}} = \frac{1 - (I - t)\frac{1-\kappa}{I}}{\sum_{m \leq t} \left(\frac{\psi_{i_m} i_m^{\frac{1-\sigma_I}{\lambda}}}{\psi_{i_1} i_1^{\frac{1-\sigma_I}{\lambda}}} \right)^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}} ,$$

and t can be solved as the highest rank of attractiveness for which non-negative targeting is unconstrained optimal if only industries along the ranking up to and including this industry are targeted:

$$i_t := \max \left\{ i_m \in \mathcal{I} : \frac{1-\kappa}{I} \leq \left(\frac{\psi_{i_m} i_m^{\frac{1-\sigma_I}{\lambda}}}{\psi_{i_1} i_1^{\frac{1-\sigma_I}{\lambda}}} \right)^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}} n_{i_1}(m) \right\} .$$

B Proofs

B.1 Proof of Corollary 2

Note first that GDP in country r is labor income of production workers plus profits arising form these activities,

$$GDP^r = \frac{\sigma_v}{\sigma_v - 1} w^r L^r [1 - \xi_E^r] ,$$

while GNI is labor income of production workers plus profits appropriated by the domestic population, i.e. the total value of all domestic inventions which we denote by Π^r

$$GNI^r = w^r L^r [1 - \xi_E^r] + \Pi^r .$$ [60]

Combining the previous two, we obtain

$$\frac{GNI^r - GDP^r}{GDP^r} = \frac{(\sigma_v - 1)\Pi^r}{\sigma_v w^r L^r [1 - \xi_E^r]} - \frac{1}{\sigma_v} ,$$

[60] We note that Π^r captures the profits due to own basic research investments as expressed in Equation (19) and due to commercialization of ideas generated by basic research investments of other countries.

and we need to show that $\frac{\Pi^r}{w^r L^r [1-\xi_E^r]}$ is increasing in r. Now, total profits accruing to the population of country r are the sum of profits earned through commercialization of domestic ideas plus commercialization of ideas from the public domain. Profits from commercialization of domestic ideas are:

$$\Pi_D^r = \eta^r \theta_D \left[\kappa \left(\pi_{i_{BR}^r} \right) + \frac{1-\kappa}{I} \sum_{i \in \mathcal{I}(r)} \pi_i \right] ,$$

implying that

$$\frac{\Pi_D^r}{w^r L^r [1-\xi_E^r]} = \frac{\eta_1(r) L^r}{w^r L^r [1-\xi_E^r]} \eta_2(\xi_E^r) \theta_D \left[\kappa \left(\pi_{i_{BR}^r} \right) + \frac{1-\kappa}{I} \sum_{i \in \mathcal{I}(r)} \pi_i \right] ,$$

which is increasing in r since each factor is increasing in r. Let $\eta_{G,i}$ denote the amount of ideas for industry i in the public domain. Profits from the commercialization of these ideas that accrue to the population in country r are then

$$\Pi_G^r = \sum_{i \leq \tilde{i}(r)} \eta_{G,i} \pi_i \frac{\tilde{L}^r}{\int_{\tilde{r}(i)}^{\bar{r}} \tilde{L}^{r'} \, dF_r(r')} ,$$

and hence $\frac{\Pi_G^r}{w^r L^r [1-\xi_E^r]}$ is increasing in r as well, which shows the desired result.

□

B.2 Proof of Proposition 3

Parts (ii) and (iii) have been shown in the main body of the text. It remains to show that the first order Condition (34) can be rewritten as in (35), and that this equation has a unique solution which corresponds to a global maximum.

Applying the chain rule, we obtain

$$\frac{\partial \tilde{L}_{BR,S}(N)}{\partial N} = \frac{\partial \tilde{L}_{BR,S}(N)}{\partial \xi_S^{\bar{r}}} \frac{\partial \xi_S^{\bar{r}}(N)}{\partial N} . \tag{B.1}$$

Differentiating (32) with respect to $\xi_S^{\bar{r}}$ yields

$$\frac{\partial \tilde{L}_{BR,S}}{\partial \xi_S^{\bar{r}}} = {F_a^{-1}}'(1-\xi_S^{\bar{r}}) \int_{\underline{r}}^{\bar{r}} L^r \left[\frac{\ln(\bar{r})}{\ln(r)} \right]^{\frac{2}{\lambda}} \frac{1}{\eta_1(r)} F_a' \left(\left[\frac{\ln(\bar{r})}{\ln(r)} \right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1-\xi_S^{\bar{r}}) \right) f_r(r) dr . \tag{B.2}$$

Differentiating (31) with respect to $\xi_S^{\bar{r}}$ yields

$$\begin{aligned}\frac{\partial N}{\partial \xi_S^{\bar{r}}} = \int_{\underline{r}}^{\bar{r}} \eta_1(r) L^r \eta_2' &\left(1 - F_a\left(\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1-\xi_S^{\bar{r}})\right)\right) \\ &{F_a}'\left(\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1-\xi_S^{\bar{r}})\right) \\ &\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} {F_a}^{-1\prime}\left(1-\xi_S^{\bar{r}}\right) f_r(r) dr \ .\end{aligned} \tag{B.3}$$

Now, using

$$\begin{gathered}\eta_2'\left(1 - F_a\left(\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1-\xi_S^{\bar{r}})\right)\right) \\ = \\ F_a^{-1}\left(F_a\left(\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1-\xi_S^{\bar{r}})\right)\right) \\ = \\ \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1-\xi_S^{\bar{r}}) \ ,\end{gathered}$$

where the last equality follows from F_a being injective, we can simplify (B.3) to

$$\frac{\partial N_S}{\partial \xi_S^{\bar{r}}} = F_a^{-1}(1-\xi_S^{\bar{r}}) \frac{\partial \tilde{L}_{BR,S}}{\partial \xi_S^{\bar{r}}} > 0 \ . \tag{B.4}$$

Using (B.1), (B.2), and (B.4) in (34) yields (35).

It remains to show that Equation (35) indeed has a unique solution that corresponds to a global maximum. To show this, we use (31) and (32) in (35) to obtain

$$\begin{gathered}\frac{\int_{\underline{r}}^{\bar{r}} L^r \left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} F_a\left(\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1-\xi_S^{\bar{r}})\right) f_r(r) dr}{(\sigma_v - 1)\int_{\underline{r}}^{\bar{r}} \eta_1(r) L^r \eta_2\left(1 - F_a\left(\left[\frac{\ln(\bar{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} \frac{1}{\eta_1(r)} F_a^{-1}(1-\xi_S^{\bar{r}})\right)\right) f_r(r) dr} \\ = \\ \frac{1}{F_a^{-1}(1-\xi_S^{\bar{r}})} \ ,\end{gathered} \tag{B.5}$$

and the result follows from noting that the left-hand side of the above equation is strictly decreasing and continuous in $\xi_S^{\bar{r}}$, while the right-hand side is continuously increasing, i.e. there exists a unique solution $\xi_S^{\bar{r}} \in (0,1)$,[61] which, in turn, implies a unique N_S from (31). Finally, the same reasoning also implies that the elasticity

$$\frac{\partial \tilde{L}_{BR,S}(N)}{\partial N} \frac{N}{\tilde{L} - \tilde{L}_{BR,S}}$$

is strictly increasing in N, i.e. the solution corresponds to a global maximum.

