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How Much Science? New Insights on a Classic Policy Challenge

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New Insights on a Classic Policy Challenge[*]

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Abstract

How much should a government invest in science? We propose a factor-based approach to addressing this classic policy challenge. We identify four key factors of optimal investment in basic research: the stage of economic development, the strength of the manufacturing base, the degree of openness, and the share of foreign-owned firms. For each of these factors, we analyse its bearings on optimal basic research investment in the context of a theoretical model with creative destruction. We then show that the predicted effects are consistent with patterns observed in the data and discuss how the factor-based approach might inform basic research policies.

Keywords: Basic Research, Economic Growth, Growth Policy
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1 Introduction

Science is a key driving force of economic growth and development. It expands the knowledge base and thus widens the scope of technological progress. In seeking to stimulate innovation and growth, governments not only set policies to shape the *republic of science*, but also channel non-trivial shares of public funds to basic research.[1] While the general case for public support of basic research is well established in the economic literature, insights that could guide policy at a more detailed level are rare. This applies even to such a fundamental policy issue as how much to invest in basic research, and one of the most pressing policy issues in the social sciences is therefore *How much science do we need?*

The literature has approached this issue by applying industry, country (typically for the US), or cross-country studies to directly estimate either the returns to basic research investments or their positive effects on productivity and GDP growth.[2] Since it is difficult to measure benefits as diverse, indirect, and time-lagging as the ones from basic research with sufficient precision, such studies do not provide a self-contained basis for policy decisions (Salter and Martin, 2001; Stephan, 2012). Moreover, the benefits of basic research investments may differ substantially across countries and depend on country-specific factors. In this article, we therefore propose to complement the empirical studies by theoretical reasoning explicitly taking into account the *factors* determining optimal basic research investments at the country level.[3] We then relate our findings to current policy discussions.

Based on a simple open economy model of creative destruction, we show that basic research has four general effects on the domestic economy. By increasing the innovation success rate of domestic firms, it increases their productivity and makes them more competitive in the world market. However, in supporting innovation, basic research also helps firms to maintain their monopoly position via new patents, and it affects input prices by tying up resources and via its effect on the overall economy. A coun-

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[1] South Korea and Singapore, for example, have stepped up their basic research investments considerably, more than doubling their expenditures as a percentage of GDP from 2000 to 2009 (*Source*: Own calculations, based on OECD (2017a)). The European Council aims to increase total (public and private) R&D spending in the European Union to 3% of GDP by 2020 (General Secretariat of the European Council, 2010). After initiating big-push investments in basic research at the beginning of the 21st century, Ireland has installed a Research Prioritisation Steering Group to identify targets for future investment (Research Prioritisation Project Steering Group, 2012).

[2] For instance, Toole (2012) considers the impact of publicly-funded basic research on the pharmaceutical industry. His analyses suggest that public basic research significantly spurs innovation, with the rate of return to these public investments being as high as 43%. The seminal studies by Mansfield (1980) and Griliches (1986) provide estimates of the productivity effects of basic research. Cf. also Hall et al. (2009) for a survey of the literature on measuring the returns to R&D in general.

[3] Throughout this paper, we will use the term ‘factors’ of optimal basic research investments to denote fundamental country characteristics that are particularly relevant in shaping the costs and benefits associated with these investments.

try's optimal basic research investments is determined by the relative sizes of these four effects, which depend crucially on structural factors of the economy. Our theory points to four such factors of optimal basic research: (1) a country's stage of economic development, (2) its manufacturing base, (3) a country's openness, and (4) its share of domestic firms owned by foreigners. We demonstrate how each of these factors influences what a country's optimal basic research investment is, thereby also illustrating the potential merits of this factor-based approach. In a subsequent assessment of real-world patterns of investment in basic research, we show that these patterns are broadly in line with our theoretical predictions, lending additional support to the view that the herein identified factors do indeed matter for countries' optimal basic research investment. Encouraged by these observations, we illustrate how the factor-based approach may be used to inform policy making in the area of basic research.

There have been first attempts to study the impact of particular country characteristics on basic research investments. Gersbach et al. (2013) study the steady state properties of investment in basic research in an open economy and examine how openness of a country impacts the size of basic research. Gersbach and Schneider (2015) study a basic research game of two countries and examine how human capital levels and market size impact basic research and whether policy coordination yields welfare gains.

The present paper[4] differs from previous work in several respects. First, we develop a substantially richer framework which includes R&D investments by private firms, distinguishes service sectors from manufacturing and incorporates high-skilled and low-skilled workers. This allows for a more comprehensive discussion of economic policy with respect to basic research investments. In particular, it enables us to take a much broader approach to the issue how central characteristics of a country—the stage of economic development, the strength of the manufacturing base, the degree of openness, and the share of foreign-owned firms—impact the way countries invest in basic research, thus moving towards a factor-based approach. Further, explicitly incorporating basic and applied research as well as high- and low-skilled workers into an open economy model with creative destruction reveals general equilibrium feedback effects of policy decisions, such as labour cost effects. In turn, solving the model is much more challenging.

The remainder of this paper is organised as follows: In Section 2, we discuss key characteristics of basic research and briefly summarise the main arguments in favour of public engagement in basic research. We develop the factor-based approach in Section 3. In Section 3.1, we describe our theoretical model. Readers who are less interested in technical details may skip this section. We identify and discuss the four effects of public basic research in Section 3.2, and discuss how the different factors impact optimal basic research investment in Section 3.3. We conclude our theoretical discussion with

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[4] The paper integrates and extends the discussion papers Gersbach et al. (2015) and Gersbach et al. (2010).

further considerations in Section 3.4. Section 4 confronts our theoretical predictions with the data. We show how our framework might be used to guide policy in Section 5. Finally, we also discuss potential limitations and highlight promising avenues for future research.

2 Basic Research: Key Characteristics

The OECD (2002, p. 30) 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 emphasizes that basic research does not provide (potentially commercial) *solutions* for specific practical problems, but supplies the *knowledge base* needed to tackle these problems. This, in turn, implies that the benefits from basic research are diverse, and typically indirect, time-lagging, and highly uncertain. The associated lack of appropriability addressed since the seminal work of Nelson (1959) and Arrow (1962) is the core reason for the need for public funding of basic research.[5] Indeed, both direct evidence for the US and indicative evidence for a selection of further OECD countries suggest that the main part of basic research is publicly funded as outlined in our working paper (Gersbach et al., 2015), so that governments inevitably have to decide on *how much* of this public good to provide.

Countries direct non trivial amounts of funds to (basic) research. On a global scale, USD 1.4 trillion are directed annually towards R&D at present (Economist, 2013). Table 1 outlines R&D expenditures as a percentage of GDP, along with the share of these funds channelled into basic research for a selection of OECD countries plus Singapore, China, one African country (South Africa), and one Latin American country (Argentina), for which the OECD reports data. This comparison reveals three main patterns: First, the share of aggregate income directed to R&D tends to increase over time. This global trend is expected to endure (European Commission, 2013). Second, roughly one fifth of total R&D expenditures is spent on basic research. As the share

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[5] Patents on 'upstream' innovations might provide some incentives for private basic research but will typically not allow firms to fully appropriate the associated gains. In any case, such patents come at the cost of potentially impeding 'downstream' commercialization of new ideas (cf. Hopenhayn et al. (2006) or Cozzi and Galli (2014) for a theoretical account of the associated tradeoffs). Hence, there is still a need for public funding. The literature also supports the view that public provision of basic research is preferable to subsidizing private basic research. Aghion et al. (2008) suggest that the fundamental trade-off involved here is one of creative control versus focus. While private firms can dictate the lines of research to the scientists they employ, scientists working in academia have creative control over their work. In the context of a theoretical model, Aghion et al. (2008) argue that early-stage research should be performed in academia. Akcigit et al. (2013) suggest that while subsidizing private basic research might, in principle, be preferable to public provision, it may not be feasible due to asymmetric information and the resulting moral hazard problem. They propose public basic research as a feasible second-best solution.

of basic research in total R&D is slightly increasing on average, the share of GDP spent on basic research has increased over time.[6] Third, industrialized countries tend to spend a higher share of their GDP on R&D than emerging countries and, hence, R&D investments are highly concentrated: In 2008, for example, 25% of global R&D investments were undertaken by the US and another 10% by Japan.

Table 1: R&D expenditures of countries[a]

	Gross domestic expenditures on R&D as a percentage of GDP		Basic-research expenditures as a percentage of total R&D expenditures		Applied-research expenditures as a percentage of total R&D expenditures[b]	
	2000	2009	2000	2009	2000	2009
Argentina	0.44	0.60	27.75	29.80	72.25	70.20
Australia	1.47	2.26[c]	25.81	20.07[c]	74.19	79.93[c]
China	0.90	1.70	5.22	4.66	94.78	95.34
Czech Republic	1.17	1.47	23.34	27.10	76.66	72.90
France	2.15	2.27	23.60	26.08	76.40	73.92
Hungary	0.81	1.17	24.24	20.62	75.76	79.38
Ireland	1.10[d]	1.76	15.84[d]	22.90	84.16[d]	77.10
Israel	4.29	4.49	17.16	13.70	82.84	86.30
Japan	3.00	3.36	12.38	12.46	87.62	87.54
Korea	2.30	3.56	12.61	18.06	87.39	81.94
Portugal	0.73	1.64	22.85	18.93	77.15	81.07
Singapore	1.85	2.24	11.75	20.28	88.25	79.72
Slovak Republic	0.65	0.48	22.77	40.80	77.23	59.20
South Africa	0.73[e]	0.87	27.75[e]	23.26	72.25[e]	76.74
Switzerland	2.47	2.87[c]	27.96	26.78[c]	72.04	73.22[c]
United States	2.71	2.91	15.95	18.75	84.05	81.25
Average	1.67	2.10	19.81	21.52	80.19	78.48

[a] *Source*: Own calculations, based on OECD (2017a). This table is a slightly updated version of the table presented in Gersbach et al. (2013).

[b] The OECD divides R&D into 'basic research', 'applied research', 'experimental development' and 'not elsewhere classified'. We amalgamate the last three items as 'applied research'.

[c] Data from 2008.

[d] Data from 2002.

[e] Data from 2001.

At a broad level, these investments in basic research are supported by the literature that

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[6] For the selection of 35 countries for which the OECD Main Science and Technology Indicators report data on basic research expenditures as a percentage of GDP, only Chile, Germany, Israel, The Netherlands, New Zealand, Slovenia, South Africa, Sweden, and Switzerland (slightly) decreased their share of GDP spent on basic research over the maximal time-span for which there is data available. For most of these countries, this maximal time-span of data on basic research is relatively short. If we limit ourselves to countries for which there is data available from the 1980s to today, the tendency becomes more pronounced: All of these 12 countries, including the US and Japan, increased their share of GDP spent on basic research substantially over the period considered, with the relative increase ranging from 27% in the case of Russia to as much as 536% in the case of Portugal, albeit starting from a low level.

identifies various beneficial effects of basic research on productivity and GDP growth. Salter and Martin (2001) survey the literature to identify six different categories of effects, including the generation of new knowledge, instrumentation, and methodologies, and providing the economy with trained scientists and access to scientific networks. Yet, as important as these insights are, they are not sufficient to guide policy at a more detailed level,[7] and we may wonder whether the observed cross-country differences are desirable, or whether the benefits from basic research justify raising the already large investments even further? We propose to address these questions using a *factor-based approach.*

3 A Theory of Optimal Basic Research Investment

To facilitate better-informed policy-making, we complement the literature by considering the *factors* determining optimal basic research investments. We develop a simple theoretical model with Schumpeterian creative destruction (Aghion et al., 2009) and identify four key factors of optimal basic research investment, which we then analyse more carefully.[8] In this model, in the process of economic growth, existing technologies are being replaced by new, improved product varieties. We will introduce a basic-research sector operated by the government into this environment, and explore how the stage of economic development, the manufacturing base, varying degrees of openness to foreign competition, and the share of domestic firms that are foreign-owned matter for basic research investment. As we identify the underlying economic drivers of such investments for a wide range of industry structures, they will also be important in dynamic extensions when the industry structure changes over time. We briefly discuss these matters at the end of this section.

3.1 Economic Environment

To analyse the factors of optimal basic research investment more carefully, we consider a small economy that is populated by skilled and unskilled households. The aggregate amount of skilled labour is $\bar{L}$ and the aggregate amount of unskilled labour is normalized to 1. Each household enjoys strictly increasing utility in consumption and inelastically supplies one unit of its labour. Final consumption goods are produced using labour, services, and manufactured intermediate goods. Manufacturing firms face a competitive fringe of domestic and foreign firms, as detailed below, and where the

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[7] In the words of Salter and Martin (2001, p. 529): '*Currently, we do not have the robust and reliable methodological tools needed to state with any certainty what the benefits of additional public support for science might be, other than suggesting that some support is necessary to ensure that there is a 'critical mass' of research activities.*'

[8] Our theoretical model is based on the discussion paper Gersbach et al. (2010).

probability of entrance by foreign firms is shaped by the economy's openness. Manufacturing firms can engage in applied research to upgrade the quality of their goods and deter entry into their market.[9] The government can foster this innovation by publicly providing basic research that is financed by an income tax. It chooses these investments to maximize the well-being of its citizens.

3.1.1 Final-Good Sector

In the final-good sector, a continuum of competitive firms produces the homogeneous consumption good y according to

$$y = L_u^{1-\alpha} \left(\int_0^{\mu} (A(i)x(i))^{\alpha} \, di + \int_{\mu}^{1} (A(i)x(i))^{\alpha} \, di \right). \tag{1}$$

The variable $x(i)$ stands for the amount of intermediate input of variety i, $A(i)$ is this variety's productivity factor, and L_u denotes the amount of unskilled labour. Intermediate inputs are divided into a fraction μ of manufactured inputs and $1-\mu$ of services. The parameter α determines the output elasticity of the production factors. The price of the final consumption good is normalized to one. In the following we will operate with one representative final-good firm. The final-good producer maximizes profits π_y

$$\max_{\{x(i)\}_{i=0}^{1}, L_u} \left\{ \pi_y = y - \int_0^1 p(i)x(i) \, di - w_u L_u \right\}, \tag{2}$$

where $p(i)$ is the price of good $x(i)$ and w_u denotes the wage rate of unskilled labour. The maximization yields the inverse demand for unskilled labour

$$w_u = (1-\alpha) L_u^{-\alpha} \int_0^1 (A(i)x(i))^{\alpha} \, di. \tag{3}$$

As unskilled labour is only used in final-good production and its aggregate supply has measure 1, we obtain $w_u = (1-\alpha)y$ for the wage of unskilled labour. Further we obtain the inverse demand functions for intermediate goods $x(i)$ as

$$p(i) = \alpha A(i)^{\alpha} x(i)^{\alpha-1}. \tag{4}$$

3.1.2 Intermediate-Goods Sector

The intermediate goods $x(i)$ are produced by skilled labour $L_x(i)$ only, using a linear technology

$$x(i) = L_x(i). \tag{5}$$

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[9] While a country's manufacturing base is a pivotal element of its innovation system (Pisano and Shih, 2012; McKinsey Global Institute, 2012), there is certainly heterogeneity within manufacturing industries in terms of the prevalence of research-driven innovation, and such innovation is also present in other sectors. There is significant applied research in specific service sectors, most notably related to industries involving Information and Communication Technologies. In a broader sense, manufacturing could hence be interpreted in the model as those industries that have high research-driven innovation.