□

B.3 Proof of Corollary 3

We show each part in turn.

(i) The first statement in part (i) follows immediately from (30). The second statement follows from observing that ξ_S^r is increasing in r whenever $\eta_1(r)(-\ln(r))^{\frac{1}{\lambda}}$ is increasing in r, which is the case if basic research productivity is more elastic in r than productivity in production.

(ii) The optimal basic research intensity $\xi_S^{\bar{r}}$ is pinned down by (B.5). This equation is neither affected by a poportionate increase of the population, $\hat{L}^r = \mu L^r$, nor by a proportional increase of skills for production, $\hat{r} = r^\mu$, nor by a proportional increase of the innate ability of each household, $\hat{a} = \mu a$. Moreover, proportionally increasing $\eta_1(r)$ is equivalent to proportionally increasing the ability of each household, which proves the first statement. A decrease in σ_v shifts the left-hand side of (B.5) upward, and is thus reflected in a higher $\xi_S^{\bar{r}}$. Finally, given that a proportionate change in $\eta_1(r)$ does not impact the optimal choice of $\xi_S^{\bar{r}}$, we consider increasing all $\eta_1(r)$, holding constant $\eta_1(\bar{r}) = 1$. For a given $\xi_S^{\bar{r}}$, this will decrease the left-hand side of (B.5) while leaving the right-hand side unaffected, i.e. this must be associated with a lower $\xi_S^{\bar{r}}$.

□

B.4 Proof of Proposition 4

We proceed in two steps: In step 1 we show that whenever $n_{\hat{i},E} > n_{\hat{i},S}$ for some $\hat{i}$, it must be that $n_{i,E} \geq n_{i,S}$ for all $i \leq \hat{i}$. In words: whenever a larger share of

[61] We consider the economically interesting case where cross-country heterogeneity in basic research productivities is small enough, such that there is always an interior solution for $\xi_S^{\bar{r}} \in (0,1)$. For example, in the limiting case where $\ln(r)^{\frac{1}{\lambda}}\eta_1(r)$ is constant over r, the left-hand side (LHS) is decreasing with boundaries $\lim_{\xi_S^{\bar{r}} \to 0} LHS = \infty$ and $\lim_{\xi_S^{\bar{r}} \to 1} LHS = 0$, while the right-hand side (RHS) is increasing with boundaries $\lim_{\xi_S^{\bar{r}} \to 0} RHS = 0$ and $\lim_{\xi_S^{\bar{r}} \to 1} RHS = \frac{1}{\underline{a}}$, implying that there is an interior solution indeed.

varieties arises from targeting industry $\hat{\imath}$ in the decentralized equilibrium, compared to the solution of the global social planner, (weakly) more varieties are targeted to all less complex industries in the decentralized equilibrium. In turn, this implies that the social planner must target a larger share of varieties to more complex industries $i > \hat{\imath}$,[62] i.e. there can never be too many varieties arising from targeting complex industries in the decentralized equilibrium.

In step 2 we show by means of two examples that both, efficient targeting and insufficient targeting to complex industries are possible.

Step 1 Suppose that $n_{\hat{\imath},E} > n_{\hat{\imath},S}$ for some $\hat{\imath}$. Then, it must be that some varieties are targeted to industry $\hat{\imath}$ in the decentralized equilibrium. Recall that the government in country r will always target the industry $i \leq \tilde{\imath}(r)$ with highest profits. Proposition 2 therefore implies that

$$\psi_i i^{\frac{1-\sigma_I}{\lambda}} n_{i,E}^{\frac{\sigma_V-\sigma_I}{1-\sigma_V}} \leq \psi_{\hat{\imath}} \hat{\imath}^{\frac{1-\sigma_I}{\lambda}} n_{\hat{\imath},E}^{\frac{\sigma_V-\sigma_I}{1-\sigma_V}} \quad , \quad \forall i \leq \hat{\imath} \ .$$

Rearranging yields

$$n_{i,E}^{\frac{\sigma_V-\sigma_I}{\sigma_V-1}} \geq \frac{\psi_i i^{\frac{1-\sigma_I}{\lambda}}}{\psi_{\hat{\imath}} \hat{\imath}^{\frac{1-\sigma_I}{\lambda}}} n_{\hat{\imath},E}^{\frac{\sigma_V-\sigma_I}{\sigma_V-1}} \quad , \quad \forall i \leq \hat{\imath} \ . \tag{B.6}$$

Now, if the social planner does not target any varieties to industry $i \leq \hat{\imath}$, it trivially holds that $n_{i,E} \geq n_{i,S}$. It remains to be shown that the same is true if the social planner targets industries $i \leq \hat{\imath}$. We distinguish two cases, depending on whether or not the global social planer targets some varieties to industry $\hat{\imath}$.

(i) Suppose the social planner targets a set of varieties with positive measure to industry $\hat{\imath}$. Condition (28) then implies that

$$n_{i,S}^{\frac{\sigma_V-\sigma_I}{\sigma_V-1}} \geq \frac{\psi_i i^{\frac{1-\sigma_I}{\lambda}}}{\psi_{\hat{\imath}} \hat{\imath}^{\frac{1-\sigma_I}{\lambda}}} n_{\hat{\imath},S}^{\frac{\sigma_V-\sigma_I}{\sigma_V-1}} \quad , \quad \forall i \leq \hat{\imath} \ . \tag{B.7}$$

Note that (B.7) holds with equality for all industries i that the social planner targets. (B.6), (B.7), and the fact that $n_{\hat{\imath},E} > n_{\hat{\imath},S}$ therefore imply that $n_{i,E} > n_{i,S}$.

(ii) Suppose the social planner targets no varieties to industry $\hat{\imath}$. Then, we must have

$$n_{i,S}^{\frac{\sigma_V-\sigma_I}{\sigma_V-1}} \leq \frac{\psi_i i^{\frac{1-\sigma_I}{\lambda}}}{\psi_{\hat{\imath}} \hat{\imath}^{\frac{1-\sigma_I}{\lambda}}} n_{\hat{\imath},S}^{\frac{\sigma_V-\sigma_I}{\sigma_V-1}} \quad , \quad \forall i \leq \hat{\imath} \tag{B.8}$$

[62] Recall that both in the decentralized equilibrium and in the solution of the global social planner it must hold that $\sum_{i \in \mathcal{I}} n_i = 1$.

for all industries i that the social planner targets. (B.6), (B.8), and the fact that $n_{\hat{i},E} > n_{\hat{i},S}$ imply that $n_{i,E} > n_{i,S}$, which proves the desired result.

Step 2 We first provide an example for inefficient targeting and then one for efficient targeting. In doing so, it will be convenient to consider a world with only two types of countries $r_1 > r_2$ and two industries $i_1 > i_2$, where $\tilde{i}(r_1) \geq i_1 > \tilde{i}(r_2) \geq i_2$.

(i) Let targeting be just efficient if every idea is targeted towards industry i_1, i.e.

$$\frac{1+\kappa}{1-\kappa} = \left[\frac{\psi_{i_1} i_1^{\frac{1-\sigma_I}{\lambda}}}{\psi_{i_2} i_2^{\frac{1-\sigma_I}{\lambda}}} \right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}} .$$

Then, for $\kappa > 0$, any positive investment in basic research in countries r_2 will result in inefficient targeting.

(ii) Let both industries have same attractiveness, i.e.

$$\psi_{i_1} i_1^{\frac{1-\sigma_I}{\lambda}} = \psi_{i_2} i_2^{\frac{1-\sigma_I}{\lambda}} ,$$

and countries r_1 account for at least 50% of the world population. Then, for any κ targeting will be efficient by Proposition 2, Corollary 1, and the fact that $\eta_1(\cdot)$ is increasing.

□

B.5 Proof of Proposition 5

In this proof, we use $\xi^r_{\tilde{S}}$ and $\tilde{a}^r_{\tilde{S}}$ to denote the solutions of the constrained social planner.

Suppose the social planner wants to generate the same number of varieties as in the decentralized equilibrium. Then because basic research is equally productive in both cases it cannot be that $\tilde{a}^r_{\tilde{S}} \geq (\leq) \tilde{a}^r_E$ for all r with the inequality being strict for some measurable set of countries, i.e. either investment patterns are identical almost everywhere or it must be that $\tilde{a}^r_{\tilde{S}} > \tilde{a}^r_E$ for some measurable set of countries and $\tilde{a}^r_{\tilde{S}} < \tilde{a}^r_E$ for some disjoint measurable set of countries. In turn, $\tilde{a}^r_{\tilde{S}} > (<) \tilde{a}^r_E$ implies that $\xi^r_{\tilde{S}} < (>) \xi^r_E$. Now, investment patterns cannot be identical by (36) in combination with sufficient skills and the fact that $\tilde{i}(r) < \bar{i}$ for some $r > \underline{r}$. What is more, $\tilde{a}^r_{\tilde{S}} > (<) \tilde{a}^r_E$ for some r implies that $\tilde{a}^{r'}_{\tilde{S}} > (<) \tilde{a}^{r'}_E$ for all $r' \geq (\leq) r$ by (36). The result then follows from noting that we may have $\xi^r_{\tilde{S}} = \xi^r_E$ for all $r \in [\tilde{r}_1, \tilde{r}_2)$, where $\tilde{r}_1 = \tilde{r}(i_k)$ and $\tilde{r}_2 = \tilde{r}(i_{k+1})$ for some industry $\underline{i} < i_k < \bar{i}$.

□

B.6 Proof of Proposition 6

For the purpose of this and the following proof, it will be useful to introduce the following notation. We will say that there is a fixed allocation scheme $\varphi = \{\varphi^r\}_{r \in [\underline{r}, \overline{r}]}$ of basic research investments to countries if, for any desired aggregate investment in basic research, $\tilde{L}_{BR}$, and every country $r \in [\underline{r}, \overline{r}]$, we have

$$\xi^r(\tilde{L}_{BR}; \varphi) = \frac{\tilde{L}_{BR}}{\int_{\underline{r}}^{\overline{r}} \varphi^r \tilde{L}^r f_r(r) dr} \varphi^r \ .$$

In other words, a fixed allocation scheme is characterized by $\frac{\xi^r}{\xi^{r'}} = \frac{\varphi^r}{\varphi^{r'}} =$ constant $\forall r, r' \in [\underline{r}, \overline{r}]$. (15) and (13) imply that for any such allocation scheme, the total number of varieties in the economy is strictly increasing in $\tilde{L}_{BR}$. Allocation scheme φ is thus associated with a strictly increasing function $\tilde{L}_{BR}(N; \varphi)$ that defines the required total amount of effective labor in basic research for every desired number of varieties N and, equivalently, with a strictly increasing function $N(\tilde{L}_{BR}; \varphi)$. We will use φ_E to denote the targeting scheme prevailing in the decentralized equilibrium and, without loss of generality, choose the normalization $\varphi_E^r = \xi_E^r$ for all r.

In Section 6 we have shown that the optimal number of varieties of the social planner is independent from the targeting of basic research investments to industries. By the same reasoning, the optimal aggregate investment in basic research is also independent from targeting when confronted with a fixed allocation scheme φ, and hence we are allowed to choose an arbitrary targeting as long as it satisfies Condition SSC. Now, suppose that the social planner adopts the decentralized equilibrium targeting of each country. With a fixed allocation scheme, the social planner's decision problem then boils down to the following:

$$\max_{\tilde{L}_{BR}} \quad C = [-e\lambda \ln(\overline{r})]^{-\frac{1}{\lambda}} \left[\sum_{i \in \mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} N_i^{\frac{1-\sigma_I}{1-\sigma_v}} \right]^{\frac{1}{\sigma_I - 1}} \left[\tilde{L} - \tilde{L}_{BR} \right] \ ,$$

$$\text{s.t.} \quad N_i = \int_{\underline{r}}^{\overline{r}} \left[\mathbb{1}_{[i = i^r_{BR}]} \kappa + \frac{1-\kappa}{I} \right] \eta_1(r) \eta_2 \left(\varphi_E^r \frac{\tilde{L}_{BR}}{\tilde{L}_{BR,E}} \right) L^r f_r(r) dr \ .$$

The optimal $\tilde{L}_{BR}$ is then the unique solution to the associated first order condition, which after some straightforward modifications reads[63]

$$\frac{C}{\tilde{L}-\tilde{L}_{BR}} = \frac{\sigma_v}{\sigma_v-1}\frac{1}{P}\frac{1}{\tilde{L}_{BR,E}} \sum_{i\in\mathcal{I}}\pi_i\int_{\underline{r}}^{\overline{r}}\left[\mathbb{1}_{[i=i^r_{BR}]}\kappa+\frac{1-\kappa}{I}\right]\eta_1(r)\eta_2'\left(\varphi^r_E\frac{\tilde{L}_{BR}}{\tilde{L}_{BR,E}}\right)\varphi^r_E L^r f_r(r)dr\ . \quad \text{(B.9)}$$

In what follows, we will show that when evaluated at $\tilde{L}_{BR}=\tilde{L}_{BR,E}$, the right-hand-side must be strictly larger than the left-hand side, implying that the social planner will invest strictly more compared to the decentralized equilibrium.