Intermediate-good firms act competitively in the labour market and compete à la Bertrand in their intermediate sector. There may be innovation in the manufacturing sector. If a firm in this sector successfully innovates, it receives a patent and is thus able to establish a monopoly position. Otherwise, perfect competition prevails. Hence the manufacturing firms are either monopolistic or fully competitive. We use w to denote the wage for skilled labour. A competitive intermediate firm sets prices equal to the marginal costs, $p_c(i) = w$, and profits vanish. Using (4), the demand for skilled labour of a competitive intermediate firm can be written as

$$L_{xc}(i) = \left(\frac{\alpha A(i)^{\alpha}}{w}\right)^{\frac{1}{1-\alpha}} . \tag{6}$$

The monopolistic intermediate firm asks a price $p_m(i) = \frac{w}{\alpha}$ for its goods, employs[10]

$$L_{xm}(i) = \left(\frac{\alpha^2 A(i)^{\alpha}}{w}\right)^{\frac{1}{1-\alpha}} , \tag{7}$$

skilled workers and earns profits

$$\pi_{xm}(i) = m\left(\frac{A(i)}{w}\right)^{\frac{\alpha}{1-\alpha}} \quad \left(m := (1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}}\right) . \tag{8}$$

To capture the idea that basic research is particularly effective in manufacturing, we normalize innovation in services to zero. These industries are then perfectly competitive, and the demand for skilled labour is given by (6).

3.1.3 Technological State, Innovation, and Foreign Entry

We assume that there is a world technological frontier which is given by $\bar{A}$ at the end of the period and grows exogenously over time in accordance with $\bar{A} = \widetilde{\gamma}\bar{A}_{-1}$, where a subscript $-j$ indicates a time lag of j periods, i.e. $\bar{A}_{-1}$ denotes the technological frontier at the beginning of the period. Essentially, we assume that the economy we model is comparatively small and has a negligible impact on the world technological frontier itself. Further, we assume that $1 < \widetilde{\gamma} \leq 2$.[11] In order to simplify the exposition and the notation, we use $\gamma := \widetilde{\gamma}^{\frac{\alpha}{1-\alpha}}$ in the remainder of the paper, which yields $\bar{A} = \gamma^{\frac{1-\alpha}{\alpha}}\bar{A}_{-1}$.

Intermediate firms differ in their technology level. We neglect the adoption costs of mature technologies, for the sake of simplicity. Considering that basic research involves important time lags, we think of a period as comprising several years. Mature

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[10] In principle, monopolists may be constrained in their price setting by firms offering lagging technologies. This will not be the case if innovations are drastic or if there are arbitrarily small entry costs for intermediate-goods producers. Limit pricing would not alter fundamentally the key mechanism at play. We focus on the monopoly solution in the current version of the model.

[11] Assuming that the productivity of an intermediate product will not increase by more than 100 % by innovation is realistic and simplifies our analysis.

technologies are then defined as those two steps behind the world's frontier and, consequently, at the beginning of the period, all intermediate firms have at least technology $\bar{A}_{-3}$. Some manufacturing firms, however, might have successfully innovated in the past and thus be closer to the technological frontier. At the beginning of the period, intermediate firms can then be of three types:

Type 1 firms produce at the current technological frontier, $A_{-1}(i) = \bar{A}_{-1}$.

Type 2 firms are one step behind the technological frontier, $A_{-1}(i) = \bar{A}_{-2}$.

Type 3 firms are two steps behind the technological frontier, $A_{-1}(i) = \bar{A}_{-3}$.

Mature technologies are publicly available, i.e. technologies $A_{-1}(i) = \bar{A}_{-3}$, while more advanced technologies are privately owned, implying that type 1 and type 2 firms can maintain a monopoly position for their respective intermediate good.[12] The competitive structure then implies that each intermediate industry is in one of three states at the beginning of the period:[13]

State 1 Type 1 leader holding a monopoly.

State 2 Type 2 leader holding a monopoly.

State 3 Two (or more) type 3 firms acting competitively.

Considering our normalization of zero innovation in services, we assume that services are always two steps behind the technological frontier. This helps saving notation and improves the exposition of the model, but is not essential. We denote the fraction of manufacturing goods in states 1, 2, and 3 by $\tilde{s}_1$, $\tilde{s}_2$, and $\tilde{s}_3$, respectively, where $\tilde{s}_1, \tilde{s}_2, \tilde{s}_3 \geq 0$ and $\tilde{s}_1 + \tilde{s}_2 + \tilde{s}_3 = 1$. The shares of states 1, 2, and 3 manufacturing goods in total (manufacturing + service) intermediate industries are then

$$\begin{aligned} s_1 &= \mu \tilde{s}_1, \\ s_2 &= \mu \tilde{s}_2, \\ s_3 &= \mu \tilde{s}_3. \end{aligned} \tag{9}$$

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[12] Small entry costs to challenge an incumbent type 1 or type 2 firm imply that a single firm possessing superior technology will be able to obtain monopoly profits, as this is the only subgame perfect equilibrium in the two-stage game: decision to enter at the first stage and production at the second stage. We will assume this structure in all state 1 and state 2 industries and assume that entry costs are positive, but sufficiently small such that they can be neglected in the analysis.

[13] Basic research, through its beneficial effects on innovation by private firms, also supports these firms in maintaining their monopoly position. Depending on the competitive structure of the economy, the implied monopoly distortions reduce social gains from public basic research. The distinction between two different stages of monopolistic firms allows to capture these effects. If instead, type 1 firms lost protection for their technology via patents or secrecy after one period and faced perfect competition if unsuccessful in innovating, the R&D incentives of type 1 firms would increase but would not qualitatively affect our results on optimal basic research investment.

The distribution of firms across technological states shapes the economy's stage of economic development. While this distribution is endogenous, depending on the private R&D decisions of the firms and, importantly, on the basic research investments by the government, the initial distribution of firms is exogenously given. In its optimization, the government takes the current distribution of firms as given, while taking into account the effect of its decision on basic research investments for the future distribution of firms. We will perform a wide range of comparative statics exercises with respect to the exogenously given initial distance to the technological frontier and the other factors.

By investing in research and development, each manufacturing firm can enhance its probability of realizing a successful innovation. A successful innovation increases the firm's technology level by a factor $\gamma^{\frac{1-\alpha}{\alpha}}$, thus allowing it to retain its relative position vis-à-vis the technological frontier. We specify the probability of a manufacturing firm innovating successfully as

$$\rho(i) = \min\left\{2\theta\sqrt{L_A(i)L_B}, 1\right\}, \tag{10}$$

where $\theta > 0$ is a parameter that captures the efficiency of research. $L_A(i)$ denotes the intermediate firm's skilled labour employed for R&D and L_B the amount of skilled labour in the basic-research sector. Basic research is publicly provided and financed by a tax on income.

Equation (10) specifies that basic research and applied research are complementary, and that basic research is a necessary input for innovation activities to take place. In this sense, innovation success is determined by the supply side, i.e. by the combination and efficiency of basic and applied research capabilities.

Basic research constitutes a public good from which manufacturing firms can benefit.[14]

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[14] We assume that basic research has important local effects. This assumption is supported by rich empirical evidence that shows that basic research, as documented in Table 1, has strong local/regional effects and fosters innovation and growth of firms located in the same region or country.

These positive effects include the supply of scientists and problem-solvers, joint research projects by universities, private companies, and spin-offs, and the establishment of and access to scientific networks. See, e.g. Jaffe (1993), Anselin et al. (1997), Monjon and Waelbroeck (2003), Audretsch et al. (2005), and Williams (2013). For domestic firms, basic research is often the first step in the innovation process (see Grossman and Shapiro, 1987, Aghion et al., 1996, Aghion et al., 2008, and Cozzi and Galli, 2009). These local/regional effects are the reason why, as reported in Table 1, even small countries (such as Iceland, Korea, and Switzerland) invest approximately the same percentage of GDP in basic research as large industrialized countries such as France or the US. A recent example is provided by Williams (2013), documenting how the public *Human Genome Project* has triggered innovations in life science companies headquartered in the US. Of course, basic research also has important international spillovers, in particular in the form of diffusion of new knowledge. Note that such spillovers are captured in our set-up: Gains from (basic research driven) innovation in the rest-of-the-world spillover to our economy through foreign entry and freely available mature technologies. And in our small open economy setup spillovers to the rest-of-the-world matter only insofar as they impact domestic gains from domestic basic research, i.e. they may be thought of as being captured in the research productivity parameter θ.

This, however, will be the case only for firms close enough to the technological frontier: Given that mature technologies can be adopted costlessly, lagging firms will not invest in applied research at all.

We model the country's degree of openness by the probability of market entry by a foreign manufacturing firm.[15] We assume that the foreign firm enters with frontier technology $\bar{A}$, produces domestically, and takes over the whole market in its industry. In each manufacturing industry i not producing at the world's technological frontier – either because the domestic intermediate firm has failed to innovate or because it has been lagging behind previously – the probability of a foreign competitor entering the domestic market is determined by σ. In manufacturing industries where the domestic firm produces at the highest possible level, foreign competitors will stay outside. This occurs in industries in which a domestic type 1 leader innovates successfully. As e.g. in Aghion et al. (2009) and Melitz (2003), we assume that there are small entry costs preventing the foreign firm from entering the market, and thus the domestic type 1 leader obtains monopoly profits. Additionally, a fraction of domestically operating manufacturing firms is foreign-owned due to past entry. To be consistent with our above assumption that foreign entrants have superior access to state-of-the-art technologies, we assume that these firms are always operating at the technological frontier as they benefit from technology transfer from their mother-companies abroad. That is, we assume that all foreign-owned firms are type 1 firms, and use λ to denote the share of type 1 firms that is foreign-owned.

Our set-up draws on the literature indicating that foreign direct investment (FDI) by leading-edge companies is a powerful mechanism to raise productivity in host countries (e.g., Baily and Gersbach 1995, Keller and Yeaple 2009 or Alfaro et al. 2010). FDI contributes directly to higher levels of productivity by transferring the best production techniques to the host country, and indirectly by putting pressure on the host country's domestic producers to improve. The most prominent examples are the US transplants of automotive companies head-quartered in Japan. Guadelupe (2012) emphasize that a lot of foreign direct investment is done through mergers with domestic firms. Our model allows to accommodate this fact by interpreting foreign entry as mergers between the foreign entrant and a domestic type-2 or type-3 incumbent where the majority of shares are held by the foreign firm.

3.1.4 R&D Decisions of Intermediate Firms

Domestic intermediate firms choose the amount of skilled labour to maximize their expected profits, taking as given the level of basic research, the entry threat of foreign firms, and the wage for skilled labour, and rightly anticipating their future profits with

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[15] To keep notation at a minimum, we will assume that there is no foreign entry into service industries. Note that with no innovation in services, entry into these industries will not matter for optimal basic research policies.

and without successful innovation. The key trade-offs involved critically depend on their distance to the world technological frontier at the beginning of the period. We discuss these next.

State 2 incumbents are threatened from two sides: Without innovation, domestic competitors will be able to catch up and they will make zero profits. This threat incentivizes them to invest in R&D which, if successful, allows them to jump ahead of their domestic competitors. Such endeavours are, however, vain if these firms are driven out of their market by foreign firms. Hence, *ceteris paribus*, state 2 incumbents will invest less in R&D in more open economies.

As opposed to that, state 1 incumbents can deter entry of foreign firms via successful innovation. Their incentives to invest in R&D will therefore be the higher, the more open the economy is. On the other hand, they are further ahead of their domestic competitors and will therefore be able to retain their monopoly position even without innovation, provided that no foreign firm enters their market. A monopoly position at the technological frontier is, however, more profitable compared to a monopoly position with lagging technology due to the higher productivity. The associated incentives to invest in applied research will depend on the innovation size γ.

Both state 1 and state 2 incumbents will respond to a *ceteris paribus* increase in the wage rate for skilled labour w by hiring less *R&D* personnel, reflecting both higher associated investment costs and lower profits due to higher production cost. They will increase their R&D investments at a given wage when the government increases L_B. This reflects the complementarity of private applied research and publicly funded basic research and is a key transmission channel for the social gains from public basic research. However, as we shall see, L_B and the R&D investments by state 1 and state 2 incumbents, L_{A_1} and L_{A_2}, respectively, need not move in the same direction when L_B changes in response to changes in the economy's parameters.

Finally, firms lagging two periods behind the technological frontier (state 3 firms) will have no incentives to invest in R&D, given the costless adoption of mature technologies.

We formally characterize the intermediate firms' optimisation regarding R&D investments in the Box 1:

Box 1 (R&D decisions by private firms)

- **State 1 incumbent**

  State 1 incumbents choose the amount of labour employed in R&D, L_{A_1}, to maximize

$$\max_{L_{A_1}} \left\{ \left(\rho(i) m \left(\frac{\bar{A}}{w} \right)^{\frac{\alpha}{1-\alpha}} + \big(1 - \rho(i)\big)(1-\sigma) m \left(\frac{\bar{A}_{-1}}{w} \right)^{\frac{\alpha}{1-\alpha}} \right) - w L_{A_1}(i) \right\}. \tag{11}$$

The maximization problem leads to the following demand for skilled labour:

$$L_{A_1} = L_B m^2 \left(\frac{\bar{A}_{-1}^{\alpha}}{w}\right)^{\frac{2}{1-\alpha}} \theta^2 \big(\gamma - (1-\sigma)\big)^2. \tag{12}$$

Considering only inner solutions for ρ_1, this implies innovation probability and expected profits for the state 1 leader in accordance with

$$\rho_1 = 2L_B m \left(\frac{\bar{A}_{-1}^{\alpha}}{w}\right)^{\frac{1}{1-\alpha}} \theta^2 \big(\gamma - (1-\sigma)\big), \tag{13}$$

$$\pi_1 = L_B m^2 \left(\frac{\bar{A}_{-1}^{2\alpha}}{w^{1+\alpha}}\right)^{\frac{1}{1-\alpha}} \theta^2 \big(\gamma - (1-\sigma)\big)^2 + (1-\sigma) m \left(\frac{\bar{A}_{-1}}{w}\right)^{\frac{\alpha}{1-\alpha}}. \tag{14}$$

- **State 2 incumbent**
  State 2 incumbents choose the amount of labour employed in R&D, L_{A_2}, to maximize

$$\max_{L_{A_2}} \left\{ \rho(i)(1-\sigma) m \left(\frac{\bar{A}_{-1}}{w}\right)^{\frac{\alpha}{1-\alpha}} - w L_{A_2} \right\}. \tag{15}$$

The solution to the problem yields

$$L_{A_2} = L_B m^2 \left(\frac{\bar{A}_{-1}^{\alpha}}{w}\right)^{\frac{2}{1-\alpha}} \theta^2 (1-\sigma)^2, \tag{16}$$

$$\rho_2 = 2L_B m \left(\frac{\bar{A}_{-1}^{\alpha}}{w}\right)^{\frac{1}{1-\alpha}} \theta^2 (1-\sigma), \tag{17}$$

$$\pi_2 = L_B m^2 \left(\frac{\bar{A}_{-1}^{2\alpha}}{w^{1+\alpha}}\right)^{\frac{1}{1-\alpha}} \theta^2 (1-\sigma)^2. \tag{18}$$

3.1.5 Equilibrium

The economy comprises the market for the final consumption good with price unity, the market for skilled labour with wage rate w, the market for unskilled labour with wage rate w_u, and a continuum of intermediate-good markets with prices $\{p(i)\}_{i=0}^{1}$. For any given investment in basic research, L_B, the economy will be in equilibrium if each of these markets clears, given the optimizing behaviour of the various agents in the economy. In Appendix A we show that for the most realistic set of parameter specifications this equilibrium exists and is unique, allowing the government to effectively maximize over these equilibrium outcomes.