The left-hand-side of (B.9) is the social planner's marginal cost of increasing $\tilde{L}_{BR}$. Using Proposition 1(ix), this can be rewritten as

$$\frac{C}{\tilde{L}-\tilde{L}_{BR}} = \frac{\sigma_v}{\sigma_v-1}\frac{1}{P}\ , \quad \text{(B.10)}$$

i.e. the marginal cost of the social planner is just $\frac{\sigma_v}{\sigma_v-1}$ times the real wage per unit of effective labor. In turn, this implies that the marginal cost for the social planner is just $\frac{\sigma_v}{\sigma_v-1}$ times the total marginal costs of national governments for the corresponding increase in $\tilde{L}^r_{BR}$,

$$\frac{C}{\tilde{L}-\tilde{L}_{BR}} = \frac{\sigma_v}{\sigma_v-1}\frac{1}{P}\int_{\underline{r}}^{\overline{r}}\frac{\xi^r_E\tilde{L}^r}{\tilde{L}_{BR,E}}f_r(r)dr\ , \quad \text{(B.11)}$$

where the equality follows from the fact that $\int_{\underline{r}}^{\overline{r}}\xi^r_E\tilde{L}^r f_r(r)dr=\tilde{L}_{BR,E}$.[64]

The right-hand-side of (B.9) is the marginal benefit of the social planner. Evaluating at $\tilde{L}_{BR}=\tilde{L}_{BR,E}$ and rearranging terms yields

$$\frac{\sigma_v}{\sigma_v-1}\frac{1}{P}\frac{1}{\tilde{L}_{BR,E}}\sum_{i\in\mathcal{I}}\pi_i\int_{\underline{r}}^{\overline{r}}\left[\mathbb{1}_{[i=i^r_{BR}]}\kappa+\frac{1-\kappa}{I}\right]\eta_1(r)\eta_2'\left(\xi^r_E\right)\xi^r_E L^r f_r(r)dr$$
$$=$$
$$\frac{\sigma_v}{\sigma_v-1}\frac{1}{P}\int_{\underline{r}}^{\overline{r}}\frac{\xi^r_E}{\tilde{L}_{BR,E}}\eta_1(r)\eta_2'\left(\xi^r_E\right)\left[\kappa\pi_{i^r_{BR}}+\sum_{i\in\mathcal{I}}\frac{1-\kappa}{I}\pi_i\right]L^r f_r(r)dr$$
$$>$$
$$\frac{\sigma_v}{\sigma_v-1}\frac{1}{P}\int_{\underline{r}}^{\overline{r}}\frac{\xi^r_E}{\tilde{L}_{BR,E}}\eta_1(r)\eta_2'\left(\xi^r_E\right)\theta_D\left[\kappa\pi_{i^r_{BR}}+\sum_{i\in\mathcal{I}(r)}\frac{1-\kappa}{I}\pi_i\right]L^r f_r(r)dr\ .$$

[63]Existence and uniqueness follow from multiplying both sides of (B.9) by $P\frac{\sigma_v-1}{\sigma_v}$. The LHS of (B.9) is then equal to 1 (see Proposition 1), while the RHS is continuously decreasing, with limits $\lim_{\tilde{L}_{BR}\to 0}RHS=\infty$ and $\lim_{\tilde{L}_{BR}\to\tilde{L}}RHS=0$.

[64]Note that $\frac{\xi^r_E\tilde{L}^r}{\tilde{L}_{BR,E}}$ in Equation (B.11) is the marginal increase in $\tilde{L}^r_{BR}$ associated with a marginal increase in $\tilde{L}_{BR}$, $\frac{d\tilde{L}^r_{BR}}{d\tilde{L}_{BR}}$.

The inequality follows from $\theta_D \leq 1$ and the fact that $\tilde{i}(\underline{r}) < \bar{\tilde{i}}$. The last term is just $\frac{\sigma_v}{\sigma_v - 1}$ times the total marginal benefits of national governments associated with the respective increase in $\tilde{L}^r_{BR}$. By Condition (20) these are just equal to the corresponding total marginal costs, i.e. to the left-hand-side of (B.9), which proves the desired result.

□

B.7 Proof of Proposition 7

Recall that for any given targeting (Appendix A.2.1) and a fixed allocation scheme of basic research investments (Appendix B.6), the social planner's optimal investment is the unique solution to

$$\frac{1}{\sigma_v - 1} = \frac{\partial \tilde{L}_{BR}(N;\varphi)}{\partial N} \frac{N}{\tilde{L} - \tilde{L}_{BR}(N;\varphi)} \ . \tag{B.12}$$

For a given allocation scheme φ, aggregate investments $\tilde{L}_{BR}$ yield

$$N(\tilde{L}_{BR};\varphi) = \int_{\underline{r}}^{\overline{r}} \int_{\tilde{a}^r(\tilde{L}_{BR};\varphi)}^{\infty} a dF_a(a) \tilde{g}(r) dr \tag{B.13}$$

varieties, where $\tilde{g}(r) := \eta_1(r) L^r f_r(r)$ and where $\tilde{a}^r(\tilde{L}_{BR};\varphi)$ denotes the research ability of the marginal scientist in country r if aggregate investments are $\tilde{L}_{BR}$ with an allocation scheme φ. Differentiating with respect to $\tilde{L}_{BR}$ yields

$$\begin{aligned} \frac{\partial N}{\partial \tilde{L}_{BR}} &= \int_{\underline{r}}^{\overline{r}} \tilde{a}^r(\tilde{L}_{BR};\varphi) \frac{\varphi^r}{\int_{\underline{r}}^{\overline{r}} \varphi^r \tilde{L}^r f_r(r) dr} \tilde{g}(r) dr \\ &= \int_{\underline{r}}^{\overline{r}} \tilde{a}^r(\tilde{L}_{BR};\varphi) \frac{[1 - F_a(\tilde{a}^r(\tilde{L}_{BR};\varphi))]}{\tilde{L}_{BR}} \tilde{g}(r) dr \ , \end{aligned} \tag{B.14}$$

where the second equality follows from $\frac{\varphi^r}{\int_{\underline{r}}^{\overline{r}} \varphi^r \tilde{L}^r f_r(r) dr} = \frac{\xi^r(\tilde{L}_{BR};\varphi)}{\tilde{L}_{BR}}$. Using (B.13) and (B.14) in (B.12), we obtain

$$\frac{1}{\sigma_v - 1} = \frac{\int_{\underline{r}}^{\overline{r}} \int_{\tilde{a}^r(\tilde{L}_{BR};\varphi)}^{\infty} a dF_a(a) \tilde{g}(r) dr}{\int_{\underline{r}}^{\overline{r}} \left[1 - F_a(\tilde{a}^r(\tilde{L}_{BR};\varphi))\right] \tilde{a}^r(\tilde{L}_{BR};\varphi) \tilde{g}(r) dr} \frac{\tilde{L}_{BR}}{\tilde{L} - \tilde{L}_{BR}} \ . \tag{B.15}$$

When confronted with allocation scheme φ, the social planner chooses aggregate investments in basic research to satisfy (B.15). The desired result then follows from noting that with a Pareto distribution of abilities $F_a(a) = 1 - \left(\frac{a}{\underline{a}}\right)^{-\tilde{\alpha}}$,

$$\frac{\int_{\underline{r}}^{\overline{r}} \int_{\tilde{a}^r(\tilde{L}_{BR};\varphi)}^{\infty} a dF_a(a) \tilde{g}(r) dr}{\int_{\underline{r}}^{\overline{r}} \left[1 - F_a(\tilde{a}^r(\tilde{L}_{BR};\varphi))\right] \tilde{a}^r(\tilde{L}_{BR};\varphi) \tilde{g}(r) dr} = \frac{\tilde{\alpha}}{\tilde{\alpha} - 1}$$

is constant, which proves that the optimal $\tilde{L}_{BR}$ is the same, irrespective of the allocation scheme. This implies that aggregate investments in the decentralized equilibrium are lower than in the social planner's solution, since $\theta_D \leq 1$ and $\mathcal{I}(r) \subset \mathcal{I}$ for a measurable set of countries, i.e. for these countries some ideas cannot be commercialized domestically.