3.2 Optimal Basic Research Investment

We now describe the government's problem regarding basic research investments. We identify four effects of basic research on the economy that the government trades off in determining the optimal amount of basic research. The particular strength of these effects and hence the resulting optimal basic research investments differ with the countries' characteristics, such as the size of their manufacturing base, openness to foreign direct investments, distance to the world's technological frontier and the share of foreign firms. Hence these "factors" determine the size of the effects basic research exerts on the economy and which play a key role in shaping optimal basic research investments. In this subsection we describe the government's problem and identify the effects of basic research on the economy. In the next section, we discuss in detail how the factors determine the sizes of these effects and thereby shape optimal basic research investments.

The government chooses the amount of basic-research labour L_B to maximize aggregate consumption c of its citizens, which is equal to total final-good production minus profits lost to foreign owners of domestically operating intermediate firms[16]

$$\max_{L_B} \quad c = y - \{\lambda s_1 + (\mu - \lambda s_1 - (1-\lambda)s_1\rho_1)\sigma\}\, \pi_{xm}(\bar{A}) \tag{19}$$

The term in curled brackets captures the profits earned by foreign entrants. The first expression in curled brackets reflects the profits by foreign-owned firms due to past entry while the other terms represent the profits obtained by the foreign entrants. These terms capture the fact that a share σ of all manufacturing sectors with domestic incumbents that did not innovate at the world's technological frontier will be taken over by foreign entrants with world-leading technology. The government decision problem involves intricate trade-offs: For one thing, basic research ties up labour that is no longer available for production, both directly and indirectly via induced private applied research. For another, it fosters productivity of domestically operating manufacturing firms, helping incumbents to deter entry by foreign and domestic competitors, and thus to maintain their market position. Depending on the value of innovations, the associated effect on the competitive structure of the economy may attenuate or amplify the effect of basic research on the wage rate of skilled labour. In what follows, it will be instructive to summarize the different effects of basic research in the following four categories. Technical details are provided in Box 2.

Productivity Effect Basic research stimulates applied research by monopolistic firms.

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[16] Income lost to foreign firms may be diminished by taxes on profits. Taxes have multiple direct and indirect effects on optimal basic research investment. The corresponding analysis is beyond the scope of this paper. We therefore assume that basic research is financed via a tax on domestic income, and refer the interested reader to Gersbach et al. (2014) for an in-depth analysis of jointly optimal tax and basic research policies.

This will improve the innovativeness of the economy, and therefore have a positive effect on aggregate productivity.

Escape Entry Effect In addition, innovative firms at the technological frontier will be able to avoid foreign entry into their industry. The associated escape entry effect of public basic research is positive, as it allows to retain monopoly profits within the country.

Monopoly Effect Basic research, however, also has undesirable side-effects on the competitive structure of the economy: By promoting innovativeness of incumbents, it helps them to maintain their monopoly position, i.e. basic research has a negative monopoly effect on aggregate welfare.

Labour Cost Effect Finally, basic research impacts the wage rate for skilled labour in many different ways: It ties up labour in R&D both directly and indirectly via applied research, and affects total labour demand in the manufacturing industries via its impact on their productivity and their competitive structure. As we show in the appendix, the net effect is positive, i.e. basic research bids up the wage rate for skilled labour. This increase in the skilled wage rate feeds back into the incentives for investment in applied research by manufacturing firms. All in all, this effect tends to be welfare decreasing, as it tends to increases the cost of intermediates for final-good producers.[17]

Box 2 (Effects of public basic research)
By inserting (1), (6), (7), (8), and (A.6) into (19), the government's objective function takes the form

$$c = \left(\frac{\alpha^2 \bar{A}}{w}\right)^{\frac{\alpha}{1-\alpha}} \frac{1}{\gamma^2} \phi(\rho_1, \rho_2) \ , \tag{20}$$

where

$$\begin{aligned} \phi(\rho_1, \rho_2) =& (1-\mu)\frac{1}{\alpha^{\frac{\alpha}{1-\alpha}}} + (1-\sigma)\left((1-\lambda)s_1\gamma + (s_2+s_3)\frac{1}{\alpha^{\frac{\alpha}{1-\alpha}}}\right) \\ & + \gamma^2(\sigma\mu + (1-\sigma)\lambda s_1)(1-\alpha(1-\alpha)) \\ & + (1-\lambda)s_1\rho_1\gamma\left((1-\sigma)(\gamma-1) + \sigma\gamma\alpha(1-\alpha)\right) \\ & + s_2\rho_2(1-\sigma)\left(\gamma - \frac{1}{\alpha^{\frac{\alpha}{1-\alpha}}}\right) \end{aligned} \tag{21}$$

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[17] For polar parametrizations with a very large value of s_2 and very low levels of σ and γ, it is possible to obtain a positive labour cost effect. Under these circumstances, an increasing wage for skilled labour is beneficial to the economy as it decreases the innovation propensity of state 2 leaders and hence reduces the share of monopolistic industries.

reflects the effect of the economy's industry structure, depending on the innovation probabilities of the leading and lagging industries. In Appendix A, we show that the optimal investment in basic research is either $L_B = 0$, or the unique solution to the first order condition associated with (20). Differentiating with respect to L_B and rearranging terms, we get for the four effects of public basic research.

Productivity Effect

$$PE = \left(\frac{\alpha^2 \bar{A}}{w}\right)^{\frac{\alpha}{1-\alpha}} \frac{1}{\gamma^2}(1-\sigma)(\gamma-1)\left[\gamma(1-\lambda)s_1\frac{\partial \rho_1}{\partial L_B} + s_2\frac{\partial \rho_2}{\partial L_B}\right] > 0 \quad \text{(PE)}$$

Escape Entry Effect

$$EE = \left(\frac{\alpha^2 \bar{A}}{w}\right)^{\frac{\alpha}{1-\alpha}} \alpha(1-\alpha)\sigma(1-\lambda)s_1\frac{\partial \rho_1}{\partial L_B} > 0 \quad \text{(EEE)}$$

Monopoly Effect

$$ME = \left(\frac{\alpha^2 \bar{A}}{w}\right)^{\frac{\alpha}{1-\alpha}} \frac{1}{\gamma^2}(1-\sigma)\left(1-\frac{1}{\alpha^{\frac{\alpha}{1-\alpha}}}\right) s_2\frac{\partial \rho_2}{\partial L_B} < 0 \quad \text{(ME)}$$

Labor Cost Effect

$$LC = -\left(\frac{\alpha^2 \bar{A}}{w}\right)^{\frac{\alpha}{1-\alpha}} \frac{1}{\gamma^2}\frac{dw}{dL_B}\left(\frac{\alpha}{1-\alpha}w^{-1}\phi(\rho_1,\rho_2) - \frac{\partial \phi(\rho_1,\rho_2)}{\partial w}\right), \quad \text{(LCE)}$$

where

$$\begin{aligned}\frac{\partial \phi(\rho_1,\rho_2)}{\partial w} =& (1-\lambda)s_1\tfrac{\partial \rho_1}{\partial w}\gamma\left((1-\sigma)(\gamma-1)+\sigma\gamma\alpha(1-\alpha)\right)\\ &+ s_2\tfrac{\partial \rho_2}{\partial w}(1-\sigma)\left(\gamma-\tfrac{1}{\alpha^{\frac{\alpha}{1-\alpha}}}\right).\end{aligned}$$

While the first two effects are welfare increasing, the last two will typically decrease welfare levels. Optimal basic research investments depend on the relative strengths of the four effects. Our analysis shows how the relative sizes of the effects depend on the structural factors of the economy: stage of economic development as reflected in the share of sectors at the world's technology frontier (s_1), the size of the manufacturing base of the economy ($s_1 + s_2 + s_3$), openness (σ), and the share of foreign-owned firms (λ). In the next section we discuss each of these factors of optimal basic research in detail.

3.3 Factors of Optimal Basic Research Investment

For each of the factors of optimal basic research investment, we now discuss how it impacts the different effects of basic research and identify its *ceteris paribus* effect on optimal basic research investment. We then corroborate this analytical discussion with a numerical exercise: We calibrate our model to match key moments in the data for and average OECD country in year 2010 and identify optimal basic research investment for the calibrated economy.[18] We then show how these optimal investments vary with the respective factor.

Box 3 (Calibration)
To calibrate our model, we first choose $\alpha = \frac{1}{2}$ to be consistent with our analytical proof of Proposition 2 (cf. Appendix A). Moreover, we choose the normalization $\bar{A} = 100$ with respect to the technology level, and consider an industry structure $\tilde{s}_1 = 0.6$, $\tilde{s}_2 = 0.2$, $\tilde{s}_3 = 0.2$, reflecting a highly industrialized country. Our choice is anticipating the result that a considerable amount of technologically advanced industries is necessary to provide enough incentives to invest in basic research. We are then left with six parameter values that need to be specified: $\bar{L}$, μ, γ, σ, θ, and λ. We calibrate these parameters to target the following moments for an average OECD member state. All moments refer to 5-year centred moving averages for the year 2010 and the sample of OECD-countries with available data. Further details on the calibration are provided in Appendix B.

First, $\bar{L} = \frac{3}{7}$ is set to reflect the average share of the labour force with tertiary education of roughly 30%. $\mu = \frac{1}{3}$ is chosen to capture that the average manufacturing share in GDP is roughly $\frac{1}{6}$. We set $\gamma = 1.5$ to get a growth rate of final-good production of around 22% in each period. In our model, basic-research investments are considered for each generation, so it is convenient to think of a period as comprising $\sim$ 10 years, which generates plausible annual growth rates. This is also consistent with the fact that basic research exhibits major time lags between investment and its effect on productivity (e.g. Adams 1990 or Mansfield 1998). $\sigma = 0.3$ is chosen as a rough approximation to the fact that inward FDI amounts to around 5% of GDP. We set $\lambda = 0.2$ which allows profits paid to foreign owners of domestic s_1 firms to correspond to royalty payments to abroad in our sample. Finally, $\theta = 11.75$ is chosen to obtain an optimal basic-research level of $L_B \approx 0.0036$. This value reproduces a share of GDP devoted to basic research that is close to 0.36%, which constitutes the average share of basic research in GDP in our sample in 2010.

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[18] Data for 2010 may have been affected by the great recession. Note that our calibration would be similar and yield qualitatively the same results when using moments for 2005 instead.

We summarize our calibration in the following table.

Parameter	Value	Moment	Data Source
α	0.5	assumption	
$(\tilde{s}_1, \tilde{s}_2, \tilde{s}_3)$	(0.6, 0.2, 0.2)	assumption	
$\bar{L}$	3/7	share of the labour force with tertiary education	World Bank (2017)
μ	1/3	manufacturing share in GDP	World Bank (2017)
γ	1.5	10-year growth rate of GDP per capita	World Bank (2017)
σ	0.3	$\frac{\text{inward FDI}}{\text{GDP}}$	World Bank (2017)
λ	0.2	$\frac{\text{royalty payments to abroad}}{\text{GDP}}$	World Bank (2017)
θ	11.75	$\frac{\text{basic research}}{\text{GDP}}$	OECD (2017a)

In Appendix A we show that the government decision prolem is well behaved in the sense that optimal basic research investments are either 0 or the unique solution to the associated first order condition. In turn this allows analyzing the ceteris paribus effect of each factor $\kappa \in \{s_1, \mu, \sigma, \lambda\}$ by considering its impact on the associated first order condition. Let $L_B^\star$ denote optimal basic research investments and consider the economically interesting cases of $L_B^\star > 0$. We then have:

$$\frac{dL_B^\star}{d\kappa} > 0 \quad \Leftrightarrow \quad \frac{d\left[(\text{PE}) + (\text{EEE}) + (\text{ME}) + (\text{LCE})\right]}{d\kappa}\Bigg|_{L_B = L_B^\star} > 0\ , \quad \kappa \in \{s_1, \mu, \sigma, \lambda\}\ ,$$

and will discuss for each factor how it impacts the various effects of basic research. We will thereby focus on the direct effects (PE, EEE, ME) and use the calibrated version of our model to illustrate that feedback effects via labour costs will typically not overcompensate for direct effects.[19]

3.3.1 Distance to Frontier / Stage of Economic Development

In our theoretical set-up, the stage of economic development matters because the closer a firm is to the technological frontier the more effective it is in deterring entry from foreign firms via its own innovation. Hence, if we bring the economy closer to the technological frontier, i.e. if we increase the share of state 1 firms, basic research allows more firms to deter entry by foreign competitors . At the same time, its impact on the competitive structure becomes attenuated as technology leaders arguably have a stronger competitive position in their domestic markets. What is more, for the most

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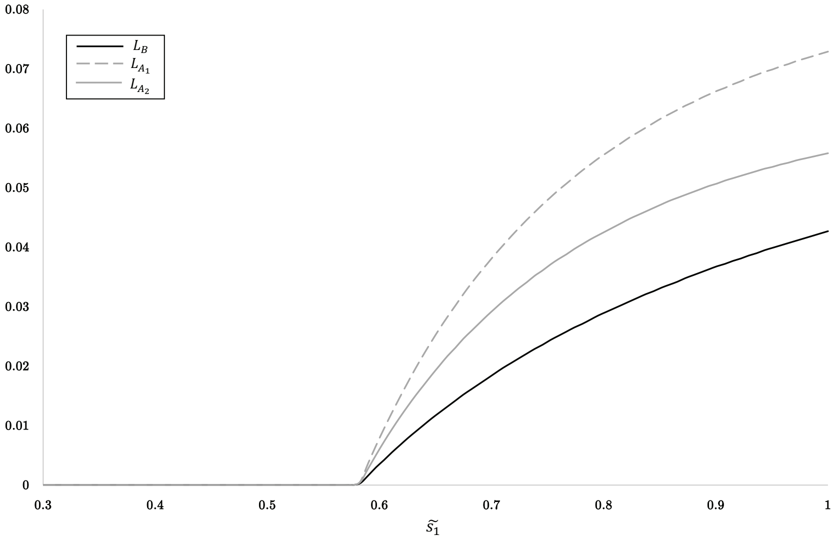
[19] The share of total labor employed in basic and applied research is small both in the data and in the calibrated version of our model (cf. Figure 1), i.e. the direct wage effect is small. Basic research may, however, have important indirect wage effects by impacting productivity and the market structure, for example.

realistic scenarios where leading firms invest more in applied research compared to lagging firms, countries closer to the frontier will also benefit from a more pronounced productivity effect of public basic research. All in all, we therefore expect countries to invest the more in basic research the closer they are to the technological frontier. As we see in Figure 1, this is exactly what we observe for the calibrated version of our model. The higher is the share of sectors at the technological frontier (s_1), the higher are the investments in basic (and applied) research.