□

B.8 Proof of Corollary 4

We show the desired result by means of examples.

For $\underline{r} \to \tilde{r}(\bar{i})$, i.e. in an environment where all countries can produce all goods at preferred quality, the targeting of basic research and the allocation of these investments to countries are efficient, and all countries will invest less in basic research when compared to the social planner solution, as long as $\theta_D < 1$.

Conversely, with a Pareto distribution of abilities and $\theta_D = 1$, and as long as $\underline{r} < \tilde{r}(\bar{i})$, the highest-skilled countries will invest more in basic research compared to the social planner solution. This will be the case because (1) with $\theta_D = 1$ the decentralized equilibrium would be efficient in the limiting case of $\underline{r} \to \tilde{r}(\bar{i})$. (2) with $r < \tilde{r}(\bar{i})$ some low-skilled countries can commercialize ideas in a subset of industries only. Thus, they invest less compared to the social planner solution, and there will be less aggregate investment in basic research by Proposition 7, implying that the total number of varieties N will also be smaller. (3) In turn this implies that expected profits of domestically innovated varieties will be higher for highest-skilled countries than in the social planner solution.[65] Hence, these highest-skilled countries will invest more in basic research compared to the social planner solution.

□

[65]Recall that targeting in the decentralized equilibrium is either efficient or too much concentrated on simple industries, in which case profits in complex industries are even higher for a given aggregate number of varieties.

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Online Appendix

C Further Considerations on the Sufficient Skills Condition

In the main body of our paper, we focused on economies with *sufficient skills* in equilibrium. In such an equilibrium, it will be the case that there is systematically more (effective) labor available in countries with high productive knowledge than needed in production of the complex goods, implying that some of this labor will need to be employed in the less complex industries, where labor in less developed countries can also operate at preferred quality. This puts downward pressure on wages for labor in industrialized countries, and implies that in equilibrium every country will be competitive in all industries, up to some threshold complexity level denoted by $\tilde{i}(r)$, which is strictly increasing in r.

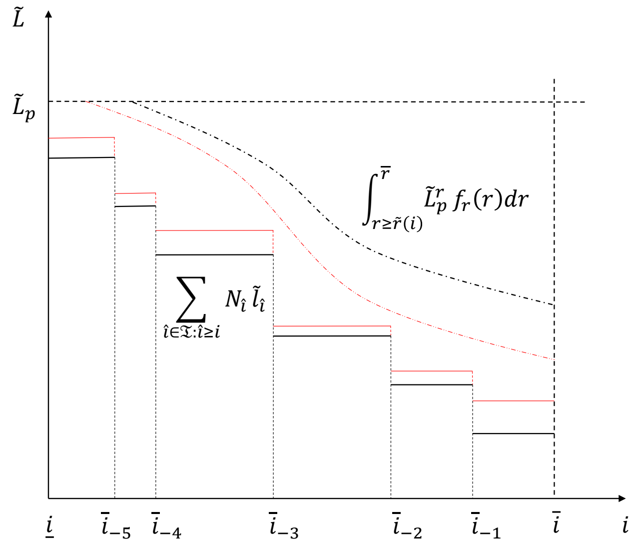
While this equilibrium exhibits the empirically attractive features that more developed countries are more diversified in international trade and that countries' exports tend to be nested,[66] it is not obvious if and when the underlying *Sufficient Skills Condition* will be satisfied in the equilibrium with decentralized basic research policies or in the optimal solution of the social planner as there are non-trivial interactions with basic research investment policies. In particular, targeting of basic research will impact the cross-industry distribution of labor demand while allocation of basic research to countries will impact the skill distribution of labor available for production. We recall the definition of SSC:

$$\int_{\tilde{r}(\hat{i})}^{\overline{r}} \left[L^r - L^r_{BR}\right] \left[\frac{\ln(\overline{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} dF_r(r) \geq \sum_{i \in \mathcal{I}: i \geq \hat{i}} N_i \tilde{l}_i \ , \quad \forall \, \hat{i} \in \mathcal{I} \ . \tag{SSC}$$

For a broad range of parameter specifications Condition SSC will be satisfied both in the decentralized equilibrium and in the social planner solution. In this appendix, we discuss one such set of parameter specifications for which Condition SSC holds. The basic argument is summarized in Figure 4. In this figure, the dashed line shows for every industry i the total global supply of effective labor for production that can operate in industry i at preferred quality, $\int_{r \geq \tilde{r}(i)}^{\overline{r}} \tilde{L}^r_p f_r(r) dr$. The solid line shows total demand for effective labor in industries with complexity i or higher, $\sum_{\hat{i} \in \mathcal{I}: \hat{i} \geq i} N_{\hat{i}} \tilde{l}_{\hat{i}}$. Condition SSC is

[66] Cf. Hausmann and Hidalgo (2011), Bustos et al. (2012), and Schetter (2018).

Figure 4: Sufficient Criteria for the Sufficient Skills Condition SSC



satisfied if the dashed line is above the solid line everywhere. In what follows, for every i we will derive a lower bound on the share of aggregate effective labor in production that has skill level $\tilde{r}(i)$ or higher, and an upper bound on the share of aggregate effective labor in production that is employed in industries with complexity of at least i. We then derive conditions such that these bounds satisfy SSC as illustrated in Figure 4 (red lines).

To derive such conditions, it will be convenient to consider the case of a Pareto distribution of basic research abilities

$$F_a(a) = 1 - \left(\frac{a}{\underline{a}}\right)^{-\tilde{\alpha}},$$

where $a \geq \underline{a} > 0$ and $\tilde{\alpha} > 1$ and which implies that

$$\eta_2(\xi) = \zeta \xi^{\alpha},$$

where $\zeta := \frac{\tilde{\alpha}}{\tilde{\alpha}-1}\underline{a}$ and $\alpha := \frac{\tilde{\alpha}-1}{\tilde{\alpha}}$. Further, to save notation we will assume that it is technically feasible to target basic research investments such that profits of the representative firm in industry i (denoted by π_i) are equal across industries.[67] This is an assumption on parameters $\{\psi_i\}_{i \in \mathcal{I}}, \lambda, \kappa, \sigma_v, \sigma_I$ and restricts cross-industry differences in attractiveness when targeting is not perfect. We next introduce a formal assumption

[67] Note that we do not assume that profits are equal in the ensuing equilibrium.

on the heterogeneity of attractiveness and the probability of success in targeting that allows equalization of profits.