Formally, (EEE) is unambiguously increasing in s_1, while (ME) is attenuated by a decrease in s_2. Moreover, a shift from s_3 to s_1 increases (PE), and so does a shift from s_2 to s_1 as long as $\gamma(1-\lambda)(\gamma-(1-\sigma)) > 1-\sigma$.[20]

Figure 1: Effect of distance to frontier: $\tilde{s}_1$ vs $\tilde{s}_2$ and $\tilde{s}_3$ ($\tilde{s}_2 = \frac{1-\tilde{s}_1}{2}$, $\tilde{s}_3 = \frac{1-\tilde{s}_1}{2}$)



3.3.2 Manufacturing Base

In our model, a *ceteris paribus* increase in the share of manufacturing in GDP corresponds to a proportional increase of the share of s_1, s_2, and s_3 industries. This will unambiguously stimulate the productivity-effect (PE) of basic research. It will further amplify the escape entry effect (EEE) and the monopoly effect (ME) via promoting innovation of a broader set of domestic manufacturing firms. For most parameter specifications, the positive effects will dominate and we may *ceteris paribus* expect countries to invest the more in basic research the broader their manufacturing base is. As shown in Figure 2, this is also the case for the calibrated version of our model: The larger μ is, the more countries invest in basic research.

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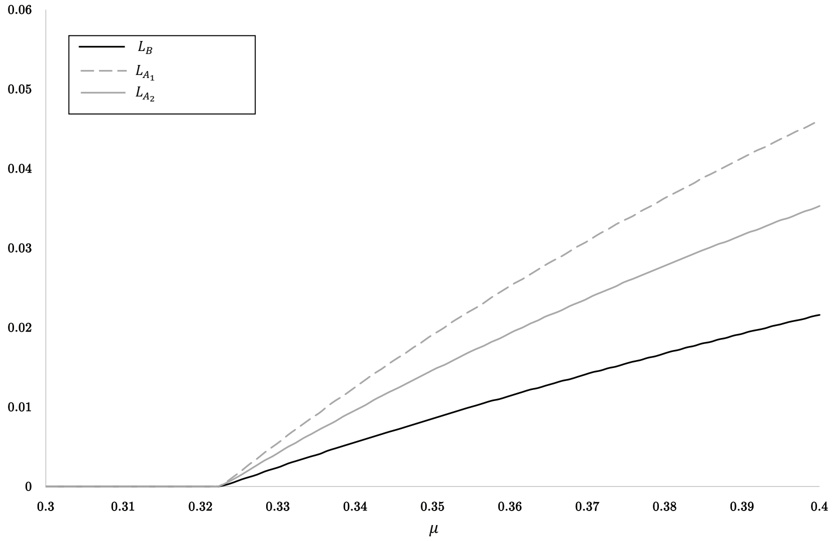
[20] Actually, the maybe more interesting comparative static is one where we shift firms from s_2 to s_1 holding constant the share of foreign-owned firms. Such a shift will increase (PE) under the weaker condition $\gamma(\gamma-(1-\sigma)) > 1-\sigma$.

Figure 2: Impact of manufacturing base



3.3.3 Openness

In our model, a country's openness matters for its optimal basic research investment because basic research supports domestic technology leaders in escaping entry by foreign competitors. Conversely, countries can try to free-ride on basic research investments from the rest of the world in that they can move closer to the technological frontier via entry of foreign technology leaders. This, of course, comes at the cost of losing monopoly profits to the foreign owners of domestically operating firms. Which effect dominates depends critically on the stage of economic development of the economy. In particular, firms close to the frontier can deter entry of foreign competitors by innovating themselves, i.e. they will *ceteris paribus* invest the more in applied research the more open their economy is. In turn, this increases the gains from public basic research. As opposed to that, technologically lagging firms may be confronted with foreign entry even if they innovate, rendering such endeavours vain, i.e. we may expect openness to have a detrimental impact on their applied research efforts. On balance, we then may expect that the effect of openness on optimal basic research is the smaller (or even slightly negative) the further away from the technological frontier a country is. As shown in Figure 3, this conjecture is corroborated by the calibrated version of our model.[21]

Formally, observe from (PE) and (ME) that lagging firms are less important for basic research policies in more open economies. This is the case for two reasons. First they may be driven out of business even if they successfully innovate ($(1-\sigma)$ smaller).

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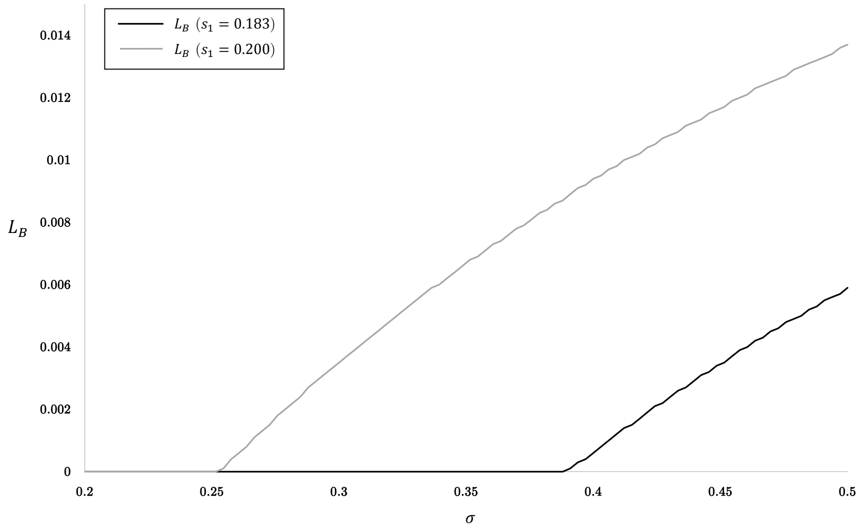
[21] For the rather low innovation size in our calibration, the relationship between openness and basic research is positive. The Escape-Entry Effect dominates the Productivity Effect as the latter is scaled by the innovation size. For larger innovation sizes, i.e. higher values of γ, basic research declines with higher levels of openness and applied research may decline or is hump-shaped.

Figure 3: Impact of openness on basic research. Grey (black) line: $\tilde{s}_1 = 0.6$ ($\tilde{s}_1 = 0.55$), $\tilde{s}_2 = 0.2$ ($\tilde{s}_2 = 0.225$), $\tilde{s}_3 = 0.2$ ($\tilde{s}_3 = 0.225$)



Second, this feeds back into their decision to invest in applied research which in turn implies a lower ρ_2 and $\frac{\partial \rho_2}{\partial L_B}$ for more open economies.[22] In the limit where $\sigma = 1$ these firms will not matter at all. As opposed to that, observe from (14) that both ρ_1 and $\frac{\partial \rho_1}{\partial L_B}$ are increasing in response to a higher σ, i.e. (EEE) unambiguously increases both because type 1 firms' innovation probability is more responsive to basic research and because they are more often confronted with foreign entrants (higher σ). In other words, ceteris paribus in more open economies more type 1 firms motivate larger investments via an amplified escape entry effect. Moreover, while the productivity effect gets attenuated by a higher σ (with lower $(1 - \sigma)$ reflecting exactly the fact that open economies can try to free-ride on foreign technological progress), a larger s_1 relative to s_2 implies that this direct effect is attenuated because the innovation probability of type 1 firms responds more to basic research in open economies ($\frac{\partial \rho_1}{\partial L_B}$ larger), while the one of type 2 firms responds less ($\frac{\partial \rho_2}{\partial L_B}$ smaller).

3.3.4 Share of Foreign-owned Firms

Regarding optimal basic research investments, a higher share of foreign-owned firms is similar in nature to a reduction of domestic type 1 leaders. Consequently, *ceteris paribus* we expect countries to invest the less in basic research the higher the ex-ante share of foreign-owned firms. For one thing, these firms are less reliant on domestic basic research for their own innovation, i.e. the productivity effect is lower. For another, with a higher share of foreign-owned firms, there are less domestic technology leaders that can be supported in escaping entry by foreign firms. In this way, a higher share

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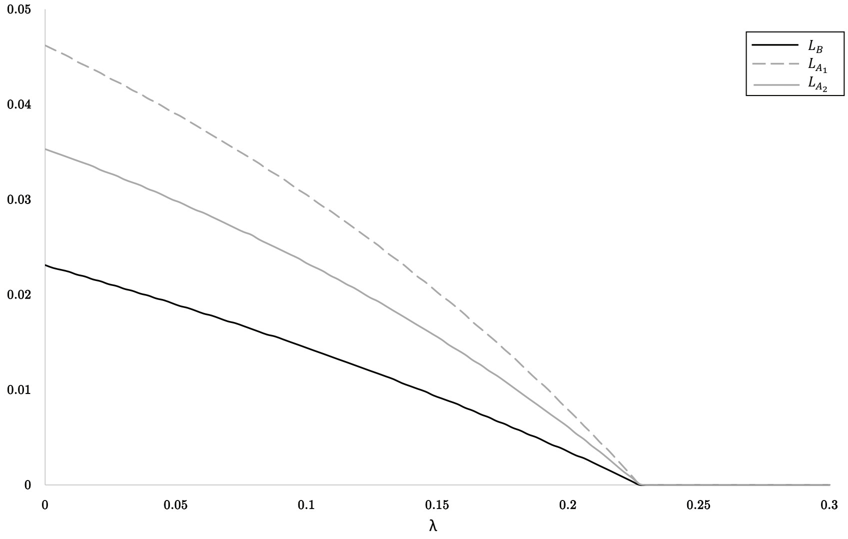
[22] Observe from (18) that ceteris paribus both ρ_2 and $\frac{\partial \rho_2}{\partial L_B}$ are lower for higher σ.

of foreign-owned firms influences optimal basic research expenditures qualitatively in the same way as a larger distance to the technology frontier. Observe from Figure 4 that this is indeed the case for the calibrated version of our model.

Formally, note that ceteris paribus both (PE) and (EEE) are smaller for larger λ.

Figure 4: Impact of share of foreign-owned firms on basic research.



3.4 Summary of Theoretical Predictions and Robustness

We end our theoretical analysis by summarizing our key results of how the different factors affect optimal basic research investments. Our main hypothesis can be summarized as follows:

Hypothesis 1

Ceteris paribus, countries invest the more in basic research

1. *the closer they are to the technological frontier,*
2. *the higher their manufacturing share in GDP,*
3. *the lower the share of foreign-owned firms.*
4. *The effect of openness on optimal basic research investments depends on a country's distance to frontier; it is greater for countries closer to the frontier. In other words, the sign of the interaction effect of openness and a country's distance to frontier on basic research investments is positive.*

The purpose of our theoretical model is to identify the effects of basic research on the economy and discuss the role of the country characteristics or factors for the size of these effects and consequently for optimal basic research investments. While the theoretical predictions how the four identified factors shape optimal basic research investments have been derived from a simple model set-up, they are robust to several extensions.

Basic research has important long-run effects. While a fully-fledged analysis of such effects is beyond the scope of the current paper, the static approach we pursue may be seen as a short-cut to introducing such effects. Any perpetuation of productivity gains, for example, would amplify the associated effects. This would impact the trade-off between current investment cost and (discounted future) gains from basic research in a way similar to a variation of research productivity. To the extent to which long-run productivity gains are taken into account by governments, we may therefore expect them to promote higher investment in basic research.

Short-sighted governments, however, may well not fully take into account such long-run effects, and a static approach may be more appropriate to understand actual policies. Still, in repeatedly updated versions of our static model important intertemporal effects are at play. In particular, past basic research investment arguably impact the economy's current stage of economic development, its manufacturing share in GDP, its competitive structure, and the share of domestic profits that accrue to the domestic population. The impact of these 'reversed causalities' on current investment decisions are all embodied in the different parameters of our theoretical model.

We also note that our model does not include leap-frogging in the sense that a successfully innovating type 2 firm will become a type 1 firm operating at the world's technological frontier. Instead, the best it can achieve from innovating is to keep their position relative to an advancing world technological frontier. Including leap-frogging would not change our results qualitatively as long as the probability of a successful leapfrogging innovation is—as seems realistic—rather small. In effect, leapfrogging would increase the escape entry effect and the productivity effect of basic research investments (cf. Section 3.2) and thus make them more beneficial, especially for economies lagging behind the world technology frontier. A similar extension could be to assume that basic research might not only help to prevent entry from abroad but also to replace foreign-owned firms which entered previously with new domestic leaders. That is, basic research helps to win back foreign-dominated sectors by supporting innovative domestic entrepreneurs. Our hypothesis that a larger number of foreign-owned sectors reduces basic research investments will still be true as long as this effect is not very strong. Another extension would be that the service sectors benefit from basic research as well. This would increase the overall productivity effect of basic research, but leave our hypothesis that a larger size of the manufacturing sector implies higher optimal basic research investments intact as long as on average, basic research is more important for innovations in manufacturing than in services.

4 Factors of Basic Research Investment in the Data

In the previous section, we developed a simple theoretical model to analyse how different factors impact a country's optimal basic research investment. The analysis underlying these insights was based on the assumption that governments seek to maximize the economic well-being of their citizens. In reality, policy-makers may well be guided by further motives as well, such as pleasing lobbying groups. In addition, governments may also be guided by more broadly defined beneficial effects of basic research such as advancements in health care or humanities, for example. Still, provided that such considerations do not introduce any systematic bias for basic research investment, we would expect to find the above relationships in the data. We therefore consider real-world patterns of basic research investment next.

Leaving aside the aforementioned political economy concerns, endogeneity problems and a lack of good data hinder a thorough identification of causal effects from the different factors on countries' basic research investments.[23] We therefore leave such identification for future research and instead explore empirical associations, building on a wide range of proxies for our four factors of interest.

In particular, we measure basic research intensity by the share of basic research investment in GDP as downloaded from OECD (2017a), and ask how these intensities are associated with our factors of interest. In our base case scenario, we choose broadly defined measures for our four factors with good availability of data: The stage of economic development is measured by a country's GDP per capita over US GDP per capita in the respective year, the strength of a country's manufacturing base by the share of manufacturing in GDP, the share of foreign ownership in domestic firms by the ratio of payments to abroad over GDP, and a country's openness by FDI inflows over GDP, and where we express all ratios in percents. The data are taken from World Bank (2017). We will then explore a broad range of robustness checks as detailed below. All of our variables are in logs unless explicitly stated otherwise in the footer of Table 2. Due to limitations of data availability and limited time variance of some of these variables, we then take 5 year centred moving averages, and keep observations for years 1983, 1988, 1993, 1998, 2003, 2008, and 2013. In our base-case scenario, we thus end up with an unbalanced panel of 7 time periods and 36 countries comprising all of the OECD member states except for Canada, Finland, Latvia, Luxembourg, and Turkey—plus Argentina, China, Romania, Russia, Singapore, and South Africa.