Assumption 3

$$\frac{\left[\psi_{\hat{i}}\hat{i}^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v-1}{\sigma_v-\sigma_I}}}{\sum_{i\in\mathcal{I}}\left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v-1}{\sigma_v-\sigma_I}}} \geq \frac{1-\kappa}{I}\ , \quad \forall \hat{i}\in\mathcal{I}\ .$$

Lemma 2

Suppose that Assumption 3 and SSC hold. Then, it is feasible to target basic research investments such that profits of the representative firms are equal across industries.

The proof of Lemma 2 is given in Appendix D.1. Intuitively, whether or not it is feasible to have equal profits in all industries will depend on the ex-ante attractiveness of industries and the probability of success in targeting basic research. With perfect targeting, $\kappa = 1$, this will be possible for arbitrary cross-industry differences in their attractiveness. On the contrary, for $\kappa = 0$, basic research cannot be targeted at all, and profits of the respective representative firm can only be equal across industries if there is no ex-ante heterogeneity in terms of attractiveness. Assumption 3 restricts cross-industry differences in terms of ex-ante attractiveness accordingly. Note that neither Assumption 3 nor Lemma 2 is based on the case of a Pareto distribution of basic research abilities.

Lemma 2 implies that as long as there are sufficient skills, targeting by the social planner and in a decentralized equilibrium where only the countries with highest productive knowledge $r \geq \tilde{r}(\bar{i})$ invest in basic research will always be such that profits are equal across industries. Any alternative targeting would imply that some industry with positive targeting will have lower profits than some other industry and, hence, both the social planner and a government in a country with $r \geq \tilde{r}(\bar{i})$ will benefit from retargeting their investments.[68]

[68] The fact that a government in country $r \geq \tilde{r}(\bar{i})$ would benefit from retargeting its investments follows immediately from the discussion of the optimal targeting in Section 5. The marginal benefit of a new variety in industry $\hat{i}$ for the social planner is

$$\begin{aligned}\frac{\partial C}{\partial N_{\hat{i}}} &= [-e\lambda\ln(\bar{r})]^{-\frac{1}{\lambda}}\left[\sum_{i\in\mathcal{I}}\psi_i i^{\frac{1-\sigma_I}{\lambda}}N_i^{\frac{1-\sigma_I}{1-\sigma_v}}\right]^{\frac{1}{\sigma_I-1}}\tilde{L}_p\frac{1}{\sigma_v-1}\frac{\psi_{\hat{i}}\hat{i}^{\frac{1-\sigma_I}{\lambda}}N_{\hat{i}}^{\frac{\sigma_v-\sigma_I}{1-\sigma_v}}}{\sum_{i\in\mathcal{I}}\psi_i i^{\frac{1-\sigma_I}{\lambda}}N_i^{\frac{1-\sigma_I}{1-\sigma_v}}}\\ &= \frac{\sigma_v}{\sigma_v-1}\frac{\pi_{\hat{i}}}{P}\ ,\end{aligned}$$

Now, as demonstrated in the main body of this paper, the share of the population employed in basic research is weakly monotonously increasing in r in both the decentralized equilibrium and the social planner solution. Further, countries' basic research investments are strategic substitutes.[69] In the proof of Lemma 3, we will make use of these observations to show that countries' basic research investments ξ_E^r and ξ_S^r are bounded from above.

Lemma 3

With sufficient skills ξ_E^r and ξ_S^r are bounded from above by

$$\gamma := \frac{\eta_1(\overline{r})^{\tilde{\alpha}}\tilde{L}(\tilde{\alpha}-1)}{\tilde{\alpha}(\sigma_v-1)\int_{\tilde{r}(\bar{i})}^{\overline{r}}\eta_1(r)^{\tilde{\alpha}}\left[\frac{\ln(\overline{r})}{\ln(r)}\right]^{\frac{1-\tilde{\alpha}}{\lambda}}L^r f_r(r)dr} .$$

The proof of Lemma 3 is given in Appendix D.2.

Lemma 3 provides an upper bound on investments in basic research if there are sufficient skills. We use this bound in the proof of Proposition 8 to derive a condition such that there are always sufficient skills in both the decentralized equilibrium and the solution of the global social planner.[70]

Assumption 4

$$\frac{\int_{\tilde{r}(\hat{i})}^{\overline{r}}(1-\gamma)\left[-\ln(r)\right]^{-\frac{1}{\lambda}}L^r\,dF_r(r)}{\int_{\underline{r}}^{\tilde{r}(\hat{i})}\left[-\ln(r)\right]^{-\frac{1}{\lambda}}L^r\,dF_r(r)+\int_{\tilde{r}(\hat{i})}^{\overline{r}}(1-\gamma)\left[-\ln(r)\right]^{-\frac{1}{\lambda}}L^r\,dF_r(r)}$$
$$\geq\frac{\sum_{i\in\mathcal{I}:i\geq\hat{i}}\left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v-1}{\sigma_v-\sigma_I}}}{\sum_{i\in\mathcal{I}}\left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v-1}{\sigma_v-\sigma_I}}}\,,\quad\forall\hat{i}\in\mathcal{I}\,.$$

Proposition 8

Let abilities be Pareto distributed and Assumptions 3 and 4 be satisfied. Then Condition SSC is satisfied in both the equilibrium with decentralized investments in basic research and in the optimal solution of the global social planner.

where the first equality follows from differentiating C and rearranging terms, and the second equality follows form using the definitions of P and $\pi_{\hat{i}}$ which implies that indeed the social planner would also benefit from retargeting his investments.

[69] Observe from Proposition 1 that profits in industry i are decreasing in the number of varieties in any other industry $\hat{i}$ and in labor employed in basic research.

[70] In principle the social planner could still find it optimal to opt for basic research investments, such that Condition SSC is violated. This, however, will not be the case as our analysis implies that the social planner would not opt for the corresponding investment even if ignoring the additional inefficiencies arising from a violation of SSC. Hence, he will certainly not decide to do so when taking these inefficiencies into account.

The proof of Proposition 8 is given in Appendix D.3. Note that Assumptions 3 and 4 are based on structural parameters of the model alone. They are sufficient but not necessary. Assumption 4 is the less restrictive, the smaller γ is. Considering that basic research activities account for a small fraction of the labor force and of the GDP therefore suggests that there will be sufficient skills for a broad set of parameter specifications indeed.[71]

D Proofs

D.1 Proof of Lemma 2

Suppose there are sufficient skills. Then, by Proposition 1, we have for any $\hat{i}, i \in \mathcal{I}$:

$$\frac{\pi_{\hat{i}}}{\pi_i} = \frac{\psi_{\hat{i}} N_{\hat{i}}^{\frac{\sigma_v - \sigma_I}{1-\sigma_v}} \hat{i}^{\frac{1-\sigma_I}{\lambda}}}{\psi_i N_i^{\frac{\sigma_v - \sigma_I}{1-\sigma_v}} i^{\frac{1-\sigma_I}{\lambda}}} .$$