When evaluating factors of basic research investment in the data, it is important to bear in mind that our theoretical predictions refer to *ceteris paribus* variations, i.e. to predictions that isolate variations of the respective factor, keeping constant all other

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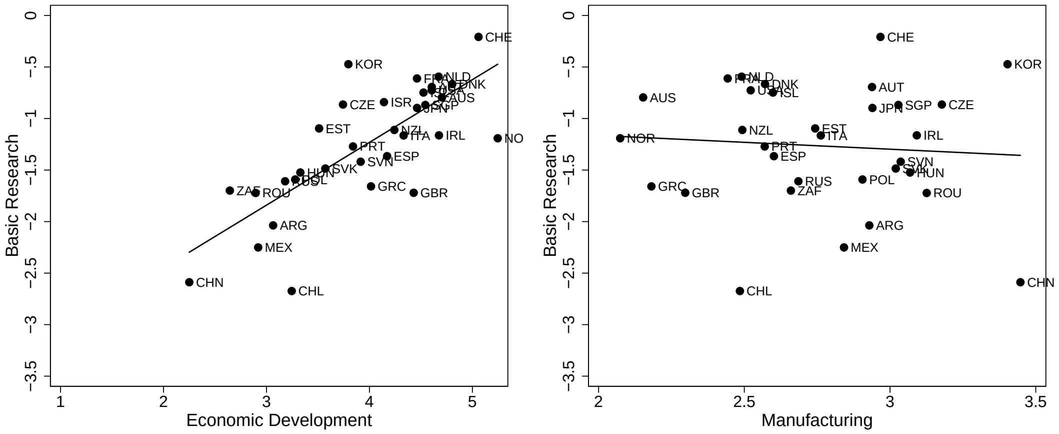
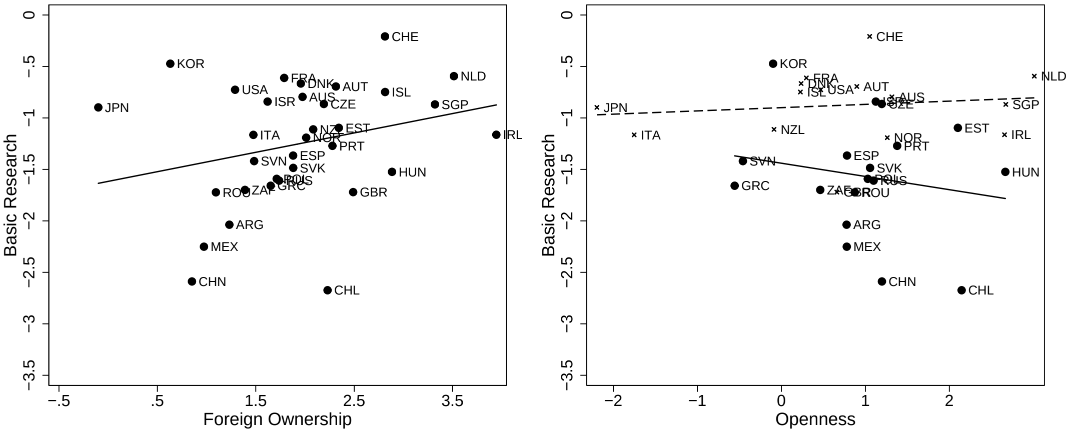
[23] There are important feedback effects from basic research to most or all of these factors. These effects should, however, be mitigated by the fact that basic research impacts the economy with major time lags (Nelson, 1959; Adams, 1990; Mansfield, 1998).

Figure 5: Correlations

(a) Economic Development (b) Manufacturing



(c) Foreign Ownership (d) Openness



Notes: In subfigure (d), observations indicated by an ‘x’ refer to countries close to the frontier (GDP per capita ≥ 65% of US GDP per capita). The dashed line is the fitted line for countries close to the frontier. The solid line for all other countries.

factors of optimal basic research investment. Figure 5 illustrates this point by means of simple correlation plots. It locates each country in our sample in charts with basic research intensity on the vertical axis and the factors of basic research investment on the horizontal axis. Motivated by Hypothesis 1, for the case of openness we split the set of countries into countries further from the frontier (less than 65% of US GDP per capia) and countries closer to the frontier.

All variables are measured in logs and refer to data for the year 2010.[24] While there is a strong positive association between economic development and basic research, as we might have expected based on our theoretical considerations, the same is not true for manufacturing, for example. On average, countries invest slightly less in basic research the higher their manufacturing share in GDP. It is likely, however, that other factors are at play, such as the fact that countries closer to the technological frontier tend to have a smaller share of manufacturing in their GDP.

In line with our theoretical predictions, we thus control for confounding factors next. In particular, Table 2 reports results for the estimation of the following equation:

$$\begin{aligned}\log(BR_{c,t}) =& \alpha_t + \alpha_c + + \beta_1 \log(D_{c,t}) + \beta_2 \log(M_{c,t}) + \beta_3 \log(FO_{c,t}) \\ & + \beta_4 \log(O_{c,t}) + \beta_5 \log(D_{c,t} \, \times \, O_{c,t}) + \epsilon_{c,t} \ , \end{aligned} \tag{22}$$

where BR is the share of basic research in GDP, D the stage of economic development of a country, M the strength of its manufacturing base, FO the share of foreign-owned firms, O a country's openness, and ϵ is an error term. The subscript c, t indicates an observation for country c in period t. Basic research may become more or less effective over time, and countries may differ in their preferences for investing in basic research, for example. We therefore account for both time-specific effects α_t and country-specific effects α_c in all of our estimations.

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[24] The qualitative patterns depicted in the correlation plots of Figure 5 are fairly stable over time with the exceptions that the manufacturing share in GDP tends to be more negatively correlated with the basic research intensity in previous years and that the correlation between a country's openness and its basic research intensity is sometimes positive and sometimes negative for countries close to the frontier, depending on which countries fall in the different subsamples. But for the early 2000s, the correlation tends to be greater closer to the frontier than for countries further from the frontier.

Table 2: Factors of Basic Research Investment

	(1)	(2)	(3)	(4)	(5)	(6)
D: $\frac{\text{GDP p cap}}{\text{US GDP p cap}}$	0.13*			0.15	0.18	0.21*
	(1.54)			(0.77)	(0.82)	(1.95)
M: $\frac{\text{manufacturing}}{\text{GDP}}$	0.60*	0.44*	1.16*			
	(1.87)	(1.36)	(1.97)			
FO: $\frac{\text{payments to abroad}}{\text{GDP}}$	-0.08	-0.07	-0.32	-0.18	-0.22	0.01
	(-0.86)	(-0.80)	(-1.17)	(-0.81)	(-1.03)	(0.13)
O: $\frac{\text{inward FDI}}{\text{GDP}}$	-0.32***	0.25*	-0.06	-0.49*	-0.42*	-0.17
	(-3.14)	(1.34)	(-1.17)	(-1.77)	(-1.64)	(-1.00)
Development × Openness	0.07**	0.02*	0.11**	0.10*	0.08	0.02
	(2.72)	(1.51)	(2.39)	(1.52)	(1.26)	(0.47)
D: patents per cap		0.09**				
		(2.11)				
D: outp-w rel productivity			0.37*			
			(1.45)			
M: outp-w AR intensity				0.34		
				(0.74)		
M: outp-w pat intensity					0.47	
					(1.06)	
M: economic complexity						0.11
						(0.62)
Observations	142	142	50	64	66	152
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

t statistics in parentheses
* $p < .20$, ** $p < .05$, *** $p < .01$

Notes: Columns report results from a fixed effect estimation of basic research intensity on the different factors, using country fixed effects. Time fixed effects have been added in all cases. With the exception of the measure of economic complexity and the FDI indicator, all variables are in logs. In each column, 'Development × Openess' refers to the interaction of the respective measures used. Standard errors are clustered by country.

Column (1) of Table 2 reports estimation results for our base case scenario. For ease of presentation, we include here and below an indicator D, M, FO, O at the beginning of the label of each control variable that points to the specific factor that is captured. Our base case scenario reveals empirical associations that are consistent with our theoretical predictions (column (1)). Countries, as they get closer to the frontier, tend to invest more in basic research as do countries with a stronger manufacturing base. Moreover, the estimation results suggest that the association between a country's openness and its basic research investment is the greater (less negative) the closer the country to the technological frontier. Finally, the coefficient on foreign ownership has the expected sign, albeit it is not significant. These relationships are economically relevant. The estimated coefficient on manufacturing, for example, implies that ceteris paribus if a country has a manufacturing share in GDP that is twice as large, it tends to invest

60% more in basic research.[25]

Table 2: Factors of Basic Research Investment

	(1)	(7)	(8)	(9)	(10)	(11)	(12)
D: $\frac{\text{GDP p cap}}{\text{US GDP p cap}}$	0.13*	0.14*	0.35	0.17	-0.00		
	(1.54)	(1.32)	(1.29)	(0.79)	(-0.01)		
M: $\frac{\text{manufacturing}}{\text{GDP}}$	0.60*	0.57*	1.38**	1.19***	1.10***		
	(1.87)	(1.70)	(2.07)	(2.82)	(2.74)		
FO: $\frac{\text{payments to abroad}}{\text{GDP}}$	-0.08			-0.22	-0.09	-0.36	-0.38*
	(-0.86)			(-0.98)	(-0.96)	(-1.33)	(-1.60)
O: $\frac{\text{inward FDI}}{\text{GDP}}$	-0.32***	-0.36**	-0.24			0.06	-0.20
	(-3.14)	(-2.28)	(-0.96)			(0.13)	(-0.11)
Development × Openness	0.07**	0.08**	0.04	0.00	0.03	0.03	-0.01
	(2.72)	(2.08)	(0.68)	(0.01)	(0.37)	(0.29)	(-0.06)
FO: $\frac{\text{royl payments}}{\text{GDP}}$		-0.05					
		(-0.80)					
FO: $\frac{\text{outw FDI income}}{\text{GDP}}$			-0.36**				
			(-2.23)				
O: FDI indicator				0.18			
				(0.09)			
O: $\frac{\text{IM + EX}}{\text{GDP}}$					-0.51*		
					(-1.35)		
DM: outp-×-rel-prod-w AR int						0.24*	
						(1.41)	
DM: outp-×-rel-prod-w pat int							0.28*
							(1.89)
Observations	142	130	46	55	142	52	56
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes

t statistics in parentheses
* $p < .20$, ** $p < .05$, *** $p < .01$

Notes: Columns report results from a fixed effect estimation of basic research intensity on the different factors, using country fixed effects. Time fixed effects have been added in all cases. With the exception of the measure of economic complexity and the FDI indicator, all variables are in logs. In each column, 'Development × Openess' refers to the interaction of the respective measures used. Standard errors are clustered by country.

Columns (2) to (13) present various robustness checks. We present further details on the exact variable definitions in Appendix C. Columns (2) to (3) consider alternative measures for a countries' distance from the frontier. In column (2) we use patents per capita as downloaded from OECD (2017b). Here and below, the interaction term

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[25] The negative coefficient on our measure for openness indicates that countries far from the frontier tend to invest the less in basic research the more open they are. The point estimates suggest that only countries very close to the frontier with GDP per capita larger than 97% of US GDP per capita tend to invest the more in basic research the more open they are. Through the lense of our model, this suggests that countries from the frontier may indeed have incentives to free-ride on technological advancement through foreign entry, and that the threat of such entry may lower investments in applied research by lagging domestic firms.

‘Development × Openness’ refers to the interaction term of the respective measures of Economic Development and Openness. In column (3) we consider an industry-specific measure of distance from the technological frontier: ouput per worker over US output per worker which we construct using country year data on gross output and employment by industry as taken from OECD (2017c). We then take the weighted sum over industries, where weights are given by a country’s output shares across industries. These alternative specifications yield estimation results that are broadly in line with our base case.

While a country’s manufacturing base is a pivotal element of its innovation system (Pisano and Shih, 2012; McKinsey Global Institute, 2012), there is certainly heterogeneity within manufacturing industries in terms of the prevalence of research-driven innovation, and such innovation is also present in other sectors. We therefore consider alternative measures for the strength of a country’s ‘manufacturing base’ in columns (4) to (6). In column (4), we measure an industry’s innovativeness by its applied research intensity as taken from OECD (2017d), i.e. we consider an ‘innovation-input’ measure, while in column (5) we consider an ‘innovation-output’ measure, patents per output. In both cases, we then derive country-year measures by forming the weighted sum over these industry measures, with the weights again given by countries’ output shares across industries. Finally, in column (6) we use a country’s economic complexity index as developed in Hidalgo et al. (2007); Hidalgo and Hausmann (2009).[26] Again, these robustness checks broadly confirm our previous findings, albeit with somewhat less significant point estimates.

Our base-line measure of the foreign-ownership of domestic firms is fairly broad. In columns (7) and (8), we consider two more narrowly defined alternatives: Royalty payments over GDP taken from World Bank (2017) (column (7)) and outward FDI income over GDP taken from OECD (2017) (column (8)), which is available for a limited period of time only. Again, these robustness checks confirm our above observations.

Columns (9) to (10) present results using alternative measures for a country’s openness. In column (9) we use the inverse of the FDI Regulatory Restrictiveness Indicator presented by OECD (2016). The concept of openness that we consider in our theoretical model is one of market entry by foreign firms which involves intricate trade-offs when it comes to basic research policies. Yet, foreign firms may serve the domestic market via exporting as well. In column (10) we therefore measure a country’s openness by the sum of imports and exports over GDP. With these alternative measures, the interaction term of economic development and openness is close to 0 and no longer significant. Also, in column (10) the coefficient on economic development is virtually 0.

Finally, one might argue that the measures of economic development and manufac-

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[26] The index values have been downloaded from http://www.atlas.cid.harvard.edu in January 2017.

turing should be integrated: The benefits from basic research investments should be higher for countries that are heavily active and close to the frontier in industries with intense research-driven innovation. In an attempt to account for this, we consider joint measures in columns (11) and (12). In column (11), we consider industries' applied research intensity and in column (12) their patent intensity. In both cases we then form a weighted sum across industries, using a countries' output shares times their productivity relative to the United States as weights. With the exception of the interaction term of economic development and openness,[27] results again accord well with our baseline specification.

To conclude, the empirical exercise in this section suggests that countries' basic research investments are indeed associated with the four factors considered here as predicted by our theory. While these analyses are no formal tests of our model and do not uncover causal relationships, they are broadly consistent with the view that the factors of optimal basic research investments considered here are indeed important determinants of real world investments. We leave a thorough empirical evaluation of causal relationships for future research.

5 Policy Implications

In this paper, we have proposed a factor-based approach to assessing the optimal level of countries' investments in basic research. We identified and discussed four factors: Distance to the technological frontier, the strength of the domestic manufacturing base, the share of foreign ownership in domestic firms, and a country's openness. For each of these factors, we discussed the various channels through which it influences optimal basic research investment based on a simple theoretical model of creative destruction. What is more, we presented a preliminary empirical assessment which suggests that the identified effects may indeed matter for policy-making in the area of basic research.

We next explore how our findings might inform basic research policies. We start with a short overview about current policy debates. Governments all over the world have been implementing major new programs in the area of basic research. South Korea and Singapore have stepped up their basic research investments considerably—more than doubling their expenditures as a percentage of GDP from 2000 to 2009.[28] The European Council aims at increasing total (public and private) R&D spending in the European Union to 3% of GDP by 2020 (General Secretariat of the European Council, 2010). With the ambition to increase its pool of scientists with state-of-the-art training, Brazil has initiated a program to support scientists going abroad (Brazilian Secretariat for Social Communication, 2011). After having initiated big push invest-

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[27] Note that in this case the interaction term does not directly relate to our theoretical predictions.

[28] Own calculations, based on OECD (2017a).

ments in basic research at the beginning of the 21st century, Ireland has assembled a Research Prioritisation Steering Group to identify targets for future investments (Research Prioritisation Project Steering Group, 2012). In 2013, Canada has announced to direct its National Research Council towards more applied research and to transform it into a *'business-driven, industry-relevant research and technology organization'* (Goodyear, 2013). At a more general level, many developed economies aim at a re-industrialization as a means to guarantee economic growth and prosperity (for example, see Obama (2013) and European Commission (2012)).

Moreover, recent efforts at national or European level to accelerate the use of digital technology entail further investments in basic research (see e.g. Bundesministerium für Wirtschaft und Energie (2016)). These efforts are often complemented by calls that funding for basic research should be increased to prevent technological slowdowns (e.g. Geim (2013)).

While this overview illustrates that countries try to stimulate research-driven innovation through multi-faceted policy reforms in the area of basic research, the question of how much to publicly invest in basic research is certainly among the most important ones in this area. Traditional approaches focusing on estimating the returns to basic research or on their beneficial effects on aggregate growth and productivity do not provide a sufficient basis for identifying socially optimal investment levels. In this paper, we therefore propose to complement such studies by systematically accounting for a country's key characteristics. While our stylized model and the empirical correlations we present cannot be used to calculate optimal spending on basic research for the economy as a whole and across disciplines or industries,[29] pursuing alternative paths to it may nevertheless explain and inform policy in the following way.

First, if we assume that countries take optimal basic research policy decisions, our results may rationalize comparably high basic research investments and, in particular, the rapid increase of these investments in certain countries. We provide several examples. South Korea invests more in basic research in proportional terms, compared to the US. This is surprising at first sight, given that South Korea is considerably lagging in terms of economic development as measured by its GDP per capita, but may reflect the fact that South Korea has a strong manufacturing base which is mostly domestically owned. Similarly, Ireland has doubled its investment in basic research before the financial crisis and has considerably caught up on these investments compared to industrialized countries such as France. Ireland is a strongly open economy, close to the frontier, and with a comparatively large manufacturing sector, which is consistent with the results of our model. Similar observations can be made for Spain, the Czech Republic, and Singapore, for example, which have all embarked on substantial increases of basic research—but at different rates. Similarly, our model can explain why small

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[29] Given that the chain from basic research to commercialized intermediate products or consumer products is typically long, uncertain, and multi-facetted, this will be a daunting task for any model.

but strongly open countries with a comparatively high manufacturing sector invest strongly in basic research—in cases like Switzerland or South Korea even surpassing the US in proportional terms. According to our theoretical reasoning, the discussed country characteristics matter for basic research investments. The same is maybe less true for a country's scale, at least if basic research has significant local effects.

These observations suggest interesting implications for R&D policies in Europe. Since the level of applied research—in our model and in the data—is in a quite stable relationship with basic research, a country's optimal R&D expenditure is expected to be strongly dependent on this country's characteristics. Hence, our analysis lends support to defining country-specific targets underlying the overall EU-2020 target of investing 3% of GDP in Research and Development (European Commission, 2014).

Second, if the government of a sufficiently advanced country takes a medium-run perspective, the prospects of basic-research-engineered growth depend on favorable country characteristics such as a strong manufacturing base and openness, taking into account that there are considerable delays between basic research research investments and commercialization.[30] If, in addition, firms benefiting from basic research are mainly owned domestically, basic-research-engineered growth will fully translate into higher domestic income.

Third, some of the factors of basic research investment might also be more directly subject to policy changes, even in the medium-run, opening up opportunities for joint policies. According to our theoretical framework, for example, it may be beneficial to jointly open up a country to foreign entry and step up basic research investments, at least for countries close to the technological frontier. This would put pressure on domestic firms to innovate and simultaneously support them in deterring entry by foreign firms.

Fourth, similar considerations apply, in principle, for countries that take a long-term view—with two important qualifications. On the one hand, long-term basic research policies may aim at changing the country's characteristics favorably, such as the stage of development, openness, or the size of the manufacturing sector. Indeed, such objectives are the explicit underpinning of policies in specific countries, most notably in Singapore or South Korea, but even in the US and the European Union, as discussed at the beginning of this section. Foundations for such policies necessitate a dynamic version of our model. Such dynamic versions can readily be constructed. For instance, the simplest non-overlapping version of our model would have the industry structure as state variable vis-a-vis a growing world technology frontier. Such a version would allow to assess the long-term benefits of today's basic research investments. While such an exercise would lend support to additional basic research investments based on dynamic gains, it would still be too stylized to provide country-specific policy recommendations.

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[30] Well-known estimates range between 6 and 20 years (see e.g. Adams (1990) and Mansfield (1998)).

On the other hand, one obvious area in which countries may try to engineer basic-research-driven growth is the New Digital Economy.[31] Despite a substantial increase in business spending on capital and services in Information and Communication Technology (ICT), this has not generated visible improvements of productivity growth yet.[32] Together with the slowdown in productivity, this has led to the hypothesis that countries may have entered long-term or secular stagnation. While the alternative hypothesis that the Digital Economy is still in its installation phase, and productivity gains will occur once we enter the deployment phase, appears to be more plausible, the gains of basic research investments in this area are uncertain at this stage. If estimates of delays between basic and applied research, and subsequent diffusion of technology in the economy, are also a guide for the New Digital Economy, the current productivity situation is no surprise and the data do not speak against additional basic research investments.

These discussions illustrate how a thorough evaluation of countries' characteristics can contribute to better informed policy-making in the area of basic research. We presented a first step in this direction. Much can be gained from future work on the nexus between fundamental characteristics of an economy and its optimal basic research policies.

First, numerous extensions of our set-up could be pursued. Such extensions might consider further country characteristics such as a country's tax policy, talent pool, or entrepreneurial environment, for example. Similarly, dynamic or multicountry versions would provide further insights into optimal basic research policies. Second, while our empirical exercise points to associations in the data that are consistent with our theoretical reasoning, it would be interesting to more thoroughly assess causal relationships in the data. Third, identifying 'sufficient statistics' for optimal basic research policies in the spirit of Chetty (2009) may help turning the directional policy implications discussed here into more specific advise. Finally, we view the factor-based approach we propose as a complement to, rather than a substitute for, more traditional evaluations of the efficient levels of basic research. Integrating these approaches would be yet another promising area for future research.

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[31] The New Digital Economy is defined in van Ark (2016) as *'the combination of mobile technology, ubiquitous access to the internet, and the shift toward storage, analysis, and development of new applications in the cloud'*.

[32] See van Ark (2016) for a review of the evidence for the US, UK, and Germany.

Appendix

A Mathematical Appendix

A.1 Details of the Economic Model

In this appendix, we provide technical details on the economic model as outlined in Section 3. For this purpose it is convenient to use $s_1^d = (1-\lambda)s_1$ to denote the number of domestic type 1 firms.

A.1.1 Equilibrium

It follows from Section 3.1.2 that the market clearing conditions in the intermediate-good markets yield prices $p_m(i) = \frac{w}{\alpha}$ in the monopolistic industries and $p_c(i) = w$ in the competitive ones. From (5), (6), and (7), we obtain the values for the supply of intermediate goods as

$$x_c(i) = \left(\frac{\alpha A(i)^\alpha}{w}\right)^{\frac{1}{1-\alpha}}, \tag{A.1}$$

$$x_m(i) = \left(\frac{\alpha^2 A(i)^\alpha}{w}\right)^{\frac{1}{1-\alpha}} \tag{A.2}$$

in the monopolistic intermediate industries and the competitive intermediate industries, respectively.

As unskilled labour is only used in final-good production and has a fixed supply of measure 1, the wage rate w_u is defined by (3). In the skilled labour market, labour $\bar{L}$ is supplied inelastically. Demand for skilled labour consists of the government's demand for basic researchers, the intermediate firms' demand for private researchers, and the demand of skilled workers for the production of the intermediate goods. Hence the market for skilled labour clears when

$$\bar{L} = L_B + \int_0^1 L_A(i)\,di + \int_0^1 L_x(i)\,di. \tag{A.3}$$

As we know from Section 3.1.3, the demand for R&D personnel depends on the state of the intermediate firm's industry. Consequently, the first integral in equation (A.3) is given by

$$\int_0^1 L_A(i)\,di = s_1^d L_{A_1} + s_2 L_{A_2}. \tag{A.4}$$

Note that the total demand for private researchers is determined by the number of industries characterized by domestic monopolies at the beginning of the period. By contrast, the demand for skilled workers in intermediate-goods production depends on the industry's technological level after innovation activities and foreign entry have occurred. This reflects our assumption that foreign intermediate firms bring leading technology along from abroad, but produce the intermediate goods within the country they entered. Accordingly, in order to determine the second integral in (A.3) we need to know how industry states evolve during the period. The following scheme displays the probabilities for levels of technology achieved by an intermediate industry. The illustration also shows the resulting market structure in terms of the mode of competition and of whether intermediate firms are domestic or foreign.

$$
\begin{aligned}
s_1^d &\leftrightarrow \left\{ \begin{array}{ccll} \rho_1 & : \bar{A}, & \text{local,} & \text{monopoly} \\ (1-\rho_1)\sigma & : \bar{A}, & \text{foreign,} & \text{monopoly} \\ (1-\rho_1)(1-\sigma) & : \bar{A}_{-1}, & \text{local,} & \text{monopoly} \end{array} \right. \\
s_2 &\leftrightarrow \left\{ \begin{array}{ccll} \sigma & : \bar{A}, & \text{foreign,} & \text{monopoly} \\ (1-\sigma)\rho_2 & : \bar{A}_{-1}, & \text{local,} & \text{monopoly} \\ (1-\rho_2)(1-\sigma) & : \bar{A}_{-2}, & \text{local,} & \text{perfect competition} \end{array} \right. \\
s_3 &\leftrightarrow \left\{ \begin{array}{ccll} \sigma & : \bar{A}, & \text{foreign,} & \text{monopoly} \\ (1-\sigma) & : \bar{A}_{-2}, & \text{local,} & \text{perfect competition} \end{array} \right.
\end{aligned}
\tag{A.5}
$$

In terms of their demand for skilled production workers, foreign-owned firms are identical to their domestic counterparts. Consequently, the total intermediate firms' demand for skilled production workers is given by

$$
\begin{aligned}
\int_0^1 L_x(i)\,di = &\left(s_1^d\rho_1 + \frac{\lambda}{1-\lambda}s_1^d + \left(\mu - s_1^d\rho_1 - \frac{\lambda}{1-\lambda}s_1^d\right)\sigma\right) L_{xm}(\bar{A}) + \\
&\left(s_1^d(1-\sigma)(1-\rho_1) + s_2(1-\sigma)\rho_2\right) L_{xm}(\bar{A}_{-1}) + \\
&\left(s_2(1-\sigma)(1-\rho_2) + s_3(1-\sigma) + (1-\mu)\right) L_{xc}(\bar{A}_{-2}).
\end{aligned}
\tag{A.6}
$$

Inserting (A.4) and (A.6) into (A.3), we obtain the equilibrium wage level in the skilled labour market. In a small parameter range, it may occur that the wage for skilled labour decreases with the level of basic research. Our focus is on the more realistic case where larger demand for skilled labour in basic research increases the skilled labour wage. Hence, we slightly restrict our parameter space in accordance with the following assumption:[33]

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[33] For Assumption 1 to be violated, $\mathcal{C}$ has to be strongly negative, i.e. s_2 has to be large and σ, γ and α have to be small. Under these circumstances, basic research has a pressure-reducing effect on the skilled labour market due to the fact that the monopolistic s_2 industries employ less skilled labour for production than the competitive s_3 industries. In particular, this effect is increased by a larger amount of s_2 industries. A lower σ increases the importance of the s_2 industries, as the likelihood that they are taken over by a foreign firm is reduced. Reducing γ lowers the technological gap between the s_2 and the s_3 industries, which reduces the skilled labour employment of s_2 industries relative to the one of s_3 industries. Finally, a lower α enlarges the monopoly distortion, which also reduces the skilled labour employment of s_2 industries relative to the one of s_3 industries.

Assumption 1
$(\mathcal{B}+\mathcal{C})\bar{L}^2 > -\mathcal{A}^2$, where

$$\mathcal{A} = \frac{\left(\alpha^2\bar{A}^{\alpha}\right)^{\frac{1}{1-\alpha}}}{\gamma^2}\left[\left(\sigma+\frac{\lambda}{1-\lambda}s_1^d\right)\gamma^2+(1-\mu)\frac{1}{\alpha^{\frac{1}{1-\alpha}}}+(1-\sigma)\left(s_1^d\gamma+(s_2+s_3)\frac{1}{\alpha^{\frac{1}{1-\alpha}}}\right)\right], \tag{A.7}$$

$$\mathcal{B} = \frac{\bar{A}^{\frac{2\alpha}{1-\alpha}}}{\gamma^2}m^2\theta^2[s_1^d(\gamma-1+\sigma)^2+s_2(1-\sigma)^2] > 0, \tag{A.8}$$

$$\mathcal{C} = \frac{\left(\alpha\bar{A}^{\alpha}\right)^{\frac{2}{1-\alpha}}}{\gamma^3}2m\theta^2(1-\sigma)\left[s_1^d\gamma(\gamma-1)(\gamma-1+\sigma)+s_2\left(\gamma-\frac{1}{\alpha^{\frac{1}{1-\alpha}}}\right)(1-\sigma)\right]. \tag{A.9}$$

We are now in a position to state:

Proposition 1
Under Assumption 1,

(i) there exists a unique equilibrium in the skilled labour market given by

$$w(L_B) = \left(\frac{\mathcal{A}+\sqrt{\mathcal{A}^2+4L_B(\bar{L}-L_B)(\mathcal{B}+\mathcal{C})}}{2(\bar{L}-L_B)}\right)^{1-\alpha}, \tag{A.10}$$

(ii) $\frac{dw(L_B)}{dL_B} > 0$.

Proof: See Appendix A.2.1.

From the equilibrium wage for skilled labour we obtain the equilibrium prices for intermediate goods from which the equilibrium quantities, the firms' profits and the equilibrium wage for unskilled labour follow. To simplify notation, we use here and below $w(L_B)$ to denote the equilibrium wage for skilled labour associated with a particular level of basic research.

A.1.2 Government Decision Problem

As stated in the main text, the government chooses L_B to maximize total final-good production, minus intermediate profits earned by foreign-owned firms,

$$\max_{L_B} \quad c = y - \left\{\frac{\lambda}{1-\lambda}s_1^d + \sigma(\mu - \frac{\lambda}{1-\lambda}s_1^d - s_1^d\rho_1)\right\}\pi_{xm}(\bar{A}). \tag{A.11}$$

It is impossible to derive an analytical solution to the problem in its generality. In our analysis of optimal basic research investment, we therefore assume that $\alpha = \frac{1}{2}$. For this special case, we can prove the following proposition, which justifies our discussion of optimal basic research investment based on the first order condition for the above decision problem.

Proposition 2
Under Assumption 1, the unique optimal L_B *is either* $L_B = 0$ *if* $\left.\frac{dc}{dL_B}\right|_{L_B=0} \leq 0$*, or the unique positive solution to* $\frac{dc}{dL_B} = 0$*.*

Proof: See Appendix A.2.2.

A.2 Proofs

A.2.1 Proof of Proposition 1

Inserting (A.4) and (A.6) into (A.3), we obtain the market clearing condition for skilled labour as a quadratic function with respect to $\widetilde{w} := w^{\frac{1}{1-\alpha}}$. Solving the market clearing condition for $\widetilde{w}$ as a function of L_B yields

$$\widetilde{w}(L_B) = \frac{\mathcal{A} \pm \sqrt{\mathcal{A}^2 + 4L_B(\bar{L} - L_B)(\mathcal{B} + \mathcal{C})}}{2(\bar{L} - L_B)}, \tag{A.12}$$

while solving the market clearing condition with respect to the equilibrium level of basic research yields

$$L_B(\widetilde{w}) = \widetilde{w}\frac{\widetilde{w}\bar{L} - \mathcal{A}}{\widetilde{w}^2 + \mathcal{B} + \mathcal{C}}. \tag{A.13}$$

To show that the equilibrium is unique, it is convenient to use (A.13), which can be rewritten as

$$L_B(\widetilde{w}) = \frac{\bar{L} - \frac{\mathcal{A}}{\widetilde{w}}}{1 + \frac{\mathcal{B}+\mathcal{C}}{\widetilde{w}^2}}. \tag{A.14}$$

We first note that as $L_B < 0$ is not feasible, the relevant range of $\widetilde{w}$ is given by $\widetilde{w} \geq \widetilde{w}_0 = \frac{\mathcal{A}}{\bar{L}}$.