Hence, the profits of the respective representative firm are the same in industries i and $\hat{i}$ if and only if

$$N_i = \left[\frac{\psi_i i^{\frac{1-\sigma_I}{\lambda}}}{\psi_{\hat{i}} \hat{i}^{\frac{1-\sigma_I}{\lambda}}} \right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}} N_{\hat{i}} .$$

Summing over all industries and rearranging terms yields

$$n_{\hat{i}} = \frac{\left[\psi_{\hat{i}} \hat{i}^{\frac{1-\sigma_I}{\lambda}} \right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}}{\sum_{i \in \mathcal{I}} \left[\psi_i i^{\frac{1-\sigma_I}{\lambda}} \right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}} , \tag{D.1}$$

where, as before n_i, denotes the share of all varieties that are in industry i. Further, remember that s_i denotes the share of all ideas that is targeted to industry i. From the discussion in Appendix A.2.1, we know that

$$s_i = n_i \frac{1}{\kappa} - \frac{(1-\kappa)}{\kappa} \frac{1}{I} . \tag{D.2}$$

(D.2) characterizes the share of all ideas that need to be targeted to industry i, such that the share of industry-i varieties in all varieties is n_i. Combining (D.1) and (D.2), we obtain

$$s_i = \frac{\left[\psi_i i^{\frac{1-\sigma_I}{\lambda}} \right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}}{\sum_{i \in \mathcal{I}} \left[\psi_i i^{\frac{1-\sigma_I}{\lambda}} \right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}} \frac{1}{\kappa} - \frac{(1-\kappa)}{\kappa} \frac{1}{I} .$$

[71] Countries devote less than 1% of their GDP to basic research (cf. OECD (2016)).

By Assumption 3, s_i is non-negative for all i and, hence, it is feasible.

□

D.2 Proof of Lemma 3

We consider a scenario where only countries with highest productive knowledge $r \geq \tilde{r}(\bar{i})$ invest in basic research and we show that their investments are bounded by γ in that case. As countries' investments are strategic substitutes, the same bound also applies if we allow investment by lower-skilled countries.

From Appendix C, we know that the highest-skilled countries would adopt the social planner's targeting if they were the only countries to invest in basic research. In such case, profits are the same in all industries and expected profits from a new variety are

$$\begin{aligned}\mathbb{E}[\pi] &= \sum_{i \in \mathcal{I}} n_i \pi_i \\ &= \frac{\tilde{L}_p}{N(\sigma_v - 1)} \ .\end{aligned}$$

With a Pareto distribution of abilities, this implies

$$\begin{aligned}\xi_E^r &= \left(\frac{\tilde{a}^r}{\underline{a}}\right)^{-\tilde{\alpha}} \\ &= \left(\frac{\underline{a}\eta_1(r)\theta_D \tilde{L}_p}{N(\sigma_v - 1)w^r}\right)^{\tilde{\alpha}} \ ,\end{aligned} \tag{D.3}$$

for the optimal level of basic research investment in country $r \geq \tilde{r}(\bar{i})$.[72] For the aggregate number of varieties we obtain

$$\begin{aligned}N &= \int_{\tilde{r}(\bar{i})}^{\overline{r}} \eta_1(r) \frac{\tilde{\alpha}}{\tilde{\alpha} - 1} \underline{a} {\xi_E^r}^{\frac{\tilde{\alpha}-1}{\tilde{\alpha}}} L^r f_r(r) dr \\ &= \int_{\tilde{r}(\bar{i})}^{\overline{r}} \eta_1(r)^{\tilde{\alpha}} \frac{\tilde{\alpha}}{\tilde{\alpha} - 1} \underline{a}^{\tilde{\alpha}} \left(\frac{\theta_D \tilde{L}_p}{N(\sigma_v - 1)w^r}\right)^{\tilde{\alpha}-1} L^r f_r(r) dr \ .\end{aligned}$$

Solving for $N^{\tilde{\alpha}}$, plugging into (D.3), and substituting in the equilibrium value for w^r yields:

$$\begin{aligned}\xi_E^{\overline{r}} &= \frac{\eta_1(\overline{r})^{\tilde{\alpha}} \theta_D \tilde{L}_p (\tilde{\alpha} - 1)}{\tilde{\alpha}(\sigma_v - 1) \int_{\tilde{r}(\bar{i})}^{\overline{r}} \eta_1(r)^{\tilde{\alpha}} \left[\frac{\ln(\overline{r})}{\ln(r)}\right]^{\frac{1-\tilde{\alpha}}{\lambda}} L^r f_r(r) dr} \\ &= \gamma \theta_D \frac{\tilde{L}_p}{\tilde{L}} < \gamma \ ,\end{aligned}$$

[72] See Equation (21) in the main part of our paper.

where the inequality follows from $\theta_D \leq 1$ and $\tilde{L}_p < \tilde{L}$ with positive basic research. This proves that ξ_E^r is bounded from above by γ. $\xi_S^r < \gamma$ follows from the fact that for the case considered, the social planner will in all countries choose investments according to (D.3), but with $\theta_D = 1$.[73]

□

D.3 Proof of Proposition 8

A necessary condition for labor market clearing is that total demand for effective labor equals total supply:

$$\int_{\underline{r}}^{\overline{r}} [L^r - L_{BR}^r] \left[\frac{\ln(\overline{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} dF_r(r) = \sum_{i\in\mathcal{I}} N_i \tilde{l}_i \ .$$

Normalizing SSC by the above equation, we obtain

$$\frac{\int_{\tilde{r}(\hat{i})}^{\overline{r}} [L^r - L_{BR}^r] \left[\frac{\ln(\overline{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} dF_r(r)}{\int_{\underline{r}}^{\overline{r}} [L^r - L_{BR}^r] \left[\frac{\ln(\overline{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} dF_r(r)} \geq \frac{\sum_{i\in\mathcal{I}:i\geq\hat{i}} N_i \tilde{l}_i}{\sum_{i\in\mathcal{I}} N_i \tilde{l}_i} \ , \quad \forall \hat{i} \in \mathcal{I} \ , \tag{SSC2}$$

i.e. there will be sufficient skills if for any industry $\hat{i}$, the share of total effective labor available for production in countries with productive knowledge $r \geq \tilde{r}(\hat{i})$ is at least as

[73]This follows from the following considerations. First, the marginal social benefit of a variety in industry i is

$$\begin{aligned}\frac{\partial C}{\partial N_i} &= [-e\lambda \ln(\overline{r})]^{-\frac{1}{\lambda}} \left[\sum_{i\in\mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} N_i^{\frac{1-\sigma_I}{1-\sigma_v}}\right]^{\frac{1}{\sigma_I - 1}} \tilde{L}_p \frac{1}{\sigma_v - 1} \frac{\psi_i i^{\frac{1-\sigma_I}{\lambda}} N_i^{\frac{\sigma_v - \sigma_I}{1-\sigma_v}}}{\sum_{i\in\mathcal{I}} \psi_i i^{\frac{1-\sigma_I}{\lambda}} N_i^{\frac{1-\sigma_I}{1-\sigma_v}}} \\ &= \frac{\sigma_v}{\sigma_v - 1} \frac{\pi_i}{P} \ .\end{aligned}$$

Second, the marginal social costs of increasing basic research in country r are

$$\begin{aligned}-\frac{\partial C}{\partial L_{BR,S}^r} &= -\frac{\partial C}{\partial \tilde{L}_p} \frac{\partial \tilde{L}_p}{\partial L_{BR,S}^r} \\ &= \frac{\sigma_v}{\sigma_v - 1} \frac{w^r}{P} \ .\end{aligned}$$

Note that these marginal social costs and benefits are just $\frac{\sigma_v}{\sigma_v - 1}$ times the corresponding marginal costs and benefits of a national government, respectively. Moreover, the social planner chooses the same targeting of basic research investment as in the decentralized equilibrium considered in this appendix, i.e. a hypothetical equilibrium where only countries with highest productive knowledge $r \geq \tilde{r}(\bar{i})$ invest in basic research. Together, these observations imply that the optimality condition for the social planner for investments in country r is indeed (D.3) with $\theta_D = 1$.

high as the share of total effective labor available for production that is demanded by industries $i \geq \hat{i}$.

As shown in Lemma 3, ξ_E^r and ξ_S^r are bounded from above by γ. It follows that for any industry $\hat{i} \in \mathcal{I}$, the LHS of SSC2 is bounded from below by the LHS of Assumption 4

$$\frac{\int_{\tilde{r}(\hat{i})}^{\overline{r}} [L^r - L_{BR}^r] \left[\frac{\ln(\overline{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} dF_r(r)}{\int_{\underline{r}}^{\overline{r}} [L^r - L_{BR}^r] \left[\frac{\ln(\overline{r})}{\ln(r)}\right]^{\frac{1}{\lambda}} dF_r(r)} \geq \frac{\int_{\tilde{r}(\hat{i})}^{\overline{r}} (1-\gamma)\,[-\ln(r)]^{-\frac{1}{\lambda}}\, L^r \, dF_r(r)}{\int_{\underline{r}}^{\tilde{r}(\hat{i})} [-\ln(r)]^{-\frac{1}{\lambda}}\, L^r \, dF_r(r) + \int_{\tilde{r}(\hat{i})}^{\overline{r}} (1-\gamma)\,[-\ln(r)]^{-\frac{1}{\lambda}}\, L^r \, dF_r(r)} \,, \quad \forall \hat{i} \in \mathcal{I} \,. \tag{D.4}$$

Moreover, as argued in Appendix C (see also Assumption 3 and Lemma 2 in Appendix C), the social planner will target basic research investments such that profits are equal across industries. Then, from Proposition 1, we know that all production firms will demand the same amount of effective labor, irrespective of their industry. The share of industry i in total effective labor, $\frac{\tilde{L}_i}{\tilde{L}_p} = \frac{N_i \tilde{l}_i}{\tilde{L}_p}$, is then equal to its share in the total number of varieties, $\frac{N_i}{N}$

$$\frac{\tilde{L}_{\hat{i}}}{\tilde{L}_p} = \frac{\left[\psi_{\hat{i}} \hat{i}^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}}{\sum_{i \in \mathcal{I}} \left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}} \,. \tag{D.5}$$

(D.4), (D.5), and Assumption 4 imply that ξ_S^r indeed satisfies condition SSC.

Finally, to prove that ξ_E^r also satisfies condition SSC we show that in the decentralized equilibrium, $\frac{\sum_{i \in \mathcal{I}: i \geq \hat{i}} N_i \tilde{l}_i}{\sum_{i \in \mathcal{I}} N_i \tilde{l}_i}$ is bounded from above by

$$\frac{\sum_{i \in \mathcal{I}: i \geq \hat{i}} N_i \tilde{l}_i}{\sum_{i \in \mathcal{I}} N_i \tilde{l}_i} \leq \frac{\sum_{i \in \mathcal{I}: i \geq \hat{i}} \left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}}{\sum_{i \in \mathcal{I}} \left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}} \,, \quad \forall \hat{i} \in \mathcal{I} \,,$$

and the result then follows from (D.4) and Assumption 4.

We proceed by contradiction. Suppose, by contradiction, that

$$\frac{\sum_{i \in \mathcal{I}: i \geq \hat{i}} N_i \tilde{l}_i}{\sum_{i \in \mathcal{I}} N_i \tilde{l}_i} > \frac{\sum_{i \in \mathcal{I}: i \geq \hat{i}} \left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}}{\sum_{i \in \mathcal{I}} \left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v - 1}{\sigma_v - \sigma_I}}} \,,$$

for some $\hat{i} \in \mathcal{I}$. Then it must hold that

$$\frac{N_{i^h}\tilde{l}_{i^h}}{\sum_{i\in\mathcal{I}} N_i\tilde{l}_i} > \frac{\left[\psi_{i^h} {i^h}^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v-1}{\sigma_v-\sigma_I}}}{\sum_{i\in\mathcal{I}}\left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v-1}{\sigma_v-\sigma_I}}} \; , \tag{D.6}$$

and $n_{i^h} > \frac{1-\kappa}{I}$ for some $i^h \geq \hat{i}$. Similarly, it must hold that

$$\frac{\sum_{i\in\mathcal{I}:i<\hat{i}} N_i\tilde{l}_i}{\sum_{i\in\mathcal{I}} N_i\tilde{l}_i} < \frac{\sum_{i\in\mathcal{I}:i<\hat{i}}\left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v-1}{\sigma_v-\sigma_I}}}{\sum_{i\in\mathcal{I}}\left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v-1}{\sigma_v-\sigma_I}}} \; ,$$

and thus

$$\frac{N_{i^l}\tilde{l}_{i^l}}{\sum_{i\in\mathcal{I}} N_i\tilde{l}_i} < \frac{\left[\psi_{i^l} {i^l}^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v-1}{\sigma_v-\sigma_I}}}{\sum_{i\in\mathcal{I}}\left[\psi_i i^{\frac{1-\sigma_I}{\lambda}}\right]^{\frac{\sigma_v-1}{\sigma_v-\sigma_I}}} \; , \tag{D.7}$$

for some $i^l < \hat{i}$. Combining (D.6) and (D.7) and rearranging terms implies

$$\frac{\psi_{i^l} {i^l}^{\frac{1-\sigma_I}{\lambda}} N_{i^l}^{\frac{\sigma_v-\sigma_I}{1-\sigma_v}}}{\psi_{i^h} {i^h}^{\frac{1-\sigma_I}{\lambda}} N_{i^h}^{\frac{\sigma_v-\sigma_I}{1-\sigma_v}}} \left[\frac{\tilde{l}_{i^l}}{\tilde{l}_{i^h}}\right]^{\frac{\sigma_v-\sigma_I}{1-\sigma_v}} > 1 \; .$$

Proposition 1 and simple algebra then imply

$$\frac{\pi_{i^l}}{\pi_{i^h}} > 1 \; ,$$

a contradiction to equilibrium targeting which requires that profits in an industry that receives positive targeting are weakly higher than in any less complex industry.

□

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