As a next step, we show that the function $L_B(\widetilde{w})$ strictly increases with $\widetilde{w}$ in the relevant range. As $\widetilde{w} \geq \widetilde{w}_0$, it is convenient to replace $\widetilde{w}$ by $x\frac{\mathcal{A}}{\bar{L}}$, where $x \geq 1$. We obtain

$$L_B(x) = \frac{\bar{L}(1 - \frac{1}{x})}{1 + \bar{L}^2\frac{\mathcal{B}+\mathcal{C}}{x^2\mathcal{A}^2}}. \tag{A.15}$$

We now need to show that $L_B(x)$ is strictly increasing in x, i.e., that

$$\frac{\partial L_B(x)}{\partial x} = \frac{\frac{1}{x^2}\bar{L}\left(1 + \bar{L}^2\frac{\mathcal{B}+\mathcal{C}}{x^2\mathcal{A}^2}\right) + 2\bar{L}^3\left(1 - \frac{1}{x}\right)\frac{\mathcal{B}+\mathcal{C}}{x^3\mathcal{A}^2}}{\left(1 + \bar{L}^2\frac{\mathcal{B}+\mathcal{C}}{x^2\mathcal{A}^2}\right)^2} > 0. \tag{A.16}$$

This condition reduces to

$$1 - \bar{L}^2\frac{\mathcal{B}+\mathcal{C}}{x^2\mathcal{A}^2} + 2\bar{L}^2\frac{\mathcal{B}+\mathcal{C}}{x\mathcal{A}^2} > 0. \tag{A.17}$$

If $\mathcal{B}+\mathcal{C} > 0$, we can estimate the left-hand side from below by multiplying the last term with $\frac{1}{x}$. This gives us

$$1+\bar{L}^2\frac{\mathcal{B}+\mathcal{C}}{x^2\mathcal{A}^2} > 0, \tag{A.18}$$

which is obviously satisfied.

We now consider the case where $\mathcal{B}+\mathcal{C} < 0$. As the left hand side of (A.17) increases with x, we know that if condition (A.17) is satisfied for $x = 1$, it will also be satisfied for $x > 1$. Inserting $x = 1$, we obtain

$$1+\bar{L}^2\frac{\mathcal{B}+\mathcal{C}}{\mathcal{A}^2} > 0. \tag{A.19}$$

This holds under Assumption 1, i.e., if $(\mathcal{B}+\mathcal{C})\bar{L}^2 > -\mathcal{A}^2$.

The strictly increasing $L_B(\widetilde{w})$ implies that there is a unique equilibrium $\widetilde{w}$ for every level of L_B. As $\widetilde{w} \geq \widetilde{w}_0$, it is clear that the larger solution with the positive sign of (A.12) constitutes the unique equilibrium. Solving for w yields (A.10).

A.2.2 Proof of Proposition 2

With uniqueness of the equilibrium wage w in the skilled labour market for given L_B, the government's problem can also be solved via the control w. We will take this path for convenience.

Inserting (13), (17), and $L_B(\widetilde{w})$ from equation (A.13), where now $\tilde{w} = w^2$, into (20), we obtain overall consumption solely as a function of w:

$$c(w) = \frac{w^4(2\mathcal{A}+2\mathcal{D}+\mathcal{E}) + w^2\bar{L}(2\mathcal{B}+3\mathcal{C}+\mathcal{F}) + (\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E}) - \mathcal{A}(\mathcal{C}+\mathcal{F})}{w(w^4+\mathcal{B}+\mathcal{C})}, \tag{A.20}$$

with

$$\mathcal{D} = \frac{\bar{A}}{16\gamma}s_1^d(1-\sigma) \quad > \quad 0, \tag{A.21}$$

$$\mathcal{E} = \frac{\bar{A}}{16}\left(\sigma\mu + (1-\sigma)\frac{\lambda}{1-\lambda}s_1^d\right) \quad > \quad 0, \tag{A.22}$$

$$\mathcal{F} = \frac{\bar{A}^2}{32\gamma^3}s_2(1-\sigma)^2\theta^2 \quad > \quad 0. \tag{A.23}$$

This is the objective function the government maximizes with respect to w. According to the arguments in the proof of Proposition 1, the relevant space is given by $w \geq w_0 := \sqrt{\frac{\mathcal{A}}{\bar{L}}}$. To prove that we have a unique maximum consumption level in the relevant space, we show that $c(w)$ is either always decreasing with w or increasing with w, reaching a local maximum, and then decreasing with w.

To analyse the slope of $c(w)$, we differentiate with respect to w:

$$\begin{aligned}\frac{\partial c(w)}{\partial w} = & \frac{-w^8(2\mathcal{A}+2\mathcal{D}+\mathcal{E})-3w^6\bar{L}(2\mathcal{B}+3\mathcal{C}+\mathcal{F})}{w^2(w^4+\mathcal{B}+\mathcal{C})^2}+\\ & \frac{w^4(\mathcal{B}+\mathcal{C})(6\mathcal{A}-4\mathcal{D}-2\mathcal{E})+5w^4\mathcal{A}(\mathcal{C}+\mathcal{F})}{w^2(w^4+\mathcal{B}+\mathcal{C})^2}+\\ & \frac{w^2\bar{L}(\mathcal{B}+\mathcal{C})(2\mathcal{B}+3\mathcal{C}+\mathcal{F})+(\mathcal{B}+\mathcal{C})\big(\mathcal{A}(\mathcal{C}+\mathcal{F})\big)}{w^2(w^4+\mathcal{B}+\mathcal{C})^2}+\\ & \frac{-(\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E})\big)}{w^2(w^4+\mathcal{B}+\mathcal{C})^2}\end{aligned} \tag{A.24}$$

It is obvious that the denominator is positive. Hence, to determine the slope, it is sufficient to focus on the numerator only. As we are interested in the relevant space $w \geq w_0 = \sqrt{\frac{\mathcal{A}}{\bar{L}}}$, it is convenient to replace w by $\sqrt{x\frac{\mathcal{A}}{\bar{L}}}$, whereas $x \geq 1$. The numerator takes the form

$$\begin{aligned}&\underbrace{-x^4\frac{\mathcal{A}^4}{\bar{L}^4}(2\mathcal{A}+2\mathcal{D}+\mathcal{E})}_{U}\underbrace{-3x^3\frac{\mathcal{A}^3}{\bar{L}^2}(2\mathcal{B}+3\mathcal{C}+\mathcal{F})}_{V}\underbrace{+5x^2\frac{\mathcal{A}^3}{\bar{L}^2}(\mathcal{C}+\mathcal{F})}_{W}+\\ &\quad\underbrace{x^2\frac{\mathcal{A}^2}{\bar{L}^2}(\mathcal{B}+\mathcal{C})(6\mathcal{A}-4\mathcal{D}-2\mathcal{E})}_{X}\underbrace{+x\mathcal{A}(\mathcal{B}+\mathcal{C})(2\mathcal{B}+3\mathcal{C}+\mathcal{F})}_{Y}+\\ &\qquad\underbrace{(\mathcal{B}+\mathcal{C})\big(\mathcal{A}(\mathcal{C}+\mathcal{F})-(\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E})\big)}_{Z}.\end{aligned} \tag{A.25}$$

We note that $\mathcal{A}, \mathcal{B}, \mathcal{D}, \mathcal{E}, \mathcal{F} > 0$, $\mathcal{F} > -\mathcal{C}$, and $\mathcal{A} > \mathcal{D}+\mathcal{E}$. The analysis can be simplified by distinguishing four cases.

1. $\mathcal{B}+\mathcal{C} > 0$ and $(\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E})-\mathcal{A}(\mathcal{C}+\mathcal{F}) < 0$
   U and V, the terms with the highest exponents of x, are negative, while all the remaining terms, W, X, Y, and Z, are positive. Hence, it is obvious that in this case, $c(w)$ either falls directly in x or w, or rises first and falls after reaching its maximum.

2. $\mathcal{B}+\mathcal{C} > 0$ and $(\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E})-\mathcal{A}(\mathcal{C}+\mathcal{F}) > 0$
   U and V are negative, W, X, and Y are positive, and Z is again negative. If Y dominates Z for $x = 1$, it is always dominating and as in the preceding case, the exponents of x can be used to state the uniqueness of a maximum consumption level. Inserting $x = 1$ in $Y + Z > 0$ leads to

$$\mathcal{A}(\mathcal{B}+\mathcal{C})(2\mathcal{B}+4\mathcal{C}+2\mathcal{F})-(\mathcal{B}+\mathcal{C})^2(2\mathcal{D}+\mathcal{E}) > 0 \tag{A.26}$$

$$\mathcal{A}(2\mathcal{B}+4\mathcal{C}+2\mathcal{F}) > (\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E}) \tag{A.27}$$

$$2\mathcal{A}(\mathcal{C}+\mathcal{F})+2\mathcal{A}(\mathcal{B}+\mathcal{C}) > (2\mathcal{D}+\mathcal{E})(\mathcal{B}+\mathcal{C}). \tag{A.28}$$

As $\mathcal{A} > \mathcal{D} + \mathcal{E}$, the inequality holds, and the existence of a unique maximum is shown.

3. $\mathcal{B} + \mathcal{C} < 0$ and $2\mathcal{B} + 3\mathcal{C} + \mathcal{F} > 0$
   U and V are still negative, W is positive, and the remaining terms, X, Y, and Z, are negative. Thus it is sufficient to show that $W + X + Y + Z > 0$ holds for $x = 1$. Arguing with the exponents of x again, $c(w)$ is then either falling all along or rising before falling continuously. Next we prove that $W + X + Y + Z > 0$ for $x = 1$:

   $$\begin{split}5\tfrac{\mathcal{A}^3}{\bar{L}^2}(\mathcal{C}+\mathcal{F}) + \tfrac{\mathcal{A}^2}{\bar{L}^2}(\mathcal{B}+\mathcal{C})(6\mathcal{A}-4\mathcal{D}-2\mathcal{E}) + \mathcal{A}(\mathcal{B}+\mathcal{C})(2\mathcal{B}+3\mathcal{C}+\mathcal{F})\\ +(\mathcal{B}+\mathcal{C})\big(\mathcal{A}(\mathcal{C}+\mathcal{F}) - (\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E})\big) > 0.\end{split} \tag{A.29}$$

   Estimating $W + X + Y + Z$ from below by using Assumption 1, the inequality reduces to

   $$\begin{split}4\tfrac{\mathcal{A}^3}{\bar{L}^2}(\mathcal{C}+\mathcal{F}) + \tfrac{\mathcal{A}^2}{\bar{L}^2}(\mathcal{B}+\mathcal{C})(6\mathcal{A}-4\mathcal{D}-2\mathcal{E}) +\\ \mathcal{A}(\mathcal{B}+\mathcal{C})(2\mathcal{B}+3\mathcal{C}+\mathcal{F}) - (\mathcal{B}+\mathcal{C})^2(2\mathcal{D}+\mathcal{E}) > 0\end{split} \tag{A.30}$$

   $$\begin{split}3\tfrac{\mathcal{A}^3}{\bar{L}^2}(\mathcal{C}+\mathcal{F}) + \tfrac{\mathcal{A}^2}{\bar{L}^2}(\mathcal{B}+\mathcal{C})(6\mathcal{A}-4\mathcal{D}-2\mathcal{E}) + 2\mathcal{A}(\mathcal{B}+\mathcal{C})^2\\ -(\mathcal{B}+\mathcal{C})^2(2\mathcal{D}+\mathcal{E}) > 0\end{split} \tag{A.31}$$

   $$3\tfrac{\mathcal{A}^3}{\bar{L}^2}(\mathcal{C}+\mathcal{F}) + \tfrac{\mathcal{A}^2}{\bar{L}^2}(\mathcal{B}+\mathcal{C})(6\mathcal{A}-2\mathcal{D}-\mathcal{E}) + 2\mathcal{A}(\mathcal{B}+\mathcal{C})^2 > 0 \tag{A.32}$$

   $$3\tfrac{\mathcal{A}^3}{\bar{L}^2}(2\mathcal{B}+3\mathcal{C}+\mathcal{F}) - \tfrac{\mathcal{A}^2}{\bar{L}^2}(\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E}) + 2\mathcal{A}(\mathcal{B}+\mathcal{C})^2 > 0. \tag{A.33}$$

   This inequality holds as all terms are positive by definition of the case we are dealing with.

4. $\mathcal{B} + \mathcal{C} < 0$ and $2\mathcal{B} + 3\mathcal{C} + \mathcal{F} < 0$
   In this case, U is negative, V and W are positive, X is negative, Y is positive, and finally Z is negative. To prove the existence of a unique maximum of $c(w)$, we first show that $V + W + X + Y + Z > 0$ holds along the entire relevant interval $x \geq 1$. $V + W + X + Y + Z > 0$ can be written as

   $$\mathcal{O} + \mathcal{P} > 0, \tag{A.34}$$

   whereas

   $$\mathcal{O} = -3x^3\tfrac{\mathcal{A}^3}{\bar{L}^2}(2\mathcal{B}+3\mathcal{C}+\mathcal{F}) + 4x^2\tfrac{\mathcal{A}^3}{\bar{L}^2}(\mathcal{C}+\mathcal{F}) + 6x^2\tfrac{\mathcal{A}^3}{\bar{L}^2}(\mathcal{B}+\mathcal{C}), \tag{A.35}$$

   $$\begin{split}\mathcal{P} =& -x^2\tfrac{\mathcal{A}^2}{\bar{L}^2}(\mathcal{B}+\mathcal{C})(4\mathcal{D}+2\mathcal{E}) + x\mathcal{A}(\mathcal{B}+\mathcal{C})(2\mathcal{B}+3\mathcal{C}+\mathcal{F}) +\\ &+x^2\tfrac{\mathcal{A}^3}{\bar{L}^2}(\mathcal{C}+\mathcal{F}) + (\mathcal{B}+\mathcal{C})\big(\mathcal{A}(\mathcal{C}+\mathcal{F}) - (\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E})\big).\end{split} \tag{A.36}$$

   By showing that $\mathcal{O} > 0$ and $\mathcal{P} > 0$ we prove the inequality. The only negative term in $\mathcal{O}$ is the last one. As it has the lowest exponent of x, it is sufficient to show that $\mathcal{O} > 0$ holds for $x = 1$:

   $$\frac{\mathcal{A}^3}{\bar{L}^2}(\mathcal{C}+\mathcal{F}) > 0. \tag{A.37}$$

The inequality clearly holds.

Analysing $\mathcal{P}$ we observe that only the last term with the lowest exponent of x is negative. Hence, again, it is sufficient to show that $\mathcal{P} > 0$ for $x = 1$ to prove that it holds for all $x \geq 1$. Setting $x = 1$ yields

$$\begin{aligned} &\tfrac{\mathcal{A}^3}{\bar{L}^2}(\mathcal{C}+\mathcal{F}) - \tfrac{\mathcal{A}^2}{\bar{L}^2}(\mathcal{B}+\mathcal{C})(4\mathcal{D}+2\mathcal{E}) + \mathcal{A}(\mathcal{B}+\mathcal{C})(2\mathcal{B}+3\mathcal{C}+\mathcal{F}) + \\ &\qquad (\mathcal{B}+\mathcal{C})\big(\mathcal{A}(\mathcal{C}+\mathcal{F}) - (\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E})\big) > 0. \end{aligned} \tag{A.38}$$

Estimating the LHS from below by using Assumption 1, the inequality reduces to

$$\begin{aligned} &-\tfrac{\mathcal{A}^2}{\bar{L}^2}(\mathcal{B}+\mathcal{C})(4\mathcal{D}+2\mathcal{E}) + \mathcal{A}(\mathcal{B}+\mathcal{C})(2\mathcal{B}+3\mathcal{C}+\mathcal{F}) \\ &\qquad -(\mathcal{B}+\mathcal{C})^2(2\mathcal{D}+\mathcal{E}) > 0, \end{aligned} \tag{A.39}$$

$$-\tfrac{\mathcal{A}^2}{\bar{L}^2}(\mathcal{B}+\mathcal{C})(2\mathcal{D}+\mathcal{E}) + \mathcal{A}(\mathcal{B}+\mathcal{C})(2\mathcal{B}+3\mathcal{C}+\mathcal{F}) > 0. \tag{A.40}$$

It is clear that the inequality holds considering the case we are dealing with.

Hence, we can now state the validity of $V + W + X + Y + Z > 0$ along the entire relevant interval. Furthermore, we know that U is negative and has the highest exponent of x. Thus in this case too, $c(w)$ either falls continuously or rises first to reach a maximum and falls subsequently.

B Calibration

In this appendix, we provide some further details on the calibration. All moments refer to average 5-year centered moving averages across all OECD-member states with available data in 2010.[34]

$\bar{L}$ is chosen to match the average share of the population with tertiary education of $\sim 30\%$ in the data. With our normalization for unskilled labor, we therefore require:

$$\frac{\bar{L}}{1+\bar{L}} = 0.3\ , \tag{B.1}$$

which implies $\bar{L} = \frac{3}{7}$.

μ is chosen to capture that the average manufacturing share in GDP is roughly $\frac{1}{6}$. Noting that in our model the share of intermediates in aggregate income is $\frac{1}{2}$ we therefore set $\mu = \frac{1}{3}$.[35]

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[34] Hence, the set of countries is not the same in all cases. The calibration and our illustrations in section 3 would qualitatively be the same when using the subset of OECD member states with data on all moments.

[35] Strictly speaking, this ignores our simplifying assumption that the industry structure is different for services when compared to manufacturing. Note, however, that taking into account this assumption

γ determines the growth of the world technological frontier in our model which drives long-run growth. In particular, the production function for final goods (1) along with $\alpha = \frac{1}{2}$ implies that with a constant state-distribution of intermediate sectors and constant basic research policies the economy grows at a rate $\sqrt{\gamma}$. In our model, basic-research investments are considered for each generation, so it is convenient to think of a period as comprising several years. This is also consistent with the fact that basic research exhibits major time lags between investment and its effect on productivity (e.g. Adams 1990 or Mansfield 1998). We therefore choose $\gamma = 1.5$ which implies a per-period growth rate of $\sim 22\%$, which corresponds to the average 10-year growth rate of GDP per capita in our sample over the past 25 years.

To calibrate λ, which captures the use of foreign-owned state-of-the-art technologies in our model, we require that associated profits match the average share in GDP of outward royalty payments for foreign-owned intellectual property such as technologies, industrial processes, prototypes, and trademarks as observed from World Bank (2017). To achieve this, note first that with $\alpha = \frac{1}{2}$ the share in GDP of profits by state-1 firms is given by:

$$s_1 \pi_{x1} = \frac{1}{2} R_{x1} s_1 \ , \tag{B.2}$$

where R_{x1} denotes revenues of a representative state-1 firm. Further, total share in GDP of intermediates is $\frac{1}{2}$, implying that

$$y = 2 \left[s_1 R_{x1} + s_2 R_{x2} + (s_3 + 1 - \mu) R_c \right] \ . \tag{B.3}$$

Using the relationships between R_{x1}, R_{x2}, and R_c as derived in footnote 35, and the expressions for s_1, s_2, s_3 given in (9), we therefore get for the share in GDP of profits

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would barely affect the calibration. To see this, note that skilled labor being the only input in intermediate-good production and (6) imply for the revenues of a competitive firm, $R_{xc}(i)$:

$$R_{xc}(i) = \alpha^{\frac{1}{1-\alpha}} w^{-\frac{\alpha}{1-\alpha}} A(i)^{\frac{\alpha}{1-\alpha}} \ .$$

Similarly, (7) and (8) imply, after some straightforward algebra, for the revenues of a monopolist, $R_{xm}(i)$:

$$R_{xm}(i) = \alpha^{\frac{1}{1-\alpha}} w^{-\frac{\alpha}{1-\alpha}} A(i)^{\frac{\alpha}{1-\alpha}} \alpha \ .$$

Now, let A_{xc} denote the technology of a competitive firm. Then, the technology of a type 1 monopolist is $A_{x1} = \gamma^2 A_{xc}$ while the technology of a type 2 monopolist is $A_{x2} = \gamma A_{xc}$. With $\alpha = \frac{1}{2}$, we therefore get for their revenues:

$$R_{x1} = \gamma^2 \alpha R_{xc}$$
$$R_{x2} = \gamma \alpha R_{xc}$$

At the beginning of the period, $\frac{3}{4}$ of monopolists are type 1. With the calibration for γ (cf. below), the weighted revenue of monopolists is then approximately equal to the revenue of a competitive intermediate firm:

$$\frac{3}{4} \gamma^2 \alpha + \frac{1}{4} \gamma \alpha \approx 1 \ .$$

by state-1 firms:

$$\frac{s_1 \pi_{x1}}{y} = \frac{\gamma^2 \alpha \mu \tilde{s}_1}{4\left[\gamma^2 \alpha \mu \tilde{s}_1 + \gamma \alpha \mu \tilde{s}_2 + 1 - \mu + \mu \tilde{s}_3\right]} \ . \tag{B.4}$$

A fraction λ of these profits accrues to the foreign-owned firms so we choose lambda such that:

$$\lambda \frac{s_1 \pi_{x1}}{y} = 0.011 \ , \tag{B.5}$$

where 0.011 are the average outward royalty payments as a share of GDP in our sample. Solving for λ yields $\lambda \approx 0.2$.

We calibrate σ such that foreign entry in our model is consistent with FDI inflows which amount to around 4.5% of GDP in our sample of countries. Mapping FDI inflows in the data to our model requires some auxiliary assumptions. Note first that FDI payments should not exceed the present value of future associated earnings. Assuming that $\frac{1}{2}$ of this net present value of profits accrues in the period under consideration implies that at least 2.25% of GDP are profits of foreign entrants.[36] According to our model, overall profits account for 50% of output by monopolistic manufacturing firms, i.e. foreign entrants must account for $\sim$ 4.5% of GDP or, equivalently, $\sim$ 27% of manufacturing output. We therefore choose $\sigma = 0.3$ as an approximation.[37] Note that different choices for σ would not change the qualitative results or the qualitative content depicted in the illustrations in the main text.

Finally, to calibrate θ, we require that the optimal choice of basic research by the government is $L_B \approx 0.0036$. This value reproduces a share of GDP devoted to basic research that is close to 0.36%, which constitutes the average share of basic research in GDP in our sample in 2010. To see this, remember that with $\alpha = \frac{1}{2}$ the share of intermediates in aggregate output is $\frac{1}{2}$, i.e. we have

$$y = 2\left[s_1 R_{x1} + s_2 R_{x2} + (1 - \mu + s_3) R_c\right] \ . \tag{B.6}$$

In turn, aggregate revenues of intermediate producers are equal to wages paid to skilled labor plus profits of monopolistic firms. Considering the profit margin of 50% and noting that the weighted average revenue of a monopolistic intermediate firm is approximately equal to a competitive intermediate firm (footnote 35), this implies for

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[36] As noted before, we think of one period as comprising several years. With a period length of 10 years, a constant income stream, and investments taking place at the beginning of each period, a annual discount rate of $\sim$ 7.2% implies that 50% of the total net present value of the investment accrue in the first 10-year period.

[37] There are several opposing forces that might lead to different specifications: On the one hand, not all domestic firms are at the frontier, which in turn implies that foreign entrants capture a disproportionate share of revenues, and FDI inflows in the data may reflect some inflows into sectors with low research-driven innovation as well. On the other, not all potential foreign entrants are successful due to the 'escape entry effect' associated with innovation by domestic technology leaders, and foreign investors in the data may have shorter planning horizons or strong bargaining positions such that actual investments are less than the present value of future associated earnings.

aggregate spending on intermediates

$$
\begin{aligned}
s_1 R_{x1} + s_2 R_{x2} + (1-\mu+s_3) R_c &= w\bar{L} + \frac{1}{2}\left[s_1 R_{x1} + s_2 R_{x2}\right] \\
&\approx w\bar{L} + \frac{1}{2}\left[s_1 + s_2\right]\left[s_1 R_{x1} + s_2 R_{x2} + (1-\mu+s_3) R_c\right] \\
&= w\bar{L} + \frac{s_1 + s_2}{4} y \ , \qquad \text{(B.7)}
\end{aligned}
$$

and hence y

$$y \approx \frac{2w\bar{L}}{1 - \frac{s_1+s_2}{2}} \ . \qquad \text{(B.8)}$$

We therefore get for the share in GDP of basic research investments[38]

$$\frac{L_B w}{y} \approx \frac{L_B\left[1 - \frac{s_1+s_2}{2}\right]}{2\bar{L}} \ . \qquad \text{(B.9)}$$

Using the targeted basic research intensity along with the other parameter values and solving for L_B, we get $L_B \approx 0.36\%$. We solve numerically for θ to meet this optimal investment, which implies $\theta \approx 11.75$.

C Data Appendix

In this appendix, we provide further details on the construction of the various variables used in our empirical analysis of Section 4.

The dependent variable and variables 'M: $\frac{\text{manufacturing}}{\text{GDP}}$', 'D: $\frac{\text{GDP p cap}}{\text{US GDP p cap}}$', 'FO: $\frac{\text{payments to abroad}}{\text{GDP}}$', 'O: $\frac{\text{inward FDI}}{\text{GDP}}$', 'M: economic complexity', 'D: patents per cap', 'O: FDI indicator', 'FO: $\frac{\text{royl payments}}{\text{GDP}}$', and 'FO: $\frac{\text{outw FDI income}}{\text{GDP}}$' have already been detailed in the main body of the text.

For the construction of the remaining variables, we first summarize any industry-level data used as follows:

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[38] Output of or wages paid to basic researchers are typically accounted for when computing GDP in practice. Considering the small share of the overall labor force employed in basic research, we ignore this effect here.

Table 3: Overview of industry aggregation

code	description
C10T14	Mining and quarrying
C15T16	Food products, beverages and tobacco
C17T19	Textiles, textile products, leather and footwear
C20T22	Wood, paper, printing, publishing
C23	Coke, refined petroleum products and nuclear fuel
C24	Chemicals and chemical products
C25	Rubber and plastics products
C26	Other non-metallic mineral products
C27	Basic metals
C28	Fabricated metal products, except machinery and equipment
C29	Machinery and equipment, nec
C30	Office, accounting and computing machinery
C31	Electrical machinery and apparatus, nec
C32	Radio, television and communication equipment
C33	Medical, precision and optical instruments
C34	Motor vehicles, trailers and semi-trailers
C35	Other transport equipment
C36T37	Manufacturing n.e.c. and recycling
C40T41	Electricity, gas and water supply
C45*	Construction*
C60T64*	Transport, storage and communications*
C70T74*	Real estate, renting and business activities*
C50T99X*	Other services*

Notes: A superscript star indicates industries with no patent data.

The level of aggregation is a compromise between level of detail of our measures and data available. We subsequently use $\mathcal{I}$ to denote the set of these industries and i to identify an element of this set.

To construct an industry-weighted measure of a country's distance from the frontier, we consider for each industry and period its output per employee relative to US output per employee using industry-level data on gross output and employment taken from OECD (2017c). We then form a weighted sum of these measures over industries, where weights are given by the country's output shares across industries:

$$\text{D: outp-w rel productivity(c,t)} = \log\left(\sum_{i\in\mathcal{I}} \frac{output_{c,t,i}}{\sum_{i\in\mathcal{I}} output_{c,t,i}} \frac{\frac{output_{c,t,i}}{employment_{c,t,i}}}{\frac{output_{USA,t,i}}{employment_{USA,t,i}}}\right) . \quad \text{(C.1)}$$

For our alternative measures of a country's manufacturing base, we first construct time-invariant measures of the research-driven innovativeness of industries. We consider two such measures: 'global' applied research investments in a given industry over 'global' output in that industry which is an input-based measure that we derive from OECD (2017c) and OECD (2017d). And second 'global' patents in a given industry over 'global' output that we derive from OECD (2017c) and OECD (2017b).[39] In both cases, we compute 'global' measures by summing over all countries with data on the respective measures in all industries in year 2007, and where we consider 5-year centered moving averages to smooth short-run fluctuations and to increase the set of countries covered.[40] We then form for each country and year a weighted sum of these measures across industries, with weights again been given by a country's output share across industries:

$$\text{M: outp-w AR intensity(c,t)} = \log\left(\sum_{i\in\mathcal{I}} \frac{output_{c,t,i}}{\sum_{i\in\mathcal{I}} output_{c,t,i}} \frac{AR_{WLD,07ma,i}}{output_{WLD,07ma,i}}\right) \tag{C.2}$$

$$\text{M: outp-w pat intensity(c,t)} = \log\left(\sum_{i\in\mathcal{I}} \frac{output_{c,t,i}}{\sum_{i\in\mathcal{I}} output_{c,t,i}} \frac{patents_{WLD,07ma,i}}{output_{WLD,07ma,i}}\right) \tag{C.3}$$

Finally, to construct our integrated measures of economic development and the manufacturing base, we combine the previously described measures of research-driven innovativeness of an industry with our industry-measure of distance from the frontier:

$$\text{DM: outp-}\times\text{-rel-prod-w AR int(c,t)} =$$

$$\log\left(\sum_{i\in\mathcal{I}}\left[\frac{output_{c,t,i}}{\sum_{i\in\mathcal{I}} output_{c,t,i}} \frac{AR_{WLD,07ma,i}}{output_{WLD,07ma,i}} \frac{\frac{output_{c,t,i}}{employment_{c,t,i}}}{\frac{output_{USA,t,i}}{employment_{USA,t,i}}}\right]\right) \tag{C.4}$$

$$\text{DM: outp-}\times\text{-rel-prod-w pat int(c,t)} =$$

$$\log\left(\sum_{i\in\mathcal{I}}\left[\frac{output_{c,t,i}}{\sum_{i\in\mathcal{I}} output_{c,t,i}} \frac{patents_{WLD,07ma,i}}{output_{WLD,07ma,i}} \frac{\frac{output_{c,t,i}}{employment_{c,t,i}}}{\frac{output_{USA,t,i}}{employment_{USA,t,i}}}\right]\right) \tag{C.5}$$

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[39] We use the inventors' country and the priority date to measure patents by country and year.

[40] We use data for year 2007 here as data in OECD (2017c) is available until 2009 only.

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